MODELLING DEPRESSIONAL STORAGE AND PONDING IN A CANADIAN PRAIRIE LANDSCAPE

by

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DECLARATION OF ORIGINALITY OF WORK

I hereby declare that this dissertaion represents my own work and where the work of others has been used it is duly acknowledged.

September 5, 1994

.....

Date

The undersigned certify that they have read and recomend to the Faculty of Social Sciences acceptance of the thesis cited above.

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signed: Dr. Neil Stuart Date

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signed: Prof. Dr. P. A. Burrough Date

External Examiner (University of Utrecht)

ABSTRACT

There is a need for accurate information on patterns of distribution of surface water in agricultural landscapes in western Canada. Artificial drainage on agricultural land has become widespread as farmers attempt to maximize their available land and minimize obstacles to efficient cultivation. There is a shortage of appropriate methods for describing, analysing and simulating the flow of surface water and its accumulation in shallow closed depressions in agricultural landscapes. Such capabilities are increasingly needed to assess the benefits and impacts of both on- and off-farm drainage. The goal of the present study is therefore to develop and test procedures to quantify the capacity to store runoff in depressions in agricultural landscapes and to estimate the extent to which this depressional storage is filled at any given time.

Analyses of the conditions controlling runoff were conducted at a single site characterised by low relief, glaciated terrain and a non-integrated drainage system. Field measurements of soil hydrological properties and observed ponding were collected for the farm-scale site during a period of spring snow melt and runoff in 1989. Automated extraction of geomorphological features from digital elevation data was used to delineate the location, extent and maximum volume of all depressions and to establish the sequence in which they would be expected to fill, overspill and drain. A highly-distributed, physically-based hydrological model (DISTHMOD) was assembled and used to simulate runoff and ponding for the selected site for the same period.

Field studies confirmed that the formation of shallow ponds in the spring was almost wholly related to rapid melting of snow and surface runoff of snowmelt. Runoff was observed to collect in all depressions of any significant size. Ponds less than 40 cm deep disappeared by mid June through a combination of evaporation and infiltration. Ponds greater than 40 cm deep generally persisted throughout the summer. Such ponds occupied lower positions in the landscape and most were in contact with a water table.

Procedures for geomorphological analysis were successful in documenting the maximum size, depth and volume of all depressions. They established hydrological inter-connectivity between depressions and coped with a hierarchy of multiple nested depressions. They are amenable to full automation and could represent an

improvement over current semi-quantitative methods of describing depressional storage and potential ponding at a farm scale in Alberta.

Simulations of surface runoff and ponding using the DISTHMOD model replicated observed patterns of pond location and depth when provided with input data based on field measurements. Depth of snow was the critical input variable as it determined the magnitude of potential runoff. Variation in the spatial pattern of snow depth affected the timing of runoff and pond formation but had little influence on maximum simulated pond volume. Simulated estimates were only similar to observed data if frozen soils were assumed to inhibit infiltration and lead to overland flow. Estimates of pond decay were similar to the observed pattern only where both infiltration and evaporation were simulated at appropriate rates immediately following initial formation of the ponds.

The analytical modelling procedures represent a first step towards the development of a suite of tools for quantitative analysis of surface runoff and ponding in agricultural landscapes with low relief and non-integrated drainage. The explicit recognition of depressions and the procedures for simulating the filling and decay of depressions represent an advance over most current models.

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CHAPTER 1

INTRODUCTION:

THE CASE FOR MEASURING AND MODELLING DEPRESSIONAL STORAGE AND EPHEMERAL PONDING AT A FARM SCALE

1.1 Overall aim of the research

This study analyses the flow and accumulation of surface water runoff, at a farm scale, in an agricultural landscape of low relief. The primary data sources are a detailed digital elevation model, hourly meteorological data for a period of spring melt and soil characterisation data for a single study site in western Canada. The goal is to develop and test procedures to quantify the capacity to store runoff in depressions in agricultural landscapes of low-relief in glaciated terrain and to estimate the extent to which this depressional storage is occupied at any given time.

The study differs considerably in emphasis from most previous efforts at hydrological modelling or landscape characterisation utilising digital elevation data. In the past, digital elevation data has usually been processed to define integrated drainage networks in areas of high relief (Band, 1989a). These were used to provide topological partitioning of watersheds for descriptive purposes (Band, 1986a,b; Lammers and Band, 1990) or for distributed modelling of rainfall runoff (Band and Wood, 1988; Johnson, 1989). Most hydrological modelling has been aimed at producing an estimate of the unit hydrograph for channel flow at some point in the channel network (Bathurst, 1986a; Beven, Kirkby, Schofield and Tagg, 1984). The present study has as its focus an analysis of the flow and accumulation of runoff in non-integrated drainage systems in glaciated landscapes of low-relief. The procedures used involve delineation of all closed depressions of significant size and establishment of the sequence and timing in which they fill up, overspill and drain. This information is needed for assessing the possible benefits and impacts of both on and off-farm drainage of surface water in agricultural areas of western Canada.

1.2 Background

The study arose from a recognized need for better information on patterns of surface water distribution and re-distribution in agricultural landscapes in western Canada. Difficult economic conditions and changes in agricultural machinery have caused farmers to become increasingly interested in draining wetlands (Alberta Water Resources Commission (AWRC), 1987). At the same time, public concern has grown about possible adverse affects of agricultural land drainage, including loss of wildlife habitat and adverse downstream impacts (AWRC, 1987).

The practice of artificial drainage of small bodies of surface water on agricultural land has recently become quite widespread as farmers attempt to maximize their land resource and minimize obstacles to uniform and efficient cultivation. This is, in part, a reflection of the difficult economic conditions facing agriculture which force farmers to attempt every possible efficiency. It is also related to increasing size and power of farm implements which make cultivation through, rather than around depressions more attractive.

1.3 Problems associated with water accumulation in prairie potholes

Shallow undrained depressions are very common in glaciated landscapes in agricultural regions of western Canada. They play an important role in surface water hydrology and are significant from both ecological (Cooch, 1969; Smith et al., 1964) and agricultural perspectives (AWRC, 1987). Such depressions have been referred to as "prairie potholes" (Smith, Stoudt and Gollop, 1964; Crissey, 1969; Stewart and Kantrud, 1969), ephemeral ponds, sloughs, closed depressions, kettles, non-permanent wetlands (AWRC, 1987) and pits (Jenson and Trautwein, 1987). The term depression is adopted by the present study to encompass all of the above usages. The term depression carries no inferences about relative permanence, size, origin or shape. Other terms appear in the present document where there is a requirement to refer to or discuss the work of other authors using their preferred terminology.

It has been recently estimated (AWRC, 1987) that there are approximately 12 million acres of wetlands in the agricultural area of Alberta of which 2 million acres are non-permanent. Non-permanent wetlands in shallow depressions in good agricultural areas are recognized to have the highest potential for artificial drainage.

From the farmers' perspective, prairie potholes are undesirable obstacles that reduce productivity and increase production costs (Figure 1.1a,b). Recent studies (Leskiw, 1987; Anderson, 1987) have confirmed this perception. Artificial drainage of non-permanent water bodies increases productivity by:

- increasing the total area under cultivation,
- improving crop quality due to reductions in weed growth, lodging and frost risk, and
- increasing flexibility and opportunity in timing and management of farming operations.

Similarly, drainage lowers production costs by simplifying field patterns and increasing working efficiency as well as by reducing overlap area for operations such as tillage, seeding, fertilizing and spraying. If costs for off-farm drainage and wildlife habitat mitigation are not assessed against individual farmers, net financial benefits can be up to 45 dollars per acre per year (AWRC, 1987). It is not surprising then that individual farmers find it financially attractive to drain non-permanent wetlands.

From the perspective of society at large, drainage of non-permanent wetlands has a net negative impact. This negative impact arises from high costs for off-farm drainage control programs and for wildlife habitat mitigation (AWRC, 1987). Agricultural land drainage can have a catastrophic impact on wildlife. For instance, drainage of non-permanent wetlands for just the five principal northern river basins in Alberta could result in losses of up to 9.1 million ducks or 54% of the total provincial duck population (AWRC, 1987).

Programmes for the conservation of migratory waterfowl run by Ducks Unlimited for the North American Waterfowl Management Plan (Koeln, Caldwell, Wesley and Jacobson, 1986; Koeln, Jacobson, Wesley and Rempel, 1988; Rude, 1987), have designated wetlands in the prairie pothole regions of Alberta and Saskatchewan as the Primary Waterfowl Production Area (PWPA) for North America (Koeln et al., 1988). In a typical year, more than 50% of all breeding ducks in North America nest in this region, which comprises less than 10% of the breeding range of waterfowl in North America (Crissey, 1969; Koeln et al., 1988). It has been estimated (EOSAT, 1987) that up to 50% of the original 200 million acres of waterfowl habitat in existence in the United States in the late 1700's has been lost since settlement and that annual habitat

losses are currently running at close to 500,000 acres per year. Losses of a similar magnitude are reported for the Canadian prairies (EOSAT, 1987). Unrestricted drainage of wetlands for agricultural use is therefore viewed as an undesirable activity from the perspective of wildlife conservation.

The recent Alberta drainage study determined that net present values of drainage were, from a social perspective, negative for every basin studied (AWRC, 1987). Drainage of non-permanent wetlands was concluded to be economically feasible only if wildlife mitigation costs were not considered. One consequence of this conclusion is that the concept of on-farm water management has become the approach preferred by regulatory agencies for dealing with excess surface water on agricultural land. The goal of on-farm water management is to redistribute excess surface water within each individual farm parcel in such a way as to reduce impediments to cultivation while simultaneously maintaining or enhancing waterfowl habitat. Redistribution within the parcel aims to prevent any increase in runoff from the parcel with its attendant, potentially negative, downstream impacts. To date, there are no suitable tools for assessing the potential impacts of redistribution prior to its implementation. Considerable interest has therefore been shown in utilizing a suitable hydrological runoff model to simulate the likely effects of redistributing ponded water within individual farm parcels. To date, no suitable model has been identified.

1.4 The case for this study

A review of pertinent literature identifies the following points to be made in justifying this study:

1. There is a growing recognition in Alberta, and indeed worldwide, of the need for improved farm-scale models and tools for assisting with the management of surface water.
2. There is a growing body of academic opinion suggesting that the issues of emerging concern in hydrology require the use of distributed, physically-based, models capable of managing spatially variable inputs and results.
3. There is a counter argument that cautions against the over-optimistic application of complex, physically-based models for predictive purposes.
4. There is widespread agreement that topography should be used as the starting point for distributed hydrological modelling.

5. There is almost universal agreement on the need to link theoretical modelling with field studies and to test theoretical simulations against independent (and spatially distributed) field data.
6. There is general recognition of the need to model at the basin or sub-catchment scale to address practical needs. This is complicated by the discrepancy between the scale at which theoretical understanding of water movement is understood and mathematically described and the (catchment) scale at which modelling is required.
7. There is an ongoing need to improve the quality of understanding of our environment and our skills for managing it.

1.4.1. The requirement for farm-scale hydrological models in Alberta

In the local Alberta context, support for this research has been provided by the recently completed study of Drainage Potential in Alberta (AWRC, 1987). It included the following among its major policy level recommendations:

- Drainage planning should be initiated at a small watershed scale within the context of multi-purpose land use planning.
- Hydro-technical modelling is required to estimate runoff conditions, especially related to farm size drainage projects
- The potential benefits of on-farm management of drainage water warrant further research.
- The productivity potential and optimal management of drained, non-permanent wetlands should be investigated.

The present study focuses on farm scale modelling of runoff with a view to providing a tool for planning, managing and assessing the potential benefits and impacts of farm scale water management.

Companion hydrologic programs carried out in support of the above policy study produced similar, but more detailed and technically specific, recommendations. Some of the major technical recommendations (W-E-R, 1987) were as follows:

- An agricultural runoff research project should be established, and properly instrumented, to collect rainfall, snowfall, temperature, hours of sunshine

and runoff information in order to provide baseline data for Alberta agricultural runoff conditions.

- More detailed hydrologic simulation modelling of an individual field/farm size project should be undertaken, using a detailed field-scale hydrological model.
- A field-scale program should be undertaken to determine areas and depths of specific wetland types more accurately. This may lead to the development of regionalized predictive equations for wetland surface area, depth and volume relationships.
- Further analysis should be undertaken to determine the effects of spring snowmelt/rain runoff events on agriculture in Alberta.
- The estimation of depressional storage volume should be more accurately calibrated by field checks and contour mapping.

Most of these recommendations are addressed to some extent by the present research. The results from this project provide baseline data on Alberta agricultural runoff conditions. They involve detailed hydrological simulations at the field/farm scale. They provide an assessment of surface area, depth, and volume relationships for one class of wetland type and accurately determine depressional storage volume for one farm-scale area. Finally, the study provides an assessment of the possible effects of spring snowmelt and snowmelt/rainfall runoff events in an agricultural context in Alberta.

1.4.2 Academic support for use of distributed, physically-based models

In the wider, academic context, there has been a growing interest in the development, calibration and field testing of distributed hydrologic simulation models (Anderson and Rogers, 1987; Dunne, 1983; Abbott et al., 1986a,b; Bathurst, 1986a,b). Existing lumped, conceptual models are widely agreed to be adequate for predicting basin outflow in terms of the unit hydrograph (Dunne, 1983; Al Soufi, 1987; Beven, 1989; van de Griend and Engman, 1985; Abbott et al., 1986a). Lumped parameter models have been criticised, however, in that curve-fitting procedures involved in calibration can make physical interpretation of the fitted parameter values very difficult (Dunne, 1983; Abbott et al., 1986a). In addition, there is a growing realization that many emerging hydrological issues have a strong spatial component and require spatially

referenced output (Dunne, 1983; Quimpo, 1984; Beven et al., 1980; van de Griend and Engman, 1985).

It has been argued that today's range of hydrological problems require " a more realistic picture of runoff conditions within drainage basins than can be obtained from lumped parameter models" (Dunne, 1983). Dunne (1983) cites, as an example, the need to predict sediment loss, water quality and landform evolution on hillslopes or entire drainage basins. Abbott et al. (1986a) agreed that conventional rainfall runoff models are inappropriate for studies of "the spatially variable effects of land use change related to agriculture and forestry practices, hazards of pollution and toxic waste disposal or general problems arising from the conjunctive use of water". Further support comes from van de Griend and Engman (1985) who argued that "optimum profit from physically-based distributed modelling is to be expected if the model is applied for the prediction of hydrological effects of localized land use changes, the consequences of spatially variable inputs and outputs, or the movement of pollutants or sediments". This enthusiasm for physically-based, distributed models is well illustrated by Anderson and Rogers (1987) who concluded that such models represented " a major turning point in hydrological research".

These arguments support the use of a distributed approach for modelling runoff at the farm scale as used in this study. Since agricultural drainage is a dramatic land use change, the modelling carried out for this study aims to provide a tool to quantify "the spatially variable effects of land use change" as recommended by Abbott et al. (1986a).

1.4.3 Reservations regarding the use of physically-based models

Beven (1989) has "questioned the widely held belief that physically-based models are in some sense superior to lumped conceptual models". He cautioned against uncritical use of such models and noted that "many of the theoretical advantages of physically -based models remain unproven in practice". He observed that there are two main aims of simulation models, namely;

a) To explore the implications of making certain assumptions about the nature of the real world system, and
b) to predict the behaviour of the real world system under a set of naturally occurring circumstances.

Beven (1989) supported the use of physically-based models for the first aim, that of improving understanding. He argued, however, that there are fundamental problems in the application of physically-based models for practical prediction in hydrology. This caution was echoed by Burt (1986) and by Loague and Freeze (1985). The advantages and disadvantages of physically-based models are explored in greater detail in Chapter 5. For the present it is sufficient to note that highly distributed hydrological models might benefit from simplified conceptual approaches to the definition of flow processes at the grid scale in place of rigorous mathematical approaches based on point scale process equations (Dooge, 1988).

1.4.4 Topography as the basis for distributed hydrological modelling

Hydrological research has consistently demonstrated the importance of topography in controlling rainfall runoff (Dunne and Black, 1970a,b; Dunne, Moore and Taylor, 1975; Kirkby, Callen, Weyman and Wood, 1976; Beven, 1978; Beven and Wood, 1983; Burt and Butcher, 1985). Despite this recognition, Beven et al. (1984) observed that "many hydrological models make little use of topographic and soil information, even though both are important in determining source areas". Similarly, Anderson and Rogers (1987) noted that "topographic controls have been subordinate to vegetation and soil information in source area models to date, despite the relative ease of measuring and including topographic information in models". They concluded that greater attention needed to be paid to explicit representation of topography and argued that "the most appropriate starting point for distributed model design relates to topographic representation of the catchment" (Anderson and Rogers, 1987).

A large number of researchers have approached the problem of spatial representation of runoff modelling from an essentially topographic or geomorphic view (Band, 1985, 1986a; Jenson, 1985; Jenson and Domingue, 1988; Silfer, Kinn and Hassett, 1987). This approach generally avoids efforts to represent mathematically the main physical processes active in runoff generation. Instead, modelling efforts are concentrated on establishing the spatial pattern of surface runoff as controlled by topography.

In most cases, these geomorphic models adopt a greatly simplified view of the physical processes governing runoff generation. Most runoff is viewed as arising from infiltration excess or saturation excess overland flow. Few attempt to model the

physical processes known to be active in the actual generation of rainfall runoff (specifically rainfall, interception, infiltration, evapo-transpiration, sub-surface flow or return flow). This simplification permits modelling of likely spatial patterns of rainfall runoff over much larger areas at much higher scales of resolution than can currently be managed with complex, process-oriented, physically-based distributed models. Concentration on the locations of rainfall runoff involves a restriction in the ability to predict the timing of runoff events.

Despite widespread practical recognition of the importance of topographically controlled depressions or "pits" in the hydrology of prairie landscapes (Koeln, Caldwell, Wesley and Jacobson, 1986; Cooch, 1969; Crissey, 1969; Smith et al., 1964), there are very few examples of hydrological models capable of explicitly recognizing "pits" or of simulating the flow of surface water into, through and out of depressions. A few 'lumped models' embrace the idea of 'depressional storage' as an adjustable attribute of conceptual watersheds (JNM, 1986). These lumped models treat depressional storage as a model coefficient which can be used to adjust the 'effective drainage area" (ibid., 1986) or variable source area (Dunne and Black, 1970a,b) for model calibration. A few geomorphic modellers have recognized and defined the extent of depressional storage using high resolution digital elevation data (Jenson and Trautwein, 1987; Jenson and Domingue, 1988; Yuan and Vanderpool, 1986). Generally this has been done in order to remove 'aberrant pits' from the data set (Hutchinson, 1989), to create integrated drainage networks for subsequent simulation of runoff rather than to support explicit modelling of flow into and through depressions.

1.4.5 Linking theoretical modelling and field studies.

A number of authors have argued forcefully for the need to link theoretical modelling with field studies (Dunne, 1983; Dooge, 1988; Anderson and Rogers, 1987; Beven, 1989). Dunne (1983) felt that "the value of theoretical models would be greatly enhanced if they are developed in close cooperation with field studies". Conversely, field experiments and data collection programs needed " to be designed in the light of rigorous, physically-based models" (Dunne, 1983). Anderson and Rogers (1987) reinforced the argument of Dunne (1983) stressing "the need for field data to correspond to model requirements" and the need for "current and future field work to be driven from modelling needs".

Beven (1989) remarked that studies attempting to compare the predictions of physically-based models with detailed hydrologic response data were rare. He also believed that "any application in which physically correct predictions are considered important must involve close cooperation between field observation and modelling" (Beven, 1989). He recommended that the application of physically-based models be carried out in conjunction with a program of field measurements, to ensure consistency between model predictions and real world processes.

Dooge (1988) observed that "unfortunately, too many hydrologists have concerned themselves with elaboration of models and with fitting them to data rather than with their objective validation". He criticised "the use of whole data series for calibration of the model and then reproduction of a figure which claims to show the excellent representation of the data by the model" (Dooge, 1988).

The present study addresses the issue of model validation by performing a runoff simulation based on detailed field data and then comparing the results of that simulation with other, independently observed field data, not used in the model construction or calibration.

One of the anomalies of many studies using physically-based, spatially-distributed, models is that the main form of output, and the measure by which the success of the model is judged, is the non-spatial unit hydrograph. The simulated hydrograph provides an estimate of the rate of flow through time at a single point in the catchment (usually the watershed outlet). If the main point is to simulate hydrograph output, then any number of lumped parameter models might suffice. It would seem reasonable to adopt the use of distributed models when some notion of the spatial pattern of hydrologic output is required.

Beven (1989) has noted that "comparison of predicted and observed hydrographs (i.e.. Rogers, Beven, Morris and Anderson, 1985; Bathurst, 1986a) is a necessary test but cannot be considered a sufficient test of models that purport to simulate the internal responses of a catchment. Anderson and Rogers (1987) concurred that "the usual use of hydrograph outflows restricts the inferential capacity of the model" and suggested that it was "perhaps better to validate with respect to spatial patterns of outcomes, such as saturated areas, for example". Klemeš (1983) also felt that "it should be possible to calibrate a catchment model against a number of spatially

distributed variables, for example phreatic surface levels, and not just in the traditional way, against the unit hydrograph".

Despite recognition that distributed models could (and perhaps should) be validated against spatially distributed hydrologic outcomes, there have been very few attempts to do so. Rohdenburg, Diekkuger and Bork (1986) compared measured and simulated values of soil moisture suction through time at a number of grid elements. Al-Soufi (1987) reported good agreement between historic and simulated water table levels for a spatially distributed, physically-based model (WSHS). Abbott et al. (1986a,b) claimed that the distributed nature of the SHE model ensured that spatial variability of catchment inputs and outputs could be simulated. Bathurst (1986a) admitted, however, that in his use of the SHE model "a further criticism might be that the ability to model spatial variations in the hydrological processes has not been tested satisfactorily".

We might therefore expand upon the conclusion of Anderson and Rogers (1987) that "unquestionably, validation is a major element in the improvement of such (distributed) models" by stressing the need for validation against spatially distributed data. The present research adopts such a distributed focus and uses distributed modelling to predict the spatial pattern of surface water accumulation. The actual, observed spatial and temporal patterns of water accumulation (ponding) are used to test and validate the model results.

1.4.6 The need for meso-scale modelling

The need for "farm scale" hydrological models for practical applications in Alberta was noted above. Dooge (1988) made some interesting and relevant observations about scales of hydrological research and the need for increased research effort at the "meso" scale. He recognized three basic classes of spatial scale in hydrology, namely; macro, meso and micro. He reflected upon the available hydrological theory and observed (Dooge, 1988) that it applied to either:

a. non-equilibrium processes at the (micro) scale of a small representative volume with constant properties, or else to
b. long term equilibrium conditions at regional or planetary (macro) scale.

Dooge (1988) concluded that "to be useful for application in the main problems of concern, hydrological theory must be applicable to and verified as valid for non-equilibrium problems at the basin (meso) scale". The observed anomalies between the scale at which problems need to be addressed (meso) and the scales at which most hydrological processes are understood and mathematically described (micro, macro) are discussed in greater detail elsewhere. The point to be taken here is that there is a strong argument for developing and validating distributed models at the meso scale of individual fields, farms and sub-catchments.

1.5 Definition of the research problem

Given the above introduction, it is clear that better information and tools are needed in order to assess properly the potential for and possible impacts of agricultural land drainage at a farm scale. It is proposed that topographically-based, distributed hydrological modelling may be able to provide the information needed to assist with on-farm water management.

The specific research problem is how best to determine where water can accumulate at the farm scale, and to estimate the extent to which it actually does accumulate at various times. Given that surface water accumulation can be a very dynamic phenomenon, it was necessary to look for some procedure that would permit the identification of relatively stable, topographically controlled, locations of surface water accumulation. Once these were known and located it was assumed that determining the relative degree to which they were occupied by runoff at any given time could be achieved.

A successful methodology for farm-scale modelling of surface water runoff and accumulation should address the following questions:

- Where are the locations for "depressional storage" of surface water within a given farm?
- What is the total storage capacity of each depression?
- How are the depressions connected to one another and what would be the sequence in which they would overflow and contribute runoff to downstream locations?
- How water tight are the depressions and how long will they retain water?

- Are there any natural depressions with sufficient storage capacity to permit drainage of other smaller depressions and consolidation in a single on-farm location?
- At any given time (to the nearest week) what is the approximate volume of water stored in any or all of the depressions?
- What might be the downstream effect of unrestricted drainage of any given depression or all depressions in terms of changes in the volume or timing of off-farm runoff?

The operational framework adopted for this research is therefore structured in terms of an exercise in physically measuring the location and extent of depressions, theoretically modelling the flow and accumulation of surface water in depressions at a farm scale and finally testing, using independent field data, the capability of the model to predict the observed distributions of ponded surface water.

The intent is to establish whether geomorphic analysis and distributed simulation modelling might be able to supply the information on likely distribution and connectivity of surface water bodies needed for an operational system for on-farm water management. Simply stated then, the theoretical research problem is:

How well can a physically-based distributed hydrological simulation model predict the distribution and accumulation of surface water in an agricultural landscape of low relief relative to actual field distributions?

1.6 Hypotheses

1. Detailed digital elevation data can be analysed to document the location, extent and connectivity of all topographic depressions in which spring runoff accumulates to form temporary ponds.
2. A highly distributed, physically-based, hydrological model can be used to simulate the actual location and extent of temporary ponding throughout the period of spring runoff.
3. Comparison of ponding predicted by a simulation model with actual ponding measured in the field at specific times during the period of spring runoff provides a useful measure of the effectiveness of the simulation model.

1.7 Objectives of the research

Given the above problem statement and hypotheses, the principal research objectives may be detailed as follows:

1. To develop and test a procedure for characterizing the 'depressional storage capacity' of farm scale agricultural landscapes of low relief in terms of location, area, volume and hydrological inter-connectivity of depressions.
2. To acquire (or develop) and test a simulation model for predicting the likely location, extent and volume of actual ponding of water in closed depressions in agricultural landscapes of low relief during a period of spring runoff.
3. To assess how the principles and techniques might find application in an operational decision support system to assist in on-farm water management and planning.

1.8 Structure of the thesis

The thesis is presented in eight chapters (Figure 1.2).

Chapter one sets out the background and rational for the research project, develops a statement of the problem and tries to succinctly identify the main hypotheses and research objectives. It concludes by giving a brief a outline of the organization and structure of the thesis.

Chapter two outlines the experimental design adopted for the research project. It includes a brief description of the conceptual design on which the project was based followed by an elaboration of the specific experimental design. It provides a general summary of the field and analytical methods used in the study.

Chapter three describes the methods and presents the results of the various field activities undertaken at the site. These activities describe the site, identify and characterise the spatial distribution and hydrological properties of the soils at the site, record the meteorological data required to measure and simulate the water balance at the site, and measure the actual distribution of ponded surface water at the site.

Chapter four describes the background, methods and results of efforts to quantify the topographical controls on where water will flow and where it will accumulate. This geomorphological analysis is used to determine the locations and size of areas of potential depressional storage and to establish how and when these depressions will overflow and inter-connect. The data on static geometry is used to define the topology of flow and pond inter-connection that forms the basis for subsequent modelling efforts.

Chapter five sets out the case for using simulation modelling to estimate the location and extent of ephemeral ponding. It describes the methods used to create and operate a highly distributed hydrological simulation model (DISTHMOD).

Chapter six presents and discusses the results of a series of simulations carried out for the Lunty site for the period of spring runoff in 1989.

Chapter seven compares the observed extent of ponding to that predicted by topographical analysis and simulation modelling. The utility and success of the computer models in predicting the locations, magnitude and timing of temporary ponding are discussed.

Chapter eight summarises the main findings and conclusions of the study and identifies oversights and opportunities for improvement or follow-up. The discussion addresses the potential applicability of the various methods for possible use in operational on-farm management of surface water.

CHAPTER 2

SUMMARY OF METHODS

2.1 Introduction

The purpose of this chapter is to provide an overview and summary of the research methods used in the thesis. The intent is to provide a synopsis to help the reader tie together the relatively independent discussions of method presented in chapters 3 through 6. It should be read as a general introduction to the research to help put the overall study in context. Individuals intending to read the complete thesis may wish to simply skim this chapter to obtain a sense of the overall design and method, since this chapter duplicates considerable material from succeeding chapters. Those interested in only one aspect of the research may find that this chapter provides a better understanding of the context for any of the single activities and the inter-relationships between activities.

2.1.1 An open landscape approach to measuring and modelling surface runoff

Most hydrological studies of surface runoff deal with individual basins with fully integrated drainage and report runoff in terms of a unit hydrograph. The methods adopted for the present research are unique in that runoff of surface water is considered at a farm-scale in terms of an open landscape characterized by non-integrated drainage into multiple depressions. Also unique is the fact that runoff is quantified in terms of the spatial and temporal patterns of accumulation or ponding of surface water.

An "open landscape" approach (Howitt, 1991) was adopted in order to facilitate the study of processes and patterns of surface water runoff in a natural landscape under normal farm management practices. The term "open landscape approach" has been used "to describe research methods and an approach to the study of landscape processes that do not restrict the location of the study with artificial boundaries or impose artificial treatments to simulate the processes under study (Howitt, 1991). This is in contrast to "bounded landscape studies" in which boundaries are placed on

specific landscape elements for the purpose of studying processes within specific, constrained locations (Howitt, 1991).

Use of an open landscape approach permits runoff to be studied in the context of conventional management units (i.e. fields, quarter sections) as opposed to individual watersheds or slope elements. Development of methods or procedures directly applicable to management units facilitates subsequent adoption of the techniques for operational use by farmers or conservation planners. The initial conceptual design for the present research envisaged the following basic activities:

- Characterise the geometry of flow and ponding of surface water at a single, selected study site.
- Simulate the magnitude and timing of surface water runoff and accumulation for a period of spring runoff at the site.
- Establish the actual extent of surface water accumulation (ponding) at specific times during the period of spring runoff.
- Compare the results of the simulated estimates of water distribution with the measured data on actual ponding.

It was felt that geographical information systems (GIS) technology would be needed to help assemble, integrate and use the data and that ultimately GIS technology would be required for any decision support system that used the procedures or models.

2.2 Experimental design

The initial concepts were realised through an explicit experimental design (Figure 1.2) that combined field study of spring runoff with analysis of geomorphological controls on runoff and ponding and simulation of predicted location and extent of ponding. The field component was designed to obtain information on the measured location and extent of temporary ponding at specific times during the period of spring runoff. Field study was also required to obtain meteorological data for input into the simulation model, soil characterisation data for parameterisation of the model and digital elevation data for determination of the topographical controls on runoff. The analytical techniques were designed to determine the geometry controlling the runoff and accumulation of surface water, simulate the likely distribution of surface water ponding and compare the actual to the predicted distributions at specific times.

2.2.1 Field methods

The Lunty study site (see 3.5.1) was selected on the basis of its hummocky topography and non-integrated, drainage pattern. The Lunty site is considered fairly typical of cultivated landscapes in the Black Soil Zone of east central Alberta.

A detailed soil survey was conducted to identify the types and patterns of distribution of the main kinds of soils at the Lunty site (see section 3.4.2). Soil profile observations were recorded at 200 grid locations and used to make a conventional soil survey map at a scale of 1:5 000.

A number of sites were selected for detailed sampling, characterisation and instrumentation using knowledge of the range of soils and landscape positions obtained during the grid soil survey. A total of 27 sites were established along two cross sectional transects selected to traverse the full range of known soils and landscape positions.

Soil pits were dug at 18 of the 27 sites. Complete descriptions of the observed soil profile characteristics were made and disturbed samples were taken from all major horizons for laboratory analysis of chemical and physical properties. These data were used to classify and characterize each soil profile.

Undisturbed core samples were obtained from each major horizon at each sample site. The core samples were used to determine bulk density and total porosity at for each major horizon at each site. These data were used to establish values for soil properties for subsequent simulation modelling efforts.

Field determinations of saturated hydraulic conductivity (K_{sat}) were made at 22 sites at three depths (0-20, 20-40 and 40-60 cm.) corresponding as closely as possible to observed A, B and C horizons. Determinations were made with a constant head Guelph permeameter (GP) using the one-ponded height technique described by Elrick, Reynolds and Tan (1989). Field measured K_{sat} was used to help assign values for hydraulic conductivity to the various soils during subsequent modelling efforts.

Twenty seven of the sites were instrumented to record volumetric soil moisture and soil moisture tension. Volumetric soil moisture was estimated using a Foundation Instruments time domain reflectometer (TDR) using procedures described by Topp

(1987) and Topp and Culley (1989). Guide rods for TDR measurement were inserted vertically into the soil to estimate volumetric moisture over depth intervals of 0-15, 0-40 and 0-60 cm. Soil moisture tension was estimated from readings of resistivity obtained from Soilmoisture Equipment Corp. Model 5201 gypsum blocks placed in the soil at depths of 15, 40, 60 and 100 cm.

TDR and gypsum block readings were recorded at regular weekly intervals from shortly after installation in late May, 1989 until October, 1989 and again from April, 1990 until October, 1990. Samples of soil were collected by hand auger at all depths at approximately monthly intervals for laboratory determination of gravimetric moisture content. These samples were collected for each recording depth and were located as close to each monitoring site as possible without disturbing the site. The gravimetric samples were used to calibrate the electronic sensors and were reserved as backup in the event the sensor data proved unreliable.

An extensive set of instrumentation for recording meteorological data was already established at the Lunty site in support of other Alberta Research Council projects (Moran, Macyk, Trudell and Pigot, 1990a; Moran, Trudell, Macyk and Cheel, 1990b). The meteorological instrumentation, described in full in Chapter 3 (3.4.5), included a tipping bucket rain gauge, a thermister for air temperature, a pyranometer for global solar radiation, a calibrated horse hair sensor for relative humidity, an anemometer to record total miles of wind and a class A evaporation pan to measure total weekly cumulative pan evaporation. Thermisters for measuring soil temperature were installed on the soil surface and at a depth of 0.2 m at the pan evaporation site. All data were recorded on a Meteograph M710 mechanical strip chart recorder. The strip charts were delineated into two hour recording intervals for a period of seven days and were changed at regular weekly intervals. Gaps in the data record were fillled using data from a second nearby site (Henderson site, 53° 4' N, 111° 56' W) also operated by the Alberta Research Council (Howitt, 1991).

A field component was involved in obtaining the digital elevation model (DEM) for the study site, but this was completed prior to the initiation of the present research. This field work was conducted by other personnel in support of a different research project (Trudell, 1989, personal communication) but was made available for the present research. A snow pack survey was also carried for this companion research project and the data made available for use in the present research.

The location, extent and depth of ponding of surface water were determined at regular intervals beginning with breakup in early April and continuing until late October in both 1989 and 1990. Stakes were driven into the ground at the centre of each pond and at four locations on the perimeter of each pond at each recording date. The four perimeter locations corresponded to the maximum extent of the pond in the N-S and E-W directions at any time. The central stake was located at the deepest point in the pond.

Ponds were staked at approximately weekly intervals from April through June and monthly, or after any period of significant rainfall, from July through to October. Level surveys were conducted at 3 different times (see 3.4.8) to determine the precise location and elevation of all stakes. The pond survey data were used to establish the location and extent of actual ponding which was then compared with the location and extent predicted by the simulation model.

The field component of this project focused on obtaining data required to operate and test the simulation model of surface water flow and accumulation. Soil mapping was used to determine the main kinds of soil, their pattern of distribution and their principal characteristics. The soil survey was then used to select sites for detailed assessment of the soil's hydrological and physical properties and for monitoring the behaviour of water in the soil. The site data on hydraulic conductivity and soil moisture-tension were used to help establish parameter values for input into the simulation model and to estimate initial conditions for soil moisture status at the start of a model run. Meteorological data were collected to provide input for the distributed simulation model (DISTHMOD). They were also used to compute a simple water balance to aid in description and analysis of the measured extent of observed ponds. The pond survey data were used to establish the location and extent of ponding at specific times in order to permit comparison with the predictions of likely location and extent of ponding made by the computer simulations. The digital elevation data were used to determine where water would flow and where it would accumulate. The processed DEM was used as a basis for defining the structure and operation of the simulation model. Collectively, the field data helped to define an overall conceptual model of the functionality and data requirements that would be required for an operational decision support system for on-farm water management.

2.2.2 Analytical and modelling methods

The Lunty study site field data were collated, verified, edited and analysed to:

- Characterize the site and report on the observed distribution of actual ponding (chapter 3),
- Assist in defining and verifying the location, extent and connectivity of sites of potential depressional storage (chapter 4),
- Conceptualise and develop a highly distributed hydrological model (DISTHMOD) for simulating overland flow of surface water and its accumulation in closed depressions (chapter 5),
- Provide input data for application of the DISTHMOD model for a period of spring snowmelt and runoff in 1989 (Chapter 6),
- Compare the observed location and extent of actual ponding to that predicted by the simulation model (chapter 7), and
- Analyse the applicability of the methods as automated tools to assist with management of surface water at a farm scale (chapter 8).

The grid soil survey data was compiled to produce a conventional soil survey polygon map at a scale of 1:5 000 (see 3.4.2). This map was converted into a grid map with dimensions equivalent to those of the digital elevation matrix (160 rows by 140 columns). The grid map of soils was reformatted into the form x,y,z (row,col,soil) and imported into a dBase III+™ data file containing one record for each grid point.

The soil samples were analysed in the laboratory for the traditional suite of chemical and physical analyses used in Alberta to characterize soils (see Chapter 3). The undisturbed cores were weighed when saturated, and again when oven dry, to determine total porosity and dry bulk density. The data were collated and checked manually for each depth at each site and then entered into a dBase III+™ data file to facilitate manipulation, reformatting and output.

The field data on saturated hydraulic conductivity obtained with the Guelph permeameter were processed according to the methods of Elrick et al. (1989) to compute triplicate estimates for K_{sat} for each depth interval at each site. These data were tabulated manually, entered into a dBase III+™ data file and then verified, edited and used to produce estimates of mean hydraulic conductivity for each site and depth.

Field measurements of soil moisture (TDR) and soil tension (gypsum blocks) were entered into dBase III+™ files. The raw TDR data were converted to estimated volumetric moisture content using the procedures described by Topp (1987) and Topp and Culley (1989). Gravimetric moisture values were multiplied by an average bulk density for a given soil and horizon to compute the equivalent volumetric moisture. Meter readings from the gypsum blocks were converted into suction (in bars) and thence into an estimated gravimetric moisture content manually, using a graph supplied by the manufacturer (Soilmoisture Equipment Corp., 1983). All data were graphed either manually or using commercial software packages (CricketGraph™, CorelGraph™). The graphs were reviewed to identify errors and omissions and changes were made to the data where indicated.

The field profile descriptions, standard laboratory analysis, soil moisture data and field measured saturated hydraulic conductivity values were assembled into a standard data sheet for reporting the characteristics of the soils at each sampled site (see Appendix 3). The site data were then sorted by soil type (series) and average values were computed for each type of soil. An overall, general description and tabulation of physical and hydrological properties was then prepared for each soil series. These data were used to assign representative parameter values to each type of soil recognised at the Lunty site. In subsequent modelling efforts the initial parameter values assigned to any given grid cell were a function of the type of soil identified at that grid cell.

Field measurements of the depth and water equivalent of snow were collected at selected locations in mid-March, 1989 and correlated to topographical indices computed from the digital elevation data following procedures described by Zebarth and De Jong (1989a). Linear regression equations were established between snow depth and the topographic indices upslope area, cross slope curvature, and down slope curvature (see 3.4.7). The best fit equation was used to predict the depth and water equivalent of snow for all grid cell elements of the DEM based on topographic index calculations for each cell. The estimated depth of snow at each grid cell was used in subsequent modelling efforts.

The principal input requirement for simulation modelling of runoff and ponding was detailed meteorological data. Meteorological data from the Lunty site were recorded on paper strip charts. These were tabulated manually to record total rainfall and

average hourly temperature, global solar radiation and relative humidity. Missing data arising from mechanical breakdown of the recording devices at the Lunty site and data on wind speed not recorded at the Lunty site were obtained from the nearby Henderson site and integrated into the Lunty data set. Cloud cover was estimated for each daytime hour according to the relative degree of depression of incoming solar radiation relative to an assumed maximum. Night-time cloud cover was estimated using a linear interpolation between the cloud cover at the close of one day and the estimated cover at the start of the next day. This was necessary since no direct measurement of degree of cloud cover was available for the site.

A final, complete dBase III+™ data file for all meteorological measurements was compiled and graphed for manual verification. This file recorded the observed values for meteorological variables at hourly intervals. A program written in dBase III+™ was used to compute the average hourly value for all variables except rainfall as the mean of the value at hour n plus hour n-1. The final data file of meteorological data consisted of the hourly total for rainfall and average hourly values for air temperature, global solar radiation, relative humidity, wind speed and cloud cover. These data were tabulated, graphed and used in subsequent modelling efforts (see Appendix 5).

Pan evaporation data recorded at the Lunty site were compiled and corrected for additions caused by rainfall. The corrected data were tabulated and keypunched into a dBase III+™ data file. The data were processed to compute the total pan evaporation for the intervals between each of the dates on which field surveys were made of the actual extent of ponding at the Lunty site. Pan evaporation data were compared to potential evapo-transpiration as estimated by several commonly used equations in order to identify the most appropriate equation to use for the subsequent simulation modelling. All equations for computing potential evaporation or evapo-transpiration were based on modifications of previously published equations as implemented in the simulation model SWATRE (Belmans, Wesseling and Feddes, 1983; Wesseling, Kabat, van den Broek and Feddes, 1989).

The pond survey data included the location and elevation of the pond centre and of the four stakes inserted to record the maximum extent and elevation of each pond at each date. These data were tabulated by date and pond ID number and keypunched into a dBase III+™ data file. The data were examined to match observed pond locations with those predicted by an analysis of the digital elevation data (DEM) (see 3.4.8). Errors in the pond survey data were identified and corrected manually prior to further

processing. A program (PONDMAP), written in dBase III+™ and compiled using Clipper™, used the pond survey data, in combination with the digital elevation data (DEM), to produce grid maps of the extent and depth of ponding at each site at each survey date and to compute the total volume of each pond at each survey date. The location, extent and depth of ponding were analysed relative to the recorded meteorological data on rainfall and snowmelt input and pan evaporation losses. The temporal pattern of observed ponding was reviewed in order to analyse how it related to the observed meteorological patterns.

The Lunty study site digital elevation data set (DEM) was processed to determine where water would flow and where it would accumulate. This processing defined what is here termed the "static geometry" governing the flow and accumulation of surface water and the inter-connectivity of depressions. An interactive set of raster based PC utilities (**Watersh**, van Deursen and MacMillan, 1991) was used to define this "static geometry". The **Watersh** utilities were modified extensively by van Deursen, in collaboration with the present author, in order to support an explicit focus on defining and describing depressions (van Deursen and MacMillan, 1991). The **Watersh** utilities are based on concepts of tracing pixel to pixel connectivity in a raster digital elevation matrix (DEM). These concepts have previously been described and implemented by numerous other authors including Band, 1986ab, 1989a,b; Jenson, 1985, Jenson and Trautwein, 1987; Jenson and Domingue 1988, Mark, 1983a,1984; Marks, Dozier and Frew, 1984, O'Callaghan and Mark, 1984; Morris and Heerdegen, 1988; and Martz and de Jong, 1988). The **Watersh** utilities were adopted in preference to any of the programs listed above because their author made them available and agreed to cooperate in modifying them specifically to address depressions. In addition, they were PC based, interactive, easy to use and accompanied by effective programs for raster editing and overlay and for two and three dimensional graphical display.

The **Watersh** utilities were used to define pixel to pixel connectivity for the Lunty site DEM and from this to establish the location and extent of initial depressional watersheds. The pit centre location; the size and volume of the depression and the locations of potential overspill or pour points were determined for each depression using a specially created option in the **Watersh** utilities called "Find-Outlet-Points". These data were extracted to an external dBase III+™ data file in which the attributes of each depressional watershed were tabulated. A semi-automated procedure was

used to establish the sequence and topology with which depressions overspilled and connected to one another.

An option in **Watersh** to "Remove-This-Pit" was used to interactively unblock each depression, as required, in order to define and compute the statistics for any larger pit in which the initial depression might be contained or nested. Schematic, two dimensional cross sectional diagrams were constructed manually to assist in visualisation of the relative location and connectivity of depressions, especially nested depressions. Data on pond connectivity and nested depressions were added to the original dBase III+™ data file to establish a complete characterisation of the location, size and connectivity for all depressions at the Lunty site. This static geometry was analysed and discussed in terms of how well it predicted the observed pattern of ponding at the Lunty site. It was also used to provide the topographical and topological information that formed the basis for subsequent simulation modelling efforts.

A highly-distributed, physically-based, hydrological model (DISTHMOD) was developed and used to simulate the location and depth of ponding at the Lunty site for a period of spring runoff in 1989. The model DISTHMOD utilised the pixel to pixel connectivity established using the Watersh utilities as the basis for directing water flow across the landscape. It further utilised the data on pond location, size, maximum volume and connectivity established using the Watersh utilities to simulate the accumulation of water in closed depressions, the overflow of depressions when full, and the inter-connection of depressions as they overflowed. DISTHMOD adopted an object oriented approach to modelling as each grid cell was defined as an object with attributes such as soil type, current moisture content in each horizon, downslope neighbour to which it drained and watershed to which it belonged. Each grid cell was also part of a larger watershed object and each watershed contained an object called a depression that had attributes such as a pit centre location, a maximum volume, a current volume and one or more locations for overspill into a neighbouring watershed.

DISTHMOD utilised a number of simple equations adapted from existing models to simulate the various component hydrological processes considered to be operative at each grid element during spring snowmelt and runoff. Equations for potential evapo-transpiration were adapted from the model SWATRE (Belmans, Wesseling and Feddes, 1983; Wesseling, Kabat, van den Broek and Feddes, 1989) with the permission and assistance of the authors. The equation for estimating hourly

snowmelt was adapted from an energy balance model described by Williams (1988) with the permission and assistance of the author. Equations for infiltration, drainage and surface retention were adapted directly from the model ANSWERS (Beasley, Huggins and Monke, 1980; Beasley and Huggins, 1981).

DISTHMOD was written in dBase III+™ and compiled using CLIPPER™. It was designed to utilise the indexing and relational look-up capabilities of a data base management system (DBMS). Indexing was used to sort the data set so that processing of grid cells occurred in an ordered sequence, by watershed, from the highest to the lowest grid element in a given watershed and from the watershed with the highest overspill elevation to the watershed with the lowest overspill elevation. Relational tables were used to permit the program to look up the attributes of the larger depressional entities and to determine the current status of a given depression (i.e. current volume, whether full, where it drained to) at any given time. Meteorological input data was stored in another relational table and read in at the start of each new time step.

DISTHMOD was used to simulate the location, extent and depth of ponding at the Lunty site at approximately weekly intervals throughout the spring of 1989. The simulations produced estimates of the location and extent of ponding at dates corresponding to the dates on which field observations had measured the actual extent of ponding at the site. Simulations were run for extreme conditions of rainfall, snowmelt, evaporation and infiltration in order to define the range of ponding capable of being simulated by the model. Once the maximum possible range of outcomes was defined, a number of simulations were run using realistic estimates for model parameters based on field measurement of soil hydrological properties and field mapping of the distribution of soil types and soil conditions. The simulated distributions were analysed to interpret the sensitivity of the model to various input parameters and to assess which, if any, of the model runs produced reasonable estimates. The simulated patterns of appearance and disappearance of ponds were analysed in relation to the patterns of ponding observed to occur at the site.

The simulated location and depth of ponding were compared with the actual observed location and depth of ponding for the eleven different dates on which field surveys of pond extent had been conducted. A qualitative analysis was used to establish the goodness of fit between the simulated and observed volume, area and depth of ponding for all mapped ponds at specific dates corresponding to the dates on which

the pond survey was carried out. This comparison was used as a measure of the success of the simulation model DISTHMOD in predicting the magnitude and timing of ponding during the period of spring runoff of interest to the present study.

The experience gained in documenting the "static geometry" of depressional storage and in developing, applying and testing the model DISTHMOD provided a basis for evaluating the strengths and limitations of the various procedures and model components for operational use.

2.3 Conclusion

Implementation of the experimental design was facilitated by separating the study into a field component (Chapter 3), a component of geomorphological analysis (Chapter 4), components for developing (Chapter 5), applying (Chapter 6) and evaluating (Chapter 7) a distributed simulation model and a summary evaluation of the relative utility of the various techniques for operational use (Chapter 8).

Presentation of the field study, geomorphological analysis and simulation modelling as separate chapters helped the author greatly in organising both the arguments and the large mass of data. It is hoped that the reader finds the description of the sequence of activities from field observation, to development of a conceptual model for depressional ponding, to aquisition of the statistics required to describe pond size and connectivity, and finally to development of an implementation of the conceptual model as embodied by the DISTHMOD model both logical and helpful. This chapter was provided to help the reader develop an appreciation of this sequence of activities and their inter-relationships. A certain amount of overlap and repetition is an undesireable, but unavoidable, result of this separation of the write-up into descriptions of the field, geomorphology and simulation activities. The repetition is often included to provide a context for readers interested in only one of the separate activities.

CHAPTER 3

FIELD STUDY:

CHARACTERISATION OF THE LUNTY STUDY SITE

3.1 Introduction

3.1.1 Overview

This chapter describes the field activities undertaken to select a farm-scale study site; characterise the soils, hydrological properties and meteorological conditions at the selected site; and to document the locations and extent of ponding at the site. The intent of the field exercise was threefold. Firstly, a variety of meteorological, hydrological and soils data was required for input and parameterisation of the simulation model described later in chapter 5. Secondly, observation of actual field conditions was required to develop the understanding of runoff and ponding used to construct both conceptual and simulation models describing these phenomenon. Thirdly, the documented extent of ponding was required as a means of assessing the performance of the model.

A critical assessment of previously published work is used to establish the context and justify the field techniques. The techniques used to collect and process the hydrological and meteorological data are described and the data recorded at the site are presented. The Lunty study site is described in terms of its topography, soils and hydrological properties. Field measurements of location and extent of ponding are presented for the period April 4 to August 28, 1989. The spatial and temporal patterns of observed ponding are then discussed in terms of the water balance for the site during the period of observation.

3.1.2 Context

The field aspects of the present study are justified in terms of the previously described need to link theoretical modelling with supporting field studies (Dunne, 1983; Dooge, 1988; Anderson and Rogers, 1987; Beven, 1989) (see Chapter 1).

The field study responded to several of the technical recommendations made in the studies on drainage potential in Alberta (W-E-R, 1987; AWRC, 1987) concerning the

need to establish baseline conditions for a farm-scale site for meteorological and hydrological conditions during spring runoff. No existing studies provide relevant local field data on the areas, depths and volumes of ephemeral ponds or describe predictive equations for wetland surface area-depth and volume relationships. Additionally, while depressional storage has been widely accepted as an important control on surface runoff and ponding and has been incorporated into lumped conceptual models of spring runoff in Alberta (JNM, 1986; W-E-R, 1987), no known studies have quantified the extent and distribution of depressional storage in farm-scale landscapes in Alberta or in any similar areas.

3.2 Justification of field methods

The following section examines the current literature and evaluates the options for field procedures required for the present study. The primary questions of interest to the present study (Figure 3.1) were:

a. Which of the available techniques is most suitable for characterising the site to predict the spatial and temporal distribution of soil properties required for input into a distributed hydrological simulation model?

b. Which of the available techniques is most suitable for estimation, or field measurement, of the principal soil hydrological properties required for the present study?

c. Which of the available techniques is most suitable for measuring or estimating the spatial distribution of depth of snow just before spring thaw?

d. Which of the available techniques is most suitable for observing surface runoff and recording the results of runoff in terms of the spatial pattern of ponding?

3.2.1 Techniques for mapping soils and predicting the distribution of soil properties

Bork and Rohdenburg (1986) noted that one of the major impediments to effective use of physically based, distributed models was the need for large amounts of data to describe the dynamics of water and matter in a highly sub-divided catchment area. They noted that for each grid element information was needed on a) the initial

conditions, b) the boundary conditions and c) the model parameters. They concluded that the collection of these data represented a major problem that limited usage of distributed models. The problem of supplying reliable data for highly distributed models has been widely recognized (Bouma, 1989; Kool, Parker and van Genuchten, 1987; Kabat and Hack-ten-Broek, 1988) and has been referred to as the "parameter crisis".

The options available for assigning a spatial pattern to the distribution of soil properties for hydrological modelling fall into two broad categories. They are a) the choropleth model and b) the continuous model (Burrough, 1986).

a) The choropleth model of soil mapping

Most traditional soil mapping has adopted the choropleth model. All applications of the choropleth model, whether manual or automated, assume that any area can be sub-divided into less variable sub-areas (Beckett and Webster, 1971). Each of these sub-areas is assumed to be more-or-less homogeneous with respect to a wide variety of soil properties (Arnold, 1979a,b). Typically, a single soil type is assumed to dominate the sub-area and the modal characteristics of the dominant soil type are used to characterise the sub-area (Wilding and Drees, 1978). Boundaries between sub-areas are frequently defined on the basis of changes in landscape position (Miller, McCormack and Talbot, 1979).

Typically, application of the choropleth model for soil mapping has relied on the development of "conceptual models" (Miller et al., 1979; Arnold, 1979a,b; Wilding and Drees, 1978). These conceptual soil-landscape models relate observed patterns of soil distribution to corresponding, readily visible, external attributes such as tonal pattern on aerial photos, vegetation, and observable topographical controls such as elevation, slope gradient, aspect, relative slope position and slope curvature. Such models form the basis for the traditional approaches to mapping soils used in Canada (Mapping Systems Working Group, 1981) and the United States (Soil Survey Staff, 1951, 1975). Borings, pits and other forms of field inspection are conducted principally to develop, test or refine these conceptual models but do not form the basis for defining soil boundaries (Arnold, 1979a,b; Miller et al., 1979). This traditional approach to soil mapping generally requires only a limited number of observations to confirm or reject the soil landscape model applied to any given landscape element. This type of mapping is used wherever a clear relationship can be discerned between

landscape position and soil properties. It is used most frequently at small to medium scales (1:30,000 to 1:250,000). The author has extensive experience with traditional methods of soil survey in Alberta (MacMillan, 1987; MacMillan, Nikiforuk and Rodvang, 1988) and East Africa (MacMillan, Green and Hignett, 1986).

In the less common instances where there is no clear relationship between the distribution of soils and observable landscape controls, soil observations at individual points may form the sole basis for construction of a soil map and for the placement of soil boundaries. This is done with minimal reference to externally visible attributes such as tonal pattern or topographical controls (Expert Committee on Soil Survey, 1987a). In such cases, it is often necessary to adopt a dense network of observation sites spaced closely enough to permit effective manual interpolation of soil properties. Sample points with similar properties are grouped manually to define soil map units containing similar soils. This type of manual mapping is most often necessary in level areas with little apparent relationship between soil distribution and observable landscape features. The author has experience with this kind of mapping at 1:25,000 scale in the lowlands of the Ottawa Valley (Marshall, Dumanski, Huffman, and Lajoie, 1979) and at a farm scale (1:5,000) at the Selian Research Station in Arusha, Tanzania (MacMillan and Green, 1986).

Typically, partitioning of landscapes into soil landscape areas has been based on manual interpretation of stereo air photos or closely spaced field observations. Pennock, Zebarth and de Jong (1987) presented an approach in which topographical indices derived from a DEM were used to segment or partition the landscape into seven distinct landform elements defined on the basis of slope gradient and curvature and upslope area count (Pennock et al., 1987). Their hypothesis was that each of the landform elements (i.e. divergent shoulders, convergent foot slopes) could be expected to exhibit a characteristic, and different, set of soil attributes. This approach is consistent with what Burrough et al. (1992) refer to as a natural classification of space into stable, naturally occurring groups. It is based on the principles of hillslope classification elucidated by Ruhe (1960) and Dalrymple, Blong and Conacher (1968).

The approach of Pennock et al. (1987) in many ways automates and replicates traditional manual methods of soil mapping. It adopts the assumption that there is a defined and consistent relationship between landscape position and soil properties. It simply utilises digital data sources and automated processing techniques to compute and delineate these landform elements. A similar, though less exact and reproducible,

result would be expected were a soil surveyor to manually interpret a stereoscopic image to define soil-landform units.

Other approaches have been used to develop automated classification rules based on an analysis of relationships observed at manually classified training sites (Su, Ransom and Kanemasu, 1989; Moore, Lees and Davey, 1991). These approaches differ from that of Pennock et. al. (1987). They are based on the premise that there is a strong association between the spatial patterns of soil and controlling topographical and edaphic variables, but that the rules governing this association are unknown, or too poorly understood, to permit effective a-priori elucidation and application. All approaches utilize the concept that individual site variables recorded at a selected number of training sites can be analysed to define a set of systematic and quantitative rules for classifying un-visited sites for which the same data set of variables is available.

One criticism of pixel-based approaches to classification is that they seldom take spatial or contextual relationships into account. They operate solely on site specific attributes and so, are unable to consider factors such as relative position in the landscape or the attributes of neighbouring cells. They are unable to replicate the human capacity to recognize characteristic spatial patterns and to classify areas according to the observed spatial pattern. A frequent consequence of this limitation is the tendency for pixel based approaches to produce salt and pepper classifications with adjacent pixels classified into markedly different classes. Neural network analysis has shown some capacity to incorporate a rudimentary consideration of spatial context into the classification process (Ritter and Hepner, 1990). Similarly, fuzzy logic (Burrough et al., 1992) has been shown to be capable of incorporating spatial context into the classification of pixels. To date, these approaches do not yet match what can be achieved by manual pattern recognition.

A valid criticism of the choropleth approach is that it creates an artificial view of the pattern of variation in soil property values in which sub-areas are assumed to be uniform across their entire extent and all change in soil properties occurs at the boundaries of units (Burrough, 1986). A further criticism of the choropleth model (Burrough, 1986) is that it assumes that a wide variety of soil properties co-vary within defined sub-areas and all property values change abruptly and synchronously at the defined boundaries.

An advantage of the choropleth model is that it generally recognises, and takes advantage of, the widely accepted relationship between landscape position and soil properties. Use of soil landscape relationships minimises the requirement for detailed field inspection or sampling. A further advantage is that it defines a single set of spatial entities to which all characterisation data apply. This greatly simplifies visualisation and management of the spatially referenced data.

b) The continuous model for mapping individual soil properties

The continuous (or isopleth) model recognises the fact that soil properties vary continuously across the landscape (Burrough, 1986). This model requires that soil properties be dealt with individually. It generally treats the spatial distribution of individual soil properties as independent of one another but some techniques (i.e. co-kriging) recognize and make use of patterns of spatial association.

Procedures for interpolating point source soil observations to a regular grid of estimated data values have been widely reported for experimental research (Burrough, 1986) but not widely adopted for operational mapping of soils (ARC, 1992; Wilding, 1988; Marsman and de Gruijter, 1986). The exception has been for detailed site studies where it has proven feasible and desirable to collect the numerous, closely spaced, observations required for effective interpolation. For example, Bork and Rohdenburg (1986) described a transferable method for the parameterisation of grid elements for a distributed hydrological model. The method was based on collection of a reasonably small number of soil measurements (thickness and texture of soil layers, specific gravity, humus content) at 300 individual sites which were then interpolated to estimate conditions at all other grid elements. The procedure used for interpolation was not described, but kriging was claimed not to yield satisfactory results.

Despite the reservations of Bork and Rohdenburg (1986), geostatistical interpolation of individual soil properties using kriging has become very popular among soil researchers. Descriptions of the use of geostatistics for soil survey have been provided by McBratney (1984), Webster and Oliver (1990) and Burrough (1986). Burrough (1986) argued that geostatistical interpolation of individual soil properties is superior to the usual alternative of establishing landscape-based classifications and mapping units and then assigning each classified area a description based on assumed average characteristics. He noted that interpolation of individual soil properties recognized the continuously varying nature of soils. He observed that all soil

properties do not co-vary exactly with landscape elements so that some soil property values assigned to landscape units will inevitably be sub-optimal.

One weakness of geostatistical interpolation is that it uses data from only a relatively limited number of examination points and fails to take advantage of the useful information available from more densely sampled data at intervening points (McBratney, 1984). Co-kriging can utilise data from a denser sampling network to improve the interpolation accuracy for more sparsely sampled variables if a correlation can be shown between the sparsely and more closely sampled variables. McBratney (1984) provided an example of co-kriging using more densely sampled values for sub-soil silt to improve the estimation of topsoil silt sampled at only one quarter the number of locations.

A valid criticism of kriging is that it fails to utilize the important information between sample points that would normally be extracted during manual interpretation of topography on stereo photos. Given the widely accepted notion of a strong and consistent relationship between topography and the distribution of soil properties, it would be reasonable to expect some researcher to have investigated the potential for using a dense grid of elevation data (a DEM) to improve estimation of a sparsely sampled soil variable using co-kriging. The present literature review uncovered no examples of such an approach.

Another common technique for predicting the distribution of individual soil properties involves the use of single or multiple regression. This requires only that there be a statistically significant relationship between the property to be predicted and some known property or set of properties. In many instances, topography or some derivative of topography, supplies the known property. For example, Bork and Rohdenburg (1986) established stochastic relationships between soil moisture values measured at various times at 25 individual monitoring sites within their catchment and both topographical and soil variables computed for the same sites. Stepwise multiple linear regressions were computed between soil moisture content or soil moisture suction and data sets consisting of the individual soil properties and topographical indices computed from a DEM. The best regression equations were used to estimate the most likely moisture content or suction at every grid element using the digital topographic indices and interpolated soil property data available for every grid element.

Once individual soil properties have been interpolated to a regular grid using either kriging, co-kriging or linear interpolation techniques, several sets of individual values are often overlain and used to classify the area for some purpose. For example, Bork and Rohdenburg (1986) applied a set of manually defined Boolean rules to a set of interpolated soil property values to define classes of soils in the Neuenkirchen research catchment. MacMillan, Nikiforuk, Krzanowski and Balakrishna (1987) adopted a similar approach for classifying soils at the Lacombe Research Station in Alberta.

Burrough (1989) has shown that overlays involving strict adherence to Boolean logic result in spatial fragmentation of the resultant classifications and in the exclusion of very similar soils from any given classification. The Lacombe Research Station data set was re-analysed by Burrough, MacMillan and van Deursen (1992) using fuzzy logic to define classes of soil suitable for the establishment of research plots. The fuzzy classification was shown to result in less spatial fragmentation and in lower rates of rejection of similar soils for any given class. This classification did incorporate an analysis of topographical controls on drainage status as indicated by slope gradient and upslope area.

The most significant limitation to wide-spread adoption of the continuous model for soil survey is that it usually requires intensive field sampling and laboratory analyses. Most approaches require a large number of quantitative point data to support interpolation or other mechanisms of spatial estimation. An additional valid criticism is that most applications of the continuous model fail to take account of, or utilise, the widely accepted relationship between soils and landscape position. Finally, there is some validity to the notion that continuous models create an unrealistic expectation of high levels of precision and accuracy. Given that many soil properties (especially hydrological properties) vary in value by orders of magnitude over very short distances, the accuracy implied by assigning different, and highly precise estimates, to every grid cell may be misleading.

The present study required a choice to be made from among the available methods for characterising the distribution of soils and soil hydrological properties. Consideration was given to trying to find, and adopt, a faster, more reliable and more automated method of producing maps of soil properties than offered by conventional manual techniques. In the end, none of the alternative methods for automated mapping were adopted. While there is reason to expect that automated techniques for classifying soils and landscapes will become increasingly successful and widely used, none has

yet to achieve widespread acceptance for operational mapping. The available automated methods were judged to require more data and a greater level of investigative effort than was feasible for the present study. Manual techniques of landscape interpretation followed by field inspection to characterise the landform units were adopted. They were judged to be the preferred approach for mapping soils and for establishing soil parameter values for hydrological modelling for the present study.

3.2.2 Techniques for characterising soil hydrological properties

The present study required spatially referenced data, for each major soil horizon, for each of the mapped soils. The data were needed to document the initial moisture content of the soil at the start on the simulation period, the thickness and total storage capacity of each horizon, the moisture content at field capacity and at wilting point and saturated and unsaturated hydraulic conductivities. In addition, knowledge of the patterns of change in moisture content of each soil and horizon through time was desirable order to develop a conceptual understanding of the dynamics of water movement through the soils at the site.

A number of alternative methods were considered for obtaining the required data. The essential choice was between a) estimation techniques and b) direct field measurement.

a) Techniques for estimating soil hydrological properties

Methods for estimating soil hydrological properties are required in cases where direct field measurements are impractical or impossible. Bouma (1989) and Bouma and van Lanen (1987) defined the term "pedotransfer functions" for the systematic use of readily available or easily measured soil properties to predict values other soil parameters which are more difficult to measure. Three main approaches for estimating hydrological properties of soils have been recognized (McBride and Mackintosh, 1984; Vereecken et al., 1990).

The first approach has been to develop correlation equations between, for example, hydraulic conductivity and more easily or frequently measured soil properties (Stevens, Lambert and Watson, 1987; Saxton et al., 1986; Bloemen, 1980; Heverkamp and Parlange, 1986; Rawls, Brakensiek and Saxton, 1982; Wösten and van Genuchten, 1988; Vereecken, et al., 1990; Ahuja, Naney and Williams, 1985; Jaynes and Taylor, 1984). Similarly, correlations have been developed to predict soil moisture content at specific suctions based on soil texture and other basic soil

properties (Saxton et al., 1986; Gupta and Larson, 1979; Bouma, 1989; de Jong and Loebel, 1982; Puckett, Dane and Hajek, 1985; Vereecken, Maes, Feyen and Darius, 1989). One criticism of this approach is that it produces tabulated estimates of moisture content or hydraulic conductivity at only specific heads (Vereecken et al., 1989). Values at intermediate heads must be estimated by linear interpolation between two bracketing heads for which estimates have been made. This makes the data harder to use for direct mathematical computation by simulation models.

The second widely used estimation technique has been to define and solve equations based on theoretically developed models relating pore size and volume to moisture content or hydraulic conductivity. The theoretical models most frequently cited are those proposed by Marshall (1958), Burdine (1953) and Mualem, (1976, 1977). This approach has been adopted by a large number of researchers (Bouma and Anderson, 1973; Ahuja et al., 1989; Ahuja, Naney, Green and Neilsen, 1984; Libardi, Reichardt, Neilsen and Biggar, 1980; Arya and Paris, 1981).

The third commonly used estimation technique is to select a mathematical function that appears to describe the shape of a soil moisture or [$K(\theta)$] characteristic curve and to then adjust the parameters of the function to obtain a best fit to observed [$\theta(h)$], [$K(h)$] or [$K(\theta)$] data. This approach was adopted by McBride and Mackintosh (1984), Ahuja, Green, Chong and Neilsen (1980), Chong, Green and Ahuja (1981) and by Vereecken et al. (1989, 1990) who provided equations for a large number of suggested functions (Wind, 1955; Brooks and Corey, 1964; Campbell, 1973; Averjanov, 1950; Irmay, 1954; Gilham et al., 1976; Gardner, 1958; Rijtema, 1965; King, 1965).

Van Genuchten (1980) combined several of the above techniques to derive a closed-form analytical expression for unsaturated hydraulic conductivity. This approach permits hydraulic conductivity to be calculated given only data for the soil water characteristic curve.

Recent studies (Ahuja et al., 1989; Kabat and Hack-ten-Broek, 1988) concluded that parameter estimation techniques were more useful when combined with scaling (Hopmans, 1987). They were deemed appropriate for estimating K_{sat} and other hydrological parameters where measured data were not available and direct measurements were not feasible.

b) Techniques for field measurement of soil hydrological properties

Bouma and Anderson (1973) have argued that direct physical measurements are always preferable to estimations, as they are both simpler and cheaper. Additionally, Kool et al. (1987) observed that since analysis of the soil hydraulic functions is ultimately directed towards field-scale processes, determination of in-situ properties is more relevant than data obtained from laboratory analysis. This advice was accepted by the present study and direct field measurements were undertaken wherever possible.

Direct techniques for estimating unsaturated hydraulic conductivity are based on solution of the inverse problem in the laboratory or under field conditions (Green, Ahuja and Chong, 1986). Recent developments in direct methods are given by Klute and Dirksen (1986). These include the instantaneous profile method, different unit-gradient methods, sorptivity methods and the crust method as reviewed by van Genuchten, Koveh, Russell and Yates (1988). Direct field methods to measure both saturated [K_{sat}] and unsaturated [$K(h)$] soil hydraulic conductivity above the water table have been described by Bouwer (1961, 1962), Bouwer and Rice (1964, 1967), Boersma (1965), Gardner (1970), Amoozegar and Warrick (1986), Green et al. (1986), and Bouma, Hillel, Hole and Amerman (1971). It is widely accepted (Bouma and Anderson, 1973) that field determination of these properties is preferable to laboratory determinations conducted on supposedly undisturbed cores (Klute, 1965). This advice was accepted for the present study.

The major problems limiting direct field measurement have been the high cost of applying the available field techniques and the requirement for multiple measurements in order to address the issue of spatial variability (Warrick and Neilsen, 1980). Elrick, Reynolds and Tan (1989) have recently described a simple, easy to use device for field determination of both saturated [K_{sat}] and unsaturated [$K(h)$] hydraulic conductivity. They claimed that measurement of the steady state flow rate using the Guelph permeameter (GP) was all that was necessary for many practical applications (Elrick et al., 1989). They pointed out that many studies had documented the large spatial variability of hydraulic conductivity (Sharma and Luxmoore, 1979; Shuh and Sweeney, 1986) with coefficients of variation of 65 percent reported for sands and up to 600 percent for clays (Topp, Zebchuck and Dumanski, 1980; Neilsen, Biggar and Erh, 1973; Warrick and Neilsen, 1980). They considered that, for many applications, it was perhaps advisable to make only order of magnitude estimates for hydraulic

conductivity. They demonstrated that the Guelph permeameter (GP) was quite adequate for generating order of magnitude estimates. The present study accepted these arguments and adopted the Guelph permeameter technique for direct field measurement of saturated hydraulic conductivity.

In addition to hydraulic conductivity, the present study required some direct measurements of soil moisture [θ], soil tension [h], bulk density and total porosity to determine initial conditions and to validate existing estimates of these parameters. The specific data requirements were for moisture content at tensions of 0-10 kPa (for estimating saturated moisture content [θ_{sat}]), 10-30 kPa (for approximating field capacity), 1500 kPa (for approximating wilting point) and for bulk density or total porosity for calculating the total storage capacity of each horizon. The options for determination of soil moisture and tension characteristics included direct field measurement or laboratory measurements on disturbed or semi-disturbed samples.

Soil matric head (h) is most commonly measured directly in relatively wet conditions ($-800 < h < 0$ cm) by means of a tensiometer connected to a pressure transducer (Feddes, Kabat, van Bakel, Bronswijk and Halbertsma, 1988). Other common, indirect, field methods (Feddes et al., 1988) include electrical conductivity as measured with gypsum blocks and vapour pressure as measured using psychrometers. Feddes et al. (1988) noted that emerging techniques showing considerable promise included measurements based on thermal conductivity (Phene, Rawlins and Hoffman, 1971) and dialectrical properties (Hilhorst, 1984). The present study chose to measure matric head using gypsum blocks.

Measurement of soil water content at numerous sites and at frequent intervals (weekly) was required for the present study. A complicating factor was that soil water content cannot be measured directly with any automatic systems for recording field data (Feddes et al., 1988). The choice for the present study was between a variety of techniques for indirect, in-situ measurement and standard gravimetric analysis of disturbed samples.

Among the options for in-situ measurement, neutron probe and gamma radiation measurement techniques were judged unsuitable because of safety considerations and difficulty with automating data capture (Feddes et al., 1988). The remaining choices were between the capacitive method (Hilhorst, 1984) and time domain reflectometry (Topp, Davis and Annan, 1980). The capacitive method is based on measurement of

the capacitance of a capacitor with the soil-water-air mixture as the dielectric medium. The water content can be determined after field calibration with an accuracy of ±0.02 $m^3 m^{-3}$ (Halbertsma, Prybyla and Jacobs, 1987). Time domain reflectometry (TDR) measures the propagation time of a radio pulse traveling along a wave guide and relates the delay in time required for the signal to return through the soil to its source to the dialectrical properties of the soil. The time delay can be directly related to the volumetric water content of the soil with a reported accuracy of ±0.02 $m^3 m^{-3}$ (Topp et al., 1980). The TDR method was selected for in-situ measurement of soil moisture for the present project.

The other option for field determination of volumetric soil moisture content is to determine gravimetric moisture content for disturbed soil samples and then convert to volumetric moisture content by multiplying by bulk density (Vereecken et al., 1989; Witono and Bruckler, 1989; McBride and Mackintosh, 1984; van den Berg, 1989). This is done frequently as both an alternative to direct field measurement of volumetric moisture content and as a check or calibration procedure for the various indirect methods of estimating volumetric soil moisture. A decision was taken to conduct periodic gravimetric sampling for the present study as a backup in case the TDR determinations proved unreliable.

The present study required data on the total volumetric storage capacity for each horizon of each soil type as well as the moisture content at 1/3 and 15 atmospheres (33 kPa and 1500 kPa). Total volumetric storage capacity is determined as the product of moisture content at saturation [θ_{sat}] times thickness of the horizon in question.

Direct measurement of [θ_{sat}] in the field is possible (Witono and Bruckler, 1989), but complicated by infrequent natural occurrence of saturation in most soils and by the difficulty of fully wetting soils in the field by manual means. A common method of estimating [θ_{sat}] is to develop a regression equation between previously observed values of [θ_{sat}] and more generally available soil data such as percent sand and percent clay (Saxton et al., 1986). Another alternative is to determine [θ_{sat}] in the laboratory by complete wetting of disturbed cores of known volume under controlled conditions (McBride and Mackintosh, 1984). Volumetric moisture content is then computed by subtracting the weight of the core when saturated from the weight when oven dry and dividing by the known volume of the core. Another laboratory approach determines the moisture content of undisturbed cores which are saturated then brought to equilibrium at some very low tension (0-10 kPa) in a pressure vessel or on a

hanging column device (Ahuja et al., 1989). This method under-estimates [θ_{sat}] if measurement at slight suction causes some macro pores in the soil core to empty (Ahuja et al., 1989).

In the absence of direct field or laboratory measurements, many authors equate the moisture content at saturation with total porosity (TP) and estimate [θ_{sat}] from a knowledge of dry bulk density and an assumed particle density (Ahuja et al., 1989; Carsel and Parrish, 1988; Rawles and Brakensiek, 1985; van den Berg, 1989; Beasley and Huggins, 1981). The present study used this method to determine moisture content at saturation.

Since [θ_{sat}] was estimated based on bulk density, the study required field measurements of bulk density. Direct measurement of bulk density in the field can be accomplished to a precision of ±30 kg m^{-3} using a field gamma ray probe (Witono and Bruckler, 1989). Direct measurement is relatively rare and most studies rely on laboratory determination of bulk density from undisturbed soil cores (Vereecken et al., 1989; McBride and Mackintosh, 1984; Ahuja et al., 1989); soil blocks carved out in-situ (van den Berg, 1989); or semi-disturbed, intact clods coated with paraffin or saran (Witono and Bruckler; 1989 McKeague, 1978). McBride and Mackintosh (1984) described a procedure in which samples for bulk density were obtained with a split-sleeve coring device which produced undisturbed cores 4.7 cm in diameter that were cut to a standard length of 3.0 cm. The dry bulk density was determined by oven drying the cores at 105° C for 48 hours following the procedures outlined by McKeague (1978). A variation of this method, used with considerable success in Alberta for several years (Macyk, 1989, personal communication), was adopted for the present study.

The two other moisture contents of direct interest to the present study are those that occur at 1/3 and 15 atmospheres (33 kPa and 1500 kPa). Determination of moisture content at specific tensions is done most commonly in the laboratory. Undisturbed or semi-disturbed cores have been used to determine moisture content at low tensions using hanging columns or low pressure chambers (Vereecken et al., 1989 [0-62 kPa]; McBride and Macintosh, 1984 [5-33 kPa]). At higher tensions (Vereecken et al., 1989 [256-1554 kPa]), disturbed samples that have been dried, ground and sieved are placed in high pressure chambers and brought to equilibrium moisture content at selected tensions. These methods generally determine gravimetric moisture content (kg kg^{-1}) directly and then compute volumetric moisture (kg m^{-3}) by multiplying by

bulk density.

Since field capacity is accepted as the moisture content of the soil after 24 hours of free drainage following saturation, a preferred alternative to laboratory determination is to measure it directly in the field. This can be done by either direct gravimetric sampling or by employing one of the indirect methods of field measurement discussed above. Field assessment of wilting point (moisture content at 1500 kPa) is often more problematic. It is often difficult to expressly cause field soils to dry out to this degree, especially deeper soils, below rooting depth. One alternative is to predict the gravimetric moisture content at -1500 kPa based on a regression equation (McBride and Mackintosh, 1984).

In the final analysis, the methods employed to measure or estimate soil hydraulic properties depend on the purpose of any given study and on the available resources and time. Direct field measurement was adopted by the present study wherever possible, but techniques for estimating relevant parameters were used where direct field measurement was not possible.

3.2.3 Techniques for measuring or estimating depth and water equivalent of snow in prairie landscapes

Snowmelt makes a significant, and often dominant, contribution to spring runoff in prairie landscapes in North America (Male, 1980). A major difficulty common to almost all snowmelt models is definition of the spatial and temporal distribution of model inputs; including specifically the measurement or estimation of snow accumulation (Leavesley, 1989). A discontinuous, or patchy, snow cover is characteristic of the relatively flat prairie and tundra regions of the northern hemisphere over much of the period of spring melt (Male, 1980). This patchy snow cover seriously restricts the applicability of many current models of spring snowmelt primarily because bare ground within the snow cover significantly alters the energy balance at the surface (Male, 1980). Leavesley (1989) concluded that "many of the major problems in simulating snowmelt runoff are related to data availability, data quality and the ability to extrapolate accurately point measurements to areal values". These concerns all applied to the present study and solutions were sought in the literature.

Point measurements along representative transects called snow courses are the most widely used technique for estimating the thickness and water equivalent of watershed snow packs in North America (Bartos and Rechard, 1973). The procedure has shortcomings associated with selection of a representative snow course and with the assumption that an index can adequately represent the mean snow water equivalent over a watershed (Bartos and Rechard, 1973). Snow depth has been shown to be more variable and to require a more dense sampling scheme than snow density, which is essentially uniform in most small watersheds (Bartos and Rechard, 1973). The best estimates of total snow water equivalent are therefore based on many point measurements of snow depth and few (as little as one) measurements of snow density in any given watershed (Bartos and Rechard, 1973). The present study accepted and adopted this advice.

A particularly relevant regional example of techniques to record and analyse snow depth and snow density is provided by Zebarth and de Jong (1989a) who analysed the distribution of snow depth and water equivalent in a hummocky landscape in Saskatchewan. The density of snow was reported to be relatively constant in all landscape positions at 0.20 Mg m^{-3} in 1986 and 0.23 Mg m^{-3} in 1987. They noted a similarity between the pattern of snow depth and the pattern of water distribution. The depth of snow increased downslope from crests towards depressions. Both depth and water equivalent of snow were well correlated to a series of topographical variables computed from a raster DEM (Zebarth and de Jong, 1989a). Snow depth increased with increasing catchment area and with increasing surface concavity in both profile and plan directions. They concluded (Zebarth and de Jong, 1989a) that "the strong correlation between snow and topography variables indicates that the distribution of snow in the landscape was controlled primarily by the topography". They were content to document the correlation between snow depth and topography and did not construct a regression equation to predict snow depth from topographical variables. The techniques of Zebarth and deJong (1989a) were adopted for the present study and used to develop a predictive equation relating snow depth to topographical variables.

3.2.4 Techniques for mapping the location and extent of surface water

A principal aim of the present research is to measure and model the location, area and depth of surface water that accumulates in shallow depressions in a prairie landscape. A key interest, therefore, was to survey the literature to identify methods with potential

for mapping the location and extent of surface water with success .

In principle, mapping the areal distribution of open surface water should be straightforward since distinguishing water from land whether by field inspection, visual interpretation of air photos or automated analysis of digital imagery is technically simple. However, several considerations complicate the procedure. One complicating factor is that the distribution of open surface water changes continuously in time. Another complication arises in determining depth of ponding from data that usually provide only indications of areal extent. The present study required a method that offered the possibility for low cost, repeatable update and that provided reliable measures of water depth and pond volume.

The main options for mapping open surface water fall into 2 principal categories, namely: a) manual interpretation of aerial photographs and topographical maps combined with field checking and b) automated interpretation of digital data (imagery or digital elevation data).

a) manual interpretation of aerial photographs and topographical maps

A survey of the literature uncovered very few examples of successful procedures for manual interpretation of aerial photographs or topographical maps to delineate small bodies of surface water. Fortunately, two Alberta studies provided detailed, locally relevant information and procedures (AWRC, 1987; MacAlpine, 1992).

The Alberta Water Resources Commission conducted a statistical inventory of wetlands in Alberta (AWRC, 1987) which was based principally on interpretation of aerial photographs. Bodies of surface water were identified manually by interpretation of aerial photographs and measurements were recorded on the numbers and relative size of water bodies in each quarter section area surveyed. The exact locations of water bodies were not explicitly mapped, as the intent was simply to count occurrences and determine extent for a tabular data base summary. The procedure involved taking a partial sample in selected areas and using the results to characterise a larger area (watershed) of interest. In the second stage of this project (AWRC, 1987) surface water distribution was completely mapped for a selected number of target watersheds. Mapping was again accomplished using manual identification of surface water features on aerial photos.

MacAlpine (1992) provided a detailed explanation of field procedures currently used by Alberta Agriculture to document the extent, depth and volume of small bodies of surface water at a farm-scale. This information is used to help farmers to develop plans for farm-scale water management. The procedures determine the locations where water accumulates after runoff and estimate the depth, volume and relative permanence of ponding. The intent is to help farmers plan to minimize off-farm release of surface water and to capture both natural runoff and artificial drainage for beneficial on-farm use.

The method currently used by Alberta Agriculture to delineate wetlands is based mainly on manual interpretation of aerial photographs. The method recommends that large scale (1:5,000) aerial photographs be interpreted to delineate all occurrences of water or wetlands (MacAlpine, 1992). The procedure requires that interpreters classify water bodies into one of six wetland types. Wetland types are recognized by differences in cultural practices (seeding date), shape, air photo tone and type of vegetation. Cultural practices and vegetation are used as clues to the relative permanence of the water bodies which is, in turn, related to depth. Classes range from very temporary ponds which are dry enough to cultivate and seed at the same time as adjacent upland areas through to late seeded depressions, wet meadows with native grasses, shallow marshes, deep marsh with cattails or bulrushes and finally open water. Each class is associated with an assumed depth of spring flooding ranging from 0.15 m for cropped depressions to 1.50 m for open water. The assigned depths are based on accumulated field experience and have proven quite reliable (MacAlpine, 1992).

MacAlpine (1992) cited experience that wetlands less than 0.4 hectares in size and 0.45 metres in depth usually loose all surface water annually, while wetlands larger than 2 hectares and deeper than 0.6 metres are usually permanent.

The procedure used by Alberta Agriculture to estimate volume of wetlands (MacAlpine, 1992) is simply to multiply the measured area of each wetland by its assumed depth and divide by 2. This assumes that the wetlands are shaped like saucers with bottoms rising in a straight line from deepest point to the wetland perimeter.

b) automated interpretation of digital data (imagery or digital elevation data)

The second option available to the present study was to use automated interpretation of digital data to determine the extent and depth to which surface water accumulated. There is much reference in the literature to the potential for using remote sensing to map surface water (van de Griend and Engman, 1985) but few examples of widespread operational use. The few studies where remotely sensed imagery has been used to classify and compute the surface area of bodies of water reported varying degrees of success (Chidley and Drayton, 1986). Success in mapping water bodies clearly decreases with the size of the water body. The effective size limits for consistent recognition using available digital data are reported to be 2.4 ha for Landsat MSS (NASA, 1977), 0.8 to 1.0 ha. for Landsat TM (Norbech, 1986; EOSAT, 1987; Koeln et al., 1988) and 0.5 ha. for SPOT MSS (Chidley and Drayton, 1986).

A significant limitation of the remote sensing method of mapping surface water, with respect to the present study, is that the data only permit estimation of the location and areal extent of open bodies of surface water. There is no provision for calculating or estimating depths or volumes. A second concern is that the assessment of relative permanence or persistence of wetlands would require multiple-date imagery. This is both expensive and unlikely to be available on a reliable basis due to cloud cover or other problems.

The second option for automated estimation of the location, depth and volume of small bodies of surface water involves the processing of digital elevation data. A small, but growing body of literature (Burrough, 1986; Jenson and Domingue, 1988; Jenson and Trautwein, 1987; Yuan and Vanderpool, 1986) provides examples of procedures for computing the depth and volume of depressions in topographical surfaces as defined by a digital elevation model (DEM). All of the above studies concentrated on defining the maximum possible volume of depressions from a DEM and none applied the procedures to compute actual volumes of water in depressions filled to a given depth at a given time. None-the-less, the same principles apply and the techniques are suitable for direct calculation of volume of water stored in a depression filled to a specified depth. These techniques (described in detail in Chapter 4) were adapted for use in the present study to compute volumes of water given a known pond centre location and pond depth.

3.2.5 Conclusion - justification of field methods

A number of conclusions pertinent to the present study arose from the evaluation of the literature detailed above.

With respect to techniques for mapping the spatial distribution of soils and soil properties, it was concluded that conventional methods using a choropleth model and based on soil-landscape relationships were preferable to automated methods for estimating the continuous distribution of single soil properties. One reason for this decision was that a strong and predictable relationship between soils and landscape position was evident at the selected site. A second justification was that estimation of the continuous distribution of single soil properties would have required a greater level of sampling, field measurement, laboratory analysis and method development than was feasible or justified. A final consideration accepted the argument of Elrick et al. (1989) that given the large spatial variability of soil hydrological properties it was preferable to strive for only order of magnitude levels of accuracy in the estimation and assignment of hydrological parameters.

With respect to techniques for characterising soil hydrological properties, it was concluded that methods involving direct field measurement should be used wherever possible. The Guelph permeameter method of Elrick et. al. (1989) was selected for determining saturated hydraulic conductivity. The time domain reflectometer method of Topp et. al. (1980) was selected for field measurement of soil moisture content but gravimetric sampling (McBride and Mackintosh, 1984) was undertaken as a back-up. Moisture content at saturation was not measured directly in the field but was estimated from bulk density according to Beasley and Huggins (1981). Bulk density was determined from field sampling using a split core method similar to that described by McBride and Mackintosh (1984). Field monitoring of soil moisture content and tension attempted to identify moisture content at field capacity (33 kPa) and wilting point (1500 kPa) for each major horizon of each soil. The field measurements were used to verify existing estimates for these values for each identified soil type and horizon.

With respect to estimating depth of snow and snow water equivalent, the work of Zebarth and de Jong (1989a) was concluded to provide locally relevant and applicable guidelines. Emphasis was placed on determining the spatial pattern of depth of snow with little consideration for snow density.

With respect to mapping the distribution, depth and volume of surface water, none of the available techniques was considered suitable on its own for the present purposes. It was concluded that direct field survey of pond location and depth combined with computation of volumes using automated processing of digital elevation data would provide the most appropriate data for the present study.

3.3 Experimental design - field study

The principal objectives of the field study were to select and characterise a farm scale study site in support of subsequent simulation modelling efforts and to document the actual, observed location and extent of ephemeral ponding at the site during a period of spring snowmelt and runoff. The specific objectives of the field study (Figure 3.1) were:

a) To locate and select a suitable, farm scale, study site with numerous depressions and available meteorological data.
b) To identify and characterise the principal soils and landforms at the study site and to describe how they responded to spring snowmelt and runoff.
c) To measure or estimate the hydrological and morphological properties of the principal soils in support of subsequent simulation modelling.
d) To monitor and record the variation in soil moisture and tension at selected locations at the site to provide input data for simulation modelling and to develop a conceptual understanding of the pattern of moisture movement through the various soils.
e) To record the values of the meteorological parameters at the site controlling hydrological inputs and losses.
f) To record the observed locations of ephemeral ponding at the study site and to document the pattern of development, growth and disappearance of ponds at the site during spring runoff.
g) To assess the observed pattern of ephemeral ponding with respect to the topographical, soil, hydrological and meteorological conditions recorded for the site.

The steps taken to select and characterise a suitable farm-scale study site and to document the location and extent of observed ponding (Figure 3.1) may be summarized as follows:

A farm scale study site characterised by numerous closed depressions containing ephemeral ponds was identified and selected. Access was obtained to the site and cooperation was secured from the farm owner/operator.

The soils and landforms at the site were mapped to establish the physical characteristics affecting the generation of surface runoff and its accumulation in ephemeral ponds.

Representative sites were selected and instrumented to determine hydrological properties of the soils and to record the seasonal fluctuations in soil moisture status affecting hydrological behaviour.

Instrumentation for recording meteorological conditions at the site was set up and monitored continuously from just before spring melt until late autumn. The meteorological data were used as input in subsequent simulation modelling efforts. Snow depth was recorded just prior to spring melt in order to assess the contribution of melting snow to runoff and pond development.

The locations and extent of all ephemeral ponds observed at the site were recorded at regular intervals throughout the period of spring snowmelt and runoff. The observed pattern and timing of ephemeral ponding was analysed in terms of the recorded meteorological inputs and site conditions. Each of the above steps is explained in the following section.

3.4 Methods - field study

Significant portions of the field study consisted of contributions made by individuals other than the present author. The author selected, mapped and sampled the site, chose the locations for instrumentation and installed the first few sites in collaboration with technical field personnel. Most of the routine monitoring and recording of meteorological conditions and pond extent was undertaken by technical field personnel while the author was in residence at the University of Edinburgh and not present to conduct ongoing investigations. The contributions of those who assisted in the field work are documented and recognised in Table 3.1.

3.4.1 Site selection and general characterisation

An evaluation of pertinent literature and consideration of expert opinion revealed that undesirable temporary ponding of agricultural lands was considered to be most extensive within the Black soil zone in Alberta. The Black soil zone receives the greatest amount of winter snowfall and spring rainfall of the agricultural regions of Alberta and experiences the lowest spring time evapo-transpiration. The decision was therefore taken to identify a suitable location within the Black soil zone at which to measure and model the spring-time runoff and accumulation of surface water.

A list of sites with appropriate topographical, climatic, drainage and soil conditions was drawn up. Sites with existing meteorological instrumentation and detailed topographical (DEM), soils or hydrological data were considered as most suitable for selection. Guaranteed long term access to the site and proven landowner cooperation were also considered important criteria for selecting a site. The site satisfying the largest number of criteria (the Lunty site) was selected for detailed instrumentation and study.

Topographical maps at a scale of 1:50,000 and aerial photographs at various scales ranging from 1:3,500 to 1:30,000 were obtained for the Lunty site. The boundaries of the area to be studied were delineated and the approximate dimensions determined from the aerial photos. The topographical map was used to describe the site in terms of its topography, local relief, drainage, slope gradients and slope lengths. The existence of numerous temporary ponds was confirmed by examination of aerial photographs of varying age and scale. The number and relative permanence of ephemeral ponds was inferred from an examination of the aerial photos and confirmed by landowner records.

The history of cultivation and land use at the site was provided by the owner-operator of the farm, Mr. Glen Lunty. Long term meteorological data for the closest Environment Canada climate station were obtained and tabulated for comparison with meteorological data recorded at the Lunty site. A preliminary description of the geology and soils at the site was prepared using published, secondary source information (Green, 1972; MacMillan, Nikiforuk and Rodvang, 1988; Moran et al., 1990a,b; Maslowski-Schutze, Li, Fenton and Moran, 1986) and unpublished site investigations (Trudell, personal communication, 1989).

3.4.2 Soil classification and mapping of the Lunty site

A detailed soil survey was conducted to identify the main types of soil at the Lunty site and to determine their spatial distribution. The soils data were collected on a regular grid with a spacing of 40 m in the N-S direction and 80 m in the E-W direction. The 40 m grid spacing was selected to capture most of the major topographical variation in the landscape. The grid locations had been accurately surveyed and marked with stakes as part of a previously conducted survey of electrical conductivity made in support of a different research project (Trudell, personal communication, 1989). Grid locations had also been surveyed at 40 m intervals in the E-W direction but there was insufficient time to visit all surveyed sites. Consequently, soil investigations were only carried out along every second surveyed line in the E-W direction. It had been hoped to return to fill in the data for the missing sites, but this did not prove possible.

A small soil pit was dug to a depth of about 50 cm at each grid location (Figure 3.2a) and a Dutch soil auger was used to complete the investigation to a depth of 100-120 cm. A standard series of observations (Table 3.2) of topographical and soil profile characteristics was recorded at each site and the site was classified at the soil series level according to the Canadian System of Soil Classification (Expert Committee on Soil Survey (ECSS), 1987b).

Field observation and classification data for each grid site were keypunched into a dBase III+™ data file. A grid map displaying the location and soil series for each investigated site was constructed by manually plotting the site number and three letter soil series code at each grid observation point onto a mylar overlay of a photographic base map of the study site. A series of grid maps of other themes of information (not presented here) was prepared at the same scale and overlain manually on the photographic base map of gridded soils data. The overlay themes included the topographic contour map, computer derived maps of slope gradient and curvature and computer plotted grid maps of electrical conductivity, depth to bedrock and depth to mean annual water table. These themes of information were analysed collectively to help produce the best possible generalised, polygon map of landscape based soil map units.

Two cross sectional transects of the study area were located so as to traverse the full range of topographical and soil conditions identified for the site during the initial grid soil survey. The locations of transects were selected so as to pass through most of a



series of 44 previously established piezometer sites installed for field monitoring of groundwater levels (Trudell, personal communication, 1989). These existing sites were adopted in order to minimize any further disruption to cultivation and to ensure maximum protection (existing piezometer sites were well marked and avoided by the farmer). Cross sectional diagrams were constructed to record and illustrate the relationships between type of soil and topographic position using data from the transect sites.

The polygon soil map was digitized using the commercial geographical information system product ARC/Info™. The ARC/Info™ utility POLYGRID was used to generate a raster image of the polygon soil map with dimensions of 160 rows by 140 columns. The raster file identified the soil map unit associated with each 5 m x 5 m grid cell at the Lunty site. These data were imported into the main dBase III+™ data file for the Lunty site and used as the basis for assigning soil parameters to grid cells during subsequent modelling efforts.

3.4.3 Characterisation of hydrological properties at selected sites

Soil pits were dug at 18 of the 27 sites and complete descriptions of the observed soil profile characteristics were made. All soil pits were at least 1 metre deep and large enough (1 by 2 metres) to permit photographs to be taken of the full profile depth. Nine sites were not described for various reasons, the principal being seasonal inundation or close similarity to nearby, previously sampled sites. Disturbed samples were taken from all major horizons for laboratory analysis of chemical and physical properties. These data were used to classify and characterize each soil profile.

Detailed soil profile descriptions of the 18 sampled sites were made according to standard Canadian procedures for describing soils in the field (Expert Committee on Soil Survey (ECSS), 1983). A standard suite of laboratory analyses (Table 3.4) was conducted to characterise the sampled soils and to aid in their classification. Methods used by the Alberta Research Council soils laboratory follow standard Canadian procedures for laboratory analysis of soils (McKeague, 1978; Sheldrick, 1984).

A truck mounted hydraulic corer (Figure 3.2b) was used at 24 of the sites to obtain (relatively) undisturbed core samples of soil from the major horizons. It was not possible to sample 3 of the 27 sites due to permanent inundation. The core samples were taken in four depth intervals; specifically 0-15 cm, 15-40 cm, 40-60 cm and 60-

100 cm. Each core was cut to an accurately measured length (usually 10 cm) and the volume of the core was determined and recorded. The core was then weighed at field moisture content and again after drying at 105 °C for 24 hours. Bulk density was calculated for each core according to the formula:

$$BD = \frac{\text{Oven Dry Weight (gm)}}{\text{Core Volume (cm}^{-3})} \qquad \textbf{(3.1)}$$

The hydraulic core method of sampling was selected in preference to manual sampling using the more conventional Uhland core sampler. Extensive local experience in comparing the two methods has shown the hydraulic core method to be both faster and more accurate (Macyk, personal communication, 1989). Total porosity was calculated as suggested by Beasley and Huggins (1981) by dividing the measured soil bulk density by an assumed particle density of 2.65 kg m^{-3}, multiplying by 100 and subtracting this sum from 100 according to the formula:

$$TP = \left(1 - \frac{BD}{2.65}\right) * 100 \qquad \textbf{(3.2)}$$

Mean values of bulk density and total porosity were calculated for each horizon at each site. The relevance of the calculated mean values was assessed through three different independent checks.

The first check involved simply comparing the calculated mean values for bulk density (BD) and total porosity (TP) at each site with those recorded in the Alberta provincial soil layer file data base for each sampled soil series. The second check was based on determining whether the calculated mean bulk density produced reasonable estimates of volumetric soil moisture content when used to convert from measured gravimetric moisture content to estimated volumetric soil moisture. The third check was based on computing an apparent field bulk density for each site and depth and comparing this apparent bulk density to the bulk density determined in the laboratory from semi-disturbed cores. The apparent field bulk density was calculated by dividing the volumetric soil moisture content recorded at each depth at each site by the gravimetric moisture content recorded for the equivalent depth and time at each site. Wherever the field measured bulk density differed consistently from that predicted by each of the three check methods, an error was suspected. Suspect values were disregarded when compiling the final estimates of field bulk density and total porosity.

Saturated hydraulic conductivity was determined at 22 of the 27 monitoring sites (Table 3.3). Four of the sites were permanently inundated and could not be sampled. A Guelph permeameter (GP) was used to measure saturated hydraulic conductivity at each of three tested depths using the one-ponded height technique described by Elrick et al. (1989). Tests were attempted within each of the three depth intervals 0-15, 15-40 and 40-60 cm at each of the 22 sites. Where possible, two or three replicate measurements were obtained in each depth interval by increasing the height (H) of the ponded head above the base of the test hole in 5 cm increments.

The values of saturated hydraulic conductivity determined by the GP were averaged by site by depth and by soil series and compared to previously existing estimates of hydraulic conductivity for each soil series. Values in serious disagreement with existing estimates were subjected to further scrutiny to determine if they could be accepted. Upon inspection, some values recorded as pertaining to one horizon, were obviously similar to those made for an overlying or underlying horizon. In such cases, it was assumed that the test zone for the GP had penetrated into a lower horizon or extended upward into an overlying horizon and the recorded value was reassigned to the appropriate horizon.

A final summary table of estimated values for bulk density (BD), total porosity (TP), field capacity (FP), wilting point (WP) and saturated hydraulic conductivity (Ksat) was prepared using reasonable, modal values for these parameters for each soil series and horizon. The modal values were based on consideration of all available sources of data including direct field measurement, indirect calculation from volumetric and gravimetric soil moisture and existing soil layer file estimates.

3.4.4 Field measurement of soil moisture status

Three different methods were used to determine soil moisture content at several depths at all permanent monitoring sites. These were time domain reflectometry (TDR), gypsum blocks and auger sampling for laboratory determination of gravimetric soil moisture. Soil moisture information was required to establish initial moisture conditions for simulation modelling. The recorded maximum and minimum moisture content for each type of soil was also used as a cross validation for estimates of moisture content at saturation (TP) and at wilting point (WP) for each soil series.

An IRAMS time domain reflectometer manufactured by Foundation Instruments Ltd. of Ottawa, Canada was used to determine volumetric soil moisture content. The principles and procedures associated with measuring soil moisture by time domain reflectometry (TDR) are documented in a series of papers by Topp and others (Topp and Davis, 1982, 1985a; Topp, Davis, Bailey and Zebchuk, 1984; Topp, 1987). TDR has been recommended as a preferred field method for repeated determination of soil moisture content in soils (Topp, 1987).

Each of the 27 permanent monitoring sites was instrumented to permit recording of volumetric soil moisture with the IRAMS device. Three sets of paired metallic guide rods 6.4 mm in diameter were inserted vertically to depths of 15, 40 and 60 cm at each of the sites. A guide frame, supplied by the manufacturer, was used to maintain a parallel separation of 5 cm between each pair of rods. The volumetric moisture content was read at approximately weekly intervals beginning after installation in June, 1989, continuing until October, 1989 and resuming again from April 1990 until June 1990. The readings applied to depth intervals of 0-15, 0-40 and 0-60 cm and were recorded directly in percent volumetric water content.

The initial TDR readings were adjusted to correct for a systematic overestimation of soil moisture by the IRAMS device as reported by Topp and Culley (1989). The generalized pooled correction equation (3.3) suggested by Topp and Culley (1989) was used to correct the TDR readings at all depths.

$$\theta_C = \theta_I + 0.08 \qquad \textbf{(3.3)}$$

where: θ_C = corrected volumetric moisture content $m^3\ m^{-3}$
θ_I = initial IRAMS volumetric moisture content $m^3\ m^{-3}$

A second correction was required to compensate for instrument malfunction under extremely wet soil conditions. The IRAMS instrument failed to return usable estimates of soil moisture for the 0-60 cm interval in cases where the soil was at, or close to, saturation throughout most of that interval. Topp (1987) noted this tendency and explained it as instrument error associated with determining travel times from digitized TDR traces. In cases where the IRAMS returned an E2 error message indicating excessive soil moisture, the moisture content of the 40-60 cm interval was assumed to be at saturation.

Estimates of the soil moisture content over the depth intervals 15-40 and 40-60 cm were calculated by differencing as detailed by Topp (1987). Topp (1987) pointed out that estimates of volumetric soil moisture calculated by the difference method had twice the variance of the original measurements. He reported a confidence interval for vertical TDR measurements of soil moisture by difference calculation of 0.096 m^3m^{-3} compared to 0.033 m^3m^{-3} for direct readings from horizontal TDR guide rods.

Model 5201 gypsum blocks manufactured by Soilmoisture Equipment Corp. of Santa Barbara, California were installed at all 27 sites. These provided a rough estimate of soil tension and corresponding moisture content. All blocks were checked and calibrated prior to installation according to procedures described by Tanner, Adams and Zubriski (1948). Blocks were installed at three depths corresponding to the TDR depth intervals of 0-15, 15-40 and 40-60 cm. The precise depth of installation was varied at each site to permit the blocks to be located within the predominant soil horizon associated with that interval. For example, in an Ap horizon of depth 13 cm, installation occurred at about 10 cm depth in order to ensure that the block was located entirely within the Ap horizon and not at, or below, the boundary between the Ap and the underlying B horizon that occurred at 13 cm. This was done to ensure that the interval sampled by the gypsum block corresponded as closely as possible to that sampled for the TDR measurement.

The gypsum blocks were read at approximately weekly intervals during the growing season using a model 5901-A soilmoisture meter. Meter readings were converted to soil suction in bars and gravimetric moisture in percent of dry weight according to graphs supplied by the manufacturer.

Soil cores were obtained at each site at approximately monthly intervals from April 1989 through to October, 1989 and again during April and May, 1990. Samples were taken from each of the depth intervals 0-15, 15-40 and 40-60 cm and analysed to determine gravimetric soil moisture content. The equivalent volumetric soil moisture content was estimated by multiplying the measured gravimetric moisture by the best modal value for bulk density for each horizon at each site. This facilitated comparison of the gravimetric moisture estimates to volumetric estimates made using TDR or gypsum blocks.

Ultimately, the gravimetric determinations were deemed to be more reliable than those provided by either TDR or gypsum blocks and were used to establish the soil moisture

characteristics of the main soil series at the Lunty site (see results section 3.5.3). The gravimetric soil samples were used to compute modal soil moisture profiles for each soil series for each of the growing season months of April to October. These modal profiles provided a record of the observed extremes of soil moisture at each depth in each type of soil. They also provided an indication of the temporal pattern of change in soil moisture with depth throughout the April - October season. Interpretation of these modal profiles permitted some assessment of the magnitude and direction of water movement through the profile from spring through to autumn.

3.4.5 Monitoring and processing of hourly meteorological data

Meteorological instruments were installed at the Lunty site to permit automatic recording of hourly values for the variables of rainfall, temperature, solar radiation and relative humidity. Instrumentation at the site (Table 3.5) included a tipping bucket rain gauge, a thermister for air temperature, a pyranometer for global solar radiation and a calibrated horse hair sensor for relative humidity. An anemometer was set up to record total miles of wind at approximately weekly intervals but did not provide hourly values for wind speed. Total cumulative pan evaporation from a Sierra/Misco Inc. class A evaporation pan was recorded manually at approximately weekly intervals from early April until late October in 1989. Thermisters for measuring soil temperature were installed at the surface and at a depth of 0.2 m at the pan evaporation site. All data were recorded on a Meteograph M710 mechanical strip chart recorder. The strip charts were delineated into two 2 hour intervals for a recording period of seven 7 days and were changed at regular weekly intervals.

Additional meteorological data were obtained from a second nearby site (Henderson site, 53° 4' N, 111° 56' W) also operated by the Alberta Research Council (Howitt, 1991). Data were obtained from this site for two reasons. Firstly, the mechanical recorder at the Lunty site was unable to operate during periods of intense cold or deep snow in late winter and early spring. The Henderson site utilised a more robust digital recording device (Omnidata Easylogger Model No. EL824) which was able to operate under these adverse conditions. It was necessary to use data from this site from March 15 until April 5, 1989 when the strip chart recorder at the Lunty site became operational. The second reason for using data from the Henderson site was that hourly wind speed was not available for the Lunty site but was recorded at the Henderson site. The requirement for hourly wind speed data was not anticipated initially and was not appreciated until after the components of the simulation model

dealing with evaporation and snowmelt had been constructed. Hourly wind speed data from the Henderson site were used to overcome this deficiency. The meteorological data were used mainly as input for simulation of snowmelt, evaporation and rainfall runoff in the distributed runoff model (DISTHMOD) described in Chapter 5.

Hourly data for the Lunty site were extracted from the individual weekly strip charts and tabulated manually. The data were then entered into a digital dBase III+™ data base file. The data for each variable were examined in both tabular and graphical form to identify entry errors, missing data, and anomalous values. The data initially extracted from the paper strip charts represented absolute values for each variable at each hour. The absolute readings on the hour were converted to average hourly values according to:

$$\text{HrAve} = \frac{\text{Val}_{(t)} - \text{Val}_{(t-1)}}{2} \qquad \textbf{(3.4)}$$

The corrected Lunty average hourly data were merged with digital data from the Henderson site for the period March 22, 1989 to April 5, 1989. Henderson site data were also inserted for a limited number of periods when instrument malfunction at the Lunty site resulted in missing or erroneous data. The resulting, merged data set was again reviewed in tabular and graphical format to identify and correct possible errors or omissions. The final, clean data set was tabulated and graphed for presentation.

Hourly estimates for degree of cloud cover were generated by interpreting the hourly global solar radiation data. The maximum clear sky global radiation observed for each hour during each weekly period of recording was noted and tabulated in a separate file. The set of all maximum possible values for each hour of the day for a given week defined an envelope representative of the expected solar radiation under cloud free conditions. A small program was written in dBase III+™ to compare the hourly average global radiation for each hourly interval to the observed maximum possible value for the cloud free envelope. The degree of cloud cover was calculated as a function of the degree of depression of the observed global radiation relative to the expected clear sky maximum according to:

$$\text{Cloud} = 1 - \frac{R_{obs}}{R_{max}} \qquad \textbf{(3.5)}$$

where: R_{obs} = Observed global radiation W m^{-2}

R_{max} = Maximum expected radiation for that hour W m^{-2}

This provided a reasonable estimate of cloud cover fraction during daylight periods in the absence of direct measurements of this variable. Cloud cover could not be estimated for night time periods by assessing the reduction in global radiation relative to an expected maximum. Instead, hourly cloud cover for the night-time period was estimated by interpolation. A program written in dBase III+™ and compiled in Clipper™ (CLOUDS.prg) scanned the hourly meteorological data set (ALLMET89.dbf) and identified the last hour with positive global radiation for each day and the first hour with positive global radiation for the following day. It then moved back one hour in the evening and ahead one hour in the morning and read the previously estimated values for degree of cloud one hour before sunset and one hour after sunrise. The total increase or decrease in cloud cover over this time period was computed and divided by the number of hours between the last evening estimate of cloud cover and the first morning estimate. This gave an estimate of the linear rate of change in cloud cover over the night time period. The linear rate of change in cloud cover was applied to compute an interpolated estimate of the expected cloud cover for each hour between sunset and sunrise the next day.

Total cumulative rainfall as well as total cumulative pan evaporation were tabulated for the period March 31, 1989 to Oct. 30, 1989. Pan evaporation was initially recorded as net change in volume of water in the evaporation pan over the period of time between the last reading date and the current reading date. The total change in volume was adjusted to account for any additions arising from recorded rainfall over the equivalent period. The corrected pan evaporation was recorded as net evaporation during each time interval and total cumulative evaporation beginning March 31, 1989.

3.4.6 Acquisition and processing of detailed digital elevation model

The digital elevation model was acquired by and for a pre-existing Alberta Research Council project (Trudell, 1989 personal communication). The DEM was produced by Alberta Forestry Lands and Wildlife using an analytical stereo plotter. It was based on specially flown 1:3,500 scale aerial photographs taken in October, 1987. Registration and rectification of the aerial photography used six (6) accurately surveyed ground targets laid out in the field to coincide with the aerial photography.

The initial DEM recorded vertical elevation in metres to three decimal places (1 mm) for points spaced at regular intervals of 5 metres in the horizontal dimension. The vertical resolution of this initial DEM was purposely degraded by rounding elevations to the nearest 0.1 metre (10 cm). The lower vertical resolution was imposed to reflect limitations in the data set more realistically. It recognized the existence of short range variation in elevation associated with furrows and ridges produced by cultivation. These ridges could be up to 10 cm in height, so changes in elevation of less than 10 cm between adjacent points were not considered significant. Such changes were considered as noise which could possibly have resulted from differences in the location of the surveyed points relative to the top or bottom of a furrow.

The horizontal resolution of the DEM (5 x 5 m) was selected for a variety of reasons. Firstly, it was small enough to capture virtually all of the major slope inflections and changes in topography. Secondly, a minimum size area for agricultural management was defined as 10 m square and sampling theory therefore calls for a sampling interval of one half the miniumum size area. The minimum size area was defined based on consideration of the size of area that could be effectively managed differently using current agricultural implements and practices. For example, a 30 foot (10 m) cultivator should be able to cultivate at least one half of its width (5) into a wet or inundated depression with passes from 2 sizes permitting the entire depression to be cultivated. Finally, a depression of 10 m square was considered a practical minimum target for consideration by the present research. Ponds smaller than 10 m by 10 m were judged unlikely to be large enough or to persist long enough to be of much significance to agricultural use of the land.

The initial DEM consisted of a regular matrix of 161 rows by 147 columns. The farm yard and buildings occupied the area covered by the last 7 columns of rows 120 to 161. Consequently, this area had not been surveyed and portions of the last 7 columns of data were incomplete. In addition, row 161 was significantly lower in elevation than row 160 and appeared to possess a systematic error. The initial DEM of 161 rows by 147 columns was therefore reduced in size to a regular grid of 160 rows by 140 columns which contained no missing or suspect data.

3.4.7 Determination of spring snow depth and moisture equivalent

Depth of snow was measured at 41 sites, corresponding mostly to existing sites of monitoring wells, on a single day (March 21, 1989) just before the onset of spring melt. The snow depth sites were selected to encompass the full range of landscape positions at the site. No determination was made of the density or water equivalent of the snow. Water equivalent was calculated using an estimated density of 0.23 Mg m^{-3} in accordance with values reported by Zebarth and DeJong (1989a) for a study site in a similar environment in the Black soil zone of Saskatchewan.

An estimate of snow depth was required at each of the 22,400 grid cells of the Lunty site DEM as input for subsequent simulation modelling of surface runoff. Two methods were adopted for estimating the depth of snow. In the first approach, an average value of snow depth was computed based on the measured depth of snow at the 41 snow sampling sites. The average snow depth was then allocated to every one of the 22,400 grid cells of the model.

The second approach was based on the observations of Zebarth and de Jong (1989a) that depth and water equivalent of snow were well correlated with topographic variables. The topographic variables profile curvature (PROF) and plan curvature (PLAN) were calculated for all grid elements using the algorithms adopted by Zebarth and de Jong (1989a) as detailed in Martz and de Jong (1988) and Pennock et al. (1987). A variable called upslope area (UPS) equivalent to local catchment area (LCAT) as used by Zebarth and de Jong (1989) was computed using the **Watersh** modelling program (van Deursen and MacMillan, 1991) described in greater detail in Chapter 4. The variables PLAN and UPS were transformed to achieve greater normality as suggested by Zebarth and de Jong (1989a). The corrected variables PLANt and UPSt were normalised using the modified natural log transformations:

$$PLANt = \ln(PLAN + 1) \text{ for } PLAN \geq 0 \qquad (3.6)$$

$$PLANt = -\ln[(-1 * PLAN) + 1)] \text{ for } PLAN < 0 \qquad (3.7)$$

$$UPSt = \ln(UPS + 1) \qquad (3.8)$$

A series of multiple regressions (WILKINSON, LEYLAND. SYSTAT, 1990) were run with snow depth at the 41 sampling sites as the dependent variable and the topographic indices UPSt, PLANt and PROF at the corresponding sites as the independent variables. The regression equation with the best fit (see Table 3.14) was applied to the topographical index UPSt computed for every grid cell to estimate the depth of snow at all of the 22400 grid cells in the data set (see Figure 3.12).

3.4.8 Determination of pond location, depth and volume

The locations of all ephemeral ponds at the Lunty site were recorded at approximately weekly intervals beginning March 31, 1989 and continuing through May 24, 1989. Observations on the location and extent of the few semi-permanent ponds remaining after this date were made until Aug. 21, 1989 at approximately monthly intervals and after any period of heavy rainfall.

The locations of ponded areas were initially recorded by inserting wooden stakes into the ground at the apparent centre of each pond and at four locations corresponding to the maximum dimensions of each pond. The stakes were marked with a unique pond identification number and the date on which they were inserted. All ponds of any significant extent that were identifiable on the day the weekly survey was conducted were staked and their approximate location and depth were recorded in a field notebook. The elevation of each perimeter stake where it entered the ground was taken to represent the maximum elevation of ponding at that site.

The exact elevation of each of the stakes was determined by transit and rod survey using a Nikon AP-5 automatic level. Distances were measured using a 100 m fiberglass tape. The stakes were surveyed at several different times in order to accommodate normal farming operations. Most of the ephemeral ponds in the cultivated portions of the site had disappeared by May 5, 1989. All stakes documenting the extent of these short-lived ponds were surveyed and removed by May 5, 1989 in order to permit the farmer to proceed with cultivation and seeding. Stakes surrounding some of the more permanent ponds were surveyed and removed during the week May 24 to June 1, 1989 and again during the week August 13-20, 1989. The location and elevation of each pond centre was also determined during the course of these surveys.

The location of each pond centre as determined by the transit survey was matched with a corresponding grid location in the 160 row by 140 column DEM. The surveyed elevation of the pond centre was compared to the elevation of the corresponding DEM grid cell. An exact match was not anticipated since the DEM grid cell represented the elevation of the closest grid point within 5 m of the surveyed pond centre, not the elevation at the exact pond centre. In addition, the DEM elevation values had been purposely rounded to the nearest 0.1 m. None the less, determining the degree of correspondence between the surveyed and DEM pond centre elevations provided a useful check of any possible registration problems.

The depth of ponding at any given date was determined by subtracting the surveyed elevation of the pond centre (the lowest elevation in the pond) from the surveyed elevation, at the intersection with the ground surface, of each stake driven in to record the maximum extent of the pond at that date. The average depth of ponding at any given date was computed as the mean of all available staked elevations (usually four). The field survey information on pond location, extent, elevation and depth at each of the pond survey dates was recorded in a dBase III+™ file (PONDSURV.dbf).

A program to compute the areal extent and total volume of each pond at each depth (PONDMAP) was written in dBase III+™ and compiled in Clipper™. The program PONDMAP (Appendix 1) read pond survey data from the file PONDSURV.dbf and acted on the indexed dBase III+™ data file (LUNTYGRD.dbf) described in detail in Appendix 10.

The PONDMAP program read from the file PONDSURV.dbf the location (row, col) and elevation of each pond centre for ponds observed to exist on any given pond survey date. It also read the pond centre elevation, the maximum elevation of ponding and the depth of ponding at that date. The program then switched to the file LUNTYGRD.dbf and located the corresponding grid row and column for each pond centre location in turn.

The file LUNTYGRD.dbf was indexed by catchment by upslope area by elevation. Each catchment corresponded to the watershed associated with one of the observed centres of ephemeral ponding. The procedures used to compute upslope area and to assign grid cells to catchments are described in detail in chapter 4. The effect of the indexing (BOTTOMUP.ndx) was to place the grid elements of LUNTYGRD.dbf into a sequential order by elevation within each depressional catchment. The first cell

encountered in any depressional catchment was the cell of lowest elevation and was therefore the pit centre. The next cell was the next highest cell in elevation in that given watershed and so on until the highest elevation cell in the watershed was reached.

The program PONDMAP relied on this sequencing to identify quickly all cells within a given depressional catchment that were lower in elevation than the maximum elevation of ponding recorded for that pond at any given date. The program simply traversed the grid cells, ordered by ascending elevation within each catchment, until it encountered the first grid cell with an elevation greater than the maximum elevation of ponding recorded for that pond and date. All other cells in the catchment were then assumed to be higher in elevation than the maximum elevation of ponding and therefore not of interest in computing pond depth or extent. As the program traversed the grid cell data file, it subtracted the elevation of each grid cell from the recorded maximum pond elevation for that date to produce a value for depth of ponding at that grid cell. The volume of water ponded over each cell was computed as simply the depth of ponding times the unit area of a grid cell (5m*5m = 25 m^2). The total volume of water in the pond was computed as the sum of the individual volumes of water at each grid element. The total area of the pond at any given date was computed as the number of grid cells in the catchment that were lower in elevation than the recorded maximum elevation of ponding and were therefore flooded (times the unit area of one grid cell).

The program PONDMAP produced two sets of output. The first set was a simple tabular database (PONDSTAT.dbf) which mirrored the information in the original PONDSURV.dbf data base but included the additional data on total pond volume, pond depth and pond area for each pond at each date computed by the program PONDMAP. The second set of output consisted of a listing of the depth of ponding computed for all 22,400 grid cell elements of the file LUNTYGRD.dbf for each pond survey date. All grid cells not flooded at any given date had an assigned depth of ponding of zero. Any grid cell flooded by ponded water at any given date was assigned a value corresponding to its computed depth of ponding. This data was reformatted into a matrix of 160 rows by 140 columns and presented as maps and three dimensional perspective views to illustrate the location, extent and depth of ponding recorded for all ponds at the Lunty site at any given date.

The maps and data bases of location and depth of ponding at selected dates were analysed to describe the spatial and temporal patterns of ponding at the Lunty site relative to the measured amounts of input from rainfall and snowmelt and losses arising from evaporation or infiltration. Several of the maps were subsequently used to assess the relative ability of a distributed hydrological model (DISTHMOD) to simulate the location and extent of actual, recorded ponding correctly.

3.5 Results - field study

3.5.1 Site selection and general description of the Lunty site

The Lunty study site (52° 40'N, 112° 7'W) is located in the Black soil zone, near the town of Forestburg about 200 km south east of Edmonton, Alberta (Figure 3.3). The region is characterised by hummocky topography, with a closed, non-integrated, drainage pattern and numerous, shallow depressions. The depressions are occupied by seasonal ponds covering about 10-20% of the land surface (Figure 3.4a). There is no evidence of an integrated drainage pattern at the site and surface water flows into local, un-drained depressions where it accumulates and remains until lost through infiltration or evaporation. Ponds may develop in depressions at up to 18 locations within the boundaries of the study area (Figure 3.4b). Six of the ponds are semi-permanent and retain water from spring to fall. The remaining ponds are ephemeral and accumulate water for short periods only, following spring runoff or major rainfall events. Ponds range from less than 0.1 to over 4 ha in size.

The Lunty site is fairly typical of cultivated landscapes within the Black Soil Zone of east central Alberta (Figure 3.3). It is part of a low-relief, undulating to hummocky till plain (Figure 3.4 a). Maximum local relief is 8 metres with elevations ranging from 721 m to 729 m (Figure 3.5). Slope gradients average 2-5 percent for most upper, convex portions of the landscape. Few slopes are steeper than 6-9 percent. Slope lengths average 75-150 m and range from 50 to 400 m. The many depressions are level to slightly convex with slope gradients of 0-2 percent.

The site occupies an area measuring 700 m by 800 m (Figure 3.4b) approximating the dimensions of a typical farm-scale management unit in western Canada (quarter section). It encompasses portions of two adjacent quarter sections legally designated

as the east half of SE 5-41-15 W4 and the west half of SW 4-41-15 W4. These quarter sections are components of a operational mixed farm operated by Mr. Glen Lunty. Normal farming operations were carried out throughout the period of research but care was taken to protect monitoring sites from disturbance or damage.

The three fields comprising the study site are cultivated annually to small grains and oilseeds. The fields have been cropped continuously for over 15 years. The timing of field operations and types of crops grown on the two quarters in 1989 are summarised in Table 3.6. The land is generally cultivated only once in the spring after spring snowmelt and runoff are completed (mid April - mid May). Seeding takes place from mid to late May and crops begin to emerge by early June. Crops are harvested in late August to September and most years the fields are left in stubble until the following spring. Most spring runoff occurs on bare stubble or fallow fields in which the soil remains frozen at some shallow depth (10-20 cm).

A graded, non-graveled, road and its accompanying ditches bisect the site from north to south. A 1 m deep ditch paralleling a graveled, county road defines the southern edge of the study area and an east-west fence line defines the northern boundary. No natural or man made features define the east or west margins of the study area.

The regional climate at the site is characterized by long cold winters and short warm summers. The 30 year long term average annual rainfall is 385 mm (Alberta Environment, 1989) and the average annual evapo-transpiration is about 700 mm . An Environment Canada weather station is located 3 km south of the site at the Forestburg power generation plant (Figure 3.3). Long term records are available for this station for minimum and maximum temperature, daily precipitation and precipitation falling as snow.

A comparison of the 1989 monthly averages for precipitation and temperature at the nearby Forestburg Plant Site AES station with the corresponding long term average data (Table 3.7) indicates that the weather during the spring of 1989 was fairly typical. February and March were colder and dryer than normal (data not shown). Overall, spring precipitation was just slightly above the long term average. Mean monthly temperature was slightly above the long term average (LTA) during all 4 months of March to June. Total snowfall for 1989 was 20 % below normal (567 mm vs. 714 mm) (Alberta Environment, 1989).

Meteorological data collected at the Lunty site indicated significant differences between conditions at the site and at the Forestburg AES station. Less precipitation was recorded at the Lunty site than at the AES site for all months except June. Rainfall was markedly lower at the Lunty site in April and May. Most spring time precipitation in the region is derived from individual convective showers. These showers are often very localized and deliver rainfall along a discrete path. Many showers follow the natural corridor offered by the Battle River valley and pass over the AES station while missing the nearby Lunty site completely. Mean monthly air temperatures were also consistently lower at the Lunty site than at the AES plant site. Temperatures at the river valley plant site are known to be affected by discharge of steam into the air and warm water into the plant reservoir. The differences in meteorological conditions between the Lunty site and the nearby Forestburg plant site AES station illustrate the problems inherent in extrapolating data from existing stations to sites even short distances away.

Regional geological studies show the study site to be underlain by non-marine sandstones, mudstones and shales of the Upper Cretaceous Horseshoe Canyon Formation (Green, 1972). This is overlain by a brownish, clay loam textured, weakly calcareous, non to moderately saline and sodic till from 1 to 15 m thick (Mac Millan et al, 1988).

Detailed site investigations (Maslowski-Schutze, Li, Fenton and Moran, 1986; Trudell, personal communication, 1989) confirm and extend this general description. The underlying bedrock consists of about a metre of very fine grained non-marine sandstone representing the Delta Sandstone unit of the Horseshoe Canyon Formation. The Delta Sandstone is underlain by inter-bedded marine shale and siltstone of the Bearpaw Formation. The bedrock surface is relatively flat and dips gently to the north east. The overlying unconsolidated material is a slightly saline to non-saline clay loam till containing minor lenses of sand and gravel. The unconsolidated material varies from 3 to 10 m in thickness overlying bedrock. Tests of the hydraulic parameters of the geologic materials (Moran et al., 1990b; Trudell, personal communication, 1989) recorded average permeabilities in the range of 1.6E-09 to 9.8E-09 m sec^{-1} for the unconsolidated till to 1.8E-09 m sec^{-1} for the sandstone bedrock and 1.6E-11 m sec^{-1} for the underlying shale. This confirms a very strong permeability contrast between the unconsolidated till and the underlying bedrock.

3.5.2 Soil classification and mapping of the Lunty site

The systematic grid survey of the Lunty site (see 2.2.1 & 3.4.2) identified 9 soil series of which 5 were sufficiently extensive to be mappable and 3 were limited in extent. The main soils (Figure 3.6) were classified as chernozemic (Haploboroll, Argiboroll), solonetzic (Natraboll, Natriboroll) and gleysolic (Natraquoll, Argiaquoll, Haplaquoll) according to the Canadian (E.C.S.S., 1987b) and US (Soil Survey Staff, 1990) systems of soil classification (Table 3.8). The full set of observations and classifications recorded at each grid survey location is illustrated and tabulated in Appendix 2. Appendix 3 tabulates all site and profile descriptions, laboratory analysis data and field determinations of physical and hydrological properties for each of the sites at which detailed field sampling and monitoring occurred.

The development, validation and application of a reliable conceptual model of soil-landscape relationships was the most significant result of the systematic grid survey and detailed site sampling. The conceptual model (Figure 3.7) is based on a clear relationship between soil type and landscape position. The topographical control of soil distribution is interpreted mainly with respect to the movement of water over the soil surface and through the soil profile.

Upper, convex portions of the landscape (Figure 3.7) consist of chernozemic (EOR) or weakly solonetzic (HER, DYD) soils (see illustrations in Figure 3.6). These upslope areas are characterised by rapid surface runoff, limited infiltration, good internal drainage and maximum depth to water table. Soils in upslope positions are predominantly well to moderately well drained and either lack solonetzic features or display relatively weak solonetzic B (natric) horizons and weak accumulations of subsoil salts. These soils occur above the normal capillary fringe of the water table and are less susceptible to salinization from below by moisture moving from the water table towards the soil surface.

Mid to lower slope positions (Figures 3.7) are characterised by solonetzic soils (DYD, KLM) (see Figure 3.6). Mid and lower slope positions experience a greater volume and slightly slower rate of surface runoff than upslope areas. Increased accumulations of surface runoff and lower slope gradients lead to a greater amount of infiltration than in upper slopes and produce an increased likelihood of saturation from above. Depth to water table is less than for upslope areas and there is a greater likelihood of wetting from below by moisture drawn up from the water table. Mid slope soils have good to

moderately good internal drainage. Moderately to strongly developed solonetzic B (natric) horizons act as impeding layers, restricting downward infiltration of water. This can result in slight mottling in the top of the B horizon indicative of pseudo-gley conditions.

Soils in lower landscape positions and depressions (Figure 3.7) are poorly to very poorly drained and are classified as Gleysols (see Figure 3.6). Soils in depressions are affected by the accumulation of surface runoff or by subsurface groundwater flow, or both. Soils in non-permanent upland depressions (COR) generally display features indicative of leaching and net downward movement of water from above. Soils in slightly elevated positions in the sloping fringe surrounding non-permanent upland depressions are only weakly gleyed (LFN) but have well developed eluvial horizons (Ae, Ahe) indicative of net downward movement of water. The central portions of all non-permanent depressions are occupied by Gleysols (COR) with strongly developed eluvial horizons (Ae, Ahe) indicative of net downward leaching.

Soils in slightly elevated locations around the perimeters of permanent depressions (FMN) (see Figures 3.6 and 3.7) are both strongly gleyed and strongly saline. They display well developed solonetzic features including a saline-sodic (natric) B-horizon and visible accumulations of gypsum and soluble salts at shallow depths. These solonetzic features are attributable to salinization of the soil by movement of salts through the capillary fringe to the surface. Closer to the centres of these depressions, the gleysolic soils (COR) (Figure 3.7) display strongly developed eluvial horizons (Ae, Ahe) indicative of net downward movement of water. Gleysolic soils (Figure 3.7) at the centres of some permanent depressions (HGT) show strong gleying and no evidence of leaching. This is interpreted as indicative of regular saturation from below with little net downward infiltration of water.

A significant feature of many of the soils described above, relative to hydrological studies, is the strong permeability contrast between highly permeable topsoil horizons (Ap, Ah, Ahe) and relatively impermeable sub-soil horizons (Bnt, Bt, Btg).

The grid survey data was used in conjunction with interpretation of aerial photos and additional data sources (salinity map, slope map, topography map, depth to bedrock map, depth to water table map) to create a polygonal soil-landscape map. This map (Figure 3.8) displays the spatial distribution of the main kinds of soils (Table 3.9) and forms the basis for the allocation of soil types to grid cells in subsequent modelling

efforts. Cross sectional transects were constructed to cut across the entire range of landforms and soil types. The 2 transects (A1-A2 and B1-B2) shown in Figure 3.8 are illustrated in Appendix 3 which also contains the data for the detailed sample sites traversed by the transects.

3.5.3 Characterisation of hydrological properties at selected sites

This section summarises the results of field measurements of saturated hydraulic conductivity (K_{sat}) and bulk density (BD) and estimation of volumetric moisture content at saturation (θ_{sat}), 1/3 bar (33 kPa) and 15 bars (1500 kPa) for the principal soils at the Lunty site.

The original field determinations of bulk density (BD) and saturated hydraulic conductivity (K_{sat}) for each sampled horizon at each transect site generate a volume of data too large to present and discuss within the body of this text. The raw data are listed in Appendix 3, Table A3.1 and summarised by soil series in Appendix 3, Table A3.2. Review of the original raw data produced significant concerns with respect to a large number of instances of missing or suspect data and large within-site variability.

Missing data are mostly related to unsuccessful measurements of BD and K_{sat} in sub-surface C-horizons. Very few tests of K_{sat} at depths greater than 50 cm produced reportable results. At all but a few sites, the rate of infiltration into the lower horizons (> 50 cm) was extremely slow and the steady state infiltration required for a valid reading using the GP apparatus was never achieved. It is reasonable to infer that the probable value of K_{sat} at these sites would be as low, or lower, than the slowest rates determined successfully for the overlying B horizon at the equivalent site. Missing or suspect data are most frequently associated with poorly drained soils in lower landscape positions. Drilling to obtain cores for the determination of bulk density and successful completion of hydraulic conductivity measurements with the Guelph permeameter (GP) were restricted by inundation or saturated conditions at poorly drained sites.

Large variability was noted in the field data for BD and K_{sat} within sites, within horizons at sites and within horizons by soil series. Upon examination of the raw field data, a significant portion of the variability in K_{sat} is judged to arise from sampling error. Within any given horizon, differences in K_{sat} of one or more orders of magnitude can usually be explained as arising from the GP test reservoir

encountering different horizon characteristics and structure as the height (H) was raised and the ponded reservoir encroached into a different horizon. The data values reported for such tests are not characteristic of the horizon to which they are nominally assigned but are usually similar to data values obtained for the overlying or underlying horizons in which the test was actually completed.

Considerable variation in bulk density (BD) is also observed for horizons where multiple samples were collected. In general, A-horizons exhibit bulk densities in the range of 0.8 to 1.3 g cm^{-3} with an average around 1.1 g cm^{-3}. A-horizon BD varies considerably within soil series and even at individual sites. The variation appears more strongly related to land use (i.e. cultivation and compaction history) than to soil classification. B-horizon BD is generally in the range of 1.35 to 1.65 g cm^{-3} with an average around 1.4 to 1.5 g cm^{-3}. Bulk density of the B-horizon is more strongly related to soil series than is the case for A-horizons. Soils with well developed Btg or Bnt horizons (COR, KLM) have higher bulk densities (1.5-1.6 vs. 1.4-1.5) than soils with loose, open Bm or Bntj horizons (EOR, DYD). Assessment of C-horizon bulk density values is complicated by the compaction observed in many of the gleyed and clayey soil series (FMN, COR, KLM). Most of the bulk densities computed for unstructured BC and C-horizons are greater than 1.55 g cm^{-3}. Compaction of the BD test core is suspected for all computed bulk densities greater than 1.70 g cm^{-3}. Most of the reasonable values for BD are from better drained soils in mid to upper landscape positions (EOR, DYD, some KLM). Most of the suspect values for BD are associated with more poorly drained soils in lower landscape positions (COR, FMN, KLM/g).

Given the wide range of variation exhibited by field measurements, and the incomplete nature of the data set, the field data are primarily used to verify and, if necessary, modify typical values of BD and K_{sat} as listed in an existing database. The Alberta soil layer file (SLF) (Tajek, personal communication, 1992) lists typical values for a variety of soil properties, including bulk density (BD), saturated hydraulic conductivity (K_{sat}) and moisture content at specified tensions (33 kPa, 1500 kPa) (see Appendix 3, Table A3.3). The field measurements of BD and K_{sat} were compared with those reported in the Alberta SLF and the SLF was modified where necessary. The final values of BD, K_{sat} and moisture content at specified tensions assigned to each soil and horizon (Table 3.10) are based on the following comparison of existing SLF data to field measurements.

A comparison of computed values of K_{sat} with those listed in the SLF (Table A3.3) reveals the following similarities and differences. Field measurements of K_{sat} vary over two orders of magnitude for Ap or Ah horizons for all Soil Series except KLM (Table A3.2). The lower values (0.1 to 1.0 mm/hr) clearly reflect measurement of infiltration into underlying, more slowly permeable, Ahe, Ae or B horizons. The higher values (1 to 20 mm/hr) more accurately reflect the infiltration rates (K_{sat}) into a loose, granular Ah or Ap horizon expected from consultation of the SLF (10 mm/hr in Table A3.3). The mean value of A horizon K_{sat} measured for all the upland and non-solonetzic soils (EOR, DYD, COR) is very similar (6-8 mm/hr) and is in close agreement with expected values as listed in the SLF (10 mm/hr). The two strongly solonetzic soils (FMN, KLM) have different values for A-horizon K_{sat} than expected. The expected value for A horizon K_{sat} for KLM soil is 1.0 mm/hr while the average measured value is 4.1 mm/hr. This is slightly lower than for the other cultivated soils and probably reflects the inhibiting influence of the underlying, slowly permeable Bnt horizon. The expected value for FMN soil is listed as 10 mm/hr (Table A3.3), but the measured average K_{sat} of 1.2 mm/hr is probably more reasonable, given the dense, massive structure typical of A horizons in FMN soil.

The mean field measured K_{sat} of B horizons (and Ahe or Ae horizons) is lower than for Ah/Ap horizons by 1-2 orders of magnitude for all soils except EOR. The averages for field determined K_{sat} are lower than the values of K_{sat} predicted by the SLF for most soil series, often by up to one order of magnitude. The predicted K_{sat} for COR soil Ae and B horizons is 3-10 mm/hr while the mean field measured K_{sat} is 0.1 to 0.3 mm/hr. COR soil at the Lunty site is clearly more slowly permeable than expected. Agreement between expected and measured K_{sat} is better for DYD and KLM soils. Both are expected to have a low value for K_{sat} of 0.3 mm/hr in some portion of the B horizon and both do exhibit low mean values of K_{sat} of 0.1 and 0.4 mm/hr respectively. The average K_{sat} in the lower portion of the B horizon (Bntj) in DYD soils is higher than predicted, likely due to the many cracks and ped faces arising from the strong prismatic structure present in this horizon. The field determined mean K_{sat} for EOR soil (16.9) is within the same order of magnitude as that predicted by the SLF (30 mm/hr). The lower portion of the B horizon in EOR soils at the Lunty site displays a slower mean K_{sat} than expected. It is likely that these lower B horizons retain some of the clay accumulation and massive structure characteristic of solonetzic B horizons and are therefore less rapidly permeable than expected. The mean K_{sat} for FMN soil B horizons is lower than expected by 1 order of magnitude

(0.4-0.7 vs. 3-10 mm/hr). The field measured means are likely more representative of FMN soils at the Lunty site than the values predicted by the SLF.

With the exception of DYD soil, there were no successful determinations of K_{sat} for any BC or C subsoil horizons. The expected SLF values for subsoil K_{sat} are all in the range of 1-3 mm/hr. The one set of successful measurements on DYD soil averages 6.1 mm/hr which is at least in the correct order of magnitude. It is assumed that K_{sat} values for the unsuccessful tests would have been less than 6 mm/hr. In the absence of any other information, the value of 3 mm/hr predicted by the SLF data base is used for the C horizons of all soils except COR and FMN for which the predicted value is 1.0 mm/hr.

In general, the Guelph Permeameter determinations of saturated hydraulic conductivity produced consistent and reproduceable results for 2-3 replicates within each horizon and site for all sites where steady state infiltration was attained. At virtually every site, replicates from within the same horizon were of at least the same order of magnitude (see Table A3.1). Differences within horizons of less than 1 order of magnitude, but as large as 400-500%, were most likely related to differences in the nature of the zone of soil being tested. The lowest (first) test of each horizon often had the possibility of being affected by, and reflecting, conditions in an under-lying horizon. In the topmost (third) test the test zone of the reservoir often impinged into an overlying horizon. Differences in K_{sat} of less than 1 order of magnitude were subsequently found to have little adverse affect on the performance of the model (see Chapter 7).

A comparison of computed values of bulk density with those listed in the SLF (Table A3.3) reveals the following similarities and differences. All A horizons (except EOR) exhibit a similarly wide variation in BD from about 0.85 to 1.38 g cm^{-3}. The geometric mean value of BD measured in the field for each series appears quite reasonable and differences from expected values (as per the SLF) are readily explained. For example, Cordel (COR) soils occur in wet depressions and usually have surface horizons characterised by accumulations of highly organic peaty material incorporated into the Ap during breaking and cultivation. The low average BD displayed by COR soil is consistent with the large content of organic matter in COR soil and is close to that predicted in the SLF. Foreman (FMN) soils have a higher surface bulk density (1.26) than predicted by the SLF. This higher BD is actually more reasonable than the SLF estimate in view of the high clay content, high sodium content, low organic matter and generally saturated conditions which make FMN soils

more susceptible to compaction than associated upland soils. The mean field measured BD for DYD and KLM soils is identical at 1.1 g cm^{-3} but differs slightly from the expected value of 1.2 to 1.3 g cm^{-3}. This would appear to indicate that the A horizons in mid to lower slope positions at the Lunty site are somewhat less dense than expected. The mean BD for EOR soil (1.3 g cm^{-3}) is identical to that predicted by the SLF.

Comparison of mean field BD for B horizons with that predicted by the SLF reveals general agreement, but also some interesting differences. The SLF data base assumes that solonetzic B horizons (Bnt, Bntj, Btnj) will be more dense than normal B horizons and assigns most solonetzic B horizons a BD of 1.6 g cm^{-3}. The mean BD of solonetzic B horizons at the Lunty site (KLM, DYD) is in the range of 1.4 to 1.55 g cm^{-3} rather than 1.6 g cm^{-3}. The mean field BD of the BC and C horizons underlying solonetzic B horizons (1.5-1.7 g cm^{-3}) is often greater than for the solonetzic B horizons and greater than predicted by the SLF (1.5 g cm^{-3}). The lower field determined values for B horizons may reflect the influence of cracks and ped faces in the strongly structured solonetzic B horizons. These cracks and ped faces would be expected to reduce the density of the soil and lead to lower bulk densities than for underlying horizons of similar texture but massive structure.

The SLF data base predicts that most C horizons will have a BD of 1.5. The mean bulk density of most sampled BC and C horizons is greater than predicted, falling in the range of 1.5 to 1.7 g cm^{-3}. This is true even for the better drained soils in upper landscape positions (EOR, DYD, KLM) in which the C horizons were not saturated at the time of sampling and compaction of the BD cores is not suspected. The field evidence supports accepting somewhat higher values for C horizon BD (1.5 - 1.6 g cm^{-3}) than given in the SLF.

A significant conclusion arising from the present effort is that order of magnitude estimates for the soil properties BD, K_{sat} and total porosity, such as those already present in the Alberta Soil Layer File, represent a valid starting point on which to base initial assignment of parameter values. Large natural variability, missing data and suspect data due to sampling error or measurement error make interpretation of detailed field data inconsistent and difficult. Field measurements are judged most beneficial when used to confirm reported SLF estimates and to identify cases where SLF estimates are probably in error and require revision. No amount of detailed field sampling would have been able to resolve the large inherent natural variability

associated with soil hydrological properties at the Lunty site. As such, simple order of magnitude estimates as recommended by Elrick et al (1989) are all that can feasibly be attained. As with the Alberta SLF, these data may already be available and may require only minimal additional sampling to verify or to identify required changes.

3.5.4 Field measurement of soil moisture status

The original TDR and gypsum block field measurements along with the corresponding volumetric moisture (θ) and head (h) calculated for each of the sites and depths at each monitoring date are listed in Appendix 4 (Table A4.1). Installation of the monitoring sites was not completed until mid May, 1989 so no soil moisture data were obtained for the months of April and May in 1989. Data were collected in 1990 for the early spring months of April and May.

Data from the years 1989 and 1990 were combined to produce a complete data set representative of the period of non-frozen soils from April to October. Volumetric soil moisture as determined by TDR was plotted against time, for each of the depths 0-15, 15-40 and 40-60 cm, for each of the dates on which it was measured (see Appendix 6, Figures A6.1-A6.5). The data were grouped by Soil Series in order to facilitate comparison of soil moisture profiles within and between Soil Series. The graphs clearly illustrate the large variability and unreliability of many of the estimates of volumetric moisture produced by TDR measurements. They also indicate that data for A and some B-horizons was consistent and credible, especially for soils in upper landscape positions (EOR, DYD, some KLM).

A considerable amount of effort was expended in installing, monitoring, tabulating, graphing and interpreting soil moisture data obtained by the TDR method. The TDR data set contained a large number of missing or suspect data values. The IRAMS device was unable to produce reportable readings for many of the 0-60 cm depth intervals and for several of the 0-40 cm intervals. Most of the sites at which the IRAMS device was unable to produce valid data were located in lower landscape positions characterised by saline or near-saturated conditions or both. Gravimetric samples collected to verify and calibrate the TDR readings did not correspond well with the TDR data (see Appendix 4, Table A4.2).

In the end, the TDR data are judged to be less reliable and less consistent than estimates of volumetric moisture obtained from gravimetric sampling. The mean

volumetric soil moisture determined by gravimetric sampling of each Soil Series at each depth and date is therefore used in place of the TDR data to illustrate soil moisture profiles for each Soil Series for each of the sampling dates (Figure 3.9). Several useful interpretations arise from examination of the mean moisture profiles.

In the first instance, the moisture profiles provide a useful check of the values assigned to each Soil Series for moisture content at saturation (KP0), at 1/3 bar (KP33) and at 15 bar (KP1500) (see Table 3.10). In the second instance, the profiles provide a graphical aid to interpretation of the dynamics of water flow through the soil at various locations in the landscape. Finally, the moisture profiles provide some evidence on which to base estimates of the initial moisture content of each of the soils immediately before spring runoff at the start of the period of simulation.

Upper to mid landscape positions occupied by Elnora (EOR) and Daysland (DYD) soils are consistently drier at equivalent dates than lower slope positions (Figure 3.9). Upper slope soils are at their wettest on April 3. They dry out until July 31 after which they re-wet to close to their maximum moisture content by September 26. The maximum soil moisture recorded for all of the horizons of both upland soils is close to, or slightly below, the corresponding estimates for field capacity (KP33) in Table 3.10. There is no evidence that any of the horizons of these upland soils approach saturation for dates recorded by the gravimetric sampling. At their driest, all horizons have moisture contents close to, or slightly above, the corresponding estimates for moisture content at wilting point (KP1500).

Elnora soils (EOR) are wetter at the surface than at depth on all dates except July 31. This supports an interpretation of a downward moisture gradient and net downward movement of soil moisture for all dates except July 31. Daysland soils (DYD) only exhibit a clear downward gradient for April 3, after which the gradient is imperceptible or slightly towards the surface. This may indicate that, after an initial period of recharge in early spring, the direction of movement of water is upwards, from the water table towards the surface.

Elnora soil is located in the highest landscape positions, receives the least amount of runoff and has the best internal drainage. The moisture content of Elnora A horizons is dependent almost completely on direct precipitation as these upslope sites receive little or no runoff. These sites consequently show a rapid response to additions of rainfall and a rapid readjustment to dryer conditions after the cessation of rainfall.

Elnora B horizons show limited systematic change through time. This suggests that downward and lateral drainage through Elnora B horizons is rapid and Elnora B horizons rapidly attain an equilibrium moisture content approximating field capacity following any recharge events.

Daysland soil is located topographically just below Elnora soil in upper to mid slope landscape positions. The graph of Daysland soil moisture change through time (Figure 3.9) more closely resembles that for Elnora than any other soil. This is consistent with the soil properties and landscape position of Daysland soil. At any given date, Daysland soils have a higher moisture content in all horizons than Elnora soils. Since Daysland soils occur lower in the landscape, these sites are expected to receive somewhat more upslope runoff than Elnora sites and to display somewhat higher levels of soil moisture. This pattern is supported by the data. The higher levels of soil moisture in these lower landscape positions may also be due to greater depth of initial snow cover or to augmentation of soil moisture by lateral subsurface flow from upslope landscape positions or upward flow from the water table.

Mid to lower landscape positions occupied by Killam (KLM) and Foreman (FMN) soils show the greatest fluctuation in moisture content and directional gradient (Figure 3.9). These mid to lower slope soils are wet almost to saturation on April 3. They dry out until July 31 or August 28 to moisture contents just above those estimated for wilting point (KP1500) for surface horizons and field capacity (KP33) for sub-surface horizons (see Table 3.10). By September 26, they recover to moisture contents similar to those estimated for field capacity (KP33) in Table 3.10. The maximum soil moisture recorded for all of the horizons of both mid-slope soils is close to, or slightly below, the corresponding estimates for moisture content at saturation (KP0) in Table 3.10. At their driest, the 2 sub-surface horizons never display moisture contents much below the corresponding estimates for moisture content at field capacity (KP33).

Both Killam (KLM) and Foreman (FMN) soils are only wetter at the surface than at depth for the initial date of April 3, 1989 after which they are always wetter at depth than at the surface. This supports an interpretation of an initial downward moisture gradient and net downward movement of soil moisture during the early phase of spring runoff of snowmelt. After the initial period of recharge in early spring, the direction of movement of water is apparently upwards, from an underlying water-table towards the surface.

Killam sites are located topographically just below Daysland soils, or Elnora soils in cases where no Daysland soil are mapped in upper slope positions. The moisture profile for Killam soils depicts patterns transitional between those observed for Daysland and Elnora sites and those recorded for Foreman or Cordel sites. Most Killam sites exhibit wetter conditions with higher values for soil moisture at any given date than recorded for Elnora or Daysland sites. The range of moisture contents displayed by Killam sites is also much greater than for Elnora or Daysland sites. The logical interpretation is that Killam sites receive a greater amount of surface and near surface runoff than Elnora or Daysland sites and develop correspondingly higher moisture contents. Killam sites are not only wetter, but remain wet for longer periods than Elnora or Daysland sites. This is interpreted to reflect a longer period of recharge of these lower slope sites by upslope runoff and through-flow. Killam A horizons become as dry as Daysland or Elnora A horizons but take longer to become as dry and remain dry for shorter periods. The B horizons of Killam sites display greater variation in soil moisture than recorded for Elnora or Daysland sites. The higher moisture content observed in Killam soil B horizons is attributed to both slow infiltration of moisture from surface runoff and to upward movement of water from the saturated zone at 60-120 cm. This is consistent with the high clay content and low permeability recorded for Killam B horizons and with the mid to lower slope position of Killam sites.

Foreman soils are located topographically just below areas of Killam in the slightly elevated fringe areas surrounding closed depressions occupied by Cordel soils. The moisture profile for Foreman soils reflects this transitional location. At any given date, Foreman soils have higher moisture contents in all horizons than Killam soils. Since Foreman soils occur lower in the landscape, this supports the interpretation that there is a greater source of soil moisture in these lower landscape positions. This may be due to greater depth of initial snow cover, to greater amounts of surface runoff and infiltration or to augmentation of soil moisture in Foreman soils by lateral subsurface flow from upslope landscape positions or upward flow from the water table.

Toe-slope to depressional landscape positions occupied by Cordel (COR) soils attain and retain the highest levels of soil moisture (Figure 3.9) at all depths and times (except for Killam and Foreman A-horizons on April 3). These depressional soils are wet almost to saturation on April 3.. They dry out more slowly than any of the other soils until reaching a moisture content close to estimated field capacity (KP33) on July 4. The data illustrated for July 31 is skewed by the absence of gravimetric samples for

several inundated depressions while several non-inundated upland depressions were sampled. By September 26 the depressional soils recover to moisture contents slightly above those estimated for field capacity (KP33) in Table 3.10. The maximum soil moisture recorded for all of the horizons of Cordel soils never quite reaches the level of corresponding estimates for moisture content at saturation (KP0) in Table 3.10. At their driest (July 31), all horizons of Cordel soil display moisture contents just slightly greater than the corresponding estimates for moisture content at wilting point (KP1500).

Cordel (COR) soils are wetter at the surface than at depth until at least July 4, 1989 after which they are slightly wetter at depth than at the surface. This supports an interpretation of a prolonged downward moisture gradient and net downward movement of soil moisture for the entire period of spring runoff of snowmelt. Not until late summer is the inferred direction of movement of water upwards, from an underlying water-table towards the surface. Even then, the gradient is minimal and unlikely to draw much water to the surface. Maintenance of high soil moisture contents and downward gradients well into summer requires that Cordel soils receive and transmit inputs of moisture originating as runoff from higher in the landscape from early April until at least early July. This is consistent with the observed pattern of rapid runoff into the closed depressions occupied by Cordel soils followed by infiltration into the soils below depressions that is mostly completed by mid June or early July.

Both the gravimetric soil moisture profiles (Figure 3.9) and the TDR soil moisture data (Appendix 4) provide field evidence to support estimates of initial moisture status and moisture content at saturation, field capacity and wilting point. In addition, they provide support for a conceptual model of runoff and infiltration used to help design the simulation model described in Chapter 5.

In the conceptual model, soils in upslope landscape positions (EOR, DYD) receive low inputs of snowmelt or runoff and do not attain or retain high levels of soil moisture. Most snowmelt runs off rapidly to lower landscape positions and only a little post-melt rainfall infiltrates into the soils under un-saturated conditions. There is little or no upward movement of water from the water-table towards the surface. Soils in lower to toe-slope landscape positions (KLM, FMN) receive much higher inputs of snowmelt and runoff which infiltrate and contribute, at least initially, to groundwater recharge. Later in the year, these soils dry out at the surface and draw water upwards

from an underlying water-table. Soils in depressions (COR) receive most of the spring snowmelt and runoff. This is retained in the closed depressions until it either infiltrates or evaporates. Infiltration proceeds rapidly in upland depressions and continues until all surface water is removed. In lowland depressions, infiltration proceeds until the height of the underlying water-table rises to the level of the pond surface.

3.5.5 Monitoring and processing of hourly meteorological data

Meteorological data are listed (Table A5.1) and discussed in Appendix 5 for the Lunty site for the period from March 22, 1989 to June 15, 1989. Hourly meteorological data are provided for the variables precipitation, global radiation, mean air temperature, relative humidity, wind speed and estimated cloud cover fraction. These date provide the basis for input to the simulation model described in Chapters 5 and 6.

3.5.6 Acquisition and processing of detailed digital elevation model

The DEM (see 3.4.6) for the Lunty site is illustrated in Figure 3.10. It is stored as a grid of 160 rows by 140 columns with a horizontal grid resolution of 5 m by 5 m and a vertical resolution of 0.1 m. The effective error of the DEM is therefore ± 0.1 metre. The DEM experienced some loss of vertical resolution when the original elevation values were rounded from 3 decimal places (1 mm) to 1 decimal place (10cm). This loss in resolution creates an impression of flatter topography than actually exists, especially along the tops of crests and ridges. The 5 m by 5 m cell size was selected to capture the variation in topography for the smallest area of land capabible of being managed differently (30 foot (10 m) cultivators and seeders suggest an effective minimum management unit of 10 m^2). In general, the 5 m by 5 m DEM faithfully captures the main topographical features of the Lunty site (depressions, slopes, knolls) with considerable detail. The DEM is used extensively for computation and illustration throughout this document.

3.5.7 Determination of spring snow depth and moisture equivalent

A selection of topographical indices including upslope area, profile curvature and plan curvature (Figure 3.11) (and others not reported here) was computed for every grid

cell in the Lunty DEM and stored in the database LuntyDRV. The topographical indices show a clear relationship to relative landscape position. Large upslope area counts occur in lower slopes, depressions and along major flow paths for surface water. Small upslope area counts are most frequently associated with crests, upper ridges and divides. Positive plan curvature was confined mostly to crests and upper ridges while positive profile curvature occurred on ridges and along divides on side slopes. The topographical indices were judged to provide a valid data set against which to evaluate depth of snow.

Data on depth of snow collected at 44 sample sites on March 21, 1989 are presented in Table 3.11. Also listed are the terrain derivatives upslope area, plan curvature and profile curvature computed for the grid cells of the DEM corresponding to the snow survey sites. Plan curvature and upslope area were transformed using modified log transforms (equations 3.6, 3.7, 3.8) to achieve improvements in normality required for statistical analysis.

Mean snow depth at the 44 survey sites was 12.88 cm with a range from 3.0 to 61.0 cm (Table 3.12). Profile and plan curvatures were both mostly negative, indicating a predominance of concavity over convexity among the sampled sites. Curvature was greater and more varied in plan (cross slope) than in profile (down slope). Transformations improved the normality of both plan and profile curvature indices.

Most of the cells with shallow depth of snow cover were associated with a low upslope area count (1-4) and positive profile or plan curvature (convexities). Similarly, cells with the greatest recorded depth of snow were generally associated with large upslope area counts (>10) and negative profile or plan curvature (concavities).

A significant correlation between snow depth and the topographical derivatives is evident in the Pearson correlation matrix (WILKINSON, LEYLAND, SYSTAT, 1990) computed using the snow pack survey data (Table 3.13). The strongest correlation was between snow depth and the log transform of upslope area (UpsT). This confirmed the initial impression that the greater the upslope area the greater the likelihood of a deep snow pack. Profile and transposed plan curvature were only slightly less strongly correlated to snow depth. In both cases the correlation was negative, confirming the findings of Zebarth and de Jong (1989a) that snow tends to accumulate to greater depths in concave portions of the landscape.

Stepwise multiple linear regression equations (WILKINSON, LEYLAND, SYSTAT, 1990) confirmed and quantified the relationship between snow depth and the selected topographical indices (Table 3.14). A majority of the variation in snow depth was explained by the transformed upslope area variable (UpsT). Stepwise inclusion of three other variables, including downslope dispersal distance (Disp - not described here), produced a slight improvement in the amount of variation explained (r increased from 0.754 to 0.800). This was achieved at the expense of a reduction in significance (F reduced from 55.348 to 17.227). There is likely a strong spatial auto correlation both in the data and in the regression residuals which affects any interpretation of significance.

All of the above regression equations were applied to the full Lunty site grid data set of topographical indices (LuntyDRV) to compute four different estimates of snow depth (maps not shown). All but the first equation estimated negative depths of snow when applied to the entire Lunty data set. This situation arose for grid cells with a very low upslope area (usually 1) combined with strong positive curvature in both plan and profile. It was reasonable that these convex, upslope grid cells should have a shallow snow cover, however a negative depth of snow was not acceptable.

The equation based solely on the transposed upslope area count produces estimates of depth of snow cover that range from a low of 1.9 cm to a high of 39.7 cm. This is a more narrow range than encountered at the snow pack survey sites, but is reasonable and does assign greater depths of snow to lower slope and depressional areas and shallow depths of snow to upslope and crest areas (see Figure 3.12). While this equation did not explain quite as much of the total variation as those with more variables, it did produce more consistently reasonable estimates and was more statistically significant than any of the others. This equation was therefore used to provide initial estimates of snow depth for subsequent simulation modelling (see Figure 3.12).

3.5.8 Determination of pond location, depth and volume

The results of field surveys undertaken on 15 separate dates to record the location, extent and maximum elevation of ponding of all ponds present on each of the field survey dates are tabulated and discussed in Appendix 6 (Table A6.1).

The pond field survey data are summarized in Table 3.15 and illustrated in Figures 3.13 to 3.15. Ponds were observed and recorded at 18 different locations for at least one survey date. The observed change in volume of each pond from one survey date to the next is summarized in Table 3.16 for each pond and date. Also included in Table 3.16 is an estimate of the maximum reduction in volume of water in each pond between survey dates likely to have been caused by evaporation. The most pertinent observations arising from a detailed analysis (see Appendix 6) of the patterns of development and decay of ponds are summarised below.

The first ponds to be observed (March 31) are all located in hollows in mid to upper landscape positions where the snow was absent, or at least thin enough to permit observation and recording of open water. Snow in upper landscape positions is thinner and melts earlier than the deeper snow in lower landscape positions. Snow drifts in lower landscape positions obscured (and prevented the observation or measurement of) several of the larger central ponds that may have been forming under the snow.

Almost all ponds develop to their fullest extent by April 4, 1989. No rainfall was recorded from March 22 until April 7 so all of the ponding observed on April 4 is ascribed to either surface runoff of melting snow or a sub-surface rise in the groundwater table. Evidence provided by companion hydrological studies (Trudell, 1992, personal communication) indicated that there was little groundwater flux during the period of initial spring snowmelt. Surface runoff of melting snow is therefore concluded to be the sole contributor to initial pond formation.

All of the shallow ponds in upper landscape positions are short lived and disappear rapidly and at an early date. Their upper landscape locations favour early melting of snow, early thawing of subsoils and rapid infiltration of accumulated ponding into the subsoil. They rapidly exhaust their supply of runoff from snowmelt and receive little or no continuing sub-surface through-flow or groundwater recharge The evidence suggests that much of the loss in volume of these ponds is due to infiltration through the bottom of the ponds. Ponds less than 40 cm in depth do not persist through-out the summer.

Most of the deeper ponds (> 40 cm) are located in lower landscape positions and are associated with larger catchments. They continue to grow until at least April 4 through inputs from both surface runoff and sub-surface through-flow from higher elevations.

One explanation for the longer persistence of these ponds is that they continued to be fed by melting snow from deeper drifts in low-lying landscape positions. Some additional growth is also likely related to ongoing contributions of moisture transported from upslope soils by near-surface or sub-surface lateral flow. Another likely contribution to continued persistence is that the soils beneath ponds in low-lying landscape positions may not thaw out as rapidly as those in upper landscape positions. Delays in thawing are inferred to lead to corresponding delays in the attainment of rapid rates of infiltration associated with non-frozen soils.

Both infiltration and evaporation are required to explain the observed patterns of reduction in pond volume. Evaporation alone was insufficient to explain all of the observed reduction in pond volumes. At ponds 185 East and West the reduction in volume was occasionally less than expected given the estimated potential evaporation. This indicates the likelihood that these two ponds receive some net recharge from sub-surface flow and suggests that they are in contact with the water table. In fact, all six of the ponds located in major depressions in the lowest portions of the landscape are quite likely in contact with the saturated zone at some point in early spring and receive some inputs from sub-surface flow.

Pond decay begins between April 4 and April 12 for all ponds. Initial rates of decay are quite rapid but then slow down. Several explanations are possible. The first is that as ponds decay, they become smaller and have less surface area for both evaporation and infiltration. A second is that infiltration below the ponds appears to slow down as the infiltration store below the ponds fills up, thereby reducing the capacity for further infiltration.

An increase in both numbers of ponds and total pond volumes occurs between June 9 and July 4/89 and is clearly related to the 66 mm of rain that fell nearly continuously over that period. This rain obviously produces surface runoff which refills the major mid and lower slope depressions. Heavy rainfall results in a continued increase in the number and volume of ponds recorded on July 11/89. The increase in volume is in excess of any losses due to evaporation or infiltration.

A final observation is that the main central ponds (185-West and 185-East) are likely hydrologically connected. This assertion is supported by the fact that ponds 185 West and East maintain the same maximum elevation through all survey dates. Water from pond 185-West likely flows into pond 185-East to satisfy some of the evaporative

demand from this pond.

Field mapping of pond location, extent and depth demonstrated that surface runoff did occur at the Lunty site and was the major contributor to initial pond formation. All initial pond development was associated with rapid runoff of melting snow over frozen soils. Because most snowmelt was rapidly transported to and stored in depressions, the majority of infiltration and groundwater recharge was concentrated in depressions. This confirms the concept of "depression focused recharge" as the dominant recharge mechanism in prairie landscapes (Lissey, 1968, 1971). The field mapping not only provided the data require to test the simulation model (Chapter 6) it also provided a basis for developing a conceptual understanding of water flow and accumulation at the Lunty site. This conceptual understanding was used to guide the development of the simulation model described in Chapter 5.

3.6 Summary and conclusions - field study

The field study provided valuable contributions to the understanding of when and how surface water ponding developed and to documenting the meteorological, soil and hydrological conditions that influenced runoff and ponding. The field study provided the data on boundary conditions and parameter values needed for input into the simulation model DISTHMOD. It also provided insights into the relative occurrence and importance of various processes involved in generating the observed runoff and ponding. This insight was useful in designing and constructing the simulation model. Finally the field surveys provided the data against which to test and evaluate the success and applicability of the final simulation model.

The pond survey data provided a framework for developing, interpreting and verifying a simulation model for surface water flow and ponding. They demonstrated that surface water flow and ponding did clearly occur under conditions of both spring snow melt on frozen soils and summer rainfall on non-frozen soils. Subsequent efforts were aimed at developing techniques for quantifying the location, extent and timing of surface water ponding through geomorphological analysis and simulation modelling.

3.6.1 Highlights and positive contributions

The principal contribution of the field study was the documentation it provided on the location, depth and extent of ponding during a period of spring runoff. The field study confirmed that surface runoff of snowmelt in the spring was the overwhelming contributor to the initial development of ponds. Runoff of melting snow was only able to occur because infiltration into frozen soils was severely limited relative to normal, unfrozen soils. Rainfall runoff during extended periods of heavy rainfall later in the year replenished ponds but never filled them to the same extent as runoff from snowmelt. Ponds less than 40 cm in depth did not persist through-out the summer, while those greater than 40 cm did.

These data confirmed patterns reported by other researchers (MacAlpine, 1992; MacAlpine, Cooper and Neilson, 1992; Hubbard and Linder, 1986; Richardson and Arndt, 1989; Woo and Rowsell, 1993, Fortin, van der Kamp and Cherry, 1991). Specifically, in their study of runoff in several farm-scale watersheds in Alberta MacAlpine et al. (1992) reported that "snowmelt rather than summer storms is the significant runoff event in small, flat, poorly drained watersheds". Woo and Winter (1993) noted that "seasonal frost prevents infiltration during the spring melt" causing "snowmelt and early spring rains to run off uplands to depressions" which "reach their highest levels of the year" at this time. Fortin et al. (1991) reported that "runoff occurs mostly at the time of snowmelt and collects locally in closed depressions". In contrast to the present study, both Woo and Rowsell (1993) and Johnsson and Lundin (1991) reported a reduced, but still significant, level of infiltration of snowmelt into frozen soils. They attributed infiltration in frozen soils to cracks from freezing and thawing.

The field study confirmed that a reduction in the size and volume of all ponds began immediately after their initial formation, at the end of the period of snowmelt. The observed reductions in pond volume could not be accounted for by evaporation alone. Reductions in pond volumes required that a considerable amount of water enter into storage in the soil beneath each pond. Companion studies (Trudell, 1994) confirmed that this water did not contribute significantly to recharge of the groundwater. Much of the infiltrated water therefore remained in storage in the soil and was available to satisfy evaporative demand later in the summer.

These observations are concordant with those of MacAlpine and Shaw (1984) who reported that "up to 60% of the initial volume of snowmelt in shallow depressions infiltrates after soil thawing". The notion that not all of the water that infiltrates beneath a pond contributes to groundwater recharge is supported by (Woo and Rowsell, 1993) and by Trudell (1993) who concluded that only a very small fraction of the water that collected in ponds percolated below the ponds as groundwater recharge. He calculated rates of recharge of 0.5 to 3.3 mm yr^{-1} which represented 0.1 to 0.9% of total annual precipitation. When expressed as total recharge per unit area of ponds the rates ranged from 6.8 to 28.6 mm yr^{-1}.

Ponds in hollows in mid to upper landscape positions appeared first and disappeared most rapidly. It was concluded that snowmelt occurred earlier in these upper landscape positions since they had a thinner initial snow cover, more exposed soil and greater exposure to solar radiation. Infiltration below the ponds occurred sooner in these upper landscape ponds as well. It was concluded that the soils below these ponds thawed sooner and were more receptive to infiltration at an earlier date than the soils beneath ponds located in lower landscape positions.

Ponds in lower landscape positions persisted longer and showed a slower rate of decrease in volume than ponds in upper landscape positions. It was concluded that ponds in lower landscape positions benefited from ongoing additions of water through continued snowmelt, sub-surface flow or near surface through-flow from upper landscape locations and from a rising water table..

The field study confirmed the existance of a strong and consistent relationship between soils and topographical position. The toposequence model supports the general observations of Moore et al. (1993) that "catenary soil development occurs in response to the way water moves through and over the landscape". The specific model developed for the Lunty site has many similarities to one described by Richardson and Arndt (1989) for a wetland site in South Dakota. Upland depressions contain ephemeral or seasonal ponds which act as sites for local groundwater recharge and contain soils which are deeply leached. Depressions lower in the landscape contain semi-permanent ponds with soils at the centre of the depression showing little evidence of leaching and soils around the fringe displaying saline and sodic features indicative of net upward movement of water in response to evaporation. Non-depressional upland soils are well drained but show little evidence of significant eluviation. Water infiltrates rapidly into the upland soils to approximately the depth of

accumulation of lime (50-100 cm). Most water that infiltrates upland soils does not contribute to deep groundwater recharge but rather is returned to the surface in response to evaporation and plant transpiration. Upland soils have good internal drainage and hydraulic conductivities 1 to 2 orders of magnitude greater than lowlying and depressional soils. Similar observations were made by Woo and Rowsell (1993).

The degree of spatial variation in field measurements of saturated hydraulic conductivity (K_{sat}) and bulk density (BD) was so great and of such high frequency that automated definition of meaningful patterns of property variation was not feasible. A relatively consistent relationship was noted among landscape position, soil classification and hydrological properties. It was concluded that the most efficient way to assign hydrological property values to every point in the landscape was to determine a reasonable modal value for each horizon of each soil series and to assign this modal value to all locations mapped as a given series. A significant conclusion arising from the present study is that order of magnitude estimates for the soil properties BD, K_{sat} and total porosity, such as those already available in the Alberta Soil Layer File, represent a valid alternative to intensive field measurement of these parameter values.

Installation error, instrument error, operator error and natural spatial variability combined to limit the utlity of field measurements of soil moisture status made using time domain reflectometry (TDR) and gypsum blocks. Change in moisture status through time was best described using gravimetrically determined soil moisture data converted to volumetric equivalent through multiplication by a mean bulk density for each soil and horizon. Analysis of soil moisture profiles produced for each major soil series at the site confirmed a clear and consistent relationship between pattern of moisture change and soil classification as related to landscape position. The simplest and most convenient way of assigning a spatial distribution to patterns of moisture change was therefore to associate moisture status with soil series and to assign all locations of a given soil series the same values for initial soil moisture.

Soil moisture monitoring provided evidence that moisture migrated from locations higher in the landscape to lower landscape positions. Soil moisture profile plots supported the conclusion that total infiltration was greatest in soils in lower landscape positions and least in upland soils. Soils in upper to lower landscape positions displayed downward moisture gradients for only a short period immediately following

spring snowmelt. The gradiants reversed soon after snowmelt was completed, supporting an interpretation of upward movement of soil moisture to satisfy evaporative demand. This is in accord with similar conclusions reported by Meyboom (1963, 1966, 1967), and Woo and Rowsell (1993). Similarily, soils in toe-slope to depressional landscape positions remained wet longer and retained downward mositure gradients indicative of continuing infiltration. These data support the concept that most recharge in such landscapes is "focused" in depressions as elaborated by Lissey (1971) and confirmed by Mills and Zwarich (1986), LaBaugh et al., (1987), Woo and Rowsell (1993), Zebarth et al. (1989b,c), Freeze and Banner (1970), Hubbard and Linder (1986).

Hourly meteorological data collected to provide input for subsequent simulation modelling confirmed the dominance of evaporation over precipitation for all intervals longer than an individual rainfall event. They also confirmed that the conditions required for the onset of spring snow melt began on March 29 and continued through to April 7. This corresponded well with the observed period of initial snow melt, runoff and ponding.

The weather at the Lunty site during the spring of 1989 was fairly typical but somewhat drier in March and April and wetter in June than normal. Temperatures were slightly above normal for all months from March onward. Total winter snowfall was about 20% below normal. The observed runoff and ponding was concluded to be representative of typical spring weather and associated runoff conditions.

The digital elevation model (DEM) of the Lunty site proved capable of representing the significant aspects of the landscape including all of the depressions that were observed to retain water. If anything, the grid resolution of 5 m. was too great for some purposes (i.e. flow paths were too concentrated to produce a realistic estimate of the diffuse, gradually changing pattern, of snow depth).

Field observations confirmed that snow accumulated to a greater thickness in lower slope positions than in upper landscape positions. These data support similar observations made by Zebarth and de Jong (1989a) and Woo and Rowsell (1993). The depth of initial snow pack was clearly shown to be related to the topographical indices of upslope area, plan curvature and profile curvature. The most satisfactory predictive equation was a simple linear regression relating snow depth to a log transform of the upslope area.

3.6.2 Oversights and opportunities for improvement

The field study expended an inordinate amount of effort on field measurements to characterise the hydrological properties of soils and to monitor the change in moisture status of soils through time. This effort did not yield significant rewards in terms of useful data. A much smaller level of effort aimed at simply verifying known values from existing data bases might have been more appropriate.

Direct observation and monitoring of surface and near-surface flow was an important element missing from the field study. The study would have benefitted from observations that confirmed the presence of surface runoff and lateral near-surface through-flow and measured the fluxes associated with these processes. This would have entailed establishment of collection pans for surface flow and lysimetrers for sub-surface through-flow. In the absence of direct observations or measurements, these processes had to be inferred from observations of ponding and soil moisture status.

A comprehensive computation of the water balance was not attempted for the study site for either of the years for which pond data and meteorological data were available. The field data would support such an analysis and while one was not essential for the purposes of the present study, a detailed analysis of water balance would be an interesting follow-up activity.

The detailed meteorological data was extremely useful but was also expensive to collect and time consuming to collate, transcribe and process. Robust digital data loggers would have been far more convenient and reliable than the mechanical strip chart recorders utilised for the present study. In view of the cost and difficulty involved in collecting such detailed meteorological data, a useful alternative for future studies might be to develop a series of locally relevant data sets based on historical records. Such data bases might contain "worst case", "best case" and "modal case" data and would allow for rapid examination of alternative scenearios without having to wait to collect current data.

The field data collected on depth of snow were adequate for the intended purpose, but could have been better. A more comprehensive field survey would have sampled a greater number of sites and collected data on moisture equivalent as well as depth. In addition, daily measurements of depth and water equivalent of snow at selected sites

during the period of ablation would have been useful for evaluating the accuracy of the snowmelt model. These activities were outside the scope of the original study objectives, however the development and validation of the snowmelt model would have been improved by the availability of such data.

The Zebarth and de Jong (1989a) approach of predicting the spatial pattern of snow depth by developing a regression equation between depth of snow and topographical indices was used with only moderate succcess. The small size of grid cells used to represent the Lunty site (5 by 5 m) produced a representation of concentrated flow paths (large upslope area) as highly discrete entities that occupied only a small portion of each watershed. Upon reflection, the predictions might have been more accurate if the flow path data had been generalised by some means. One approach to generalisation would be to pass a moving average filter over the flow path data set to produce a more diffuse representation of flow. A second would have been to adopt a different algorithm for computing upslope area (see Quinn et. al., 1991). A third would have been to represent the terrain using a much larger size of grid cell so that all cells in lower landscape positions were computed to have a large upslope area. A more diffuse pattern of upslope area would have resulted from analysis of a DEM using any of the above three approaches. This would, in turn, have resulted in a more uniform and representative estimate of distribution of depth of snow

The role of soil temperature as it influenced infiltration and hydraulic conductivity could have been documented better. Field measurements of rates of infiltration into frozen soils would have confirmed the assumptions about reduced rates of infiltration under frozen conditions. Field measurements of soil temperature at several depths at sites in several landscape positions would have been useful for confirming assumptions about differences in the rates and dates at which soils thawed and the effects of freezing and thawing on infiltration.

CHAPTER 4

GEOMORPHOLOGICAL ANALYSIS:

DOCUMENTING THE GEOMETRY GOVERNING THE FLOW AND ACCUMULATION OF SURFACE WATER

4.1 Introduction

4.1.1 Overview

This chapter describes the development and application of a procedure for computing the extent and size of locations of depressional storage at a farm scale in an agricultural landscape of low relief. The intent is to locate all possible sites where ephemeral or semi-permanent ponds would form in a typical agricultural landscape and to establish a systematic procedure for documenting the topographical and topological controls determining where such depressional storage occurs and how it is inter-connected. The procedure makes use of a number of computerised techniques for automated feature extraction from digital elevation data. A review of the use of similar techniques by others is presented in order to place in context the techniques adopted for this study. The suite of interactive watershed modelling utilities (**Watersh**) used to define depressional storage is described in detail as are the efforts made to apply these utilities to the Lunty study site. The procedure is shown to be capable of locating and documenting all sites having some potential for depressional storage at the Lunty site. The topological data produced by application of the described procedures are used as the framework for subsequent modelling (Chapters 5&6).

4.1.2 Context

Ephemeral ponding is a recurring management problem for many prairie farmers. The potential severity of ephemeral ponding on any given farm is largely governed by topographical control of the location and extent of depressional storage and the size of catchments contributing to each depression. A related problem is the potential on or off-farm impact of draining or consolidating ephemeral ponds. At issue here is where the drained water will go, and whether there is sufficient depressional storage elsewhere on a farm to retain it or whether it will escape off-farm where it may damage ditches or flood land belonging to other landowners.

The concept of depressional storage is well established and has been used as the basis for lumped conceptual models of surface water flow at a farm scale in agricultural areas of Alberta (JNM., 1986; WER., 1987; Jensen and Wright, 1987). Despite this acceptance, few studies to date have attempted to quantify the actual extent and distribution of depressional storage in farm-scale landscapes in Alberta.

Recent studies in Alberta (WER., 1987) have recommended that: "the estimation of depressional storage volume should be more accurately calibrated by field checks and contour mapping" and that "field scale programs be undertaken to determine areas and depths of specific wetland types with a view to developing regionalized predictive equations for wetland surface area, depth and volume relationships". No studies of this nature have been published to date for Alberta conditions.

One of the few studies to consider methods explicitly for automated surface depression analysis was conducted by Jenson and Trautwein (1987). Jenson and Domingue (1988) applied these techniques to determine the water storage capacity of glaciated pothole terrain in North Dakota. Their technique involved subtracting an original gridded elevation matrix from one in which all possible depressions had been removed. The resulting difference map showed the maximum depressional storage capacity. Connectivity between depressions was established by locating all potential pour points between adjacent depressions and identifying the lowest as the overflow point.

Jenson and Domingue (1988) noted that "because of the low, rolling topographic relief of the terrain, manual delineation and flow modelling of potholes would have been extremely time consuming". They recommended automated feature extraction of geomorphic and hydrological information. The present study postulates that automated procedures offer advantages in comparison to current manual techniques and undertakes to develop and test suitable automated procedures.

4.2 Background and justification of methodology

4.2.1 Techniques for automated feature extraction

Automated techniques for extraction of geomorphological and hydrological features have been developed for several forms of elevation data (Figure 4.1), namely;

'pits' to an elevation equivalent to that of the rim of the 'pit' (Figure 4.3 c). This effectively removed the disruptive effect of topographic 'pits' and allowed for definition of continuous stream channels (Figure 4.3 d).

Band (1986a) used preprocessing filtering to minimize topographic 'pits' and then manually attended to any gaps in the computed network structure in an interactive post-processing operation. He presented a variety of thinning algorithms aimed at reducing groups of initially nominated stream or ridge pixels to individual connected channel or ridge lines only one pixel in width (Figure 4.3 e). Wood (1990) reviewed the various approaches used to define and link channel and ridge networks and suggested several extensions for line elimination and line joining.

4.2.4 Hydrological features based on pixel connectivity and flow paths

Techniques based on the calculation of topological connectivity have been argued to be more rigourous for defining not just stream channels, but all routes of potential overland flow. These involve tracing the likely routing of surface runoff from every pixel through its neighbours to an outflow point or a terminating depression (Figure 4.4). This physically and hydrologically reasonable approach has been described by O'Callaghan and Mark (1984) and Mark (1983a,b) and used by Miller (1984), Band (1986b), Bork and Rohdenburg (1986), Morris and Heerdegen (1988) and Martz and de Jong (1988).

Two different computational algorithms have been used to define flow path geometry. One involves sorting the pixels in order of elevation and tracing pixel to pixel connectivity from the highest downward (Mark, 1983a; Bork and Rohdenburg, 1986). Program listings for such an approach have been published by Martz and de Jong (1988). The second algorithm requires an ability to hold an entire matrix of elevation values in computer memory (Mark, 1984). It begins with the lowest elevation pixel, climbs the path of steepest ascent through all connected pixels until a ridge or edge is encountered, then falls back through the path counting and recording the number of upslope pixels. It then starts again on the next highest pixel and continues recursively until all possible paths have been evaluated. This approach has been used successfully by Marks et al. (1984) and Band (1986b).

Both of these pixel routing approaches produce essentially similar output. The primary product (Figure 4.4 a) is a matrix, identical in dimensions to the input matrix,

in which each pixel is assigned a drainage direction into the lowest of its downslope neighbours. A second matrix is then computed containing values for the upslope catchment area calculated as the number of upslope pixels linked to and contributing flow to the target pixel (Figure 4.4 b). All pixels connected by flow paths to a given target pixel are viewed as belonging to a single watershed or catchment (Figure 4.4 b). These routing procedures exhaustively define pixel to pixel drainage connectivity for every element of an elevation matrix. This connectivity equates to runoff flow paths given conditions of impermeable soil surface and uniform, constant rainfall (Bork and Rohdenburg, 1986).

In some more complex algorithms the runoff value is calculated as the total hypothetical runoff passing through the pixel from upslope pixels where each pixel is allowed to drain, wholly or partially, into as many downslope neighbors as exist (Bork and Rohdenburg, 1986; Quinn et al., 1991). Martz and de Jong (1988) computed one set of values for local catchment area (LCAT) for each pixel and another set for what they called a global catchment area (GCAT). Global catchment area was calculated after processing to remove the disruptive effects of topographic 'pits'. Bork and Rohdenburg (1986) computed and stored not only the size of the catchment area above each pixel but also the average slope of this unique catchment area for each pixel.

Stream networks (Figure 4.4 c) can be approximated at various levels by setting threshold values for catchment area above which a pixel is considered to belong to a drainage channel (Band, 1986b, Morris and Heerdegen, 1988). Bork and Rohdenburg (1986) used a threshold method similar to that described by Band (1986b) to define drainage channels but modified the procedure to consider average curvature as well as absolute size of the upslope catchment area.

4.2.5 Automated recognition of higher order objects or entities

Perhaps the most ambitious use of geomorphic feature extraction techniques based on elevation data is concerned with automated partitioning of the landscape into hydrologically significant entities. Further processing can be applied to stream channels identified as described above, in order to group and label stream networks automatically (Band, 1986b; Band and Wood, 1988)(Figure 4.5 a). Complementary drainage divides (Figure 4.5 b) can be delineated by procedures very similar to those described for stream channels (Band, 1989b). Drainage channels and water divides

can be intersected to define areal land units (Figure 4.5 b) such as watersheds, sub-watersheds (Miller, 1984, Band, 1986a) and 'slope facets' via automated procedures (Band, 1986 a,b; Band and Wood, 1988; Band, 1989a).

Band (1985; 1986a,b; 1989a,b) described a suite of processing algorithms designed to permit automatic delineation of drainage entities using digital elevation models. His objective was to partition landscapes into ecologically and hydrologically significant sub-units (Figure 4.5 b). This approach minimized storage of redundant information at each grid point by agglomerating grid data into larger 'slope facet' units. These were treated as fundamental drainage entities acting as distributed sources of storm runoff (Band, 1986a; Band and Wood, 1988) or as ecologically and hydrologically distinct landscape units (Band, 1989a,b,c). Band (1985) emphasised that terrain data were not merely another data layer. Terrain data provided the fundamental information used to "organize the watershed into a set of non-overlapping drainage regions that exhaustively cover the surface and are hydrologically connected by their position in an hierarchical stream network system" (Band, 1985).

These larger entities were argued by Band (1986a,b) to offer a number of advantages for hydrologic modelling. They reduced processing requirements relative to the total number of initial grid squares used to define them. They represented complete fields or objects that could be assigned representative parameter values when modelling runoff response. They allowed for unambiguous definition and storage of explicit connectivity between entities thus avoiding the time consuming pixel to pixel tracking of drainage paths used by pixel based techniques. Storage of redundant data was reduced by computing statistical descriptions for certain attributes (ie slope, aspect, curvature) based on all of the pixels included in the entity but stored just once as a basic description of the larger object. Finally, Band (1985) noted obvious advantages for information processing that arose from the ability to organize entities hierarchically in a rooted tree graph. These benefits included automatic generalization of information to different scales and tracing and aggregation of all regions upstream or downstream of a point.

Depressions, or pits represent a unique type of higher order object or feature of hydrological or geomorphological significance (Figure 4.5 c). With the exception of Jenson and Domingue (1988), Jenson and Trautwein (1987) and Yuan and Vanderpool (1986), pits have been considered to be aberrations or data errors by virtually all those concerned with the extraction of geomorphological and hydrological

data from gridded DEM data sets (Hutchinson, 1989). Even Jenson and Domingue (1988) largely regarded depressions as impediments to the definition of an integrated drainage network and were mostly concerned with devising a hydrologically consistent technique for removing depressions. Their analysis of depressional storage capacity in glaciated pothole terrain was largely a by-product of their principal efforts at watershed delineation.

Yuan and Vanderpool (1986) explicitly calculated the location and extent of pits or lakes in simulated terrain of differing complexity (Figure 4.5 c). They noted that the most complex part of their program involved the treatment of depressions but still only found the final outlet, or pour point, for each depression and filled the depression by adjusting the elevation of all points in the catchment below that level to the elevation of the pour point.

Miller (1984) carried automatic feature encoding to its logical conclusion in proposing a conceptual framework for a comprehensive spatial data structure for hydrologic applications. He used automatic feature extraction to define the entities, attributes and relations demanded by a relational model for a hydrologic spatial information system. Miller (1984) began by defining the prototype data structures for primitive spatial entities which were used to define and describe higher order spatial objects for areas of land or water.

Until recently, geomorphological and hydrological analysis of digital elevation data was mainly done by individual researchers using custom written programs. Lately, suites of programs for conducting these analyses have been packaged into user friendly toolboxes and released into the public domain (Jenson and Domingue, 1988; Wood, 1990) or offered as commercial GIS systems (Silfer et al., 1987; Johnson, 1989).

4.2.6 Conclusion - justification of methods

Overall, grid based techniques for automated extraction of hydrological and geomorphological features are by far the most common and easy to use. They have a distinct advantage in topological and computational simplicity. It is quite easy to define the topological relationships governing water flow between cells and to compute geomorphic or hydrological criteria at each grid cell. Disadvantages include

the large storage and computational overheads associated with fixed sized entities and the arbitrary size and shape of the grid cells used to subdivide the area of interest.

A clear direction of recent geomorphological research into DEMs has been toward development of automated procedures for identification of higher order entities or spatial objects. These are often envisaged as components of a hierarchical network of hydrological units. Very little existing research has recognized the role of pits or depressions as essential components of any hydrological network and none has elaborated effective procedures for computing and describing a hierarchy of depressions and how they interconnect with one another and with the overall hydrological network. The present research aims to address some of the limitations of current procedures relative to describing and coping with the existence of pits.

4.3 Experimental design - geomorphological analysis

A fundamental objective of the present research was to determine where surface water would flow and where it would accumulate in a farm-scale landscape characterised by low relief. It was assumed that landscapes of interest would be dotted with numerous individual depressions and that they would not possess a well established pattern of integrated surface or sub-surface drainage. An "open landscape" approach (Howitt, 1991) was adopted in order to facilitate the study of processes and patterns in a realistic, natural landscape setting under normal farm management practices.

The primary questions of concern in determining the spatial pattern of water flow and accumulation in the landscape of interest were:

a) where would water flow? (ie along what paths?) and where would it accumulate (ie where are depressions located?)
b) what was the extent of the area contributing flow to any given depression?
c) what was the size and volume of each depression where water could accumulate?
d) where would the water from a given depression flow once that depression had been completely filled to its maximum or 'overspill' volume?

In determining the geometry of surface runoff and accumulation, it was assumed that most runoff of interest occurred as over-land flow or near surface through-flow. This assumption recognized the prevalence of frozen ground conditions during spring

runoff that effectively reduce infiltration to zero (JNM, 1986). It therefore followed that the direction of flow and the specific flow paths followed by runoff could be considered as relatively static, or stable, features of the landscape, controlled solely by the geometry of the land surface. Similarly, the location and size of depressions and their hydrological inter-connectivity were viewed as stable landscape features not subject to significant change over the scales of time and space of interest to this study. The experimental design adopted to assess this static geometry governing the flow of surface water is outlined in Figure 4.6 and discussed in detail in the following section.

4.4 Methods - geomorphological analysis

4.4.1 The Watersh utilities for hydrological modelling

A suite of interactive, PC based, watershed modelling utilities (**Watersh**; van Deursen and MacMillan, 1991) was used to define the "static" features controlling the flow and accumulation of surface water. The **Watersh** utilities were made available by their author (W. van Deursen) who cooperated in making modifications and extensions that facilitated explicit modelling of flow into depressions and characterisation of depressions (see Table 4.1). These changes were made at the suggestion of and with the assistance of the current author.

The **Watersh** utilities are based on a simple raster representation of space and act on a regular grid of elevation data. Numerous similar algorithms have been described by other authors including Band (1985, 1986a,b, 1989), Miller (1984), Mark (1983a), O'Callaghan and Mark (1984), Martz and de Jong (1988), Jenson and Trautwein (1987) and Morris and Heerdegen (1988). The fundamental concepts and core algorithms used in **Watersh** are based principally on those given by Marks et al. (1984) with extensions similar to those proposed by Jenson and Domingue (1988).

The **Watersh** utilities were used to calculate flow directions, flow paths, upstream element counts and catchment areas (Figure 4.4); to locate and document the volume and extent of depressions (Figure 4.5 c) and to determine the hydrological connectivity between depressions (Figure 4.5 c). The sequence of steps by which this was accomplished is outlined in Figure 4.6.

4.4.2 Obtaining and preprocessing a gridded digital elevation model (DEM)

A gridded digital elevation model (DEM) was obtained for the Lunty study site. The DEM was produced photogrametrically from specially flown 1:3,500 scale aerial photographs. The initial DEM recorded vertical elevation in metres to three decimal points (1 mm) for points spaced at intervals of 5 metres in the horizontal dimension. The vertical resolution of this initial DEM was purposely degraded by rounding values to the nearest 0.1 metre (10 cm). Actions taken to obtain and preprocess the DEM are described in greater detail in Chapter 3 (see sections 3.3.6 & 3.4.6).

4.4.3 Computing local direction of flow (LDD) and locating pit centres

In using the **Watersh** utilities to determine where water would flow, all runoff was viewed as arising from Hortonian or saturation excess overland flow (Dunne, 1983, van de Griend and Engman, 1985). Field observations (Chapter 3) confirmed this to be a reasonable assumption, at least for the period of early spring snowmelt and runoff.

The principal factor influencing the geometry of surface runoff was taken to be the shape of the land surface and, in particular, the direction of maximum down-slope gradient. Water was assumed to flow in the direction of maximum down-slope gradient from each grid element to its lowest down-slope neighbour. If a grid element had no lower down-slope neighbours but had one or more neighbours of the same elevation the maximum gradient was 'flat' and a 'logical' flow direction was computed. Any grid element entirely surrounded by elements of higher elevation was recognized as a 'pit' element and taken to be the centre of a sink or depression.

The local direction of flow (drain direction) was taken as the direction of steepest descent from the centre cell of a 3 x 3 moving window to one of its eight surrounding neighbours (Figure 4.7 a) The slope, or weighted drop (Jenson and Domingue, 1988) was calculated as the difference in elevation between the centre cell and the neighbour cell, divided by the distance between the cells ($\sqrt{2}$ for diagonal neighbours and 1 for non-corner neighbours). The local drain direction was coded using the numbers 1 through 9 (Figure 4.7 b) as described by Morris and Heerdegen (1988). In cases where the maximum down-slope gradient was identical for more than one neighbour

element, the local drain direction was assigned to the last grid cell for which the maximum slope applied (ie the number closest to 9). This arbitrary assignment resulted in a slight preferred orientation for flow directions towards the north and northeast.

The use of the numbers 1 through 9 in the particular orientation illustrated in Figure 4.7 b was chosen to facilitate subsequent adjustment of flow directions, in particular the reversal of flow directions. Any flow direction can easily be reversed by simply subtracting its assigned value from 10. For example 10 - 9 = 1 and 10 - 1 = 9.

A special case was recognized for grid cells along any of the edges of the matrix (Figure 4.7 c). These cells do not have a full complement of 8 neighbour cells. In such cases, it is impossible to know whether the missing neighbour cells are higher or lower than the centre cell being processed. Consequently, it is not possible to know with certainty the correct flow direction for that cell. The normal approach in such circumstances is to treat the edge of the data set as an infinitely deep sink and direct all flow from edge cells off the edge of the data set into the "outside world". For the present exercise, it was decided instead to treat the edge of the data set as an infinitely high barrier so that drain directions for any edge cell were selected to flow to the lowest of the available neighbours rather than to the outside world (Figure 4.7 c).

Preventing flow to the outside world was adopted in order to minimize the number of individual catchments defined from the data set during subsequent processing. Any catchment connected to the outside world is incompletely defined regardless of the choice made above. It was simply considered more convenient to have fewer and larger incomplete edge catchments with which to deal.

Any grid cell entirely surrounded by cells of higher elevation was recognized as a pit element and was assigned a drainage direction of 5 (Figure 4.7 d). Pit elements were also recognized in those cases where one or more neighbour elements were at the same elevation as a pit element but all neighbour cells had previously assigned logical flow directions flowing into the pit element. Unlike most other raster approaches to geomorphic flow modelling, the **Watersh** utilities do not fill pits by flooding them to their outlet elevations as a preliminary preprocessing step. Each pit cell therefore represented the termination of all flow paths in the catchment contributing flow to that point. Each pit cell is the centre of a depression of fixed volume and extent fed by a

watershed of fixed dimensions. The locations of all pit cells (row, column) were recorded and used to map the likely location of all possible depression centres.

Flat elements were recognized where no neighbour cells were lower than the central cell but one or more neighbours were identical in elevation (Figure 4.8). Flow directions were ambiguous for flat areas so additional processing was required to determine logical drain directions. Most existing algorithms are known to contain directional bias in the assignment of flow direction to flat areas. Wood (1990a) showed how the order in which cells or watersheds are processed can affect the assignment of flow directions and the allocation of cells to different catchments (Figure 4.8 a).

The original **Watersh** algorithms were modified to achieve improved allocation of flow directions to flat elements and to enable computation of flow paths across flat areas, particularly flat areas within depressions. The changes required that flow direction be allocated across flat areas in a stepwise fashion as illustrated in Figure 4.8 b. This stepwise allocation ensures that flow paths grow back from the nearest cell with a defined downslope direction of flow, if any such cell exists (Figure 4.8 b i&iii). In the case of a perfectly flat depression or lake, flow directions grow in from an outside cell with a defined flow direction pointing into the lake, one cell at a time, at an equal rate from all edges of the depression (Figure 4.8 b ii).

The efficacy of the improved algorithm is demonstrated by applying it to a hypothetical DEM representing an extreme case of predominantly flat cells (Figure 4.8 c). Local directions of flow are allocated in a uniform and consistent pattern with flow always directed towards the nearest cell with a defined flow direction for a flat plateau and from the outside edge towards the centre for a flat lake. The resulting allocation of cells to watershed areas is equal and consistent.

4.4.4 Computing up-slope element counts and defining watersheds

Once every grid element was assigned a local direction of flow, pixel to pixel connectivity was used to establish the topology of flow across the landscape. Flow paths and catchment areas were computed by connecting cells according to their assigned flow directions. Pit centres were used as starting points in a recursive procedure (called Go-Upstream) for defining flow paths and catchment areas. All grid

elements whose flow paths terminated at the same location were considered to belong to a single catchment. Depressions were identified wherever flow paths for a given catchment terminated at a pit element. Such catchments were regarded as depressional catchments.

The Go-Upstream procedure works by going to a starting cell and repeatedly calling itself. When called, it causes the location of the current centre cell to move up through the data set into the neighbour cell with the highest elevation that also has a flow direction pointing into the current centre cell. This procedure is repeated until a cell is reached that has no higher neighbour cells with drain directions pointing into itself. Such a cell is either at the edge of the data set or represents a divide cell.

When the procedure has climbed up as high as it can and has encountered a divide cell, it labels that cell with an integer number used to identify all cells which drain uniquely to the initial starting point. This is the catchment ID number. At the same time, it computes and stores to a variable called Upslope-Elements, a number representing the number of cells upslope of the current cell. In the case of a divide cell, there are no other cells upslope of it and it is assigned an upslope area of 1.

When a divide cell has been reached and the procedure can no longer go upstream, it falls back down following the drainage direction into the previous centre cell. Upon arrival at this lower cell it attempts again to go-upstream into any higher cell that has not already been labeled and that has a drainage direction pointing into the current centre cell. If it can, it climbs up this new upslope path until it reaches a new divide cell then starts falling back again. If it cannot climb up to any higher cell it labels the current cell with the unique catchment ID and records the total number of elements upslope of the current cell to the variable Upslope-Elements. This procedure continues until all cells higher than the initial starting cell and having drainage paths leading into it have been labeled with the unique catchment ID and have been assigned a value for the number of upslope elements.

For this application, pit centres were always selected as the seed points or starting points for invoking the recursive Go-Upstream algorithm. The data matrix was scanned for pit centres identified by the value of 5 for flow direction. The Go-Upstream procedure was then used to climb upstream from each pit centre until all cells flowing into that pit were identified and processed.

The Go-Upstream algorithm was used to determine the total number of grid cells upslope of any given cell and to assign a unique catchment identifier number to all cells that drained into each pit cell starting point. The upslope element count represents the total number of grid cells upslope of a given cell and connected to it by a defined flow path. The catchment ID identifies all grid cells which drain uniquely to the same pit centre as belonging to the same watershed or depressional' catchment. Both of these terrain derivatives were used in the distributed modelling described in subsequent chapters.

4.4.5 Locating pour points and computing statistics for depressions

A procedure called Find-Outlet-Points was added to the initial **Watersh** algorithms to provide a tool to assist in computing and documenting depressional storage capacity. It was used to compute a pit list table containing details of the total area of each watershed; the maximum area, volume and depth of the depression contained within each watershed and the locations and elevations of overflow or pour points for each watershed (Figure 4.9 and Table 4.2).

The Find-Outlet-Points procedure was applied sequentially to each pit centre. It operates by going to the identified pit centre element and invoking the previously described Go-Upstream algorithm to climb up through all upstream elements draining into the initial pit centre starting element. Each new grid cell is checked to determine if any of its neighbours belongs to a different watershed and if it does, the central cell is recognized as a boundary cell. Each time a boundary cell is identified, the elevation of the boundary cell and the elevation and watershed ID number of all neighbouring cells not belonging to the initial starting watershed are checked. The neighbour cell with the lowest elevation is recognized as a possible overspill point from the initial catchment into its neighbour (Figure 4.9 a).

The elevations of the boundary cell (InElev) and its neighbour overspill cell (OutElev) are compared to determine which is greater. The larger value is recognised as the elevation to which water must rise to overspill from the initial catchment into its neighbour (PourElev, see Figure 4.9 b). A record is maintained of the row, column, catchment ID and elevation for each pair of grid cells found to possess the lowest pour elevation between the initial catchment and each of its neighbours. If a lower pour point into any neighbouring catchment is encountered then all data pertaining to the

currently recorded overspill location into that catchment are replaced. When all edge or boundary cells have been checked, the recorded values are taken to represent the locations and elevations of pairs of grid cells along the catchment boundary with the lowest recorded pour elevations (see Table 4.2).

A second stage of this procedure computes the volume of water required to fill the depression before overspill will occur and the maximum area of the resultant pond (Figure 4.9 c). The assumption is made that water will rise to the lowest of the possible pour elevations and that any further increase in water volume will result in overflow into the neighbouring catchment. The algorithm compares the elevations of all the potential pour points into neighbouring catchments and selects the lowest. This is viewed as the actual pour elevation. The initial catchment is then traversed again by the Go-Upstream algorithm and any grid cell with an elevation less than or equal to the pour elevation is identified. The elevation of each such cell is subtracted from the pour elevation to calculate the height of water required to flood that cell to the pour elevation. Multiplication of this height by the unit area of the grid cell provides an estimate of the volume of water above that grid cell. When all grid cells with elevations lower than or equal to the pour elevation have been identified, the total volume of water required to fill the depression to the pour elevation is computed as a simple sum of all grid cell volumes. The area of the pond is computed as equivalent to the number of grid cells identified as lower in elevation than the pour elevation (see Figure 4.9 c).

The Find-Outlet-Points procedure prints the statistics for each investigated catchment to the screen and, optionally, will print the results to a user identified ASCII file. The content of the reported data is illustrated in Table 4.2 for watershed number 23. The total area of watershed 23 is 1360 grid cells of unit dimension. The pit centre (seed point) is located at row 52 column 42 at an elevation of 722.7 m. The pond centred at this location has a maximum volume of 7.5 m times the unit area (25 m^2) of a grid cell (187.5 m^3) and an area of 52 grid cells (1300 m^2). Each neighbouring watershed that borders on shed number 23 is identified by its unique catchment number under the column Next-Pit. In-Row, In-Col and In-Elev refer to the row, column and elevation of the cell within the source watershed (23) which is the potential pour point (lowest cell) between the source watershed and the identified neighbour. Out-Row, Out-Col and Out-Elev are the row, column and elevation of the corresponding lowest point in the neighbouring watershed. The higher of these two points determines the pour

elevation, which is the elevation to which water must rise to first escape from the source depression.

In the example given (Table 4.2), the lowest pour elevation is 722.9 m and occurs between watersheds 23 and 33. This indicates that watershed 23 will overspill into watershed 33 at the indicated location once the volume of water stored in depression 23 exceeds 7.5 m (times the unit area of 25 m^2).

The Find-Outlet-Points procedure may be applied to a single catchment, to all catchments or to a selected number of catchments identified in a separate ASCII file. In the present research, it was initially applied to the entire DEM to identify and characterise all initial (first order) depressional watersheds. It was subsequently used to document individual higher order watersheds created by linking two or more of the initial first order watersheds whose ponds were nested within a larger subsuming depression.

4.4.6 Analysing pond statistics to determine pond connectivity for storage in a DBMS

An important consideration in assessing the topology governing the flow of water into, through and out of depressions is to know where water will flow once the depression in which it is initially contained is full to its overspill elevation. The following semi-automated procedure was used to determine this information.

The pit list table described above (see Table 4.2) was used to determine all possible locations of overspill between each depression and all of its neighbours. This information was transferred into a dBase III+™ database table (see Table 4.3) and a small program was written to scan the data file to identify the record or records having the lowest overspill elevation between any given catchment and all of its neighbours. All records for a given catchment in which the reported pour elevation was higher than the minimum pour elevation for that catchment were deleted. In most cases this resulted in the identification of a unique overspill location into a single neighbouring catchment for any given pit or depression (Figure 4.10 a).

In instances where catchments had two or more potential overspill locations at the same elevation (Figure 4.10 b), all such records were left in the data table during automated processing. A manual procedure was subsequently used to identify and

select one of these pour points as the most likely location for overflow. The second most likely pour point was also identified during manual review. The manual processing was done in order to simplify subsequent modelling efforts.

The manual decision making was aided by the production of idealised two dimensional cross sections to illustrate the relative location of each pit along with its base elevation, overspill elevation and the neighbour pit (or pits) into which it could flow (see Figure 4.10 b,c). These two dimensional cross-sections assisted in the visualisation of pond connectivity and were used to help decide where flow from a given catchment should be directed in the cases where there were two or more possible overspill locations at the same elevation. They also were useful in that they served to group the large number of initial depressional catchments into a smaller, more manageable, number of linked super-catchments.

Initial efforts to define connectivity by means of a single pointer to a single neighbouring watershed were found to be inadequate for subsequent modelling efforts. Consequently, the initial pond table database structure (Table 4.3) was modified to permit recognition of both a primary and a secondary pour point. Overspill was judged most likely to occur at the primary pour point, but, if required, could also occur at the secondary pour point. For example, in Figure 4.10 b, if C overspilled into D but D was full and spilled back into C then a second choice was recognized for overspill from C into B. Two pointers were found to be adequate to deal with all occurrences of multiple pour points even in cases where as many as 5 adjacent watersheds had pour points at the same elevation.

4.4.7 Identifying and documenting nested depressions

The manual procedure used to assign pond connectivity and determine overspill locations was complicated by the existence of nested depressions within the data set. The term "nested depression" is coined to describe the situation that occurs where initial or lower order depressions coalesce and are flooded or subsumed by larger, higher order depressions (Figure 4.10 c). This situation occurs wherever two or more depressions overspill into one another and can not subsequently overspill into any other neighbouring catchment at the same overspill elevation. In such instances it is necessary to determine the pit list characteristics of the new higher order depression before continuing with the consideration of pond connectivity and the assignment of overspill locations.

The procedure for deciphering the hierarchy of nested depressions involved joining the lower order watersheds according to their computed connectivity, rebuilding the catchment data set and recomputing the pit list data for the new depression. The depressional catchments were processed in order, from those with the lowest pour elevation to those with the highest pour elevation (Figure 4.10 c). All neighbouring watersheds sharing the same pour elevation were required to be joined together before the new, larger, catchment was rebuilt and the pond statistics computed for it.

The enhanced pit removing option added to the **Watersh** utilities was used to create a new higher order watershed by connecting the various lower order watersheds identified as having overspilled to form a nested depression. This was done by removing those pits designated as having overspilled into a neighbour pit with the same pour elevation. The new combined watershed was given a unique watershed ID number one larger than the last defined watershed. It, and all of its neighbouring watersheds, were then rebuilt using the **Watersh** procedure Find-Watersheds-From-A-File. Rebuilding from a file enabled each watershed to retain its original identification number through each reprocessing step.

The characteristics of each new watershed and its associated depression were then determined using the previously described **Watersh** procedure Find-Outlet-Points and this data was written to an ASCII text file. A single record containing the most likely overspill elevation and pour point was identified and imported into the dBase III+™ data base pond table. This record was used to establish the new volume and the location at which the new, larger pit would overspill and the watershed into which it would deliver its overflow. The ASCII file and the schematic cross section were reviewed to determine if the new catchment had two or more possible pour points at the same elevation. If so, the second most likely pour point was identified and recorded in the new record added to the dBase III+™ data table.

4.4.8 Procedure used to remove pits to link lower order depressions

Pit removal (Figure 4.11) was done interactively and selectively using the **Watersh** procedure Remove-This-Pit. The option Remove-This-Pit worked by starting at the pit centre and climbing uphill using the previously described Go-Upstream algorithm until it had located the lowest possible overspill point. Once this overspill point had

been located, the local drain direction for this cell was changed to point into the lowest of its neighbours belonging to any watershed other than the initial watershed from which the search began. The algorithm then fell back from the pour point to the depression centre according to the drainage direction assigned to each cell along the single flow path from that point to the pit centre. At each cell along the path, the drainage direction was changed to point back into the last cell above it from which the algorithm had just come (Figure 4.11 a). The newly assigned drain directions cause any flow arriving at the 'old' pit centre to continue on flowing up-hill, out of the initial depression and into the neighbouring depression passing through the lowest possible pour point.

The pit or pits to be removed were identified, using the schematic cross sections, as those depressions deemed to be overspilling into a common base pit to form a nested depression (ie pits 1,2,3 & 4 in Figure 4.10 c). The pit or pits to be removed were then located inter-actively using the display capability available in the **Watersh** utilities. The option Remove-This-Pit was selected and the pit was removed. At all times a further option was activated which modified the initial elevation matrix during pit removal by changing the elevation of all grid cells within the pit being removed to equal the overspill or pour elevation (Figure 4.9 c). This was done in order to avoid a computational problem in the **Watersh** utilities that produced incorrect estimates of total depression volume whenever the terrain did not climb continuously from pit centre to the overspill point (see discussion later in this section).

A number of rules of thumb were developed to help decide the order in which to remove pits (Figure 4.12). It should be pointed out that the intent of the procedures described here is to define the geometry of depressions in order to compute the relevant statistics regarding pit volume, pit connectivity and overspill location. These procedures should not be confused with top-down methods used to describe the hydrological processes of filling and overspill of a series of cascading reservoirs.

The first rule of thumb adopted was that pits would be removed in order of pour elevation, from the bottom up. All pits sharing any given pour elevation (except the single remaining seed pit) had to be removed (into the seed pit) before any pits with higher pour elevations could be removed. This ensured that all pits that could possibly be flooded by a higher order subsuming pit were amalgamated before the higher order pit was recognized and created (Figure 4.12 a).

The second rule of thumb (Figure 4.12 b) imposed the constraint that where several pits shared the same pour elevation, overspill should be into the pit with the lowest base (pit centre) elevation. Where two or more pits had the same pit centre as well as pour elevation, overspill was directed into the pit with the largest catchment area (ie number of upslope elements at the pit centre). This sequence was adopted in order to support subsequent modelling efforts where grid elements were processed in order, by catchment, by elevation, by upslope area. It was necessary that the last (or sometimes the first) cell in this sequence always be the actual pit centre element. These rules ensured that the pit centre identified for higher order pits was always the lowest cell in the new, amalgamated watershed and that it had the largest number of elements upslope from it.

The third rule of thumb involved computing a statistic referred to as volume-to-area-ratio (V/A-Ratio). The ratio of a pit's volume to its total catchment area (V/A-ratio) was taken to approximate the relative magnitude of effective runoff that would be required to flood a given pit to its capacity. This statistic was used to estimate the likely amount of runoff required before a given pit would fill and overspill to its neighbour. It was used to identify the most likely sequence for pit overspill for cases where two or more pits shared the same pour elevation and were connected but rules one or two didn't apply. The pit with the smallest V/A-Ratio (least amount of runoff required to fill) was assumed most likely to overspill and was selected for pit removal first and removed into its closest neighbouring watershed (Figure 4.12 c).

The V/A-Ratio statistic was subsequently used to estimate the volume of water that would be required to flood a higher order subsuming depression to the level where it would overspill into its neighbouring catchment with the lowest pour elevation. This information was utilized in the construction of connectivity dendograms used to illustrate the topology of connectivity between depressions.

The fourth rule of thumb required that circular flow be enforced to ensure that all pits sharing a common pour elevation would all be connected before any connections could be made to pits of higher elevation. Circular is used here in reference to following a path of pointers in the pond database in such a way that the pointers always lead back to the starting pit record after all pits at the same elevation have been traversed. It does not refer to water flowing in a circular pattern. It is achieved by including pointers in the fields DRAINSTO and NEXTPIT that direct the algorithm to follow a circular path and always return to the initial starting pit before moving up to any pit

with a higher pour elevation. This rule was imposed in order to support subsequent dynamic modelling in which it was essential that there be some way of ensuring that all pits at any lower level in the nested hierarchy of pits were full before any water was directed into overlying or subsuming pits (see Figure 4.12 d)

A corollary to the first rule of thumb was that no pit located above a nested depression and contributing flow into the nested depression was ever removed until it became the lowest neighbouring pit into which the nested pit could possibly drain (Figure 4.12 a). It was removed only after the statistics pertaining to the volume of the lower, nested pit and its connectivity had been established using the procedures documented previously. This rule defies the logic implicit in the concept of V/A-Ratio which suggests that a higher pit with a small V/A-Ratio should fill and overspill long before a lower, nested pit with a very large V/A-Ratio would be in a position to overspill back into the higher pit. The problem with allowing higher pits to overspill in sequence, according to their V/A-Ratio, is that these pits then cease to be recognized and it becomes impossible to compute the volume of water that would be required to fill the lower nested depression before it would overspill into the (now removed) higher pit. The information on pit volume for each possible stage of pit inundation was essential for subsequent modelling efforts. This justified ignoring the logical sequence of pit overspill implied by V/A-Ratio and instead imposing an order determined by pour elevation.

4.4.9 Rebuilding higher order watersheds after pit removal

The option Find-Watersheds-From-A-File was used to rebuild the data set after any group of linked depressions had been removed to create a new, higher order depressional catchment. This procedure operated using the previously described Go-Upstream algorithm to label all grid cells draining to a given pit cell as belonging to a uniquely numbered watershed. The only difference here was that the location of grid cells to use as starting points for building the catchments and the unique numbers to use to label each catchment were read from a file instead of being located and assigned automatically by the program.

The **Watersh** procedure Write-Short-Report had been used initially to write to an ASCII file (named current.cat) a listing of the location (row, column) catchment number and area for all of the initial first order catchments. As catchments were removed using the pit removing option, the reference to these catchments in the file

current.cat was also removed and the identifying number of the new seed point was changed to that of the new higher order nested depression. When watersheds were subsequently rebuilt using the procedure Find-Watersheds-From-A-File, the program did not attempt to rebuild watersheds for former pits that had been removed using the pit removing option and whose reference had been deleted from the file current.cat. Rebuilding watersheds from a file had the beneficial effect of maintaining the initial unique catchment ID numbers for any previously identified watersheds so that ID numbers did not change unpredictably with each rebuilding of the catchment data set.

4.4.10 Computing catchment statistics for higher order watersheds

The procedure Find-Outlet-Points was used after each new higher order depression was created in order to produce the information required to characterise these new watersheds and their associated depressions. The information was written to a temporary ASCII file named so as to readily identify the watershed to which it applied (ie 136.rep). Manual inspection of the resulting report file was carried out to identify the neighbour watershed into which the new higher order watershed was most likely to overspill. In most cases this was straight forward as there was a single identifiable lowest pour point into one of the neighbouring watersheds. For those few higher order depressions that had multiple pour points, the previously described procedures were re-applied to decide which of two or more choices to select and in what order.

It was necessary to process the data on pit volume further in all cases where new, larger depressions formed from the coalescence of two or more smaller depressions. Subsequent modelling efforts required knowledge of not only the total volume of the new depression but also the portion of that total volume (VolToFill) not associated with previously defined depressions (see Figure 4.11 b). The pit volume computed and recorded in the pit list table consisted of both this differential volume increase (VolToFill, ie vol. C in Figure 4.11 b) and the volume previously computed for the initial seed pit contained within the new larger pit (ie vol. B in Figure 4.11 b).

The volume computed by Watersh for higher order pits does not include the volume of any lower order nested pits that have been removed to create the new watershed (ie vol. A in Figure 4.11 b). The volumes of these nested pits were not included in the computation because the procedure used to remove pits changed the elevation data set. When a pit was removed, the elevation of every grid cell in that catchment lower than

the pour elevation was reset to equal the pour elevation. Consequently, these depressions disappeared from the elevation data set and were not recognised when a volume was computed for any new higher order depression.

This idiosyncrasy was imposed by a limitation in the **Watersh** algorithm used to calculate pit volume. The algorithm produced incorrect estimates for total pit volume if it encountered a situation where the Go-Upstream routine had to actually go down-hill in its progression from the pit centre to the lowest pour point. In order to avoid this problem, the option to modify the elevation matrix was always selected when removing or unblocking pits. This option simulated the complete filling of the depression being removed by changing the elevation of all cells in that watershed lower than the pour elevation to be equal to the pour elevation. As a result the Go-Upstream algorithm did not encounter any situations where it had to go down-hill and the volume estimates produced were dependable. They did not, however, automatically account for the volumes of any lower order, nested depressions that had been removed to produce the new, larger watershed.

The following procedure was used to produce values for both the total volume of any new combined depression and the incremental increase in volume (VolToFill) of the new pit over and above the volume of all lower order nested depressions contained within it. Firstly, for any given higher order depression there was only one single lower order depression that could possibly still exist as a seed point as far as the elevation data set was concerned. All other lower order depressions would have been removed from the data set during pit removing. This lower order seed depression was identified and its volume was subtracted from the computed pit volume of the new depression. This produced an estimate for the differential increase in volume of the new depression (VolToFill) over the volume of the nested depressions it subsumed. All lower order pits subsumed by the new higher order pit were then identified and the sum of their individual volumes was computed. This sum represented the total volume of all pits subsumed by the new larger pit. It was regarded as the total previous volume and stored in the data base in a field named PREVOL. The sum of PREVOL and VOLTOFILL was computed and considered to represent the correct total volume of the new depression including all of its contained depressions.

4.4.11 Computing the statistic volume-to-first flood

A new statistic called volume-to-first-flood was defined after it was found to be required for use in the DISTHMOD simulation model (see section 6.3.3). This statistic is calculated for every grid cell in the data base that can be inundated by water stored in any of the potential ponds. It is a measure of the volume of water that must collect in a pond before the cell in question first becomes covered by pond water. The statistic is calculated only after all of the data pertaining to the volume and connectivity of pits, especially nested pits, has been calculated. The statistic is used in the DISTHMOD model to determine if a given grid cell should be treated as inundated when the pond in which it is located is known to contain a given volume of water.

The procedure for computing volume-to-first-flood (see Appendix 9) requires that all of the raster data for elevation, upslope area, watershed number and drainage direction be translated into a relational data table structure and that all pit data also be present in a data base table. The grid data table is then indexed from the bottom up by catchment, by elevation and by the reciprocal of upslope area. The algorithm passes through the grid data base in sequence starting from the lowest point (pit centre) in the lowest watershed and progressing upwards, one watershed at a time. At each new elevation, it computes the volume of water in the pond that would be sufficient to flood a cell at that elevation. This value is then stored in the grid data base as an attribute of each cell. Clearly, the statistic can only be computed for cells that lie within a defined pit (i.e. equal to or lower than the pour elevation of the largest depression within which the cell is contained) so it is not computed for all cells.

The data on volume-to-first-flood for the Lunty site are not presented in this chapter (see Chapter 6 section 6.5.2) but the concept and methods are presented here since the statistic does represent a geomorphological index.

A second statistic called mm-to-first-flood was also defined and calculated. It represented the mm of rainfall that would be required to fall on a given watershed in order to fill a given pond to the estimated volume-to-first-flood computed for a given grid cell. It is calculated by dividing the volume-to-first-flood computed for each grid cell by the area of the watershed that contributes runoff to the depression at the time that the cell is first flooded.

Since runoff from a large catchment area will produce a given volume of ponding sooner than runoff from a smaller catchment area, this statistic presents a measure of the relative likelihood that a given cell will flood (all things being equal). Considerable effort was devoted to computing this statistic and to trying to use it to convert mm of rainfall into a map depicting cells affected by ponding after any given amount of rain or runoff. This effort ended up being abandoned as a blind alley since the approach broke down when all things were not equal (i.e. some ponds contained pre-existing volumes of water at the beginning of a runoff event, or infltration had removed water rapidly from one pond but not another between runoff events).

Although use of the statistic mm-to-first-flood was abandoned for the purposes of the present research, it is still thought to have some potential as a geomorphological indicator of the relative likelihood of inundation for all cells that might potentially be flooded in a given area.

4.4.12 Summary of methods used to analyse depressional storage and inter-connectivity

The procedures (Figure 4.6) described above were used to process a detailed gridded DEM for the Lunty study site to define the geometry describing where water would flow and where it would accumulate and the topology controlling how depressions were inter-connected.

A detailed gridded DEM was obtained for a farm sized study area that had the low relief and disrupted drainage characteristic of agricultural landscapes in Alberta where temporary ponding of runoff water is considered a problem. The resolution of the DEM was 0.001 m in the vertical dimension and 5 m in the horizontal dimension. The 5 m horizontal resolution was considered adequate for delineating the depressions larger than 10 m^2 of interest to this study. The original 0.001 m (.1 mm) vertical resolution of the DEM was degraded by rounding the elevation values off to the nearest 0.1 m.

Attempts were made initially to remove spurious pits and pits smaller than a given minimum area or volume. This was attempted in order to restrict consideration to a limited number of pits of significant size and volume. Ultimately, this approach was rejected and all depressions of non-zero volume were retained in the data set. In a few instances the procedure used to assign drainage directions to flat areas resulted in the

identification of two or more pseudo-pit centres in a flat area. These pseudo-pit centres and the pour points connecting them were all at the same elevation and the respective pits had zero-volume. It was necessary to remove a small number of these zero-volume pits prior to commencing the analysis.

The DEM was processed using a suite of interactive PC based watershed modelling utilities (**Watersh**) (van Deursen and MacMillan, 1991) to determine the following attributes for each grid cell:

a) the local direction of drainage (LDD),
b) the number of upslope elements (UPS),
c) the watershed or catchment to which each cell belonged (CAT)

These data were output as a matrix of integer values to an ASCII file of 160 rows by 140 columns. This ASCII file was treated as a grid map for purposes of display and analysis when using the **Watersh** program and related raster manipulation utilities.

The topological data computed above and stored in matrix form was reformatted into the structure ROW, COLUMN, ELEVATION, LDD, UPS, CAT and imported into a relational data base table of similar format (LuntyGRD) set up using dBase III+™. This data base table was used as the basis for subsequent dynamic modelling efforts.

The **Watersh** procedure Find-Outlet-Points was applied to the matrix of elevation values for the Lunty site to compute data characterising each initial, or first order watershed, its associated depression and its potential pour points to neighbouring watersheds and to write that data out to an ASCII text file. These data were reviewed manually to determine the most likely sequence of hydrological connectivity between adjacent watersheds. Watersheds were assumed to connect once their depressions had filled to a maximum volume and any excess volume was able to escape to some neighbouring watershed. Nested depressions were recognized wherever two or more initial depressions coalesced and formed a new, larger depression from which water could not escape except by rising to a new and higher overspill elevation.

Two dimensional cross sectional diagrams based on the watershed and pit characterisation data described above were produced to illustrate the topographical and topological relationships between adjacent watersheds. These two dimensional diagrams were used to help visualise the relationships between adjacent watersheds

and to make decisions regarding where to direct water flow from any watersheds that could potentially flow into two or more neighbours. A number of rules of thumb were developed to assist in deciding what sequence to follow in unblocking pits and to determine into which pit flow should be directed where flow into more than one neighbour was possible.

The watersheds illustrated by the two dimensional cross sectional diagrams were reviewed in order of elevation from bottom to top according to their pour elevations and decisions were made regarding their likely connectivity. Numerical pointers identifying the most likely neighbour into which each initial watershed would drain and the row-column location at which this overflow would occur were assigned to record this connectivity. Each watershed was allowed to overspill or drain sequentially into up to two adjacent watersheds (primary and secondary) once it had filled to overflowing.

A second graphical device was incorporated into the schematic cross sections to help illustrate watershed connectivity. It portrayed the linkages between watersheds in the form of a dendogram. The unique watershed ID numbers were listed below each schematic pit illustration as the horizontal axis of the dendogram while the volume of runoff (in mm) at which each nested depression was projected to overspill was indicated on the vertical axis. Vertical lines projecting downward from each notional pit location were truncated and joined horizontally to represent a linkage between two ponds at a certain volume of runoff. The volume of runoff at which a given pit overspilled and connected to its neighbour was estimated according to V/A-Ratio = Volume of pit/Area of contributing watershed. The concept of V/A-Ratio may be taken to represent the minimum amount of rainfall that would be required to fill any given depression assuming 100% runoff with no infiltration and no evaporation.

A data base file called PONDATA was created to record and store the information about each watershed and its associated depression that was required for subsequent modelling efforts. As each higher order watershed was identified and decisions made regarding its connectivity, data characterising that watershed were added to the PONDATA data base. The structure and information content of the PONDATA data base table is given in Table 4.3. The critical information in the PONDATA file pertained to the connectivity between watersheds and the volume of the depression associated with each watershed.

A numerical pointer indicating the ID number of the watershed to which each watershed drained was recorded in a field in the PONDATA data file called DRAINSTO. A second pointer (NEXTPIT) was defined and used for cases where circular flow or nested depressions required that a depression have a second option for overflow. This option was used in cases where pointers might direct overflow from an initial depression into its neighbour and thence by some route back into the original depression. In such cases, a second pointer was identified and stored in the PONDATA data file in a field named NEXTPIT. This second pointer was directed into a completely different watershed, often a higher order watershed subsuming the original depression.

The information recorded on pit volume included total volume of the depression associated with each watershed (TOTVOL), the portion of that volume (PREVOL) associated with lower order subsumed depressions (if any) and the difference (VOLTOFILL) between the total volume and the volume of any previously defined depressions.

The PONDATA table was viewed as complete once all internal watersheds, including nested depressions had been filled to the level where their only remaining overspill was to the outside world or to an external watershed already known to drain to the outside world. Once the PONDATA table was completed, the complete hierarchical network of depressions and linkages between depressions was considered to be defined. This permitted the schematic cross sections illustrating depressional size and connectivity to be finalised. It also permitted the construction of plan views (maps) delineating the location, extent and volume of all possible sites of depressional storage for the Lunty site.

4.5 Results - geomorphological analysis

4.5.1 The gridded DEM for the Lunty site

The revised DEM used as the basis for all subsequent processing and analysis is described in Chapter 3 and illustrated in Figure 3.10. The DEM captures the topography at the Lunty site with sufficient precision to enable definition of the location and size of all major depressions and their corresponding catchment areas.

4.5.2 Local direction of flow and location of pit centres

The local direction of flow (LDIR) is clearly related to and controlled by topography as illustrated in Figure 4.13. There is a clear differentiation of flow directions between slopes facing east (purples and light blue) and slopes facing west (greens and light gray). North and south facing slopes are less common at this site. This terrain derivative establishes the basic control for flow across the landscape and into depressions or pits. All grid cells with a local direction of flow of 5 were numbered sequentially and identified as potential pit centres. A total of 115 initial pit centres were identified (see figure 4.16).

4.5.3 Upslope area and extent of initial catchments

The number of grid elements upslope of any given grid element is illustrated in Figure 4.14. Cells with a large number of upslope elements (brighter colors in Figure 4.14) represent potential paths for overland flow. Cells with only a single upslope element (themselves) represent local divides. Pit centres have the largest local upslope element counts since all flow paths for a given catchment lead to and terminate at depression centres.

The extent of the catchment or watershed contributing flow to each of the initial 115 depression centres is illustrated in Figure 4.15. Each catchment is allocated a unique sequential number initially assigned to its depressional seed point. The large number of small catchments is indicative of minor noise in the DEM arising from the discrete nature of the grid sampling scheme. Any grid point with no higher neighbours gives rise to an initial (first order) depression and its associated catchment.

4.5.4 Pond statistics including pour points

Table 4.4 lists the relevant statistics for each of the 115 initial pit centres (Figure 4.16) as well as for the 30 potential nested depressions that may subsume the initial depressions. The statistics provided include the location (row, col.) of each pit centre, the size of the watershed contributing flow to each pit centre, the volume and area of the pond associated with each pit centre and the location and elevation of the lowest pour point between a given watershed the neighbouring watershed into which it drains.

Twenty seven of the 115 initial depressional catchments were identified as edge pits. Edge pits either have pit centres located at row 1 or 160 or column 1 or 140 or their lowest pour point is located at a grid element along the edge of the data matrix.

The pit volume is correctly reported as zero for all edge catchments terminating in pit centres at the edge of the data matrix. It is not possible to compute a correct volume for any edge pit since terrain conditions in the outside world beyond the known data matrix exert control over the flow and accumulation of water at these locations. Data in the column Vol-To-Flood represent a calculation of the volume for an artificial depression computed as if an infinitely high barrier existed at the edge of the matrix. The volume reported for Vol-To-Flood is therefore that which would be required to flood the edge pit if it were prevented from flowing off-farm from the edge of the matrix and had to overspill into one of the defined watersheds at the lowest pour point between it and any of its defined neighbours. This artificial volume was computed and stored in the data table in order to offer the possibility for making a partial estimate of ponding at these edge locations during subsequent modelling efforts.

4.5.5 Pond connectivity

Pond connectivity was established based on the data reported in Table 4.4 and used to construct schematic diagrams to illustrate and verify the sequence in which ponds were linked to one another or coalesced to form larger nested depressions (Figures 4.16 to 4.20).

Figure 4.16 shows the location of each of the 115 initial first order depressions and illustrates the connectivity between these depressions. Catchments are restricted from directing flow to the outside world.

Figure 4.17 illustrates pond connectivity and nested depressions for the main interior catchments. These are the only catchments that are completely defined and do not extend outside the boundary of the DEM. The topological description of these catchments given in Table 4.4 and Figure 4.17 is therefore complete and accurate. A maximum of 8 different levels of higher order nested ponding is illustrated in Figure 4.17. The initial first order ponds are shown to have the potential to coalesce into successively larger higher order subsuming ponds.

Pond 132 represents the pond of maximum volume and extent. If the entire area were to be flooded to the point where pond 132 was full, excess water would subsequently escape to the northern edge of the study site through watershed number 5. When full, pond 132 would have a maximum volume of 3902 metres times the unit area of a grid cell (5*5=25) or 97,550 m^3 and an area of 3595 grid cells or 89,875 m^2. It would have a maximum depth of 2.5 m.

A companion research project (Trudell, 1992 personal communication) required an answer to the question "what is the total amount of rainfall that would be required to fill pond 132 to its overspill volume assuming zero infiltration and zero evaporation?"

A simple calculation of volume to fill (3902.3) divided by the area of the contributing watershed (8149) gives a rough approximation of the amount of rainfall that would be required to fill this pond (478 mm). Consideration of the fact that pond 137 would contribute runoff to pond 132 after it was itself full (ie. after 167.4 mm of rainfall) requires that a small adjustment be made to allow for the contribution of excess runoff from the watersheds contributing to pond 137 after it becomes full. This adjustment revises the estimate of mm of rainfall required to fill pond 132 downward slightly to 435.9 mm. Given zero infiltration and zero evaporation, the main central depression would flood to capacity and overspill into the adjacent property to the north after 436 mm of rainfall. This volume is similar to a normal yearly rainfall total for the area.

The significance of this calculation is that it the other researcher (Trudell) was able to conclude that the depression could very well have filled to capacity regularly during the periglacial period immediately following deglaciation. This information helped estimate the maximum volumes of water potentially involved in the removal of chloride ions from the geological materials in the area.

Figure 4.18 illustrates pond connectivity and nested depressions for catchments contributing flow to the southern edge of the study area. Many of the watersheds and ponds illustrated in Figure 4.18 are only partially defined since portions of their catchments are located outside the area encompassed by the DEM. It is only possible to identify 3 nested ponds with any degree of confidence. Ponds 135, 139 and 136 are defined for depressions whose lowest pour point is into one of the defined watersheds and not directly to the outside world. These ponds, as well as most of the other first order ponds, connect ultimately to pond number 109 which has as its lowest pour point a grid cell at the edge of the data matrix. It may be possible that

topographic conditions outside the area encompassed by the DEM could constrain flow from pond 109 and cause back-up resulting in further nested ponding but it is not possible to know this from the information available. In actual fact, pond 109 is constrained by topography not contained within the available DEM and does back up to result in further nested ponding that can not be properly defined with the available DEM data.

Figure 4.19 illustrates pond connectivity and nested depressions for catchments contributing flow to the western edge of the study area. Many of these watersheds are incompletely defined as they include regions outside the area defined by the DEM. Flow is predominantly into a cluster of shallow depressions centred at the first order ponds 54 and 45. Two levels of nested depressions subsume pond 54 and three levels subsume pond 45. The highest order ponds ultimately connect to one another and to pond 59 which has its lowest pour point at the edge of the data matrix. Since DEM data for the area to the west of pond 59 is lacking, it must be assumed that water will escape from pond 59 and all pits linked to it at the pour elevation of 723.0. In actual fact, the region to the west of pond 59 forms a closed basin which would cause water to back up into the area of ponds 125 and 126, flooding them and creating higher order subsuming depressions. The estimated extent and volume of depressions in this area is therefore almost certainly less than what actually exists and would be calculated if the DEM were to extend west to encompass all regions contributing flow to the identified depressions.

Figure 4.19 also illustrates the connectivity of depressions situated in the south west corner of the study area. These depressions are centred on first order pond 94. Four levels of nested ponding are identified before the highest order pond (142) overspills to the outside world. Pond 142 has two possible pour points, both at the same elevation (725.9 m). One leads into catchment 63 and thence to pond 59 as described above. The second pour point is at the edge of the data matrix at row 154 col. 1. The primary pour point was chosen to be into catchment 63 in order to simplify subsequent modelling efforts. It is unlikely that this depression will ever overspill at either location as this would require over 145 mm of runoff with no evaporation or infiltration.

Figure 4.20 illustrates pond connectivity and nested depressions for catchments contributing flow to the northern edge of the study area. Most of these watersheds are incompletely defined as they include regions outside the area defined by the DEM.

Flow is predominantly off the edge of the matrix into the outside world to the north of the study area. A significant number of watersheds along the eastern edge of the study area contribute flow to a pond centred at pit number 13 in the north east corner. There is a large pond here in reality, but the incomplete nature of the DEM for this area precludes identification and documentation of the correct extent and volume of this pond. The topography outside the area encompassed by the DEM is known to constrain flow away from pond 13 and would lead to backup and the creation of nested depressions at this site.

Ponds 144 and 145 are artificial ponds that were arbitrarily created after all legitimate nested depressions (116-143) had been identified and characterised. These two ponds represent incomplete estimates of the potential depressional storage that would exist if flow away from the edge of the matrix to the outside world were to be constrained by an infinitely high barrier. Ponds 144 and 145 were defined and added to the PONDATA table (Table 4.4) in order to examine, during subsequent modelling efforts, the effect of modelling accumulation of water in ponds defined using incomplete elevation data. They are purely arbitrary but do permit some ponding to be simulated in a location known to accumulate water.

Figure 4.21 illustrates the location and maximum computed extent of ponding for all depressions located at the Lunty site and reported in Table 4.4. A number of ponds recorded and mapped during the field survey are notably absent or are much smaller than documented by the field survey. All of the missing or undersize ponds are located at the edge of the DEM elevation matrix or drain off the edge at a very shallow depth. Ponding in these depressions could not be adequately estimated since data from outside the DEM were required to fully define and constrain ponding in these depressions. Given this limitation, the maximum computed extent of potential ponding for the non-edge depressions agrees well with the observed locations of ponding documented and illustrated in chapter 3.

4.6 Summary and conclusions - geomorphological analysis

The geomorphological analysis conducted using the **Watersh** utilities demonstrated the potential utility of processing digital elevation data to document the location, size, volume and hydrological connectivity of depressions in an agricultural landscape with non-integrated drainage.

4.6.1 Highlights and positive contributions

The tools provided by the **Watersh** utilities were able to identify and describe successfully all major depressions except those located at the edge of the data matrix. The **Watersh** tools, in combination with the Lunty DEM provided a fast and accurate method for identifying the locations, extent and maximum storage volume of all areas of potential depressional storage at the Lunty site. The pond and watershed statistics reported in Table 4.4 could provide a basis for computing volume/area/depth relationships for ephemeral ponds in shallow undrained depressions in agricultural landscapes. The pit connectivity data contained in Table 4.4 and illustrated in Figures 4.18 to 4.22 provide all of the information required to predict the volume and depth at which a given depression will overflow, the location (pour point) at which water will overspill from the full depression into its neighbour, and the location (or locations) to which the escaping pond water will flow and accumulate.

The geomorphological analysis techniques respond effectively to a recognized need for better tools for defining "depressional storage". Specifically, MacAlpine et al. (1992) reported that "accurately defining the "effective" drainage area was a common difficulty" at all of their sites and that "runoff monitoring was complicated by variations in the areas contributing to runoff events". They concluded that "defining depressional areas and estimating their storage volumes should be incorporated into the determination of design runoff volumes and on-farm storage requirements". They suggested that "air photo interpretation, field surveys and mapping can refine this estimate".

The tools and procedures developed for the present study represent an improvement over the techniques described by MacAlpine et al. (1992). They produce all of the data required to complete a detailed analysis of the geometry controlling the location, size, maximum storage volume and inter-connectivity of areas of depressional storage in an agricultural landscape. The procedures are more accurate, faster and easier to apply than current methods that rely on laborious manual interpretation of air photos, detailed contour maps and field measurements.

The development of procedures and tools for documenting hydrological connectivity between depressions and computing the hierarchy of "nested depressions" was significant and represents another unique contribution of the present study. The geomorphological analysis demonstrated that depressions can be "nested" within one

another and that a hierarchy of nested depressions can be elaborated. Computation of the maximum storage volume of any depression, the location(s) at which it overspills and the depression in which overspill will accumulate provides valuable information for planning on-farm water management or drainage projects.

The analysis demonstrated that pits or depressions do exist in a typical agricultural landscape in Alberta and that a DEM with a horizontal resolution of 5 by 5 m and a vertical resolution of 0.1 m is capable of identifying and measuring all depressions of meaningful size (provided they are entirely encompassed within the DEM). A clear conclusion is that preprocessing of DEMs to remove depressions in such terrain to create fully integrated drainage networks would create an invalid rendering of the drainage environment. The true drainage environment is strongly influenced by topographical pits which delay and retain runoff, focus recharge in depressional areas and presumably accumulate sediment and other material transported with runoff water and deposited when that water ponds. Any attempt to accurately represent the actual drainage environment must recognize and account for the existence of depressions.

4.6.2 Oversights and opportunities for improvement

In retrospect, the decision to degrade the horizontal resolution of the DEM data set to 0.1 m prior to geomorphological analysis was probably wrong. Comparisons of actual to simulated depth and volume of ponding (Chapter 7) revealed several instances where the maximum depth and volume of ponding was seriously underestimated by the geomorphological analysis. This situation arose in cases where rounding to the nearest 0.1 m reduced the elevation of the overspill or pour point and increased the elevations assigned to cells on the floor of the pond (especially the pond centre). It would have been preferable to retain the original vertical resolution of the DEM at 0.001 m and pre-process the DEM to remove all of the very small depressions arising from noise in this precise data set. This would have resulted in more accurate estimates of the depth and volume of all depressions.

Another opportunity not pursued in the context of the present research was an analysis of volume/area/depth relationships for depressional ponding. All of the data required to conduct such an analysis were computed and stored in the watershed and pond statistics databases. Previous studies (Hubbard and Linder, 1986; MacAlpine, 1992) used manual measurements of pond depth and planimetric measurements of pond area from aerial photographs to develop these relationships. Pond volume is traditionally

computed using equations that assume the pond bottom can be approximated as a straight line (MacAlpine, 1992) or a curved surface (Hubbard and Linder, 1986) between contours. Woo and Rowsell (1993) presented regression equations relating pond area to pond depth. The geomorphological analysis calculated pond depth, area and volume for every grid cell that could possibly be inundated at the Lunty site. The Lunty database could be used to develop volume/area/depth relationships. The generic methodology of geomorphological analysis could be applied to any area to develop databases for extending and verifying these relationships.

Another opportunity for future research would be to investigate further the utility of the statistics volume-to-first-flood and mm-to-first-flood as terrain derivatives indicative of the likelihood of flooding or soil wetness. The concept of a measure mm-to-first-flood was developed in an attempt to estimate the relative sequence in which depressions would fill up and overspill. It represents the mm of runoff that would be required to fill a depression to any given volume. The concept proved inapplicable for the purposes of the present research but still retains value. If calculated for every cell in a DEM it might represent an improvement on the statistic upslope area as a measure of potential soil wetness. It would avoid the problem of computing a low upslope area, and therefore a low likelihood of wetness, for grid cells in low-lying landscape positions that happen to have no upslope cells draining into them.

Finally, it should be possible to fully automate the rather laborious manual procedures for establishing linkages between pits, selectively removing lower order pits subsumed by a larger over-lying pit, and computing the volume and connectivity of the resulting higher order pits. The manual and semi-automated procedures used here were necessary to develop the concepts and ensure that application of the concepts produced valid results. Now that this has been demonstrated, it should prove possible to reproduce the logic of these procedures as computer code. This would improve the utility of the procedures greatly.

CHAPTER 5

MODEL DEVELOPMENT:

DEVELOPING A MODEL TO SIMULATE FLOW AND ACCUMULATION OF SURFACE WATER AT A FARM SCALE

5.1 Introduction

5.1.1 Overview

This chapter describes the development of a model (DISTHMOD) for simulating the dynamic behaviour of surface water at a farm-scale in a landscape of low relief in east central Alberta. Application of the model is described in chapter 6. The model is intended to provide a tool for predicting the variation in location, extent and depth of ephemeral ponding of surface water during the period of spring melt and runoff. Modelling approaches reported in the literature are reviewed in order to justify and place in context the techniques adopted for this study. The custom-written distributed hydrological model created for the present research (DISTHMOD) is described in detail.

The essential innovation of the model, and the focus of the present research, is the definition of a computational framework that recognises the existence of closed depressions and permits explicit simulation of flow of runoff into, through and out of depressions.

5.1.2 Context

The timing and frequency with which ponds develop and disappear in agricultural landscapes are major concerns for on-farm water management. The location and extent of ponding varies considerably through time as a function of inputs, losses and antecedent moisture conditions. Attempts to understand and predict the behaviour of ephemeral ponding must account for this variation in runoff, accumulation and losses through time.

To the farmer, the goal of on-farm water management is to identify ponds that flood to a sufficient depth and persist long enough that they present an impediment to cultivation and seeding in the spring. It is to the farmer's advantage to minimise the area affected by such ponding.

To the wildlife conservationist, ephemeral ponds represent a critical wetland resource. The goal of on-farm water management in this case is to identify which ponds may be suitable as nesting, breeding or staging habitat and to protect and enhance such ponds.

Diversity of wetlands is a critical requirement for waterfowl habitat (MacAlpine, 1992). Even, shallow, temporary ponds play a role in waterfowl life cycles. Small, temporary wetlands that form early in the spring are important in attracting waterfowl, spreading them across the landscape and providing rich, early feeding (MacAlpine, 1992). Territorial waterfowl, especially ducks, are attracted to areas with a high density of waterbodies and complex shorelines (MacAlpine, 1992). Shallow pools and field depressions that fill with snowmelt in early spring are the first open waterbodies available to migrating waterfowl. The aquatic invertebrates in these pools are essential feed for waterfowl hens building up protein for egg production (MacAlpine, 1992). Nesting generally begins in early May and requires semi-permanent waterbodies with well developed upland cover. Ducklings require the combination of open water and fringes of tall grass, cattails and rushes provided by these wetlands as well as the food sources provided by submerged plants and invertebrates. Waterfowl move to larger marshes and lakes in July and August, once hatchlings are able to fly.

Not all ponds provide suitable waterfowl habitat. Ponds lacking a fringe of suitable vegetation may attract waterfowl to nest but be unable to provide adequate shelter or forage. Agricultural activities such as clearing and cultivating around the margins of sloughs, summerfallow cultivation and intensive use of marginal land dramatically reduce important upland cover and reduce the chances of waterfowl survival (MacAlpine, 1992).

The optimum condition for waterfowl conservation is, therefore, one that maximises diversity in the size, duration and depth of ponds. The initial requirement is for a large number of individual small ponds to attract and shelter migrating waterfowl. These ponds can disappear by early May. The next requirement is for semi-permanent ponds to provide nesting habitat. They must provide upland cover in the shoreline fringe and

last sufficiently long (July or August) to support the development of hatchlings to the stage where they can survive relocation to a larger communal pond. Finally, there should ideally be one or more larger ponds or lakes in close proximity that persist throughout the summer and offer sufficient food and security to permit birds to survive until fall migration. Information on both size and duration of ponding is of interest, therefore, to the wetland conservationist.

It is proposed that an ideal tool for on-farm water management should support the sometimes conflicting needs of farmers and conservationists. Both require an ability to predict where water will accumulate under existing natural conditions, how large an area will flood, when and under what conditions ponding will be initiated and how long ponding will persist at any given location. In addition, since both activities are pre-disposed to redistributing water to achieve some desired goal an ability is also required to predict the likely result of altering drainage patterns and redistributing water. Redistribution may promote greater persistence and dependability of wetland habitat in support of wildlife conservation or it may achieve a net reduction in area affected by ephemeral ponding in support of increased farming efficiency.

The model described herein responds to this need for tools to analyse the distribution and redistribution of surface water in agricultural landscapes and to the current lack of suitable tools.

Current procedures for assessing whether a given location will develop a pond and how long that pond is likely to persist rely predominantly on image interpretation supplemented by field inspection. The private wetland conservation agency Ducks Unlimited presently maintains a major ongoing program of periodic mapping throughout the prairie provinces (Koeln et al., 1988). This program collects information on the locations where major ponds regularly develop and attempts to estimate the length of time these ponds generally persist. The program utilises multiple sets of satellite imagery obtained at a number of time periods supplemented by field visits for verification of satellite classifications (EOSAT, 1987). The data obtained provide an inventory of wetland habitats. They are used for regional identification of prime habitat and for selection of sites for protection or enhancement. The data do not provide information suitable for supporting design or engineering work at any given site. In particular, such data are unsuitable for estimating the possible consequences of changes to the drainage pattern arising from natural changes in climate or man imposed changes in land use or drainage conditions.

Alberta Agriculture provides support to farmers interested in on-farm water management through its central Drainage Branch and its regional district agriculturalists and drainage engineers. These individuals rely predominantly on manual interpretation of aerial photos to assess the location and persistence of ponds. Farm records of pond location and persistence are the initial source of information. On-site field examination is used to verify farmer records and to confirm likely persistence as interpreted from observations of wetland vegetation types. Assessment of the potential impacts arising from proposed alterations to the drainage pattern and the resulting redistribution of surface water is limited to what can be accomplished through manual estimation of patterns of flow interpreted from aerial photographs and topographic maps (MacAlpine, 1992).

Recently, hydrological simulation models have been advanced as a superior means of estimating the potential impacts of artificial drainage or slough consolidation at the farm scale (Jensen and Wright, 1985; JNM, 1986). The recently completed study on Alberta's drainage requirements (WER, 1985) specifically recommended that more detailed hydrological simulation modelling be undertaken for a farm sized project using a detailed field-scale hydrological model.

The model QUALHYMO has been used successfully in Alberta to estimate changes in the runoff hydrograph at the outlet from a farm arising from proposed or actual systems of artificial drainage (JNM, 1986). A central feature of the QUALHYMO model is its use of the concept of depressional storage in which the effective area contributing flow to the outlet point varies according to the extent to which depressional storage is filled at any given time. Areas contributing flow to wetland depressional stores do not contribute flow to the outlet point until the wetland is full to its overspill volume (see chapter 4).

A major limitation of the QUALHYMO model with respect to analysis of ponding at the farm scale is that the depressional stores exist only as conceptual entities in the model. They have no physical location and are never actually located or measured. They are used as calibration parameters in the model and are varied empirically in order to get the predicted outflow from the basin to match the observed outflow for the calibration period. The lumped nature of this model therefore makes it inappropriate to use to address the question of where, and to what extent, water will accumulate in the individual locations of depressional storage on any given farm.

In order to assess the variation in location and extent of ephemeral ponds at a farm scale properly, a simulation model is proposed that permits explicit recognition of the location and volume of all potential sites of depressional storage. The model is highly distributed in its representation of space (see section 5.2.3). It is also able to produce reliable predictions of the magnitude and timing of ponding that would arise from changes imposed by artificial drainage or altered land use. It avoids the black box approach to modelling based on empirical calibration in favour of a physically-based model. It uses a deterministic approach to represent actual physical processes involved in the generation of runoff and ponding (see discussion below).

5.2 Analysis of previous research and justification of methods adopted for the DISTHMOD model

The following section presents a review and analysis of existing research in hydrological modelling as it applies to simulating runoff and accumulation of surface water. The intent is to develop a context for the decision to develop and apply a purpose-built simulation model (DISTHMOD) and to provide a justification for the methods adopted for implementation in DISTHMOD.

5.2.1 Reasons for using simulation models

Beven (1989) noted that simulation models are primarily used for two purposes; namely to:

a) improve understanding of (hydrological) processes
b) predict likely behaviour in the real world

In addressing the problem of ephemeral ponding outlined above, the primary interest is with (b), predicting likely behaviour. For the present research, the modelling objectives were:

a) to predict the locations where small, ephemeral ponds will develop in a farm scale landscape of low relief
b) to predict the timing with which ponds appear, grow to their maximum extent and disappear during a period of spring melt and runoff

c) to predict the approximate extent, depth and volume of ponds at approximately weekly intervals through-out a period of spring melt and runoff.

d) to permit examination of the possible consequences of redirecting flow or ponding through artificial drainage.

The principal requirement of any simulation model adopted to achieve these objectives was that it should be able to predict both the location and the timing of ephemeral ponding. This information was required to a fairly high degree of spatial precision (e.g. 5 m horizontal and 0.1 m vertical). High resolution was less essential with respect to temporal precision. It was considered necessary to know much water would accumulate in depressions at different time periods but, for most purposes, knowledge of the extent of ponding at weekly intervals was considered sufficient. A relatively low resolution in the representation of process was considered acceptable because:

a) the aim of the modelling was prediction rather than detailed understanding of process

b) many hydrological processes (i.e. infiltration, evaporation) are not particularly active at the time of year for which modelling was envisaged. These processes could be greatly simplified or ignored.

5.2.2 Types of modelling approaches

Hydrological models (Figure 5.1a) differ in the scale and manner with which they represent:

a) Space

b) Hydrological processes

c) Time

With respect to space, hydrological models are typically viewed as being either lumped or distributed (Novotny, 1986). Within this broad classification, they are often further sub-divided according to whether the internal workings of the model are based on a deterministic or stochastic representation of the processes governing flow or perhaps on some empirical combination of the two (Figure 5.1 a). In terms of the time dimension, simulations may be either continuous or event-oriented (Novotny, 1986).

In practice, many models do not fit neatly into a rigid classification system as illustrated in Figure 5.1a. Instead, the way in which models represent space, hydrological processes and time varies along a continuum as illustrated in Figure 5.1b. The distinctions between lumped and distributed spatial representations are often blurred (Beven, 1989), whilst even the most complex physically based, process models make use of empirical or stochastic calibration coefficients in order to obtain 'satisfactory' results. Models with complex representation of process and detailed representation of space invariably require short time steps to maintain stability and are therefore less suitable for long term or continuous simulations.

A critical question is what degree of representation of space, hydrological process and time is required for any given problem? For the present research, the principal requirement was to identify the optimum degree of representation of space, hydrological process and time for simulating the development and disappearance of ephemeral ponds at a farm scale.

5.2.3 Representation of space in hydrological models

In terms of the space dimension, hydrological models vary from no representation to highly distributed with detailed representation of space in two or three dimensions (Figure 5.1b). Anderson and Rogers (1987) reviewed the issue of dimensionality in distributed models and noted that while three dimensional representation is desirable, two dimensional considerations usually present a realistic maximum at the present. The important spatial concerns with respect to the present hydrological model are:

a) With what degree of resolution is space represented?
b) What data structure is used to represent space?

a) Degree of spatial representation

Existing approaches to representing space in hydrological modelling range from lumped models with no explicit representation to distributed models which may be highly disaggregated with respect to space (Figures 5.2 to 5.5).

Lumped models (Figure 5.2) are essentially aspatial. They treat the entire area to be modelled as a single unit with no spatially referenced inputs, internal controls or

outputs (Novotny, 1986). Drainage units are conceptualized as uniform homogeneous entities which can be assigned average characteristics and conditions. An entity receives inputs of precipitation and produces outputs in the form of channel runoff as measured by the unit hydrograph. Conversion of inputs to outputs is usually effected by developing stochastic equations based on a set of calibration rainfall-runoff events.

Variable source area models (Figure 5.3) (Hewlett and Hibbert, 1967; Betson, 1964; Engman and Rogowski, 1974; Beven, 1977a; Lee and Delleur, 1976) accommodate the observation that runoff producing areas within a catchment may be highly dynamic, expanding and contracting depending upon soil moisture status (Dunne and Black, 1970a,b; Dunne et al., 1975; Hewlett and Nutter, 1970; Kirkby et al., 1976; Beven and Kirkby, 1979; Anderson and Burt, 1978a,b; Anderson and Kneale, 1980, 1982; Heerdegen and Beran, 1983; O'Loughlin, 1981. 1986; Bonnel et al., 1984; Bernier, 1985). Many do not, however, assign physical locations to the various spatial units. The variable source areas remain as conceptual or idealised entities with no physical locations. While such models attempt to account for spatial differences in inputs and outputs, they do not accurately specify locations of spatial variation. The QUALHYMO model (JNM, 1986) discussed previously falls into this category.

Semi-distributed models (e.g.. Rogers et al., 1985; Loague and Freeze, 1985, Beven et al., 1984; Villeneuve et al., 1986; Bravo et al., 1970; Knisel, 1980) provide some degree of representation of space and of spatial variation in hydrological inputs, controls and processes (Figure 5.4). The spatial entities (or sub-watershed units) are often highly idealised and do not accurately reflect actual locations or physical shapes (Figure 5.4a). Such sub-division allows for the definition and representation of smaller units within the catchment. It is assumed that there is less variation of soil and landscape factors affecting runoff within the smaller units than in the watershed as a whole. It is also assumed that the sub-units provide an improved means of simulating variable source area contributions.

Distributed models (Abbott et al., 1986ab; Bathurst, 1986ab; Rohdenburg et al., 1986; Al-Soufi, 1987; Beven, 1985; Beasley and Huggins, 1981; Foster and Lane, 1987; Loague, 1988) divide the system into numerous discrete entities (Figure 5.5) and compute water balances within each unit and flow fluxes between units. Distributed models permit spatially varying inputs, processes and outputs to be represented in a highly disaggregated manner. An implicit, and often suspect assumption (Novotny,

1986), is that each spatial element has uniform system parameters (e.g.. soils, permeability, slope, crop cover, etc.).

It is claimed that this disaggregated representation offers the potential for more accurate simulation by providing a means of recognizing and using information on the spatial variation of controlling parameters and hydrological processes (Abbott et al., 1986a; Bathurst, 1986a). Arguments for use of distributed models include the increasing need to understand the various characteristics of runoff within the catchment (Dunne, 1983) and to predict the spatially varying effects of land use changes (Abbott et al., 1986a). Lumped parameter models can only provide output information for one location whereas distributed models offer the possibility of predicting output conditions at all locations within the system (Novotny, 1986).

Space may therefore, be represented in an abstract manner (as in lumped or conceptual variable source area models) or in a physically-referenced manner (as in distributed and semi-distributed models).

In the context of the present research, there is a requirement for a highly-distributed, physically-referenced representation of space. The modelling objectives determined the resolution at which space needed to be represented. It was desirable to know the location, extent and volume of all areas of surface ponding larger than 10 m diameter and greater than 0.1 m in depth. The rationale for these limits is that large, modern equipment can generally manage to cultivate ponds smaller than this or shallower than this. Additionally, ponds of such small dimensions do not generally persist long enough to prevent seedling emergence or to damage crop growth.

To obtain the required spatial resolution it was necessary that any model selected or developed be capable of operating on elemental units with maximum horizontal dimensions of 5 m by 5 m. In order to apply the model to a typical farm management unit in Alberta (quarter section) it needed to be capable of encompassing an area with minimum dimensions of 800 m by 800 m. The specific study site chosen to test the model is 700 by 800 m. Assuming a 5 metre spacing in the horizontal dimension, this required that any selected model be able to address at least 22,400 individual elemental units in the horizontal plane alone.

b) Structure used to represent space

The three most common spatial data models used to represent space are irregular polygonal entities, triangular irregular networks (TINs) and regular square grids (see Figure 4.1 in Chapter 4). Considerable difficulty is associated with using either irregular entities or TINs for defining depressions and simulating flow into depressions. No examples were discovered of previous successful use of either of these structures for simulating flow of runoff into and through depressions.

The present modelling objectives required a functionality for identifying and filling small, localized depressions with small vertical increments of water. This required functionality influenced the choice of an appropriate spatial data model. Investigation of irregular polygon and TIN spatial data models revealed both to be unsuitable. Both were found to lack suitable algorithms for recognizing and accumulating water in depressions in a continuously varying fashion. Even if such algorithms had existed, the requirement for a vertical resolution of 0.1 m and a horizontal resolution of 5 m would have necessitated the definition of such a large number of TIN or polygon spatial entities as to be prohibitive. In practice, very few existing models utilize a TIN data structure and those that adopt an irregular polygonal structure tend to be quite limited in the number of polygons they are designed to handle. The most suitable choice for representing space was, therefore, to specify a simple raster or grid spatial model. A detailed grid data structure was judged most suitable for determining the location and extent of individual ponds with the required degree of spatial resolution.

5.2.4. Types of physical processes represented in hydrological models

Selection of an appropriate model requires consideration of two further issues relative to the representation of process, namely:

a) Which hydrological processes to represent
b) How to represent the selected processes

The selection of processes to include in a model depends partly on the kind of problem to be addressed and partly on the nature of the watershed area in question. It also depends somewhat upon the choice of how, and at what level of spatial resolution,

processes will be represented. The nature of the watershed area and of the problem to be addressed may strongly influence the mechanisms by which runoff will occur. These will, in turn, determine which processes and sub-processes are important in producing and controlling runoff. It is therefore important to determine which of the potential mechanisms contributing to runoff might be operative at the study site.

Field research (Figure 5.6a) has identified and described a variety of mechanisms contributing to the production of rainfall runoff (van de Griend and Engman, 1985; Kirkby, 1978; Dunne, 1983). The critical mechanisms, for the present study, are Hortonian overland flow (1), saturation overland flow (3) and infiltration excess overland flow (2). Formation of ponds in early spring is primarily related to overland flow on soils which are either frozen at a shallow depth or saturated at the surface, or both. Once spring snowmelt is completed and soils are thawed, most observed runoff is attributed to rainfall rates in excess of infiltration capacity. Other mechanisms operative to a lesser extent at the selected site include unsaturated (4) and saturated (5) sub-surface flow, subsurface return flow (6) groundwater seepage flow (7) and groundwater flow (8). None of these contribute significantly to the initial formation of ponds at the study site during spring runoff.

The mechanisms giving rise to rainfall runoff are governed by a number of controlling processes and sub-processes (Figure 5.6b). There is widespread agreement on the identity of the major processes and sub-processes governing runoff (Abbott et al., 1986; Bathurst, 1986a; Rohdenburg et al., 1986; Anderson and Rogers, 1987; Beven et al., 1984; Al-Soufi, 1987; Villeneuve et al., 1986). Detailed accounting of the water budget of a hydrologic system needs to account for inputs, losses, storage, lateral or downward movement and finally outputs.

a) Inputs: precipitation and snowmelt

Snowmelt provides the main source of spring runoff resulting in the initial formation of ponds in the study area (see chapter 3). Snow melt is controlled by a variety of factors that influence the amount of energy delivered to and transferred through the snow. These include cumulative heat input, daily radiation input, heat released by rainfall passing through or freezing in the snowpack and the thickness, density, thermal conductivity and hydraulic conductivity of the snowpack itself. Simple snow melt models are often based solely on accumulating heat inputs as cumulative degree days starting with the first day with temperatures over 0° C (e.g. JNM, 1986, Abbott

et al., 1986). These may be modified to consider the additional factor of number of hours of sunshine per day (Villeneuve et al., 1986). These are usually empirically based equations relating observed inputs of heat or sunshine to snow melt output. Relatively few hydrological models (cf. SHE, Morris, 1982, 1983) use deterministic, process-based, energy balance equations to model snowmelt. An energy balance approach is adopted by the present model in view of the importance of snowmelt to spring runoff in Alberta. A development of the energy balance equation as used in the DISTHMOD model is provided in Appendix 7.

In most hydrological modelling, precipitation inputs are determined either from actual measured data or from design storm simulated data. The choice depends upon the objectives of the modelling and the availability of data. Measured inputs may be summarized in time steps of minutes, hours, days or monthly totals. The time step interval of rainfall input has an important influence on the appropriateness of all subsequent process equations. Individual downpours of short duration may create high input rates exceeding the infiltration capacity of the soil. Lumping rainfall inputs into hourly or daily totals causes these individual periods of infiltration excess to be lost, the daily rainfall rate usually being much smaller than the daily infiltration capacity of the soil. For the present study, rainfall input is based on field measurements in time steps of 1 hour. This ensures that input rates can exceed infiltration capacities and can lead to surface runoff for major rainfall events.

b) Canopy interception

Vegetation cover intercepts rainfall before it can reach the soil surface. The amount of interception is proportional to the size, shape and density of vegetative cover (Abbott et al., 1986b). Water is lost from the canopy by evaporation and reaches the soil surface through variable rate stem flow and canopy drip (Abbott et al., 1986b). Most physically based models attempt to account for canopy interception storage and transmission. Common approaches (Abbott et al., 1986b; Bathurst, 1986a; Rogers et al., 1985) adopt the Rutter model for canopy interception (Rutter et al., 1971, 1975) or use simple conceptual models (Beven et al., 1984) in which an interception store must be filled before any infiltration can take place to the soil surface. Evaporation is allowed from the interception store at the potential rate until it is empty. The DISTHMOD model makes no attempt to account for canopy interception or evaporation from the canopy. The justification for ignoring interception is that there is

little or no vegetation during the period of spring snowmelt and runoff of interest to the present study.

c) Evapo-transpiration

Evapo-transpiration represents a loss of water from the surface to the atmosphere. Hydrological simulation models must attempt to account for losses arising from the separate but inter-related processes of evaporation and transpiration. Many models combine the calculation of canopy interception and evaporation losses from the canopy with computation of soil and vegetation evapo-transpiration. The more comprehensive models (e.g. SHE - Abbott et al., 1986b) attempt to partition evapo-transpiration into separate components and to compute them individually. Partitioning is usually based on the relative proportions of bare soil to vegetation cover.

No attempt is made in the present study to account for transpiration due to the absence of vegetative cover of any significance during the period of spring runoff. Equations for estimating potential evaporation were reviewed (see Appendix 8) and the Penman equation (Penman, 1948) was selected as most appropriate. A full explanation and development of the Penman and other equations for potential evaporation is given in Appendix 8.

d) Infiltration

Infiltration is the process by which rainfall and snowmelt inputs move into the soil system. It is a critical component of most rainfall runoff models that attempt to account for processes. Once water has infiltrated into the soil system its passage to the watershed outlet will invariably be delayed or prevented altogether. Infiltration is principally controlled by two factors, the soil potential gradient at the surface and the hydraulic conductivity of the soil (which itself is a function of soil moisture potential). Water which cannot infiltrate during the period of one time step will be available for surface runoff. This creates a requirement to select time steps that are compatible with the rates at which rainfall inputs, infiltration and runoff actually occur.

The most comprehensive way of representing infiltration mathematically is through the use of "finite difference representations of the theoretical partial differential equations of mass, momentum and energy conservation" (Bathurst, 1986a). The commonly used equations are the Richard's equation for unsaturated flow and the Darcy equation

for saturated flow (Feddes et al., 1988; Rose, 1985). Soil matrix tension is the dominant force in creating a gradient and driving the moisture flux in this approach. More empirical approaches to estimating infiltration include those proposed by Holtan (1961) and Green and Ampt (1911).

In reality, infiltration is affected by a large number of factors in addition to matrix flow. Surface crusting (Rohdenburg et al., 1986; Smith, 1984; Rose, 1985) and cracking have been shown to exert a significant influence on infiltration rates. Osmotic and thermal gradients may significantly alter infiltration rates (Feddes et al., 1988). Ponding in micro-depressions at the surface can create gravitational heads that are not accounted for in most models (Bresler, 1987).

For the present study, complex equations involving differential calculus were impractical due to the very high spatial resolution of the data set and the consequent large number of grid cells. Additionally, since field studies had indicated that most runoff occurred during snowmelt when the soil was frozen and had very low rates of infiltration, there was little need to simulate infiltration with a high degree of precision. Simulation of infiltration was mostly important as a means of removing water from ponds once runoff had ceased.

e) Unsaturated sub-surface flow

Flow in the unsaturated soil zone is similar to infiltration and is modelled using the same equations. Flow rates vary according to the soil potential gradient and the unsaturated hydraulic conductivity. The hydraulic conductivity, in turn, is dependent upon the soil water content and matric potential.

Even the most comprehensive hydrological models (e.g. Abbott et al., 1986b; Feddes et al., 1988) assume unsaturated zone flow to be one dimensional (vertical). Additionally, most models treat all water movement as arising from matric flow through soil micro-pores. In reality, unsaturated flow has been known to operate in three dimensions ever since the general migration of unsaturated water downslope was first observed by Hewlett (1961). Mechanisms other than matric flow have also been widely recognized to contribute to unsaturated zone flow. These are attributed to rapid flow through soil macropores formed by cracking (Bouma and Dekker, 1978; Beven and Germann, 1981, 1982; Germann and Beven, 1981), decaying roots (Mosley,

1982), biological burrowing (Bonnel et al., 1984) and dissolution (van de Griend and Engmann, 1985).

For the present study, unsaturated sub-surface flow is not considered to be a major contributor to the generation of runoff or the formation of ponds. Some estimate of unsaturated sub-surface flow is required to help diminish pond volumes by permitting infiltration into soils beneath ponds. It is also required in order to permit simulation of removal of moisture from surface horizons in order to compute a value of surface moisture to estimate infiltration rate at the surface. One dimensional movement is simulated only in the downward direction under the assumption that gradients and net moisture movement are downwards during the spring period of low evaporation and high surface soil moisture.

f) Saturated sub-surface flow

Under saturated conditions soil moisture content and consequently soil hydraulic conductivity achieve constant values. Matric potential also becomes constant reducing matric potential gradients to zero. This greatly simplifies calculation and modelling of saturated flow in comparison to unsaturated flow. The primary force driving saturated flow is difference in gravitational head. Flow may occur in all three dimensions, but most current hydrological models restrict consideration to the two horizontal dimensions (Abbott et al., 1986b).

Analysis of hydro-geological data at the study site indicated that almost none of the water that infiltrated at convex upland sites eventually reached the saturated zone (Trudell, 1992, personal communication). Almost all recharge of the saturated zone occurred beneath depressions in either upland or lowland depressions. (ibid, 1992). This observation reduced the need to incorporate a simulation of saturated sub-surface flow in the DISTHMOD model.

g) Saturated overland flow

Saturated overland flow occurs when precipitation and snowmelt inputs exceed losses arising from infiltration and evapo-transpiration. The direction of overland flow is controlled by topographic shape (ie the local slope direction). The rate of overland flow is primarily a function of depth of surface water accumulation, surface slope gradient, and friction resistance to flow in the x and y directions. The deeper the

surface water and the steeper the local slope, the greater the head difference and hence the faster the flow. Similarly, the rougher the surface over which flow must take place, the greater the resistance and therefore the slower the flow.

No attempt is made in the DISTHMOD model to vary rates of overland flow according to slope gradient, flow velocity, roughness coefficients or catchment morphology. The justification is that the problem being addressed requires data on pond extent only at weekly intervals. Precise timing of runoff due to overland flow is therefore not of great importance.

h) Channel flow

Channel runoff is generally faster than overland flow, though the processes are essentially similar. The main differences are that water in a channel usually follows the shortest, most direct route with the highest possible downslope gradient. It also accumulates to a greater depth than in overland flow, thereby reducing friction coefficients. These factors contribute to more rapid flow. Because it moves downslope rapidly, water in a channel is less likely to be delayed or lost through infiltration or evaporation than water engaged in overland flow. Comprehensive models attempt to simulate channel flow and overland flow separately (Abbott et al., 1986b). Factors influencing channel flow include chennel pattern, the cross sectional area of the channel, the channel bed slope and the channel roughness as measured by Manning's n or the Strickler k coefficients. A sink term will usually be included to allow for evaporation, rainfall, and lateral inflow- outflow between the stream and the aquifer (Abbott et al., 1986b).

Channel flow is not deemed of significant importance for large-scale studies of farm-sized areas with no permanent streams. It is therefore not included in the DISTHMOD model.

i) Summary of processes to be represented in DISTHMOD

The modelling objectives of the present study determined the functionality required with respect to the representation of process. It was considered that a suitable model should target runoff and ponding that occurred during the spring melt period, since ponding at this time is of the greatest interest to both farmers and conservationists. Cool temperatures and frozen soil conditions in the spring minimize the importance of

certain processes to runoff generation and increase the relative contributions of others. It was assumed that evaporation would be low given low air temperatures. Transpiration was also assumed to be minimal given that most cultivated land would be fallow in the spring and not covered by transpiring vegetation and that existing native vegetation would be mostly dormant. Simplified representation of infiltration into soils was deemed acceptable since most soils are frozen at some shallow depth during the main period of spring melt.

The most important processes for any suitable model to simulate were, therefore, identified as rainfall and snowmelt (to determine inputs), saturated overland flow (to determine throughputs) and ponding in depressions (as an expression of output). Additional desirable model capabilities were identified as an ability to simulate evaporation from open water or the soil surface, infiltration, drainage and storage of moisture in the soil and potentially, sub-surface flow.

5.2.5 Techniques used to represent physical processes in hydrological models

Hydrological models attempt to reproduce the effects of the physical processes involved in the generation of runoff through the conversion of inputs into outputs. This conversion is effected by some transform function (Figure 5.1 a) usually controlled by:

a) stochastic equations based on statistical analysis of observed past behaviour, or
b) deterministic equations based on mathematical representation of physical processes known to influence runoff, or
c) some empirical combination of the two above approaches.

Hydrological models may vary considerably in the degree of complexity with which they represent any simulated process or combination of processes. Figure 5.1 b illustrates a continuum from simple black box representations based on observed statistical patterns to complex differential equations based on theoretical understanding of the mechanics of individual processes. A number of classes may be recognized along this continuum. These are discussed below.

a) The black box (stochastic) approach

The black box approach is most commonly associated with lumped parameter models. Long term records are obtained for input in the form of precipitation and output in the form of recorded stream flow or runoff. Statistical analyses determine the relationship between input and outputs, often allowing for storage. Convolution techniques are commonly used to relate inputs to outputs through the use of empirical curve fitting coefficients (see Figure 5.2). Loague and Freeze (1985) describe statistical procedures used to develop black box equations including a) regression equations, b) convolution curve fitting (i.e. the unit hydrograph), and c) quasi-physically based equations. They recognize that some equations utilize physically based parameters (i.e. slope, soil hydraulic conductivity) and some (regression, unit hydrograph) use only curve fitting parameters which have no physical significance.

The black box approach is relatively simple but requires a large amount of local data on inputs (snowmelt, rainfall) and outputs (stream flow). A major drawback is that the equations developed by this method are specific to the location used to develop them and need to be re-developed or re-calibrated for use in a different location. Additionally, such equations are of little use for attempting to estimate the effects of changes in land use or artificial drainage. They are only applicable to the conditions in place during the period of record used to develop them. Black box techniques were judged unsuitable for the present research because the proposed model was expected to be used to predict the effects of changes in land use in uncalibrated basins with little or no record of hydrological inputs or outputs.

b) The empirical approach

Empirical models introduce an element of physical reasoning into process representation but continue to rely on evaluation of statistical patterns to relate input to output. For example, the USDA SCS curve runoff number approach (Hawkins, 1980; Rallison, 1980; Wood and Blackburn, 1984) recognizes that a number of physical factors including soil texture and permeability, slope gradient, crop cover and surface roughness are instrumental in controlling runoff. This approach uses field trials to measure runoff produced from numerous plots with differing combinations of these physical factors. Statistical relationships are then established between measured runoff and controlling factors. These statistical relationships are used to estimate the

likely magnitude of runoff in other areas depending upon the combinations of controlling factors present in these new areas.

The empirical method provides no improved understanding of the physical means whereby the various controlling factors influence the process of runoff. There is simply an improved ability to related observed combinations of conditions to likely outputs. Empirical equations often require re-calibration to properly represent local conditions. They are, however, relatively easy to use and can provide useful estimates. Empirical equations were considered for use in the present study but in most cases were rejected in favour of more physically-based equations. The primary justification for not adopting emperical equations was the need to validate and, possibly, recalibrate equations developed for a specific area and set of conditions for use in another area and a different set of conditions.

c) The quasi-physical (conceptual) approach

Conceptual models use physically based reasoning to identify the various sub-processes considered important in controlling runoff generation. They then attempt to simulate the behaviour of these sub-processes using simple, conceptually based, equations. For rainfall runoff, the critical sub-processes (see Figure 5.6b) are widely recognized as rainfall, snowmelt, interception, evapotranspiration, infiltration at the soil surface, unsaturated sub-surface flow, saturated sub-surface flow, overland flow and channel flow.

Several examples of quasi-physical conceptual models may be cited (Beven et al., 1984; Villeneuve et al., 1986, Wallach, 1991). It is common in these to represent unit areas as consisting of a limited number of reservoirs or stores (Figure 5.7). Each store can be assigned a maximum storage capacity and perhaps a threshold capacity below which it will not pass on any water (Beven et al., 1984). The maximum storage capacity in soils is related to total porosity times total height or volume of a store. The threshold value is frequently set to represent field capacity. Fixed, or variable rates can be assigned to control input into or losses from any store. In soils these are conceptually equivalent to infiltration rates and saturated or unsaturated hydraulic conductivities. Processes such as precipitation, evapo-transpiration, sub-surface and overland flow can inter-act with stores and remove or add water at specified rates. The various individual parameters are often assessed using empirical

field calibrations (Beven et al., 1984) or simple regression equations (Villeneuve et al., 1986).

The conceptual approach introduces sound physically based reasoning and permits detailed accounting of water budgets for storage and delayed movement. The equations governing inputs, movement and losses are greatly simplified relative to physically based models, however, and are not based on rigorous mathematical representation of physical processes. The mathematical representation of process is simplified to permit more rapid computation and to require less detailed input data. These characteristics were seen as advantageous in the context of the proposed model. Quasi-physical, conceptual equations were adopted to represent most processes requiring intensive computation at an individual grid scale.

d) The physically based (deterministic) approach

The deterministic approach assumes that the various processes contributing to runoff generation are well understood and can be represented by mathematical descriptions of the individual sub-processes and their overall interaction. Physically based models attempt to provide a comprehensive description of process behaviour articulated in the form of mathematical equations (Anderson and Rogers, 1987). In the most advanced examples (SHE, IHDM, DESM) most processes are simulated using "finite difference representations of the theoretical partial differential equations of mass, momentum and energy conservation" (Bathurst, 1986a). The most commonly used equations in hydrological modelling are the Richard's equation for unsaturated flow, the Darcy equation for saturated flow and the St. Venant equations for free surface flow (Feddes et al., 1988; Rose, 1985).

A stated advantage of this approach is that, in principle, the variables and parameters which control these equations can be measured in the field and can be physically interpreted (Anderson and Rogers, 1987). It is claimed that use of equations and parameters having physical significance improves the ability to interpret models and permits improved calibration on the basis of physical reasoning (Abbott et al., 1986a, Bathurst, 1986a). It is also argued that since the models are based entirely on measurable parameters, it should be possible to apply them to un-gauged catchments with no recorded flow measurements to assist in calibration.

A major disadvantage of the deterministic approach is the large amount of site-specific data required as input to a deterministic model. A companion concern is the large numbers of inter-related parameters often required to describe the physical processes being modelled (Beven, 1989). Once a model requires more than a few parameters to describe the bahaviour of the system, it becomes difficult to keep track of inter-relationships and to know if "good results" are a result of correct parameter assignment or simply a fortuitous combination of estimates.

At present, even the most detailed representation of space achieved by existing, comprehensive, physically based models (see Figure 5.5) is inadequate for the functionality required by the proposed application. For example, Bathurst (1986a,b) divided the Wye catchment into a total of 171 square elements of dimensions 250 by 250 m for use with the SHE model. Similarly, Rohdenburg et al. (1986) defined 206 grid elements ranging in size from 50 by 50 m to 100 by 100 m in their application of the SHE model to the Neuenkirchen catchment. Al-Soufi (1987) represented the Nolsjon catchment using 910 cubic nodes of which 70 were in the horizontal plane and had dimensions of 250 m by 250 m. Even with this relatively low number of elemental units, the various authors reported major difficulties with determining all of the detailed input data required for the physically based equations and noted the sensitivity of the physically based equations to minor variations in input values (Bathurst, 1986a,b).

Physically based process equations usually require the use of very short time steps in order to maintain computational stability. They also require significant amounts of computer time to solve. This effectively limits their use not only to areas that have not been too finely differentiated in space but also to problems that do not have a long time frame. In effect, physically based, process equations are better suited to event oriented modelling than to continuous simulation. This limitation provided another reason to define specifications for the representation of process in the proposed model in such a way as to minimize the requirement for rigorous, physically based equations.

e) Summary of how to represent process in DISTHMOD

The functionality required of the proposed model with regard to how it represented hydrological processes was strongly influenced by the very high degree of spatial resolution demanded by the model objectives. It was not considered feasible to select a model that represented hydrological processes using complex, deterministic,

physically based equations requiring iterative solutions. Such models were considered inappropriate considering the very large number of elemental units required to achieve the desired spatial resolution and the large number of time steps required to run a continuous simulation for several months.

Given the stated modelling objectives, process must necessarily be represented in a less computationally intensive (and therefore less realistic) fashion than adopted for most existing physically-based, distributed models. A more abstract, less realistic, representation of process fortunately also demands a less detailed representation of time. Support for such an approach is provided by Dooge (1988) and by Burt (1985) who noted that since "observed flow mechanisms were poorly defined in mathematical terms, there was some merit in the development of pseudo-physical or conceptual models".

For the present study, therefore, a combination of quasi-physical and deterministic approaches were adopted. The choices are justified in terms of the desire to create a model that could be used to predict the pattern of runoff and ponding under both current natural conditions and future conditions created by proposed artificial drainage or changes in land use. The requirement for very high spatial resolution argued for adoption of simpler quasi-physical approaches for processes to be simulated at every grid cell (i.e. infiltration, sub-surface flow). Deterministic approaches were deemed feasible and desirable in cases where a process was to be simulated only once in each time step for all grid cells (i.e. potential evaporation) or for some scaled combination of grid cells (i.e. snowmelt). Consideration of the conditions operative at the site during the period of interest (springtime) permitted some processes (canopy interception, transpiration, groundwater flow) to be excluded from the model.

5.2.6 Representation of time in hydrological models

It is important to select a time step for modelling that is appropriate to the desired application and that is in harmony with the degree of resolution with which space and process have been represented. Recognizing that there is a continuum of time scales over which hydrological models may operate (Figure 5.1 b), most hydrological models in practical use may still be regarded as either a) event oriented or b) continuous (Figure 5.1 a).

a) Event oriented modelling

Many modelling activities have as their objective simulation of the likely effects arising from discrete events (Novotny, 1986). Destructive runoff is often associated with single, low frequency, high magnitude rainfall events. Such events are usually of short duration but require detailed representation of time using many, short time steps (measured in minutes). It is often necessary to adopt a detailed representation of both space and process for these models. It is frequently not practical to continue such simulations for long periods of time (months or years). Event oriented modelling is often used to improve understanding of flow processes or to investigate the likely consequences of changes in controlling variables (such as land use change). It is not suited to long term simulation of ongoing flow conditions (Novotny, 1986).

b) Continuous modelling

Continuous simulations of patterns of hydrological change over months or years, require a different approach and longer time steps. It is generally not feasible to run continuous simulations with time steps of minutes or hours for long periods of time. Similarly, detailed representation of hydrological processes becomes less feasible as time steps or model element sizes increase. One limitation is the time required to compute results continuously where there is detailed representation of process. The other problem is that larger time steps lead to lumping in time which alters the way in which input data are treated by process based equations.

c) Summary of represention of time in DISTHMOD

The time step functionality required to meet the present modelling objectives was based mostly on considerations of the frequency with which updated information on ponding extent was required. It was judged that it would be sufficient to know the extent and volume of ponded water on a weekly basis for most farm management concerns. However, it was considered necessary to be able to predict the extent of ponding at these weekly intervals over a period of up to four months (March - June). This imposed a requirement for continuous modelling for periods measured in months. In contrast, simulation of the processes of snowmelt, rainfall runoff and infiltration required an ability to operate in time steps measured in hours. This suggested that the proposed model should operate in time steps as long as one day (or possibly even one week) and as short as one hour. The solution was, therefore, to

vary the time step, utilising a short hourly time step for event oriented modelling during periods of rainfall or snowmelt and a longer daily time step at all other times as suggested by Hughes (1993). Specification of time steps measured in hours to days provided a further argument against the adoption of detailed, process based equations.

5.2.7 Choosing between models focused on space from those focused on process and time

Selection of an appropriate approach for the planned model requires making choices with respect to the degree of representation allotted to space, process representation and time as identified above. In this respect, it is possible to recognize two broad groups of hydrological modellers whose primary focus is respectively a) space and b) process and time.

a) Models focused on space

A geomorphic school of modellers (Band, 1985, 1986a,b, Marks et al., 1983, 1984; Mark, 1983a,b, 1984; Jenson, 1985; Jenson and Trautwein, 1987; Jenson and Domingue, 1988; Morris and Heerdegen, 1988; Moore et al., 1988; Hutchinson, 1988) concentrate on locating runoff in space. Their interest is in where water will flow and accumulate. They are generally less interested in the timing of water flow or in simulating the physical processes which control water flow. The results of their work are usually expressed as maps of catchment areas, flow paths and drainage networks (see chapter 4).

This group is closely associated with the use of geographical information systems (GIS) and with linking hydrological models to GIS. They use spatial information systems to input, collate, organize, and display the spatially varying input data and to display the output results. Increasingly, their hydrological modelling tools are being explicitly integrated with commercial (Silfer et al., 1987; Weibel, 1987; Weibel and Heller, 1990; Jenson and Domingue, 1988) or custom (Johnson, 1989) GIS packages.

b) Models focused on process and time

In contrast, the hydrologic group of modellers (Beven, 1977a, 1985; Beven and Kirkby, 1979; Beven et al., 1984; Abbott et al., 1986ab, Bathurst, 1986ab; Rogers et

al., 1985) focus on time and process. They concentrate on describing the timing of water flow. They are interested in the physical processes which control water flow and with the timing of water arrival at a specified point, usually a basin outlet or gauging station. They are generally less interested in the specific pathways or locations of flow or the spatial patterns of output. Their results are generally expressed as stream discharge rates displayed as unit hydrographs.

This group is less strongly associated with the use of GIS as a tool for collating input data, integrating data and models and displaying output results. Most of these models are "stand alone batch programs" with limited capability for interactive display of input or output data.

There has been a degree of convergence recently between the two distinct schools of modelling described above. For example, Bork et al. (1986) and Rohdenburg et al. (1986) applied the detailed processing of digital elevation data characteristic of the geomorphic school of modelling in their use the physically based, distributed SHE and DESIM hydrological models. Similarly Al-Soufi (1987) and Bathurst (1986ab) included detailed assessment of topographic control in their use of physically based hydrological models. Beasley and Huggins (1981) structured the ANSWERS model around the concept of topographic control of flow vectors and drainage directions. Meanwhile, Johnson (1989) described a geomorphically based approach (MAPHYD) which incorporated a number of commonly accepted (but less physically based) hydrological models to calculate storm hydrographs at any point in a distributed watershed.

5.2.8 Summary - justification of methods adopted for the DISTHMOD model

A search was made for an existing hydrological model that could be used to estimate the volume of water flowing across the landscape and accumulating in depressions at the study site during the period of interest. Some of the models considered included ANSWERS (Beasley and Huggins, 1981), TOPMODEL (Beven et al., 1984) and the Système Hydrologique Européen (SHE) (Abbott et al., 1986 a,b).

No single existing model was wholly suitable for the present problem. Most did not accommodate the existence of depressions in the terrain data set and required the removal of such "sinks" to produce fully integrated drainage networks as a

precondition of operation. In addition, none offered the combination of spatial and temporal resolution required for the problem at hand. The highly detailed mathematical representation of process incorporated in the deterministic SHE and ANSWERS models effectively limited the spatial resolution to a few hundreds or, perhaps thousands, of grid elements, whereas the spatial resolution required for this project demanded tens of thousands of elements. The equations used for detailed representation of hydrological processes generally required short time steps measured in minutes, or at most hours and were therefore more suitable for short duration, event-oriented, modelling than for the continuous simulation of processes over periods measured in months as required for the present study. As a consequence, it was deemed necessary to construct a purpose-built model specifically designed to simulate the accumulation of runoff in depressions.

Creating the DISTHMOD model to address the present problem clearly required a trade-off between degree of representation of space, time and process. In reviewing options applicable to the present problem, those models which provided a realistic and comprehensive representation of process were invariably restricted with respect to the detail with which they could represent space. It is simply not feasible to compute, using available hardware, all of the process equations for areas represented by tens or hundreds of thousands of grid elements. In contrast, topographically based flow routing models were able to depict the paths of surface water flow quite adequately, but were invariably limited in their ability to represent process and compute realistic volumes of flow.

The present study, therefore, sought to extract benefit and ideas from both the geomorphic and process-based schools of modelling. The requirement to depict locations of depressions and ponds with a high degree of spatial precision argued for adoption of the methods of flow routing advanced by the geomorphical group. The desire to apply the model to un-calibrated basins, using parameter values determined in the field, argued for physically-based representation of process as adopted by the hydrological group of modellers. The final approach adopted in producing the DISTHMOD model reflects the compromise between geomorphical and process-based modelling approaches.

5.3 Experimental design - model development

Having determined the geometry governing the flow and accumulation of surface water (see chapter 4), a second fundamental objective of the present research was to estimate the extent to which the identified depressions were filled with water at any given time during the period of spring runoff. This required a model able to simulate the dynamic effects of the main processes controlling the location, magnitude and timing of surface water runoff and ponding. The questions of primary concern in determining the magnitude and timing of surface water flow and accumulation were:

a) How much water was flowing over or through the landscape and arriving at any given depression during any given period of time?
b) How much water was lost from any given depression during any given period of time?
c) How much water was present in any given depression at any given time during the period of interest.

The steps taken to develop a model capable of simulating the flow of surface runoff and its accumulation in depressions (Figure 5.8) are summarised as follows:

The specific problem of flow of surface water in agricultural landscapes of low relief and its accumulation in closed depressions was analysed to identify the objectives required of the present effort to model this phenomenon and the functionality needed by any model used to attain these objectives (see section 5.2). A search was undertaken to identify and obtain a model that provided the required functionality. No, single, existing model provided all of the required capabilities.

A customised model suitable for simulation of flow at a farm scale and accumulation of spring run-off in localized depressions was conceptualised and constructed. The model (DISTHMOD) was designed to be highly distributed in order to permit the identification and simulation of ephemeral ponds as small as 25 m^2. It incorporated physically based or pseudo-physically based equations for the main hydrological processes considered to be active during the period of spring runoff of interest.

The philosophy of the model was defined in order to assist with selection of an appropriate model structure and the identification of appropriate hydrological

processes to represent. The model structure borrowed heavily from several existing models based on topographically controlled routing of surface flow. Equations and concepts used to simulate hydrological processes were extracted or modified from a number of existing models including ANSWERS (Beasley and Huggins, 1981), SWATRE (Belmans et al., 1983), TOPMODEL (Beven et al., 1984) and an un-named energy balance snowmelt model (Williams, 1988).

5.4 Results - model development

The DISTHMOD model (Distributed Infiltration Stores for Topographically controlled Hydrological Modelling of Depressions) was created expressly for the present research project. It was designed to permit a highly distributed representation of space while adopting a simplified conceptual approach for the simulation of hydrological processes. It combines the previously discussed techniques of geomorphic modelling, used to define the spatial pattern controlling the flow and accumulation of surface water, (see Chapter 4) with simple, pseudo-physically based hydrological modelling algorithms used to account for losses and delays occurring during the generation of runoff.

The development of the model benefited greatly from input by individuals other than the present author. Several individuals generously provided access to computer code for modelling various sub-processes (i.e. evaporation, snowmelt, runoff geometry) and actively assisted the author to understand, adapt and apply the code. Some components of the present model were extracted virtually intact from published descriptions of other models (i.e. ANSWERS). Table 5.1 explicitly identifies and acknowledges the main contributions to the development of the present model made by other individuals.

5.4.1 Philosophy of the DISTHMOD model

DISTHMOD was designed to simulate the runoff of surface water in agricultural landscapes with low relief and disrupted, or non-integrated, drainage. Its primary use was envisaged to be for estimating the location and extent of surface water ponding in depressions during and immediately following the period of spring snowmelt and runoff.

The principal requirements of DISTHMOD were that it should simulate the accumulation of water in depressions (ponding) with a high degree of spatial resolution (10 m^2) and a relatively low level of temporal resolution (weekly or daily). While some representation of the processes controlling the generation, flow and accumulation of runoff was viewed as necessary, the requirement for very high spatial resolution dictated that process had to be represented as simply and efficiently as possible. This was necessary in order achieve reasonable computing times for processing very large data sets for relatively long periods of time (up to 12 weeks).

DISTHMOD was conceived as a highly-distributed, physically-based hydrological model. The highly-distributed spatial representation was essential because the desired output consisted of a detailed identification of the spatial pattern of ponding in depressions. A physically-based approach was selected in acceptance of the widely held view that physically-based models offer greater potential for predicting watershed behaviour than black box or empirical models (Abbott et al., 1986 a,b). In principle, such models are preferable because by using physically based equations based on parameter values that are theoretically measurable in the field they do not require an extensive hydrological record for their calibration (Bathurst, 1986; Anderson and Rogers, 1987).

DISTHMOD uses simple equations and algorithms adapted from existing models where ever possible to represent the individual hydrological processes contributing to runoff. The current efforts were not aimed at developing new equations to simulate these processes. Rather, the emphasis for the present research was on developing a control framework and a routing algorithm that would permit explicit modelling of the flow of surface water across and through landscapes of low relief and its accumulation in shallow, often nested depressions.

5.4.2 Structure of the DISTHMOD model

DISTHMOD uses a raster, or grid cell approach to represent space. Any area of interest is sub-divided into an n-row by m-column matrix of grid squares (Figure 5.9). The raster spatial data model permits both input (rainfall, snowmelt, evaporation, soil data) and output (runoff, ponding, soil moisture) values to be specified to a high degree of spatial resolution.

Each grid element (Figure 5.9) is conceptualised as a hydrologic response unit composed of four separate stores; a surface detention store (S0) an infiltration store (S1), and two sub-soil stores (S2, S3) that can be either unsaturated or saturated. A water balance is computed for each store at each grid cell. The water balance takes into account infiltration into the soil, losses to the saturated zone and losses from surface detention or the upper store to evapo-transpiration. Any water in excess of the surface detention store remaining on the surface after infiltration and evaporation is available for runoff. All runoff from a given grid element is directed into its lowest downslope neighbour according to the previously described **Watersh** procedures for computing local direction of flow (see Chapter 4). Grid elements are grouped by watershed, or catchment based on data produced by using the **Watersh** utilities.

Each catchment area is treated as a cascade of grid cell reservoirs. Grid cells are processed from the highest downwards along flow paths defined for each catchment (Figure 5.10). Cells are processed by elevation within each catchment starting with the catchment with the highest overspill point elevation and proceeding to catchments with successively lower overspill points. Excess water available for runoff in any grid cell is passed to its down-slope neighbour and the water is allowed to cascade down-slope. In each time step, water in all grids is capable of being delivered to the pit centre if it is not lost by evapo-transpiration or delayed by surface detention or infiltration along the way.

Each time a pit centre cell is processed, the model checks to determine what volume of water is currently stored in the pit and assesses whether any new additions of water (runoff) can be accommodated in the pit. If any new additions cause the total storage volume of the pit to be exceeded then any water in excess of the total storage capacity is passed on to either an overspill location or placed into a higher order subsuming depression. In a similar fashion, losses due to evaporation and infiltration are computed for every cell that is known to be inundated during any given time step. Losses are summed for each watershed and the total amount of potential loss is compared to the total volume of water recorded as stored in the pit at the start of the current time step. If the volume of water in the pit is greater than the total computed loss then the current volume of water in the pit is recomputed as the initial volume minus losses. If the potential volume of water loss is greater than the volume in the pit, the program reduces the current volume of water in the pit to zero and checks to see if there are any underlying (lower order) pits from which the remaining loss can be subtracted (i.e. pond 4&5 underlie pond 120 in Figure 5.10).

A relational data base model is used for storing, retrieving and processing the data (Figure 5.11). All data required for operating the model is stored in one of five relational tables and processing is accomplished using programs written in a data base programming language (dBase III+™ compiled with Clipper™) rather than a more traditional programming language such as FORTRAN or C.

The five relational tables containing all the input data required to operate DISTHMOD (Figure 5.11) are:

a) a SETUP file of user specified input and output choices
b) a METDATA file of meteorological input data
c) a GRIDDATA file of data pertaining to each grid cell
d) a SOILDATA file of data describing the various soils
e) a PONDDATA file of data pertaining to each depression

The DISTHMOD program directs output to three user-selected database tables and will also produce an ASCII file of estimated depth of ponding for every grid cell for user defined check dates. The ASCII file is easily reformatted to produce a grid map of estimated depth of ponding for the given date. The output files produced by the program (Figure 5.11) are:

a) a dBase III +™ file listing the relevant statistics for each pond at any given check date automatically named PONDS<DayNo>.DBF where DayNo is the Julian day number for which output is being produced..
b) a dBase III +™ file recording, for each grid cell, the current estimated moisture status for each of the four (4) conceptual stores (S0-S3) and the estimated depth of ponding. This file is automatically named as SOIL<DayNo>.DBF.
c) an ASCII file consisting of a sequential listing of the estimated depth of ponding for each grid cell in the data matrix ordered from top left to bottom right. This file is automatically named POND<DayNo>.TXT
d) a dBase III +™ file containing a listing of the Julian day number, hour, watershed ID number and volume of runoff escaping from any watershed that overspills off the edge of the grid matrix. This is automatically named as FLOW89.DBF and must be manually renamed to save the results of any given run.

A full description of the content and function of each of the 5 input files is provided in Appendix 11 (see Tables A11.1 - A11.5)

5.4.3 Overview of processes represented in the DISTHMOD model

Only those hydrological processes believed to be dominant in the generation or removal of runoff during the period of spring runoff are presently represented in the DISTHMOD model (Figure 5.9). DISTHMOD uses relatively simple equations and conceptual models to represent these hydrological processes. Most of the equations were extracted from existing hydrological models and implemented either exactly as described for those models or with minor modifications. Process representation in the model is characterised by the following features:

a) rainfall rate is read directly from pre-recorded rain gauge data
b) delivery of meltwater from the snowpack (snowmelt) is simulated using a solution of the energy balance equation modified from that presented by Williams, (1988)
c) infiltration of water into the surface soil is simulated using a modified version of the Holtan (1961) equation as described for the ANSWERS model (Beasley and Huggins, 1981).
d) drainage of water from the surface soil into lower horizons is simulated using the drainage function presented in the ANSWERS model. Modifications have been introduced based on a model of cascading stores as suggested by Beven et al. (1984) and Vandenburg (1986).
e) potential evapo-transpiration is estimated using one of five physically based equations presented in the model SWATRE (Feddes et al, 1988; Belmans et al., 1983) (with minor modifications and appropriate coefficients)
f) actual evaporation occurs at the maximum potential rate from ponded surface water while evaporation from the bare soil surface is estimated as the lesser of the potential evapo-transpiration or the maximum potential flux from the soil at a given moisture status and conductivity.
g) surface roughness arising from furrows and ridges causes some surface water to be retained in micro-depressions which must be filled before runoff can occur (after ANSWERS, Beasley and Huggins, 1981)

h) overland flow is simulated (for the present) by simply passing to its down slope neighbour all water in excess of that retained in micro-depressions remaining on the surface of a grid element after evaporation and infiltration have been computed.

5.4.4 Logic and equations used in the DISTHMOD model

This section outlines the specific logic or mathematical equations used to quantify the various processes represented in the model DISTHMOD.

a) Rainfall

Rainfall and snowmelt are the source of input of water into the system. The rate of rainfall is considered uniform over the farm sized areas of interest to this study. Rainfall is measured directly using a tipping bucket rain gauge and recorded for hourly intervals.

b) Snowmelt

Snowmelt is a major contributor to spring runoff as the rate at which melt water is delivered to the soil surface can be very high and the rate of infiltration into the soil can be very low when the soil is frozen at or close to the surface.

Snow melt is computed using a modification of the energy balance equation (Male, 1980) as implemented by Williams (1988). The basic energy balance equation is:

$$\frac{\partial S}{\partial t} = Q_s + Q_a + Q_e + Q_h + Q_v \qquad \textbf{(5.1)}$$

where: $\frac{\partial S}{\partial t}$ is the rate of change of heat storage associated with changes in snow temperature, melting or freezing. The energy flux densities Q, expressed in W m^{-2} are positive if energy is directed into the snow. They include:

Q_S = absorbed short wave radiation
Q_a = longwave radiation from the atmosphere
Q_e = longwave radiation emitted from the snow surface
Q_h = convective transfer of sensible heat between the air and surface

Q_v = latent heat transfer between the air and surface by evaporation, condensation and sublimation

Complete details of the equations used to estimate each of the individual component energy fluxes in the above equation (5.1) are given in Appendix 7. Also included in Appendix 7 is a listing of the dBase III+® program used to implement the equations.

In the snow melt sub-model, the snow pack is viewed as a continuous cover with a finite negative heat store (S). The heat store (S) is computed principally as a function of average temperature and snow water equivalent (density times height) of the snow pack according to:

$$S = \overline{\rho} hc\left(\overline{T} - T_m\right) + L_f W \qquad \textbf{(5.2)}$$

where $\overline{\rho}$ is the mean density of the snow (approximately 220 kg m^{-3}), h is the depth of the snowpack (m), c is the specific heat capacity of ice (approximately 2100 J kg^{-1} $°K^{-1}$), $\overline{T}$ is the mean temperature of the snow (°K), T_m is the melting temperature of snow (273.15 °K), L_f is the latent heat of fusion (taken as $3.34*10^5$ J kg^{-1}), and W is the total liquid water content of water stored in the snow (kg m^{-2}).

The energy balance is computed for each time step based on the above equation (5.1). If the balance is positive, it is applied to warm the snow pack and decrease the negative heat store. If it is negative, it cools the snow pack and increases the negative heat store. Once the temperature of the surface of the snowpack has been brought to the melting point (0°C), any further net input of energy results in the generation of a volume of melt water in proportion to the latent heat of melting of snow. If there is any snow beneath the surface at temperatures less than freezing the heat storage in the snow pack may still be negative. In this case, meltwater percolates into the snow and re-freezes, releasing latent heat which warms the underlying snow. Eventually, heat from radiation and from re-freezing within the snowpack raises the negative heat storage term to 0 and the snow is isothermal at 0 °C. At this point any further positive input of energy goes into melting the snow at a melt rate M equal to the sum of the energy input (equation 5.1) divided by the latent heat of fusion (L_f). Any negative input of energy lowers the temperature at the snow surface and reduces the heat storage term below zero, temporarily stopping snowmelt.

Liquid water (W) produced by melting is not immediately released from the snowpack but is allowed to build up in voids and pores in the snow until it exceeds an arbitrarily defined liquid water holding capacity (W_C) for the snow. W_C is taken as 5% of the water equivalent of the snowpack at its current density and height after suggestions by Williams (1988) and Anderson (1968). When W reaches W_C, any further meltwater is assumed to drain from the snow and the water equivalent of the snow (WE) is re-computed to reflect the volume of meltwater lost in the current time step.

The LOSS of water from the snowpack during any given time step is computed as:

$$LOSS = \left(\frac{S - S_{max}}{L_f} \right) \tag{5.3}$$

where $S = \sum_{1}^{5} Q_i$ the sum of the energy terms from (5.1) above re-computed with the snow surface temperature set to 0 °C, $S_{max} = L_f W_C$, and L_f = the latent heat of fusion of ice. This LOSS is taken as the estimated volume of snowmelt produced during any given time step from a snowpack of given initial depth.

It is considered impractical to apply the snowmelt equations discussed above to all grid elements for all time steps. Instead, a scaling approach is adopted which involves pre-computing the estimated volume of snowmelt for each hourly time step for a limited number of reference depths of snow ranging from 5 cm to 200 cm. During model runs, the initial depth of the snowpack at any given grid element is read and the two reference depths bracketing this actual depth are determined. The amount of meltwater computed to be produced at that element during a given time step is estimated by linear interpolation between the two values for the bracketing reference depths.

c) Infiltration

Infiltration is computed using the Holtan (1961) equation as implemented in the ANSWERS model (Beasley and Huggins, 1981). The equation is:

$$F_{max} = FC + A\left(\frac{PIV}{TP} \right)^{P} \tag{5.4}$$

where:

F_{max} = infiltration capacity with surface inundated

FC	=	final or steady state infiltration capacity
A	=	maximum infiltration capacity in excess of FC
TP	=	total volume of pore space in the control depth
PIV	=	volume of water that can be stored within the control depth prior to its becoming saturated
P	=	dimensionless coefficient relating the rate of decrease in infiltration rate to increasing soil moisture content

This equation requires six infiltration parameters to be specified for a given soil type, namely; total porosity, field capacity, depth of the control zone, steady state infiltration rate (*FC*), and two empirical unsteady state coefficients (*A* and *P*). These data are specified in the SOILDATA file for each soil type recognized at the site.

The equation reproduces the observed pattern of rapid infiltration into dry soil followed by a slowing of infiltration with wetting until a steady state rate is reached upon complete saturation of the infiltration zone. In this form, the independent variable controlling the rate of infiltration is the soil water content of the topmost, or infiltration, store (*S1*) expressed as *PIV*. The soil antecedent water content as of the preceding time step is recorded in the GRIDDATA file for the topmost soil layer (*S1*) in the field S1THETA and is updated after each time step. The volume of water that can be stored in *S1* at a given time is computed according to *PIV(1)* = *TP(1)* - S1THETA.

In keeping with the ANSWERS approach to infiltration, water that cannot infiltrate immediately during a given time step is viewed as accumulating in micro-depressions as surface retention. Water stored in surface retention is available for continued infiltration during periods of zero rainfall or snowmelt. Water stored in micro-depressions inundates only a portion of the surface of any grid element. The proportion of the total grid element area experiencing infiltration from inundated micro-depressions is estimated using the following equation from the ANSWERS model:

$$FWA = FH^{(1-RC)} \qquad \textbf{(5.5)}$$

where *FWA* is the proportion of the area of the grid element inundated by free water, *RC* is the roughness coefficient and *FH* relates the current volume of water stored in

surface micro-depressions (*DEP* expressed as depth in mm) to the maximum roughness height (*HU*) according to:

$$FH = \frac{(DEP / HU)}{RC} \tag{5.6}$$

The roughness coefficient (*RC*) is essentially a shape factor which describes the frequency and severity of the roughness. The maximum roughness height (*HU*) establishes the maximum depth of surface storage and is physically measurable. In the present exercise it is taken as equal to the average height of cultivation furrows.

Infiltration is computed first for the proportion of the total grid element area not affected by inundation (1 - *FWA*) only if there is some input from rainfall or snowmelt. Infiltration is then computed for the proportion of the grid element affected by inundation (*FWA*) whenever there is any recorded volume of water in surface storage. This approach has the effect of reducing the effective area over which infiltration from water in surface storage can occur and will consequently often result in a reduced estimate of the magnitude of the infiltration flux.

d) Drainage

As in the ANSWERS model, water is allowed to drain downward through the soil profile at a maximum drainage rate computed according to:

$$DR = FC\left(1 - \frac{PIV}{GWC}\right)^3 \tag{5.7}$$

in the order S3 -> S4, S2 -> S3, S1 -> S2 so that water is removed from any lower store before any drainage occurs from an overlying store. For each time step, the drainage rate from a given store into its underlying store is computed according to equation (5.7) above using the recorded value of antecedent moisture content (SnTHETA) to compute *PIV*. This potential rate is then compared to the previously computed drainage rate of the lower store (ie the maximum rate at which water could enter the lower store) and the lower value selected. Next, the estimated drainage flux is compared to the amount of room in the lower store available for accepting inflow from the overlying store (*PIV*). The amount of outflow from an upper store into a lower store is not permitted to exceed the remaining storage capacity of the lower store (*PIV*).

The effect of using this conceptual model of cascading stores is to reduce the drainage flux from upper to lower soil layers whenever underlying soil layers have lower rates of drainage or are full. Under these conditions, lower layers cannot accept incoming drainage water at the potential rate calculated for drainage from the overlying layer. This sometimes results in the infiltration store (S1) becoming full when it cannot drain into a lower store. In such circumstances, infiltration is reduced, or prevented, and the potential for saturation excess runoff of rainfall is increased.

e) Potential evaporation

Estimates of potential evaporation are produced using one of five different equations (Table A8.1) as implemented in the model SWATRE (Belmans et al., 1983). A full discussion of the theoretical background pertaining to these equations and the computational logic used in their implementation is presented in Appendix 8.

No attempt is made in the present model to account for canopy interception, evaporative losses from the canopy or losses arising from transpiration from growing vegetation. These omissions are made deliberately, since the focus of the modelling exercise is on predicting the runoff of surface water generated during and immediately following spring snowmelt. During this period, agricultural fields are covered by either snow, bare soil or a low stubble left from the crop harvested the previous autumn. Under these conditions of low to no vegetative growth, it is expected that canopy interception of rainfall and moisture losses by transpiration will both be minimal. Consequently, evaporation from open bodies of surface water or from saturated or nearly saturated surface soils is taken to be the main mechanism for moisture losses to the atmosphere.

Each of the above equations was used to compute an estimate of the maximum potential evaporation at the study site for each hourly time step for the periods March 22 - June 15, 1989. A comparison was made between evaporation volume predicted by the various equations and measured pan evaporation at the Lunty site. Readings of cumulative pan evaporation had been taken at the site at approximately weekly intervals throughout the non-freezing periods of April-November 1988 and 1989 (see Chapter 3). The estimated weekly total evaporation produced using each of the five equations was compared to 0.7 times measured total pan evaporation for corresponding weekly periods and found to be comparable.

The Penman equation was determined to provide the best estimate of potential evaporation for the study site for the periods of interest and is used for all model runs. This best fit may be explained by the fact that the Penman equation estimates evaporation losses from a shallow free water surface while most of the other equations consider the contribution of transpiring vegetation to moisture losses. Since there is little or no vegetal growth during the period of interest it is not surprising that an equation designed to estimate evaporation performes better than others designed to account also for losses arising from transpiration.

The basic Penman equation used to predict potential evaporation is:

$$E_t = \frac{\Delta R_n / L + \gamma E_a}{\Delta + \gamma} \qquad \textbf{(5.8)}$$

where E_t is the potential evapo-transpiration, delta (Δ) is the slope of the temperature - vapour pressure curve at air temperature T, R_N is the net radiation balance, L is the latent heat of vapourisation, gamma (γ) is the psychometric constant (taken as 0.667) and E_a is the component of evaporation due to aerodynamic processes.

A full development of the mathematics and logic involved in the implementation of the Penman and other equations is given in Appendix 8.

f) Actual evaporation

The rate at which losses due to evaporation actually occur is a function of the potential rate of evaporation modified by the moisture status of the surface. Water is lost at the full potential rate when the amount of open water held on the surface of a grid element is equal to or greater than the amount predicted to be lost at the potential rate. Surface water may be held in surface retention or may be involved in depressional ponding. If the amount of water held on the surface is less than that which would be removed at the maximum potential rate then all of the water at the surface is removed and the remaining potential evaporation is used to remove water from the soil. Water bound in the soil is removed at a rate equal to the lesser of the remaining evaporation potential or the maximum possible flux through the soil at its current moisture content. The upward loss of water from the soil is estimated as:

$$UPLOSS = DR1 * DeltaT \quad \textbf{(5.9)}$$

where *DR1* is the drainage rate estimated according to equation (5.7) and *DeltaT* is the time period (in hours) over which this rate of movement is effective. If the moisture content of the soil falls below a critical threshold taken to represent the wilting point of the soil (*S1WP*), the rate of movement of moisture through the soil is set to zero and no further evaporation losses from the soil are permitted until the moisture content of the soil rises above the wilting point.

g) Surface retention

DISTHMOD adopts the concept of surface retention as presented in the ANSWERS model. Surface retention is viewed as the volume of water that must fill micro-depressions on the soil surface before any runoff can begin. It is estimated as in the ANSWERS model (Beasley and Huggins, 1981) according to:

$$DEP = HU * RC * \left(\frac{H}{HU}\right)^{\frac{1.0}{RC}} \quad \textbf{(5.10)}$$

where *DEP* is the volume of water in depth units (mm) stored in surface retention at a given time, *HU* is the height of maximum micro-relief (mm), *H* is the actual height of water above datum (mm) in storage in the micro-depression and *RC* is an empirical roughness coefficient used to describe the shape of the soil surface. Values for *HU* range from 100 - 130 mm and for *RC* from 0.48 to 0.59 as suggested by Beasley and Huggins (1981 p. 40).

A value for maximum surface retention is required for the present model. At maximum retention H = HU and the maximum retention (MAXDEP) is calculated as:

$$MAXDEP = HU * RC \quad \textbf{(5.11)}$$

Any water not removed by infiltration or evaporation must first fill the micro-depressions responsible for surface retention. Only after these micro-depressions are filled to maximum storage capacity (*MAXDEP*) can runoff by overland flow begin.

h) Overland flow

Any water in excess of the surface retention capacity remaining on the surface of a grid element after losses due to infiltration and evaporation is available for surface runoff by overland flow. In the present model, all surface water in excess of surface retention is passed to a single downslope cell in the direction of the maximum downslope gradient. This approach to overland flow differs from the ANSWERS model in which a proportion of outflow from a given grid element is directed into up to two adjacent row or column elements according to the direction of steepest downslope gradient.

Delivery of overland flow to a single downslope neighbour simplifies the computation of downslope drainage connectivity considerably. There is little loss in utility for the present purposes since all runoff eventually arrives at the same location, a depressional centre, and it is the volume of water at this location that is of primary interest.

Many models of overland flow, including ANSWERS, introduce a flow relation based on Manning's equation to account for delays in flow of water from one element to its neighbours. No attempt is made in DISTHMOD to compute such a time delay factor. All water involved in overland flow during a given time step continues to move downslope until it either infiltrates into the soil or evaporates in downslope cells or it arrives in a depression from which it cannot escape. This omission is justified on the basis that the minimum time step used (1 hour) is large in comparison with the size of grid elements (5 m) and the maximum distances over which water may travel (100 - 200 m). Under these conditions, it is assumed that any water available for overland flow will traverse an entire flow path within a single time step. It is therefore not feasible to introduce a time delay factor for flow from one grid element into another.

i) Ponding

The ultimate function of the model DISTHMOD is to estimate the volume of water accumulating as ponding in surface depressions. Any water involved in overland flow that arrives at a designated depressional centre or pit element is added to the volume of water stored in the pit centered at that location. Any water lost by evaporation from grid elements currently flooded by any depression is removed from the volume of water recorded as being stored in the depression centred at that location.

A logical procedure is used to identify the characteristics of the depression centred at a given location and to increase or diminish the volume of water recorded as stored in that depression. The procedure involves pre-computing data about the location, volume and connectivity of all possible depressions, including nested depressions. This data is recorded in a separate relational table (PONDDATA) which is accessed every time a pit centre grid element is encountered during processing of the GRIDDATA data file. The procedure checks to see if the volume of water recorded as currently stored in the depression is less than the maximum storage capacity pre-computed for that depression. If the current volume is less than the maximum volume, the depression is considered to be "NOT FULL" and runoff generated during the current time step is added to the volume currently in the depression. This continues until the volume of water stored in the depression reaches the maximum storage volume.

Once a the current volume of any given depression equals its maximum volume, the depression is considered "FULL" and any additional input must be directed elsewhere. Pointers are used to direct overflow from a filled depression to an appropriate location. Two conditions may exist when a depression becomes filled to its maximum capacity (see Figure 5.10).

In the first possible condition, the initial depression overspills at a defined pour point and the overflow cascades down slope into a separate depression with a current elevation of ponding lower that the pour elevation. The procedure determines the location of this pour point from the PONDATA table and any water in excess of the maximum storage capacity of the initial depression is delivered to the grid cell at this pour point from where it continues to flow downhill towards the next depressional centre.

In the second possible condition, the initial depression overspills into an adjacent depression that is already full to the same overspill elevation and itself spills back into the initial depression. In such a case, if there are no other potential pour points at the same elevation from which overflow can escape, a new, larger subsuming depression is recognized with a higher pour point and a larger maximum storage capacity. Any volume of water in excess of the maximum storage capacity of the initial depression is added to the current volume of the subsuming depression until its maximum storage capacity is attained. Once a subsuming depression is determined to be FULL the

pointers are followed again to determine whether this depression in turn overspills into a down-slope catchment or into a yet higher order subsuming depression.

A similar procedure is used in the cases where loss by evaporation or infiltration from grid cells inundated by ponding has exceeded input from runoff and has resulted in a net loss of water from the depression of interest during the current time step. In such cases, the pointers in the PONDDATA table are followed to determine the identity of the highest order pond currently flooding a given pit centre. The volume of water stored in this pond is decreased by an amount equal to the estimated net loss by evaporation. Once the current volume in any depression is reduced to zero, the pointers in the PONDDATA file are re-traversed to determine if there are any lower level ponds centered at that grid element that still have a defined volume of water in storage. If a lower level pond exists, the pointers in the PONDDATA file are reset to their original condition, the appropriate volume of water is removed from the lower level pit, and its status is changed to "NOT FULL". If losses continue to exceed additions, this sequence may be repeated until water is removed from all depressions centred at a given pit centre.

5.4.5 Operation of the DISTHMOD model

DISTHMOD runs on any IBM compatible PC. It is advisable to operate DISTHMOD on the fastest possible PC for very large data sets representing highly discretised areas. Since the model utilises a database programming language (dBase III+™) and is constantly reading and writing to database files, it is advisable to transfer all large database files that are used frequently by the program to a virtual disk in computer RAM. This greatly speeds up the program since reads and writes to a RAM disk are much faster than to a file on a fixed hard drive.

For the present study, the Lunty study site was represented by 22,400 discrete grid cells each with 4 moisture stores (S0-S3). Initially, DISTHMOD was run for hourly time steps for each of the 22,400 grid cells for each of the 2040 hours between March 22, 1989 and June 15, 1989. Each of these model runs required more than one week to run to completion on an IBM 12 mhz 286. This performance was judged to be unacceptable.

DISTHMOD was subsequently modified to accept variable time steps. The modification permitted hourly time steps to be lumped, up to a maximum of 24 hours,

provided there was no rainfall or snowmelt input. The program reverted to hourly time steps for every hourly record for which any rainfall or snowmelt was recorded in the METDATA input file. This compromise allowed the program to run to completion on a 33 mhz 486 in a more realistic time span of 12 hours. The variable time step ensured that DISTHMOD operated on as short a time step as possible during periods of rainfall or snowmelt input that might produce runoff. Lumping hourly inputs of rainfall or snowmelt into daily totals would invariably create a situation in which daily infiltration capacities would consistently exceed daily rates of rainfall or snowmelt. No runoff would be calculated by the model under such conditions. The effect of lumping hourly time steps is less noticeable for periods with no inputs of rain or snowmelt. The focus of the program during these time steps is to compute a water balance for each grid cell based on net infiltration within the soil column and evaporation from the soil or from ponds into the atmosphere. These processes are less sensitive to computation using longer (lumped) time steps.

5.5 Summary and conclusions - development of the DISTHMOD Model

The DISTHMOD model was developed, in the absence of an appropriate existing model, to implement and test some concepts pertaining to the simulation of surface runoff and its accumulation in multiple nested depressions. It is quite crude and limited in comparison to many, more comprehensive, physically-based, hydrological models. None-the-less, it proved very capable of performing the functions required of it. The model is not considered suitable for widespread distribution and use in its present form. Any widespread use would require reprogramming to re-implement the concepts on a more powerful platform using more efficient computer code.

DISTHMOD was written in a data base programming language (dBase III+™ compiled in Clipper™) and made use of capabilities and constructs associated with relational data base languages. The programming used to implement DISTHMOD is crude in comparison to more traditional programming languages such as C++ or Pascal. It is the contention of the author, however, that adoption of a data base programming approach offeres several distinct advantages.

A program listing and detailed explanation of the DISTHMOD model is given in Appendix 11. Summary comments regarding positive and negative aspects of model development are given here.

5.5.1 Highlights and positive contributions

The unique feature of the model is its ability to account for flow into closed depressions and to model explicitly the spatial pattern of growth, overspill and decay of ponds in depressions. In this, it is unlike any distributed model known to the author. Some existing lumped or variable source area models (e.g. QUALHYMO, JNM, 1986 and SOIL, Johnsson and Lundin, 1991) adopt a conceptual representation of depressional storage but do not calculate storage volumes explicitly nor do they indicate the physical locations of depressions.

An additional unique feature of the model is its use of the indexing capabilities of a relational database management program to control the order of processing of grid cells. This ensures that cells are processed in a hydrologically correct order along flow paths, from highest to the lowest cell within each watershed. Watersheds are processed in order of decreasing overspill elevation to ensure that excess runoff from a higher watershed is always computed before any processing of a lower watershed begins. This physically reasonable ordering is lacking in many existing distributed hydrological models which process cells from left to right and top to bottom with no consideration of patterns of flow. This can give rise to situations in which a water balance is computed for a given grid cell and runoff passed to a lower cell before runoff from a higher neighbour cell has been received. This is hydrologically incorrect and is remedied by the indexing approach utilised in DISTHMOD.

Another positive feature of the model is its adoption of a variable time step with short time steps (1 hr) during rainfall and snowmelt events likely to result in runoff and longer time steps (up to 24 hr) during the intervals between rainfall or snowmelt. In this sense, DISTHMOD recognises that "fixed-interval hydrological models suffer from the problem of either "overkill" during relatively dormant process periods in short interval models, or loss of resolution during active process periods in long interval models" (Hughes, 1993). It adopts the compromise solution quoted by Hughes (1993) of operating "on a relatively coarse time-scale between events and then switching to an event type model, operating at shorter time intervals, for the duration of specific events". It responds to Hugh's (1993) concern that "less attention has been given to temporal resolution in models than has been given to the spatial resolution".

The model utilises the concept of a linear cascade of inter-connected reservoirs. In this sense it is similar to cascade models described by Bevin et al., (1984), Wallach (1991) and Beasley and Huggins (1981). In fact, a significant component of DISTHMOD represents a re-implementation of concepts and equations detailed by Beasley and Huggins (1981) for the ANSWERS model. The simplified representation of process used in DISTHMOD to compute a water balance at each grid cell can be considered both an attraction and a limitation. Restricting the number of processes represented and adopting simple equations for those processes which are represented makes it feasible to apply the model to a highly distributed spatial model. The use of relatively simple equations for process is in accord with principles advocated by Bevin (1989) and adopted by Beasley and Huggins (1981), Woo and Rowsell (1993) and Chiew and McMahon (1990).

The implementation of DISTHMOD using a database programming language (dBase compiled using CLIPPER) is a final attribute that has both positive and negative aspects. One advantage is that the higher level data base language greatly reduces the need to program for input or output (I/O). The database approach also greatly facilitates relating one set of data to another. For instance, the soil field in the main GRIDDATA file LuntyGRD acts as a pointer to the appropriate record in the selected SOILDATA file that contains all of the data about each soil's hydrological characteristics. Another advantage is the ease with which data can be input, output and interfaced with a wide variety of GIS. Many existing, stand-alone distributed models do not interface easily with geographical information systems (GIS). However, most GIS are directly interfaced to one or more relational data base management systems. Implementation of DISTHMOD in a data base programming environment increases the ease with which the model can access data in a GIS or direct results for output in a GIS. Disadvantages of adopting a database programming language approach include slower performance, restricted mathematical functionality and limited portability across hardware platforms.

5.5.2 Oversights and opportunities for improvement

Options for improving the DISTHMOD model fall into two main categories. The model could be improved by a) increasing the number of processes represented and the sophistication with which they are represented or b) decreasing the number and the mathematical precision of process representation and substituting simpler surrogates that encompass a variety of processes. Both alternatives have merit.

The argument in favour of increasing complexity is that DISTHMOD does not adequately represent all of the important processes active in producing runoff and removing accumulated water from ponds. The most immediately evident deficiency is the inability of the current model to simulate changes in soil temperature and to estimate the corresponding effect on hydraulic conductivity and infiltration rate. The coupled soil water and heat flow model (SOIL) described by Johnsson and Lundin (1991) is a good example of how DISTHMOD might be improved to account for soil temperature effects. SOIL is a single profile, non-distributed model, but it does illustrate incorporation of comprehensive solutions of heat flow and water transport differential equations. In addition to heat flow, the DISTHMOD model could be improved by adding components for estimating water removal from surface and sub-surface horizons by plant roots (transpiration), canopy interception and evaporation, upward movement of soil moisture in response to matric head gradients directed towards the surface, lateral near-surface throughflow and sub-surface groundwater flow. All of these are lacking in the current implementation.

Similarly, representation of some of the processes presently included in the model could be made more exact. The infiltration equations could be replaced with more comprehensive equations based on numerical solutions of partial differential equations. The procedures for computing surface runoff could be enhanced to account for time delay in runoff. The snowmelt and evaporation equations could be made to apply to individual grid cells or to groups of cells with similar aspect, illumination, fetch, and landscape position.

While the suggested changes would make DISTHMOD more complete, their inclusion would greatly increase both the complexity of the model and the requirements for input data and calibration. The more complex the model, the more difficult it is to parameterise, run and interpret (Beven, 1989). This points toward the second option, that of simplifying the DISTHMOD model.

Beven (1989) has suggested that physically-based models that attempt to simulate all of the hydrological processes thought to be relevant are often wildly over parameterised He observes that there may not only be a large number of parameter values associated with such models but that these parameters may take on different values in different grid squares. He notes that there may be a great many combinations of parameter values, parameter distributions and boundary conditions

consistent with observed behavour. This increases the difficulty of interpreting results or determining which combination most properly reflects "reality". Beven (1989) also questions the validity of assumptions that small scale physical equations can be applied at the much larger scale of grid squares in distributed models. He argues that current physically-based models are in fact still "lumped conceptual models" and suggests that it is perhaps better to recognise this and to develop equations that represent an integration of the processes active at the lumped scale of individual watersheds or sub-watersheds.

In the spirit of Beven's (1989) arguments, the modelling approach used in the present study could probably have benefitted from simplification with respect to both process and space. Computation of water balances and overland flow for the 22,400 grid cells was not particularly necessary or successful. This highly discretised representation of space could clearly have been simplified to a semi-distributed representation of individual depressional watersheds with little loss of functionality. Representation of process within each watershed could also have been simplified.

The present model processes each individual grid cell within each pond in order to estimate evaporation from the pond and infiltration into soils beneath the pond. In the distributed DISTHMOD model, pond area is computed explicitly by identifying every grid cell that is inundated at a given pond volume. The same effect could be achieved by simply computing the area of each pond at each incremental change in volume and storing this information in a look-up table. The alternative, semi-distributed approach could simply compute evaporation and infiltration once for each depression based on the area of the depression retrieved from the look-up table for the currently recorded volume of the pond. Similarly, runoff could be computed once, for each watershed in each time step. Estimates could be based on 100% contributing area during periods of frozen soil (as done in the present DISTHMOD model) and on some smaller percent of contributing area during rainfall onto non-frozen soils. Estimates of contributing area could be a funtion of antecedent moisture conditions and catchment morphology as suggested by Beven et al., (1984) for TOPMODEL.

In fact, one of the original aspirations of the present study was to locate or construct a semi-distributed, conceptual model in addition to a distributed, physically-based model and to compare the efficacy of both. This became impossible due to the level of effort required to create the distributed model DISTHMOD and to complete the field work required to provide data for parameter input and model validation. It is suggested that

a suitable follow-up project would apply the concepts inherent in a semi-distributed, conceptual model such as TOPMODEL (Beven et al., 1984) to the Lunty site using the defined depressional catchments as the framework for defining the semi-distributed model entities.

The experience gained in constructing, applying and evaluating the DISTHMOD model leads the author to favour the second approach for improvement. That is, simplification with respect to the representation of both process and space. This is consistent with the intended use of the model as a tool for making predictions of how much water will pond at particular locations and particular times. If the intended use of the model were to be as a tool for developing improved understanding of hydrological processes in depressional landscapes, then the choice would be to increase complexity.

CHAPTER 6

MODEL APPLICATION:

USING DISTHMOD TO SIMULATE FLOW AND ACCUMULATION OF SURFACE WATER AT A FARM SCALE

6.1 Introduction

6.1.1 Overview

This chapter presents the results of efforts apply the DISTHMOD distributed simulation model to the Lunty study site to simulate spring snowmelt, runoff and ponding. The preprocessing steps required to provide data to operate the model are presented and discussed. Next, the results from ten different runs of the model DISTHMOD are presented.

6.1.2 Context

Application of the DISTHMOD model recognized the previously cited need to relate model development and validation to field studies. Data and knowledge obtained from field studies at the Lunty site were instrumental in developing specifications for DISTHMOD, in providing realistic values for input parameters and in providing a means of evaluating model performance.

The present study took place within the context of a broader set of research activities undertaken at the Lunty site (Moran et al., 1990a,b; Trudell, 1989, personal communication). The companion research studies had as their general goal the characterisation of soil and hydrological conditions at a "natural, pre-mined site" in an area used for surface mining of coal. The natural conditions were to be used as base-line data against which to compare post-mining conditions in reclaimed landscapes. The companion studies provided a considerable base of data for the Lunty site. This limited the amount of new data that had to be collected expressly for the present research. The companion studies also highlighted the need for more and better tools for simulating the flow and accumulation of surface water. Companion efforts to

characterise patterns of soils and groundwater flow all pointed to the important role played by the flow and accumulation of surface water in determining these patterns.

6.2 Experimental design

The objective of applying the DISTHMOD model at the Lunty site was to produce a series of predictions of the volume, extent and depth of surface ponding at specified dates during a period of spring runoff. The period of runoff selected for simulation was from March 22 to June 15, 1989. The results are used to evaluate the performance of the model in comparison with field measurements of volume, extent and depth of ponds over the same time period. The steps taken to apply the model (Figure 6.1) are summarised as follows:

A number of preprocessing steps were completed before the model could be run. These steps were required to define the topological structure controlling the geometry of flow and to collate input data or assign parameter values. Meteorological data were obtained for the Lunty site, then tabulated and reformatted as average hourly values. These were further processed to estimate potential evapo-transpiration and potential snowmelt for each hourly time interval. Data from a detailed grid soil survey were used to construct a soil map for the site which was used to assign soil types to each grid cell. Data from field measurement of hydraulic conductivity and field monitoring of soil moisture variation were used to assign values for hydraulic conductivity, field capacity, wilting point initial moisture content and moisture content at saturation to all soils. Data on the location, volume and topological connectivity of all sites of potential ponding were extracted from the previously described definition of surface geometry (chapter 4) and reformatted for use in DISTHMOD.

The model (DISTHMOD) was run using the measured data and a variety of different assumptions and boundary conditions. Initial runs were conducted to define the maximum and minimum runoff and ponding predicted by the model for hypothetical extreme conditions of maximum inputs and no losses (run 1) followed by minimum inputs and maximum predicted losses (run 2). These runs were conducted to define the maximum range of predicted ponding in the hope that the observed extent of actual ponding would be bracketed by these extremes. Subsequent runs investigated the effects of altering the procedures by which total snow depth (and therefore snowmelt) was estimated and altering the initial rules governing evaporation and soil drainage so as to analyse the relative contributions of these processes to simulation results. Runs

3, 4 and 5 assumed an artificially large depth of snow of 400 mm and varied the dates and rates at which infiltration was allowed to proceed. These runs identified the critical importance of snow depth in producing reasonable estimates of pond depth and volume so runs 6 through 10 primarily investigated the effects different approaches to estimating the depth of snow at the site. These runs also investigated the sensitivity of the model to estimated rates of infiltration and evaporation given reasonable estimates of snow depth.

The output from each run was saved as a series of maps and tables documenting the simulated location, extent, depth and volume of ephemeral ponding for each of 11 dates on which actual pond extent was surveyed. The simulated extent of ponding is compared with the actual measured extent in chapter 7.

6.3 Methods - pre-processing operations used in DISTHMOD

The preprocessing steps required in order to run the DISTHMOD model are listed in Figure 6.1 and discussed below.

6.3.1 Pre-processing of DEM to define geometry of flow

This activity has been fully described elsewhere (see Chapter 4). This preprocessing step provides the essential information on cell to cell connectivity and flow paths. It is analogous to the preprocessing program ELEVAA used to construct the master data file for the ANSWERS model (Beasley and Huggins, 1981). One significant difference is that, unlike ANSWERS, DISTHMOD permits, and specifically encourages, the retention of situations in which computed drainage directions define topographical depressions or pits. A second significant difference is that DISTHMOD permits drainage from each cell to only a single downslope neighbour whereas ANSWERS permits drainage from a cell to two or more neighbours. The **Watersh** utilities used to define cell to cell flow paths for DISTHMOD are more automated and user friendly than those described for ANSWERS (Beasley and Huggins, 1981).

Other data computed during this pre-processing step include the initial (first order) watershed to which each cell belongs and the upslope area count for each grid cell. The upslope area statistic (see Chapter 4) is used to ensure that cells are processed from highest to lowest along flow paths. In the (not infrequent) case of two adjacent

cells having the same elevation, the cell further along the drainage path towards the depression will always have a value for upslope area that is at least 1 cell greater than its upslope neighbour. The database indexing procedure used to order cells for processing makes use of this fact by including upslope area as one of the fields used to create the sequential index file.

Procedures described in chapter 4 were used to document the location, maximum volume and overspill locations of all depressions in the Lunty site DEM. The rules governing flow from topographically higher to lower depressions or from hierarchically lower order depressions into overlying higher order depressions developed and applied in chapter 4 formed the basis for the pond connectivity statistics required to operate DISTHMOD.

6.3.2 Reformat topographical and pond data into relational tables in a DBMS

The DISTHMOD GRIDDATA dBase III+™ file was defined initially as consisting of 6 fields, specifically ROW, COL, ELEV, DDIR, SHED, UPSLOPE. Data for each of fields 3-6 was initially formatted for the **Watersh** utilities as an ASCII matrix of 160 rows by 140 columns. A utility called KRTtoCOL was used to reformat the 160 by 140 matrix for ELEV into a long ASCII file in the form ROW, COL, ELEV. In this utility, row 1, col 1 represented the top left hand corner of the matrix and cells were read and reformatted by row by column from top left to bottom right. This reformatted data were imported into the first 3 fields of the dBase III+™ file described above. A similar utility (KRTtoIMG) was used to reformat the matrices DDIR, SHED and UPSLOPE into ASCII files consisting of 22,400 lines of data with each line representing data for one row and column. The data were ordered from top left to bottom right as for KRTtoCOL. These reformatted ASCII files were imported into the fields DDIR, SHED and UPSLOPE in the GRIDDATA file.

Once these data were imported, a utility program written in dBase III+™ was used to determine the database record number (RecNo()) of the grid cell to which each cell drained. A field called DREC was added to the database structure and the value of the record number to which each cell drained was added to this field. This field provided a convenient means of locating the downslope cell to which any given cell drained. The relational database program used for DISTHMOD (dBase III+™ compiled using Clipper™) provided a facility for direct access to records based on the record number

(RecNo()). The program was able to jump directly to the desired record if the record number was given. This feature was used to permit the program to jump directly to the record for a specific grid cell and deliver runoff for any instance where runoff was computed to occur into that cell. The same mechanism was used to jump back to the initial starting cell after runoff was delivered so that processing could continue following the pre-defined order established by indexing on SHED, ELEV and UPSLOPE AREA.

Another preprocessing step involved adding a field called SHEDORD to the Lunty GRIDDATA file. Each of the 115 original watersheds was assigned a number between 1 and 115 to indicate the order in which that shed was to be processed by DISTHMOD. The order was determined by examining the PONDDATA table presented in chapter 4 to determine the elevation of the pour point for each watershed and the watershed to which each drained. The watershed with the highest pour elevation was assigned an order number of 1. The watershed with the lowest pour elevation, into which all higher depressions drained was assigned the number 115. The database indexing procedure operated in numerically ascending order so that smaller numbers were processed first. Consequently the watershed with SHEDORD=1 was processed first, 2 second and so on.

6.3.3 Compute volume-to-first-flood (FLODVOL)

The statistic volume-to-first-flood (see 4.4.11) was computed for every cell in the GRIDDATA database and stored in a field named FLODVOL. This statistic enabled the model DISTHMOD to compare the volume of water stored in a given pond at a given time with the volume of water that would be required to accumulate in the pond before it first flooded a particular cell. The volume of water currently stored in a specific depression was maintained as an attribute of the pond object in the relational table PONDDATA. As DISTHMOD processed cells from highest to lowest in each watershed, it checked the volume of water required to first flood each cell and compared this to the volume of water recorded as currently stored in the pond associated with that watershed. If the volume-to-first-flood was greater than the volume of water currently stored in the pond, then DISTHMOD concluded that the cell in question was not inundated. The first cell encountered in which the volume-to-first-flood was less than or equal to the current volume of water stored in the depression was deemed to be flooded. The elevation of this cell was recorded as the current pond

elevation (PONDELEV) and it was assumed all other cells in the current watershed were also flooded to this depth (all subsequent cells being equal or lower in elevation).

Computation of the statistic volume-to-first-flood was achieved using a pre-processing program written in dBase III+™ and compiled using Clipper™. A complete listing for this program is provided in Appendix 9. This program utilized both the PONDDATA file detailed in chapter 4 and the GRIDDATA file described in Appendix 11. The program computed the statistic volume-to-first-flood for all cells lower than the pour elevation of the initial 115 first order watersheds. After each of these was processed, it reassigned any watershed which, on overspill, became part of a new, larger, higher order watershed to this new watershed. The number of the new watershed was determined by following the pointers for DRAINSTO and NEXTPIT in the previously described PONDDATA file. The process of computing volume-to-first-flood was continued until a value for this metric was assigned to every grid cell that could possibly be flooded for all depressions defined at the site.

6.3.4 Index GRIDDATA file by catchment, by elevation and by upslope area

The main DISTHMOD program and several of the utility preprocessing routines (PONDMAP, FLOODVOL) made use of the indexing capabilities provided by a relational database system. Indexing was used to sort grid cells into a defined order for processing. DISTHMOD required the definition of an index file named TOPDOWN.ndx in which grid cells were arranged in a sequential order by watershed, by elevation and by upslope area. The intent was to ensure that grid cells were processed such that all cells in a watershed with a higher overspill elevation (POURELEV) were processed before any cells in any watershed with a lower pour elevation. Within a given watershed, each cell was required to be processed by elevation, from the highest to the lowest. The lowest cell was always a pit centre cell. Upon encountering this cell, DISTHMOD invoked a series of procedures to total additions from runoff or snowmelt and losses from evaporation or infiltration and then to add or remove water from the pond object as defined and described in the PONDDATA file.

Indexing based on elevation alone was insufficient to ensure that grid cells were always processed in the proper order along flow paths from highest to lowest. There were frequent cases where two or more neighbouring cells had identical elevations. In

such cases, the statistic upslope area was used to determine which of the two cells to process first. The cell with the higher upslope area count could be confidently determined to be downslope of any neighbour cell of identical elevation as upslope area was computed by adding the value of the upslope area for all upslope cells to the next lowest cell along a flow path. Adding consideration of the value of upslope area to the indexing function ensured that all cells were processed sequentially, along flow paths, and that the final cell processed was always the pit centre cell (cell with the highest upslope area).

The command syntax used to produce the index file TOPDOWN was:

INDEX ON ((SHEDORD*10^7)+((735.0-ELEV)*10^5)+UPSLOPE) TO TOPDOWN

The index was based on sorting the records associated with each cell in ascending order based on the calculated value of the above expression. The field SHEDORD contained an integer number from 1 to 115 in which 1 was assigned to the watershed with the highest overspill elevation and 115 to the watershed with the lowest pour elevation. The elevation of each grid cell (ELEV) was subtracted from an arbitrary number (735.0) larger than the highest recorded elevation (728.6) so that the highest elevation produced the smallest number and the lowest elevation produced the largest. Upslope required no modification as upslope area was already ordered sequentially from smallest number for the first cells requiring processing to largest number for the last cell requiring processing.

6.3.5 Collate and input meteorological data required for DISTHMOD

It was necessary to produce a complete digital file of meteorological data (METDATA) to provide input for DISTHMOD. The actions taken to produce and collate the data for the file METDATA are documented in chapter 3. A dBase III™ file with the structure documented in Appendix 11 (Table A11.2) was created and populated with the initial recorded and calculated meteorological variables (PREC, TEMP, RADIA, RH, WIND, CLOUD) for each hourly time step from March 22 to June 15, 1989. Data on soil temperature at three depths (0-15, 15-40 and 40-60) were added to the meteorological file. These were required to provide a basis for determining whether to treat a given conceptual soil store as frozen during any given time step. The

DISTHMOD model had no internal mechanisms for computing or estimating soil temperature or determining if the soil was frozen at any depth.

A variety of activities (described in chapter 3) were conducted to modify the original meteorological data and to graph it to check for possible input, instrument or calculation errors. The data were imported into METDATA for final use only after all validation and editing had been completed.

6.3.6 Estimate snowmelt potential for various reference depths

Once the meteorological data were validated and input, the snowmelt sub-model described elsewhere (section 5.4.8 and Appendix 7) was run to estimate the volume of potential snowmelt for each hourly time step for 16 reference depths ranging from 5 cm to 200 cm. The METDATA file was modified to create the fields required to store intermediate and final calculations made by the snowmelt program for each depth and time step.

The estimated timing of snowmelt for reference depths corresponding to the observed range of depths of snow recorded at the Lunty site (5 - 70 cm) was compared with field observations of the days in early April during which snowmelt was observed to be active. Correspondence between observed and predicted timing provided encouragement for accepting and applying the results of the snowmelt sub-model.

6.3.7 Assign soil types and hydrological properties to all grid cells

The grid soil map illustrated in Appendix 2 (Figure A2.1) was reformatted using the utility KRTtoIMG and imported into the field SOIL in the GRIDDATA file named LuntyGRD. This action served to assign a soil code to each of the 22,400 grid cells.

The model DISTHMOD required estimates for saturated hydraulic conductivity (FC) for each soil store at each grid cell as well as estimates of the moisture content of each of the soil stores at saturation (TP), field capacity (FP) and wilting point (WP) (surface store S1 only). In addition, it required an estimate of the initial moisture content of each store for each soil at the start of a given model run (time zero). The values for percent moisture at the three specific moisture contents were assigned to each store for each soil based on hypothetical extreme values, on existing data and on

results provided by the field study (see Chapter 3 and Appendix 3). The estimates of initial moisture content for each soil and store were based on assumed hypothetical extremes or on soil moisture profiles derived from field data (see Chapter 3 and Figure 3.9).

The values for percent moisture content were converted into volumes of water present in each store at a given moisture content by multiplying the thickness of the store (mm) by the percent volumetric moisture content at a specific moisture status (i.e. saturation, field capacity, wilting point). The model initially required gravimetric water capacity (GWC) to be computed according to the ANSWERS model specifications (Beasley and Huggins, 1981) as the difference between the volume of water stored at saturation (VolTP) and at field capacity (VolFP). Some later runs of the model permitted drainage to a lower moisture content defined by the wilting point (WP) as this was more representative of observed field behaviour. In these cases the variable GWC was computed as VolTP - VolWP for each store. It no longer represented the volume of water subject to gravitational drainage to field capacity but rather the volume of water subject to removal if the soil were to dry out to the wilting point. A final data requirement of DISTHMOD was for an estimate of the initial volume of water present in each soil store at time zero for any given run.

Procedures described in the ANSWERS manual (Beasley and Huggins, 1981) were used to develop estimates for each of the ANSWERS model soil parameters required for use in DISTHMOD. Four sets of soil property conditions were defined for the various runs of the model DISTHMOD.

Set one (SOIL1) was designed to produce maximum runoff. All soils in SOIL1 were assigned a maximum storage capacity (VolTP) of zero and a drainage rate (FC) of zero. The initial moisture content was not significant under these conditions and was therefore set to zero for all soils.

Set 2 (SOIL2) was designed to produce minimum runoff. All soils in SOIL2 were assigned a maximum storage capacity (VolTP) based on a total porosity (TP) of 50% times the estimated thickness of the store. All soils were assigned identical drainage rates (FC) of 20, 5 and 2 mm hr^{-1} for stores S1, S2 and S3 respectively. The initial soil moisture status for each soil and store was set to equal the minimum estimate for moisture content at field capacity for each soil.

Set three (SOIL3) was designed to represent the best estimate of the true mean values for saturated hydraulic conductivity and percent moisture at saturation, field capacity and wilting point for each soil and store. These values were based on a combination of existing data and field determinations as described in chapter 3. The estimate for initial moisture content of each store of each soil was based on soil moisture profiles derived from field monitoring of soil moisture (see Chapter 3 and Figure 3.9).

Set four (SOIL4) treated the soil variables as calibration parameters to be adjusted in order to achieve better estimates for infiltration than were achieved using values based on field measurements. There was a requirement to assign significantly lower rates for steady state drainage (FC) for most soil stores and to adjust the lower limit for soil drainage to approximate the wilting point (WP) in order to more closely reproduce the observed behaviour of the soils at the Lunty site. The initial moisture content for each soil and store was based soil moisture profiles derived from field monitoring of soil moisture.

6.3.8 Compute potential evaporation

The potential evaporation sub-model described elsewhere (section 5.4.4 and Appendix 8) was applied to the data in the METDATA file to estimate potential evapo-transpiration for each hourly time step using each of the 5 equations extracted from the SWATRE model. Model coefficients were determined and assigned by editing the SETUP file described in Appendix 11. Coefficients were adjusted several times to produce increasingly reasonable estimates of evapo-transpiration by all equations. The evaporation model used the albedo estimated by the snowmelt model for a reference depth of 20 cm of snow as input for hourly time steps during which the ground was snow covered. The final values of potential evapo-transpiration computed by each of the 5 equations for each time step were stored in the METDATA file in fields named after each of the respective methods. These data provided the basis for estimating the potential evaporation at a given hourly time step for every grid cell in the GRIDDATA file.

No attempt was made to modify potential evaporation to recognize differences in aspect, slope, snow cover, surface roughness or surface cover (land use) at different grid cells. This would have necessitated adjusting values for radiation, wind speed, temperature and other meteorological variables to reflect differences at each grid cell caused by topographical and land use changes. This would not have been feasible for

all 22,400 grid cells for all 2040 hourly time steps. It might have been possible to adopt a scaling approach similar to that used for estimating snowmelt. A limited number of groups of grid cells with similar topographical and land use characteristics (i.e. SW aspect, low slope, bare soil) might have been defined and meteorological variables adjusted to reflect assumptions about how different orientations and land uses might affect inputs. A separate estimate of evaporation by each of the methods might have been generated and saved for each group of cells. This also was judged impractical and not implemented. The assumption was made that conditions were similar enough for all grid cells to justify a single estimate of potential evaporation applicable to all grid cells during any time step.

6.3.9 Compare estimated potential evaporation to observed pan evaporation

Potential evaporation as estimated by each of the five equations extracted from SWATRE was compared with observed pan evaporation as recorded at the Lunty site at approximately weekly intervals. The hourly values of potential evaporation computed by each of the 5 equations were summed for periods corresponding to the dates between which field measurements of pan evaporation were recorded. The simulated potential evaporation was graphed against the observed pan evaporation and against 0.7 pan evaporation. Differences between the observed and simulated values were noted and analysed. The equation providing the best fit to the observed pan evaporation data was identified and selected for use in subsequent modelling efforts.

6.3.10 Estimate height and roughness of furrows

The height and roughness of furrows responsible for surface detention was estimated following guidelines provided in Appendix B.2 of the ANSWERS manual (Beasley and Huggins, 1981 p. 40). The ANSWERS surface storage parameters HU and RC were estimated for each of the mapped soil series instead of for each individual grid cell. Each soil series corresponded with changes in land use that affected ridge height and surface roughness. The Haight (HGT) and Cordel (COR) series were located in depressions that were uncultivated or at least unploughed, for the spring period. They were assumed to have maximum smoothness (0.30) and minimum roughness height (10 mm). Foreman (FMN) series was mostly associated with uncultivated, grass covered verges surrounding depressions and was also considered to have a smooth surface (0.30) and a shallow roughness (15 mm). The remaining series (KLM,

DYD, EOR) were all associated with cultivated upland landscape positions. These cultivated locations were all covered by a low stubble and had not been cultivated since the previous spring. They were therefore considered to have a relatively smooth surface (0.35) and a shallow roughness height (20 mm).

No attempt was made to vary roughness height to reflect orientation of cultivation relative to slope gradient. It was understood that roughness height would tend towards zero for grid cells where the direction of cultivation was parallel to the direction of slope gradient and towards maximum depth where cultivation was perpendicular to slope. This information was not recorded and would have been difficult to assign to each of the 22,400 grid cells individually.

6.3.11 Finalise or alter pond connectivity pointers or volume statistics

This step was introduced to permit the development and investigation of "what if" scenarios. The PONDDATA table could be modified to change pond connectivity pointers or volume statistics to simulate the effects of artificial drainage. For example, if one were interested in examining the implications of using artificial drainage to consolidate several higher ponds into a single pond at a lower elevation all that was required was that the pointers in the PONDDATA table that determined where overspill would be directed be changed to point to the new consolidation pond. Complete and immediate drainage from the upper ponds could be simulated by altering the statistic VOLTOFLOOD in the PONDDATA file to zero for each of the depressions to be drained. If the VOLTOFLOOD was zero all runoff arriving at that pit centre would be immediately directed to the overspill location (directed to the new consolidated pond). Partial drainage (such as would be achieved through installation of a standpipe with an outlet at a fixed elevation) could be achieved by specifying a new value for VOLTOFLOOD equivalent to the volume of the pond to be drained when flooded to the elevation of the standpipe outlet. Any volume of water in the pond in excess of this holding volume would be directed to the consolidation pond.

A few minor modifications of the original PONDDATA file were made to permit simulation of ponding in the northeast corner at watershed 13 whose depression was located at the edge of the data matrix. Pointers and volume statistics were revised to permit accumulation here even though lack of data about the terrain outside the current

DEM should have precluded recognising a depression in this location. No serious efforts were made to develop and test artificial drainage scenarios as described above.

6.3.12 Specify types of output and dates for output

The final preprocessing step prior to running the model DISTHMOD was to specify the dates on which output was required and the type of output required on any specified date. This was accomplished by locating the day and hour in the METDATA file that most closely matched the time at which each of the field surveys of pond location and extent was carried out. A numeric code of 1-5 was inserted in the field OUT to identify the kind of output required for that day and hour. The codes are explained in Appendix 11.

6.4 Methods - application of the DISTHMOD model

The DISTHMOD model was applied to the Lunty site data set for a variety of hypothetical and observed conditions applicable to the spring of 1989 (see Table 6.1). Two initial runs were made to determine conditions of maximum and minimum hypothetical runoff and ponding (runs 1 & 2). These represented the extremes of conditions over which the model was expected to operate. Subsequent runs were undertaken to investigate the sensitivity of the various component sub-models and to assess the performance of the model under increasingly realistic conditions.

Run 3 set infiltration to zero and simulated the combined influence of evaporation and surface retention on runoff from an initial depth of snow of 0.4 m. Run 4 was a repeat of run 3 except that infiltration was permitted at rates based on mean saturated hydraulic conductivity for each soil type. Infiltration rates were assigned to each of the three stores for each soil based on field measurements and estimation procedures outlined in the ANSWERS manual (Beasley and Huggins, 1981). Infiltration was allowed to occur for every time step. Run 5 was a repeat of run 4 except that infiltration was not permitted until after the dates April 12, 22 and May 2 for stores S1 to S3 respectively. This had the effect of simulating reduced infiltration for dates on which the soil was deemed to be frozen.

Run 6 and subsequent runs differed from all previous runs mainly with respect to the assigned initial depth of snow. For run 6 the initial depth of snow was set to the mean initial depth (0.13 m) recorded at the 44 snow pack survey sites. Otherwise run 6 was

similar to run 5 in that infiltration was prevented until April 12, 22 and May 2 for each of the three soil stores by setting the soil temperature of the stores to below zero until after those dates. For run 7 the initial depth of snow estimated for each of the grid cells was based on a regression equation developed between depth of snow and upslope area count (see Table 3.14). The mean initial depth of snow estimated for all grid cells by this method was 7.54 cm.

For run 8 the regression equation used to estimate the initial depth of snow was modified to produce a deeper snow pack with a mean depth for all 22,400 grid cells of 0.2 m. Infiltration was allowed to proceed in all soil stores after April 5, 1989 but lower rates were assigned for steady state infiltration for all soils (database SOIL4). Run 9 was similar to run 8 except that the regression equation was again altered to produce estimates for initial depth of snow that averaged 0.15 m for all 22,400 grid cells. A further change was that the minimum water content to which a soil store could drain was reduced to approximate wilting point instead of field capacity as in the ANSWERS model. This was done in recognition of the knowledge provided by field studies that soil moisture content at most sites varied between a maximum of field capacity and a minimum of wilting point for most dates on which field determinations were made.

Run 10 was a repeat of run 9 in which infiltration was set to zero for all soils. This results of this run were compared to those of run 9 to evaluate the relative contributions of infiltration and evaporation to reductions in pond volume as simulated in run 9.

6.5 Results from the pre-processing operations

This section presents results of preprocessing operations not already discussed elsewhere (i.e. Chapters 3&4). The preprocessing operations produced data required for operation or configuration of the main DISTHMOD model.

6.5.1 Reformatting of topographical and topological data

a) Results

The reformatted topographical data formed the basis for the main GRIDDATA file (LuntyGRD.dbf). That portion of the LuntyGRD.dbf file concerned with basic

topographical and topological data is reproduced as Table 6.2 for an arbitrary selection of 50 of the 22,400 grid cell records. Table 6.2 illustrates how the various individual N by M matrices were merged into a single database file with each grid cell identified by its ROW, COL location and each of the other fields in the data base corresponding to an attribute of the grid cell (i.e. its elevation ELEV).

b) Discussion

The field DDIR contains an integer value corresponding to the local direction of flow (Drain Dir) computed by the **Watersh** utilities. The drainage direction corresponding to each of the numbers 1 through 9 has been discussed elsewhere (see Chapter 4, Figure 4.7). Similarly the field UPSLOPE contains a value for the number of cells upslope of the current cell that drain through the current cell. Computation of the variable UPSLOPE using the **Watersh** utilities is fully described in chapter 4 (see Figure 4.14).

The record number of the dBase III+™ record of the cell to which drainage occurred was calculated by determining if the drainage direction was toward a cell in the current row (DDIR = 4,5,6), the row above the current cell (DDIR = 7,8,9), or the row below the current cell (DDIR = 1,2,3). The computed value of the row of the drainage cell (DROW) was therefore either DROW = ROW ; DROW = ROW - 1; or DROW = ROW + 1. Similarly, the value for the column of the drainage cell (DCOL) was computed as DCOL = COL for DDIR = 2,5,8; DCOL = COL - 1 for DDIR = 1,4,7 or DCOL = COL + 1 for 3,6,9. Once the row and column numbers of the drainage cell were computed, the record number corresponding to this grid cell was calculated according to the formula :

$$DREC = ((DROW-1) * 140) + DCOL \qquad \textbf{6.1}$$

This calculation made use of the fact that the dBase III+™ file records were ordered sequentially starting with the cell in the top left corner (ROW = 1, COL =1) and proceeding through all the columns of row 1 then to row 2 column 1 and so on to finish at ROW = 160, COL= 140 (for the current Lunty data set). Knowing the record number of the cell to which drainage occurred, the program DISTHMOD was able to jump directly to that record whenever any runoff was computed to occur (and then jump back to the original starting cell). This direct access to downslope records meant that the program didn't have to search the entire data base for the cell with

ROW=DROW and COL=DCOL each time there was a requirement to pass runoff to the downslope drainage cell.

The number of the initial (first order) watershed to which each cell belonged was stored in the field SHEDNO. It was not necessary to establish or store a value for SHEDORD for higher order ponds that subsumed any of the 115 initial first order ponds identified for the Lunty site. The DISTHMOD program always started with initial first order ponds and determined through following pointers in the PONDDATA table, whether the current first order pond was presently subsumed by any higher order ponds. Merging cells from different initial first order watersheds into higher order watersheds was accomplished by having pointers from two or more initial first order watersheds point to a higher order watershed in the PONDDATA table. This avoided the difficult, and time consuming, problem of reassigning all grid cells in the GRIDDATA file to higher order watersheds every time two ponds coalesced. Similarly, it avoided the even more difficult problem of reallocating grid cells to their original lower order watersheds each time that a higher order pond dried up to the extent that it separated into two or more constituent lower order ponds.

6.5.2 Volume-to-first-flood

a) Results

Values for the measure volume-to-first-flood computed by the pre-processing program FLOODVOL were stored in the field FLODVOL illustrated in Table 6.2. The metric FLODVOL is only valid for cells that would be inundated by any of the ponds defined by the DEM as described in chapter 4. Cells that would not be flooded by any known pond were assigned an arbitrary value of 9999.99 for FLODVOL. This was greater than the largest value for FLODVOL computed for the highest cell in the largest volume pond (POND 143). The map of computed volume-to-first-flood (FLODVOL) (Figure 6.2) illustrates the maximum possible extent of ponding for the Lunty site and the volume of water that would be required to initially flood any given cell. The map of FLODVOL corresponds very well with the location and extent of known ponds (see chapter 3, Figures 3.13 - 3.15) with the exception that the surveyed ponds never achieved their maximum possible extent.

b) Discussion

The metric volume-to-first-flood represents an important component of the logic used by DISTHMOD to determine whether to treat any given cell as inundated during any given time step. If this measure were not pre-computed, the model would have had to find some other way of determining whether a grid cell was inundated at any given time. To determine this "on the fly" for every cell in every pass through the GRIDDATA file would have been prohibitive. By pre-computing this measure and storing it as an attribute of each grid cell, the program DISTHMOD was able to rapidly determine whether to consider any given grid cell as flooded at any given time. This was accomplished by simply comparing the value for the metric FLODVOL to the most recently computed value for the volume of water currently stored in the depression into which the given cell drained.

The metric volume-to-first-flood represents an interesting addition to the selection of terrain derivatives commonly used to characterise landscape morphology. It provides a different measure of the likelihood of a given cell being inundated or saturated. It is a superior measure of this likelihood than the similar derivatives upslope area count or downslope dispersal distance. Cells close to a depression do not always have a large upslope area count and cells far from a depression do not always have similarly long downslope dispersal distances.

Quinn et al. (1991) introduced a modification of the method for calculating upslope area that was intended to improve the ability of the derivative upslope area to recognise coherent areas of high potential for saturation in lower landscape positions. It assumed that drainage from upslope cells passed through all neighboring downslope cells in proportion to the slope gradient from the central cell into each neighbour. The intention was to ensure that all cells in lower landscape positions were assigned the largest possible value for upslope area count. The effect was to produce more diffuse zones of large upslope area count in contrast to the sharply defined flow paths produced by the more common method of allocating all drainage to the steepest downslope cell. Neither of the methods of computing upslope area, however, will assign a large upslope area to a cell in a lower landscape position that is higher than all of its immediate neighbours (i.e. a local ridge cell).

Since the method used here for computing volume-to-first-flood works upslope from the lowest cell in any given watershed (the pit centre) through successively higher cells, it orders cells in sequence in terms of their relative likelihood of becoming inundated (or saturated). This avoids the problem of not recognizing the high likelihood for flooding for isolated ridge cells in lower landscape positions.

One improvement on the measure volume-to-first-flood that was examined but not found useful in the present context is to compute the mm of rainfall instead of the volume of water required to first flood a cell. This is achieved by assuming an impermeable surface and complete runoff. Under such conditions, the mm of rainfall required to produce the volume of water computed to inundate a given cell is equal to the computed volume-to-first-flood (FLODVOL) divided by the area of the watershed (SHEDAREA) contributing runoff to the depression (VARATIO in the table PONDDATA). This provides a more equitable measure of the likelihood that a given cell will be inundated as depressions fed by large catchment areas will achieve a given volume faster than similar sized depressions fed by smaller catchments.

The strong relationship between the measure volume-to-first-flood and landscape position is readily apparent in Figure 6.2. All cells in lower (depressional) landscape positions are recognized to have a high likelihood of inundation or saturation. There are no isolated ridge cells in lower landscape positions assigned values indicative of a low likelihood of inundation. This represents an improvement on the "salt and pepper" spatial pattern produced by the measures upslope area or downslope dispersal area.

It should be noted that it is theoretically possible to produce an estimate for volume-to-first-flood for every cell in a data matrix, even those not expected to flood given the known DEM elevations and pond maxima. This could be accomplished by disallowing flow off the edge of the data matrix and treating the edge as an infinitely high barrier. Flow would be contained completely within the known DEM and all cells would eventually be inundated by a final pond covering the entire area. This pond would be artificial, and all volumes beyond those computed for depressions defined by the known DEM would be arbitrary, however the relative values for volume-to-first-flood or mm-to-first-flood would remain valid.

The measures volume-to-first-flood and mm-to-first-flood are most applicable to terrain characterised by non-integrated drainage and numerous non-connected

depressions. They are less appropriate for use in areas of high relief and integrated drainage where the alternative measures of upslope area and downslope dispersal area remain preferable. Within the context of areas with low relief and non-integrated landscapes, however, the measures volume-to-first-flood and mm to first flood are concluded to produce more coherent and more reliable indices of the likelihood of inundation or saturation for any given cell.

6.5.3 Indexing of grid cells by catchment, by elevation and by upslope area

a) Results

The effect of indexing cells by catchment order (SHEDORD), by elevation (ELEV) and by upslope area (UPSLOPE) is illustrated in Table 6.3. This table is identical to Table 6.2 except that the grid cells have been reordered according to the indexing criteria. Examination of the order in which cells are listed reveals that all cells in the watershed with the smaller value for SHEDORD would be processed before any cells in the watershed with the next higher value for SHEDORD. Additionally, each cell within a given watershed is ordered by elevation from the highest down. Any two cells with the same elevation are ordered according to upslope area such that the cell with the lower upslope area appears first. This ensures that flow across flat areas proceeds along flow paths from the first flat cell in the flow path to the last. The effect is to ensure that all upslope cells are processed and any runoff from them in the current time step is computed before any lower cell to which they drain is processed.

b) Discussion

The notion of defining an order for processing cells which ensures that all cells above the current cell have been processed and runoff from them delivered to the current cell before it is processed is not widely implemented in existing distributed hydrological models. There is no indication in the documentation for the models ANSWERS (Beasley and Huggins, 1981) SHE (Abbott et. al., 1986) or DESIM (Rohdenburg et. al., 1986) that cells are ordered to ensure processing of upslope cells before downslope cells. This is despite the considerable efforts taken by all three models to construct data bases in which each cell is assigned a defined flow direction to one or more downslope cells. A typical approach used in many grid based distributed models is to alternate passes through a matrix such that the first pass proceeds from top left to

bottom right and the next goes from bottom right to top left. This at least ensures that passage of runoff from a given cell to its downslope neighbour is not consistently out of sequence for every time step (only alternate ones).

Some very computationally complex algorithms that place cells in a sequential order along flow paths such that all upslope cells are processed prior to any downslope cell have been elaborated in several recent papers (Gandoy-Bernasconi and Palacios-Velez, 1990). The database indexing approach used in DISTHMOD is, by comparison, extremely simple to understand and to implement. It achieves the same effect as more complex approaches but requires virtually no programming and doesn't consume computer memory storing flow paths in one dimensional memory arrays. It is contended that the database indexing approach adopted for DISTHMOD is an elegant, simple and effective way of ensuring that runoff through grid cells cascades from one to the next along defined flow paths.

6.5.4 Estimation of snow melt for reference depths of snow

a) Results

The snowmelt sub-model (Chapter 5 and Appendix 7) was used to estimate volumes of snowmelt (mm) for hourly time steps for reference depths ranging from 5 cm to 200 cm. Since the maximum depth of snow recorded during the snowpack field survey in March, 1989 was 61 cm, results are listed in Appendix 10 for depths from 5 to 70 cm only. A summary of daily totals of meltwater production (mm) for reference depths between 5 and 70 cm for the period from the start of modelling until all snow had melted is presented in Table 6.4.

b) Discussion

The earliest date for which snowmelt was estimated was March 23, 1989 for a reference depth of 5 cm (Table 6.4). The last date for which any snowmelt was computed was April 14, 1989 for a reference depth of 70 cm. Air temperatures were above zero on March 23 and 24 but fell below zero for all hourly time steps for the period March 25-28 (Figure A5.1 in Appendix 5). Air temperatures were above zero for a significant portion of each day from March 29 onwards (appendix 6). The very shallow depths of snow (5 and 10 cm) were estimated to be completely melted during the two days of above zero temperatures on March 23 and 24, 1989. Snowmelt was

initiated during these two days for all reference depths less than 60 cm. Snowmelt continued for the reference depths of 15 and 20 cm for the dates March 25 And 26 when air temperatures never rose above zero. There was no melting for any reference depth computed for March 27 but melting resumed on March 28 for reference depths of 15 and 20 cm. Some melt water was produced for every succeeding day from March 29 until all snow had melted for all reference depths except 70 cm which began melting on March 30. Deeper reference snow depths were estimated to first begin melting at later dates than shallower reference depths and required a longer period to completely melt.

The dates on which snowmelt was estimated to occur for the various reference depths corresponded closely to the observed conditions at the Lunty site in late March and early April, 1989. Some minor snowmelt did occur before March 31, 1989. It was reflected in accumulations of water in shallow depressions in upland landscape positions recorded by the March 31 pond survey (Figure 3.33 a). Initial snow cover was thinner in upland landscape locations so early snowmelt was expected to be more likely in these locations. Snowmelt had produced some runoff into large ponds in lower landscape positions by March 31, 1989 but it had not been possible to record the extent of water in these ponds because of the continued presence of deep snow in lower landscape positions. Most of the snow at the Lunty site had melted by April 4 and most ponds had achieved their maximum extent as recorded by the pond survey of April 4, 1989 (Figure 3.13 b). Pockets of deeper snow in lower landscape positions continued to melt and to feed into and maintain the larger ponds until at least April 12, 1989 (Figure 3.13 c).

On the whole, the snowmelt sub-model appeared to produce reasonable and consistent estimates of the timing and magnitude of snowmelt for the various reference depths from 5 to 70 cm. The continued melting estimated for the reference depths of 10 and 15 cm for the dates March 25, 26 and 28 when air temperatures never rose above zero initially raised some concern. This concern was alleviated by confirmation from the literature that snowmelt can and does proceed at temperatures below zero. Temperatures on March 25 and 26 were just 1-2 degrees below zero and there was considerable cloud cover and high relative humidity. It can be assumed that the heat stored in the snowpack was sufficient to maintain some melting until such time as air temperatures below zero were able to lower the mean temperature of the snowpack to below zero. The dates on which snowmelt was predicted to begin for the various reference depths agreed well, therefore, with observed field conditions and the period

of time over which snowmelt was predicted to continue agreed well with the observed period of spring snowmelt.

The maximum daily rate of estimated snowmelt for any reference depth was 33 mm day $^{-1}$ for a reference depth of 70 cm. Typical daily rates ranged from about 7 to 20 mm day $^{-1}$. Hourly rates were typically less than 2 mm hr $^{-1}$ with the maximum rate being a single hour with 5 mm of melt water produced. A comparison of daily rates of snowmelt with estimated values for saturated hydraulic conductivity for the main soils at the Lunty site (see Table 3.13) suggests that all volumes of daily snowmelt predicted by the snowmelt sub-model would be subject to complete infiltration if the soils were unfrozen and able to accept infiltration at their estimated saturated hydraulic conductivity (3 - 10 mm hr $^{-1}$). Snowmelt inputs in excess of infiltration capacity would occur for some soils for the few hourly time steps in which the rate of melting (3 - 5 mm hr $^{-1}$) exceeded the saturated hydraulic conductivity estimated those soils (3 - 5 mm hr $^{-1}$).

Since infiltration proceeds faster into unsaturated soils than saturated soils, the saturated hydraulic conductivity can be taken to represent a minimum rate for infiltration into unfrozen soils. Since runoff of snowmelt was recorded by field surveys, the soils were clearly not able to permit infiltration at rates equal to or greater than the daily (or hourly) rates of production of snowmelt. The obvious implication of this comparison is that the soils were frozen and that the estimated infiltration rates were not applicable for frozen soils. Measurements of soil temperature at the site confirmed that the soils were frozen both at the surface and to a depth of at least 60 cm for at least one site well into April, 1989. Adjustments were made to the main DISTHMOD model to permit assignment of infiltration rates of zero for frozen soils. The snow melt model was judged to produce realistic estimates for hourly volumes of meltwater generated for various reference depths and for the timing of meltwater generation.

6.5.5 Assignment of hydrological properties to Soil Series

a) Results

The estimated soil hydrological properties assigned to each of the five main soils (and the disturbed road area) for each of the four sets of conditions are detailed in Table 6.5.

b) Discussion

For the first two (2) runs of DISTHMOD all soils were assigned identical hydrological properties designed to produce maximum (run 1) and minimum runoff (run 2) respectively. Maximum runoff (SOIL1) was achieved by assigning zero storage capacity and zero saturated hydraulic conductivity to all three conceptual stores defined for all soils (Table 6.5). Minimum runoff (SOIL2) was achieved by assigning a maximum value for drainage rate, saturated hydraulic conductivity and storage capacity to all conceptual stores (horizons) of all soils. The values chosen were 15 mm hr^{-1} for store S1, 5 mm hr^{-1} for store S2 and 5 mm hr^{-1} for S3.

For most subsequent runs, the SOILDATA file (SOIL3) was edited to assign reasonable values for soil hydraulic properties based on field data (see chapter 3). Final steady state drainage rate (FC mm hr^{-1}) was the most critical parameter and was assigned values in the range of 2.4 to 4.9 for S1, 0.2 to 6.9 for store S2 and 0.8 to 1.8 for S3. Moisture content at saturation (TP %) was assigned based on field determined bulk density and field measurements of soils in their saturated state. Values for TP ranged from 51 to 59% for S1, from 43 to 45% for S2 and from 40 to 43% for S3. Total volumetric storage capacity for each store for each soil was calculated as total porosity times total store thickness.

The values used for store thickness corresponded to modal values for observed horizon thickness for the A, B and C horizons of the various soils. The ANSWERS equations used to estimate infiltration have been reported to be very sensitive to the assigned thickness of the infiltration store (S1) (Beasley and Huggins, 1981). This store is theoretically equivalent to the thickness of the A horizon, but in practice it has frequently been set to some fraction (0.3 - 0.5) of the thickness of the A horizon (Beasley and Huggins, 1981). Reducing the thickness of the infiltration store reduces the volume of water required to saturate the store thereby leading to more rapid development of saturation excess overland flow. For the present research, the thickness of the infiltration store was maintained at the measured thickness of the A horizon for all soils for all runs.

The maximum hourly rate for rainfall for the period of study was 5.5 mm hr^{-1} for a single hourly time step on June 10, 1989 (see Appendix 5). The maximum estimated rate of snowmelt for any hourly time step was 5 mm hr^{-1} for a single hourly time step

(see Appendix 10). The saturated, steady state infiltration rate (FC1) for the infiltration store (S1) of all soils ranged from 2.4 to 4.9 mm hr^{-1} and the total volumetric storage capacity (GWC) ranged from 28 to 86 mm. Given that FC1 is a minimum rate for infiltration into saturated soils and that the soils were seldom close to saturation, it was not expected that the measured rates of rainfall or snowmelt would lead to either saturation or infiltration excess runoff for the period of this study.

6.5.6 Comparison of simulated evaporation to observed pan evaporation

a) Results

The hourly estimates for potential evaporation made by each of the five equations are not presented. Instead, Table 6.6 presents a comparison of the total evaporation estimated by each of the five equations extracted from the model SWATRE (Belmans et. al., 1983) with the total pan evaporation recorded at the Lunty site at approximately weekly intervals in the spring of 1989. The evaporation pan was first set up on March 29, 1989. It was reset on March 31 due to problems with freezing and snowfall. The first valid reading was obtained on April 5, 1989.

b) Discussion

It is clear from Table 6.6 that estimates of potential evaporation produced by the Penman equation were most closely similar to the weekly totals of observed pan evaporation. The Penman equation slightly over estimated evaporation in comparison with the observed pan evaporation for the first few weeks of April (until April 27). Throughout May and June, the Penman estimates were slightly lower than the recorded pan evaporation. This was especially true for the periods ending on May 15 and June 15. Total evaporation estimated by the Penman equation for the period March 22 to June 15, 1989 was 265 mm. This was considerably less than the 349 mm measured for pan evaporation for the equivalent period. It is, however, reasonably close to the figure for 0.7 pan evaporation (245 mm). Pan evaporation is often reduced by 0.7 to correct for overestimates of actual evaporation associated with pan evaporation procedures.

It is possible that some of the above noted discrepancy was due to errors in reading pan evaporation, in compensating for rainfall in the pan evaporation calculation or to

losses from the evaporation pan not caused by evaporation (i.e. animals drinking from pan). Part of the discrepancy was also due to the fact that the hourly estimates produced by the five equations were totaled for periods that did not correspond exactly to the times at which the pan evaporation readings were taken (the exact hour of reading the evaporation pan was not recorded). Considering that all of the discrepancy could not be ascribed to error in the equation estimates, the Penman equation produced reasonable estimates for potential evaporation that corresponded acceptably with the observed pan evaporation.

6.6 Results from application of the DISTHMOD model

This section presents abbreviated results from each of ten different runs of the model DISTHMOD. Other runs were completed but are not reported.

Each run of the model produced a large volume of output. A total of 11 grid maps were produced for each run. Each grid map depicted the extent and depth of all ponds on one of the eleven dates for which field pond survey data were available (or for the last day of collated meteorological data, i.e. June 15). Each run also produced eleven different versions of the PONDDATA file, one for each output date. The PONDDATA files were reviewed to determine the volume of water stored in each pit for each time step. This was accomplished by identifying the highest order depression for any set of nested pits. The sum of the values stored in the fields VOLINPIT and PREVOL was determined and multiplied by 25 (to convert from grid units to m^2). This represented the total volume of water stored in the depression (and all subsumed or nested depressions) as estimated by the simulation model DISTHMOD for the given time step. Additional output data produced by the model included a database file named FLOW89 which contained a value for mm of runoff for each time step for edge cells or edge pits at which runoff that could not be contained in a known pond escaped off the edge of the data matrix. Data from this file were not reviewed or analysed.

The grid maps of pond extent and depth were plotted and reviewed to visually assess the extent of ponding simulated for each output date for each run. It was judged impractical and unnecessary to include a minimum of 30 pages of grid maps depicting the extent and depth of all ponds for all dates of all runs. A single set of grid maps is presented in chapter 7 to illustrate the simulated extent and depth of all ponds for the simulation model run (9) judged to produce the most reasonable results. All other grid maps were reviewed and filed but were not included in this document.

A compact reporting format consisting of a single page template for each run was devised and adopted. The template listed the principal differences between each run in terms of input data, initial conditions and assigned parameter values. This was followed by a table listing, for each survey date, the simulated volume of water stored in each of the depressions corresponding to ponds mapped during the field survey. These data were extracted from the PONDDATA file as described above.

The PONDDATA file also contained entries for simulated volume of water in ponds other than those identified during the field survey. Data for these ponds were not included in the results tables. These data were excluded because they were determined to consistently apply to either extremely small pits (1 or 2 grid cells) that would not have been recorded by the field survey or to incompletely defined pits at the edge of the data matrix that did not actually exist.

Most incompletely defined edge pits had been assigned an artificial storage capacity determined by computing the volume of water that would be contained in the depression if it were constrained by an infinitely high barrier at the edge of the matrix (see Chapter 4). This artificial volume could never be truly correct as the elevation data required to completely define edge depressions was unknown (being outside the available DEM matrix). In some cases, ponds did occur for artificial edge depressions where topography outside the matrix constrained flow and created a real depression. In other cases, the topography outside the matrix did not constrain flow and no depression actually existed. All simulated volumes for edge pits were therefore subject to error arising from unknown conditions outside the area of the DEM and do not represent a valid test of the model.

Following the table of simulated pond volumes in the standard template is a short discussion of the significance of the results presented in each table. The limited amount of space available in the template restricts the discussion to only the most significant aspects of each run. Each discussion reviews the simulated pattern of ponding for each run and evaluates the reasonableness of the results in light of field knowledge of temporal and spatial patterns of ponding. Grid maps of the extent and depth of ponding for the eleven reporting dates are presented and discussed in chapter 6 for the run (run 9) judged to most closely reflect actual field conditions and parameter values.

6.6.1 Results from run 1

Objective of the run:	Simulate maximum runoff conditions		
Estimated Depth of Snow Pack:	400 mm		
Method of estimating evaporation:	None (evaporation turned off)		
Maximum depth of surface retention:	0 mm (none)		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	0.0 mm hr^{-1}	0.0 mm hr^{-1}	0.0 mm hr^{-1}
Julian day soil temp goes above 0:	none (166)	none (166)	none (166)

Table 6.7 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 1

Pond Field Survey No.	DEM Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5	37.5
182	13	762.5	762.5	762.5	762.5	762.5	762.5	762.5	762.5	762.5	762.5	762.5
8	14	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5	32.5
184	19	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0
6	23	187.5	187.5	187.5	187.5	187.5	187.5	187.5	187.5	187.5	187.5	187.5
3	34	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
185-EAST	35	1922.9	14259.8	17825.5	17825.5	18441.1	18612.5	18903.1	19055.2	22333.1	22539.9	29132.0
185-WEST	36	2367.8	14259.8	17825.5	17825.5	18441.1	18612.5	18903.1	19055.2	22333.1	22539.9	29132.0
2	50	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5
194	54	1177.5	1177.5	1177.5	1177.5	1177.5	1177.5	1177.5	1177.5	1177.5	1177.5	1177.5
173	57	347.1	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5	327.5
5	58	132.5	152.5	152.5	152.5	152.5	152.5	152.5	152.5	152.5	152.5	152.5
155	64	970.0	970.0	970.0	970.0	970.0	970.0	970.0	970.0	970.0	970.0	970.0
157	70	855.6	2365.7	2780.0	2780.0	2875.7	2907.5	2949.0	2974.5	3478.4	3510.3	4498.9
197	83	800.0	1255.0	1255.0	1255.0	1255.0	1255.0	1255.0	1255.0	1255.0	1255.0	1255.0
9-WEST	88	135.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0	135.0
9-EAST	90	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0	40.0
189	94	1046.9	2722.3	3203.6	3203.6	3308.5	3343.4	3389.0	3416.9	3969.0	4004.0	4682.5

Discussion:

With no evaporation and no infiltration, all snowmelt and runoff was directed into ponds or escapes off site at the edge of the data matrix. Most ponds filled to their maximum volume very rapidly, with just the limited amount of snowmelt (31 mm) estimated to occur before March 31 for an initial snowpack of 400 mm. Two ponds (5 & 197) did not fill to their maximum overspill volume until April 4, 1989. The four largest ponds (185-EAST), 185-WEST, 157 & 189) continued to increase in volume for all dates and never reached their maximum overspill volume. Ponds 185 east and west merged to become a single large pond by April 4, 1989. The absloute magnitude of simulated pond volumes was an order of magnitude greater than observed pond volumes. These results do not replicate the observed pattern of rapid filling of ponds followed by continuous reduction in volume and extent beginning by April 12, or at the latest by April 19 (see Table 3.15). With no provision for loss of volume by evaporation or infiltration, ponds were unable to diminish in volume or area. These results simply provide an estimate of the maximum likely extent of ponding under conditions of maximum input and no loss.

6.6.2 Results from run 2

Objective of the run:	Simulate minimum runoff conditions		
Estimated Depth of Snow Pack:	50 mm		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	50 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	15 mm hr^{-1}	5 mm hr^{-1}	6 mm hr^{-1}
Julian day soil temp goes above 0:	first (81)	first (81)	first (81)

Table 6.8 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 2

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
182	13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
184	19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185-EAST	35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185-WEST	36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
194	54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
173	57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
155	64	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
157	70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
197	83	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9-WEST	88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9-EAST	90	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
189	94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Discussion:

No runoff what-so-ever was simulated under the conditions specified for this run of the model DISTHMOD. None was expected given that inputs of snow melt and rainfall (maximum of 5 mm hr^{-1}) never occurred at a rate in excess of the assigned rates for infiltration and drainage. The rates assigned for steady state infiltration capacity (FC) for each horizon were large, but were within the range of values for saturated hydraulic conductivity measured in the field using the Guelph permeameter (see Chapter 3).

The interpretation placed on these results is that, in order for runoff from snowmelt to occur, either rates of snowmelt and rainfall for short intervals (< 1 hour) are much greater than the hourly rates used here or that rates of infiltration into the soil must be significantly less than the maximum rates recorded in the field and used for this simulation. Runoff from snowmelt most likely benefits from low rates of soil infiltration associated with frozen soils.

6.6.3 Results from run 3

Objective of the run:	Investigate if evaporation alone can explain the observed reduction in pond volumes.		
Estimated Depth of Snow Pack:	400 mm		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	0.0 mm hr^{-1}	0.0 mm hr^{-1}	0.0 mm hr^{-1}
Julian day soil temp goes above 0:	none (166)	none (166)	none (166)

Table 6.9 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 3

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	37.5	37.5	34.1	28.0	24.5	18.8	13.4	11.3	24.4	17.5	33.6
182	13	762.5	762.5	723.3	654.4	612.3	546.7	469.1	416.7	606.1	526.1	719.6
8	14	32.5	32.5	28.3	20.7	16.2	9.2	4.1	3.4	20.5	11.8	28.2
184	19	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0	545.0
6	23	187.5	187.5	166.1	128.5	105.2	69.3	41.4	26.7	187.1	143.3	170.1
3	34	10.0	10.0	9.2	9.0	9.6	8.9	7.7	7.1	9.5	8.6	9.0
185-EAST	35	969.8	9836.3	12508.3	11700.9	11256.7	10493.7	4421.7	4098.4	4429.1	4022.6	4490.9
185-WEST	36	1390.5	9836.3	12508.3	11700.9	11256.7	10493.7	5086.8	4768.9	5030.9	4630.0	5206.1
2	50	209.9	375.0	326.9	242.7	190.7	110.5	23.1	16.1	82.6	23.9	137.1
194	54	941.6	1177.5	1069.5	880.0	764.8	584.4	411.6	320.9	603.6	430.4	917.6
173	57	209.9	375.0	326.9	242.7	190.7	110.5	33.3	21.0	82.6	32.5	137.1
5	58	80.7	152.5	136.1	107.4	89.5	62.1	40.9	30.1	52.1	38.3	67.9
155	64	810.8	970.0	902.3	784.0	710.0	596.9	477.9	397.8	588.4	477.2	894.4
157	70	527.6	1665.3	1865.1	1731.8	1654.5	1538.5	1384.7	1275.0	1405.1	1267.2	1462.7
197	83	483.8	1255.0	1194.4	1088.2	1022.3	921.0	795.5	707.2	819.0	707.4	906.0
9-WEST	88	135.0	135.0	122.3	100.0	86.8	65.5	46.8	37.8	100.9	75.0	122.6
9-EAST	90	40.0	40.0	35.3	27.0	24.2	16.7	7.6	5.4	40.0	30.6	40.0
189	94	617.2	1956.5	2135.0	1920.8	1799.1	1611.3	1362.0	998.4	1329.6	1131.9	1307.9

Discussion:

With infiltration set to zero, all snowmelt and rainfall ran off. Snow melt occurred on March 24 and every day from March 29 to April 5 with maximum hourly rates never exceeding 5 mm hr^{-1}. All ponds increased in volume up to April 4. The four largest ponds (185 E&W, 157, 189) continued to increase in volume until April 12. Evaporation caused all ponds to reduce beginning on either April 4 or April 12 and continuing until May 24 when an increase in volume related to rainfall in excess of evaporation occurred. All ponds decreased between May 24 and June 1 and increased between June 1 and June 15 in response to more rain. The pattern of pond growth and decay produced by this simulation is not at all similar to that observed in the field. The absolute volume of simulated ponds was consistently an order of magnitude greater than that of observed ponds. No simulated ponds completely dried out and disappeared. The large inputs from an initial depth of snow of 400 mm greatly over-estimated the initial volume and extent of ponds.

6.6.4 Results from run 4

Objective of the run:	Simulate both evaporation & infiltration		
Estimated Depth of Snow Pack:	400 mm		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	4.9 mm hr^{-1}	6.9 mm hr^{-1}	1.8 mm hr^{-1}
Julian day soil temp goes above 0:	Mar 22 (81)	Mar 22 (81)	Mar 22 (81)

Table 6.10 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 4

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
182	13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
184	19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185-EAST	35	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185-WEST	36	0.0	3.9	2.2	1.1	0.6	0.5	0.5	0.5	0.5	0.5	0.5
2	50	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
194	54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
173	57	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	58	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
155	64	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
157	70	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
197	83	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9-WEST	88	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9-EAST	90	0.0	0.0	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
189	94	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Discussion:

As with run two (2) virtually no runoff or ponding occurred when infiltration into the soil was simulated using modal values for steady state infiltration rate (FC). Different values of FC were assigned to each horizon (store) of each major soil based on field measurements of saturated hydraulic conductivity. Values ranged from 2.7-4.9 mm hr^{-1} for the surface horizon (S1), from 0.2 - 6.9 mm hr^{-1} for S2 and from 0.6-1.8 mm hr^{-1} for S3. Very small accumulations of water developed in ponds 185-East and 9-East. These occurred because the soil in the area occupied by the farm road was assigned an infiltration capacity of zero and therefore produced a very small amount of runoff.

The model is very sensitive to rate of infiltration and to total thickness of the infiltration store. No runoff occurs when the final steady state infiltration rate exceeds hourly rates of rainfall or snowmelt or when the infiltration store (S1) is so thick that it can accept and transmit all inputs. This run indicated that some mechanism was required to at least temporarily reduce infiltration rates if the model was to predict any ponding at all.

6.6.5 Results from run 5

Objective of the run:	Simulate effect of reducing infiltration to zero for periods when the soil was frozen.		
Estimated Depth of Snow Pack:	400 mm		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	4.9 mm hr^{-1}	6.9 mm hr^{-1}	1.8 mm hr^{-1}
Julian day soil temp goes above 0:	Apr 12 (102)	Apr 22 (112)	May 2 (122)

Table 6.11 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 5

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	37.5	37.5	20.6	14.7	10.8	7.7	3.2	0.0	0.0	0.0	0.0
182	13	762.5	762.5	580.8	513.2	422.9	349.8	224.9	155.0	155.0	155.0	155.0
8	14	32.5	32.5	11.8	4.9	3.2	2.0	0.2	0.0	0.0	0.0	0.0
184	19	545.0	545.0	545.0	545.0	545.0	545.0	458.2	297.9	240.5	134.8	49.7
6	23	187.5	187.5	88.1	53.1	27.0	6.4	0.0	0.0	0.0	0.0	0.0
3	34	10.0	10.0	5.1	5.0	2.5	0.7	0.0	0.0	0.0	0.0	0.0
185-EAST	35	969.7	9836.7	10911.7	10113.3	4202.8	3750.1	2491.7	2073.4	1868.3	1422.7	910.0
185-WEST	36	1390.8	9836.7	10911.7	10113.3	4802.6	4368.6	3595.3	2985.6	2705.5	2070.0	1380.9
2	50	209.9	327.5	169.7	89.2	20.2	10.1	0.0	0.0	0.0	0.0	0.0
194	54	941.6	1177.5	670.5	482.8	325.6	201.1	83.9	28.8	17.0	0.0	0.0
173	57	209.9	327.5	169.7	89.2	22.8	4.0	0.0	0.0	0.0	0.0	0.0
5	58	81.9	152.5	77.7	51.0	32.0	17.0	4.3	0.0	0.0	0.0	0.0
155	64	810.8	970.0	657.8	543.3	405.1	295.8	148.5	63.9	37.0	0.0	0.0
157	70	527.8	1665.4	1591.0	1469.5	1277.3	1138.8	876.5	690.9	593.5	418.5	219.2
197	83	483.8	1255.0	972.4	867.4	714.3	593.3	375.7	212.4	150.6	37.4	0.0
9-WEST	88	135.0	135.0	74.3	53.4	37.4	24.8	9.1	0.0	0.0	0.0	0.0
9-EAST	90	40.0	40.0	10.8	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
189	94	617.2	1956.5	1700.9	1503.9	1201.7	992.9	614.5	383.0	285.7	150.8	39.1

Discussion:

Because infiltration was set to zero until the first day with S1 soil temperatures above 0° C (April 12) this run is identical to run 3 up to that date. Ponds filled up to their maximum by April 4 or April 12 and steadily decreased in volume thereafter. Unlike run 3, simulation of infiltration allowed the smaller ponds to completely disappear by May 10 to May 17. This was later than, but closer to, the dates the ponds were observed to disappear. The estimated volume of all ponds not limited by overspill was an order of magnitude greater than recorded by the field survey (see table 3.22). This indicates that either the inputs from a 400 mm snowpack (88 mm) were too large or that infiltration was not set to begin soon enough . Arbitrarily setting infiltration to zero for dates on which the soil temperature was estimated to be below freezing produced runoff, unlike run 4 where infiltration permitted from day one prevented development of runoff. The total volume of inputs (depth of snowpack) and the dates and rates for simulating infiltration were the variables exercising the strongest influence on the validity of model results.

6.6.6 Results from run 6

Objective of the run:	Investigate effect of assigning mean snow depth (130 mm) to all cells		
Estimated Depth of Snow Pack:	130 mm		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	4.9 mm hr^{-1}	6.9 mm hr^{-1}	1.8 mm hr^{-1}
Julian day soil temp goes above 0:	Apr 12 (102)	Apr 22 (112)	May 2 (122)

Table 6.12 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 6

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	36.6	34.6	18.0	13.8	9.9	6.8	2.8	0.0	0.0	0.0	0.0
182	13	750.9	727.8	547.7	485.0	394.7	321.6	202.5	155.0	155.0	15.0	15.0
8	14	31.3	28.9	8.6	4.4	2.8	1.6	0.0	0.0	0.0	0.0	0.0
184	19	532.1	506.6	310.6	255.9	188.6	135.5	74.7	38.4	25.9	7.8	0.0
6	23	181.1	168.3	71.2	46.2	20.1	0.0	0.0	0.0	0.0	0.0	0.0
3	34	10.0	10.0	5.1	5.0	2.5	0.7	0.0	0.0	0.0	0.0	0.0
185-EAST	35	1118.0	1067.7	713.5	589.7	416.7	305.9	139.7	53.5	30.8	14.5	0.0
185-WEST	36	1534.1	1465.1	1030.4	868.3	667.5	515.4	293.8	150.5	111.1	32.5	3.9
2	50	219.7	191.3	18.0	9.9	4.7	2.2	0.4	0.0	0.0	0.0	0.0
194	54	974.6	956.7	453.2	323.8	186.2	117.6	46.3	7.2	0.0	0.0	0.0
173	57	219.7	191.3	32.5	19.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	58	86.2	76.5	25.0	13.0	6.5	3.4	0.0	0.0	0.0	0.0	0.0
155	64	886.3	846.0	535.0	448.2	310.0	221.4	95.9	37.5	10.0	0.0	0.0
157	70	575.0	551.6	368.2	309.3	228.7	149.5	96.0	50.4	32.7	8.8	1.7
197	83	525.7	496.7	271.1	206.7	118.7	49.2	12.2	0.6	0.0	0.0	0.0
9-WEST	88	131.4	124.0	65.1	49.1	33.0	20.4	6.8	0.0	0.0	0.0	0.0
9-EAST	90	93.9	36.7	11.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
189	94	676.6	639.5	365.5	288.8	200.7	132.3	56.7	19.8	13.5	0.0	

Discussion:

The volume and duration of ponding simulated by this run closely reflected the pattern of ponding observed in the field. All ponds achieved their maximum extent by March 31 and shrank after that date. Absolute volumes estimated for most ponds were close to observed volumes except for some pits where the true volume of the pond was not properly defined by the DEM. All ponds known to completely dry up were simulated to disappear at or close to observed dates. The model was slow to remove the last vestiges of water from ponds. The result was that very small amounts of water persisted in simulated ponds for dates when observed ponds were dry. The main discrepancy between the estimated and observed ponding was for the main central ponds (185-E&W) for dates beginning May 17. The model estimated that these ponds would be considerably smaller than recorded and that they would be continuously diminishing in volume. The observed central ponds diminished in volume very slowly after May 17. These main central ponds were replenished by runoff or by recharge from a high water table for the period after May 17.

6.6.7 Results from run 7

Objective of the run:	Investigate the effect of using estimated snow depth based on a regression equation.		
Estimated Depth of Snow Pack:	variable (mean depth is 7.5 cm)		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	4.9 mm hr^{-1}	6.9 mm hr^{-1}	1.8 mm hr^{-1}
Julian day soil temp goes above 0:	Apr 12 (102)	Apr 22 (112)	May 2 (122)

Table 6.13 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 7

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	21.4	20.0	8.5	6.1	3.6	2.4	0.0	0.0	0.0	0.0	0.0
182	13	350.1	364.0	227.7	180.5	155.0	75.3	22.6	0.0	0.0	0.0	0.0
8	14	20.2	20.2	1.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
184	19	311.8	307.6	179.3	134.8	95.4	64.4	28.1	9.6	6.2	0.0	0.0
6	23	187.5	187.5	88.0	53.1	27.0	6.4	0.0	0.0	0.0	0.0	0.0
3	34	9.9	9.7	7.6	6.6	3.2	0.6	0.0	0.0	0.0	0.0	0.0
185-EAST	35	430.9	453.4	309.8	221.9	137.3	85.8	26.3	1.7	0.7	0.0	0.0
185-WEST	36	654.4	664.9	394.2	317.9	196.3	135.0	46.0	20.6	11.4	3.6	2.5
2	50	25.7	23.5	8.6	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
194	54	540.5	581.9	187.2	140.6	64.8	16.6	2.0	0.0	0.0	0.0	0.0
173	57	28.3	25.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	58	30.3	27.2	3.5	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
155	64	400.3	406.4	202.9	151.9	78.9	47.9	0.0	0.0	0.0	0.0	0.0
157	70	180.4	157.0	127.0	113.4	72.4	50.0	13.0	5.6	3.8	1.1	0.0
197	83	201.3	199.2	63.1	41.6	18.7	2.5	0.0	0.0	0.0	0.0	0.0
9-WEST	88	65.0	59.5	74.3	53.4	37.4	24.8	9.1	0.0	0.0	0.0	0.0
9-EAST	90	40.0	38.5	10.8	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
189	94	255.5	261.1	198.2	143.9	86.4	48.9	12.9	0.9	0.0	0.0	0.0

Discussion:

This run was identical to the previous run (6) except that the mean depth of snow for all 22400 grid cells as estimated by the regression equation (table 3.20) relating snow depth to upslope area was 75.4 mm. This was considerably less than the mean snow depth for the 44 snow pack sample sites. The thinner snow pack produced less runoff and smaller ponds than simulated using a mean snow depth of 130 mm. None of the ponds achieved volumes as great as recorded in the field or simulated using a mean snow depth of 130 mm. Varying the depth of the snow pack had the effect of prolonging the period required to complete snow melt. Most of the snow melted by March 31 but areas of deeper snow continued to produce melt water until April 12. The result was that some of the larger ponds in lower landscape positions continued to grow until April 4 as a result of inputs from snow melt from deeper portions of the snow pack. This pattern differed from run 6 in which all snow melt was completed by March 28 and all ponds were at their maximum extent by March 31.

6.6.8 Results from run 8

Objective of the run:	Investigate effect of estimating snow depth based on modified regression equation.		
Estimated Depth of Snow Pack:	variable (mean depth is 19.1 cm)		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S 1**	**S 2**	**S 3**
Maximum Infiltration Rate (FC):	1.5 mm hr^{-1}	2.3 mm hr^{-1}	1.0 mm hr^{-1}
Julian day soil temp goes above 0:	Apr 5 (95)	Apr 5 (95)	Apr 5 (95)

Table 6.14 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 8

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	37.5	37.5	16.2	11.3	8.4	4.7	2.6	0.0	1.8	0.0	0.5
182	13	762.5	760.9	540.9	445.4	377.9	295.3	209.8	147.1	142.1	94.9	72.4
8	14	32.5	32.5	5.8	3.2	2.0	0.5	0.0	0.0	0.0	0.0	2.8
184	19	545.0	545.0	300.8	227.3	176.8	121.8	75.7	45.6	50.2	29.0	43.0
6	23	187.5	187.5	73.0	37.1	17.8	0.0	0.0	0.0	0.0	0.0	10.4
3	34	10.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185-EAST	35	1524.5	1776.3	1432.7	1226.8	1071.9	859.4	628.8	455.6	442.6	281.3	193.3
185-WEST	36	2414.2	3017.7	2229.8	1883.6	1652.7	1358.5	1057.1	819.6	795.6	157.5	441.0
2	50	280.2	294.1	20.2	6.8	2.2	0.0	0.0	0.0	0.0	0.0	1.0
194	54	1177.5	1175.6	566.8	375.8	256.1	139.5	79.4	38.6	76.6	35.0	89.2
173	57	47.5	47.5	31.3	6.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	58	124.5	130.3	42.4	23.3	9.5	5.6	0.9	0.0	1.4	0.0	5.9
155	64	970.0	970.0	587.7	443.6	339.1	225.2	130.3	69.9	71.1	25.8	28.6
157	70	1198.8	1301.7	950.0	801.1	696.3	568.1	437.8	339.2	326.6	233.5	176.1
197	83	698.9	790.5	493.9	357.7	255.5	167.9	64.9	34.1	44.2	17.8	32.2
9-WEST	88	135.0	135.0	71.6	46.2	34.4	18.9	9.7	3.3	7.3	1.5	8.8
9-EAST	90	40.0	40.0	8.2	0.4	0.0	0.0	0.0	0.0	2.3	0.0	21.8
189	94	1221.4	1310.0	759.2	563.0	425.7	281.1	181.0	112.2	115.8	60.9	60.0

Discussion:

This run was similar to the previous run (7) except that the original regression equation was modified to produce an estimated mean depth of snow of 191 mm. This was closer to the mean snow depth measured for the 44 snow pack sample sites. A second difference was that all soils were assigned lower rates for steady state infiltration rate (data base SOIL4 in Table 6.5) than had been used previously. To compensate for the lower rates, the date at which the soil was deemed to become unfrozen was moved up to April 5 and infiltration was able to occur after that date. The thicker snow pack produced more runoff and larger ponds than observed in the field or simulated using a mean snow depth of 130 mm. Varying the depth of the snow pack prolonged the period required to complete snow melt. Most of the snow melted by March 31 but areas of deeper snow continued to melt until April 12. As a result some of the larger ponds in lower landscape positions continued to grow until April 4. Evaporation and infiltration exceeded inputs from runoff after April 4 and all ponds were reduced in size by April 12.

6.6.9 Results from run 9

Objective of the run:	Investigate effect of modifying estimated snow depth to mean of 150 mm		
Estimated Depth of Snow Pack:	variable (mean depth is 150 mm)		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	.5 mm hr^{-1}	2.3 mm hr^{-1}	1.0 mm hr^{-1}
Julian day soil temp goes above 0:	Apr 5 (95)	Apr 5 (95)	Apr 5 (95)

Table 6.15 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 9

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	37.5	36.4	15.1	10.9	8.0	4.7	2.6	1.0	1.7	0.0	0.5
182	13	761.9	761.0	538.5	443.6	375.3	293.3	207.9	145.7	140.9	93.8	71.7
8	14	32.5	31.6	5.6	3.2	2.0	0.4	0.0	0.0	0.0	0.0	2.8
184	19	545.0	540.6	293.2	218.9	168.1	118.0	71.9	43.3	49.8	28.6	42.9
6	23	187.5	187.5	63.8	33.0	13.4	0.0	0.0	0.0	0.0	0.0	9.9
3	34	10.0	9.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
185-EAST	35	987.2	1065.0	700.8	504.9	404.8	270.6	147.7	85.4	105.0	36.2	82.5
185-WEST	36	1460.2	1531.1	1005.9	765.6	620.8	436.8	289.8	174.9	190.3	112.3	148.8
2	50	199.1	186.9	36.9	3.6	0.8	0.0	0.0	0.0	0.0	0.0	0.6
194	54	984.5	993.6	521.2	268.8	168.1	100.8	45.6	20.4	60.5	19.3	80.5
173	57	47.5	47.5	19.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	58	104.0	100.1	30.6	11.5	7.1	3.3	0.1	0.0	0.7	0.0	5.6
155	64	835.8	881.2	374.1	366.2	261.6	184.0	89.0	49.2	55.9	10.6	23.3
157	70	565.9	597.3	256.4	288.1	227.2	161.3	107.1	67.5	75.6	42.5	63.0
197	83	516.2	542.5	256.4	165.2	99.0	41.9	14.7	2.0	9.6	2.8	21.2
9-WEST	88	135.0	134.7	92.7	56.9	44.0	28.5	13.2	6.8	10.8	3.0	10.5
9-EAST	90	40.0	39.6	16.5	3.5	1.4	0.0	0.0	0.0	3.3	1.5	22.0
189	94	748.6	745.9	362.2	251.7	186.2	112.9	58.5	23.9	26.5	13.6	55.0

Discussion:

This run was identical to the previous run (8) except that the original regression equation was modified to produce an estimated mean depth of snow of 150 mm. This was closer to the mean snow depth measured for the 44 snow pack sample sites. This run retained from run 8 the lower estimated values for steady state infiltration rate (data base SOIL4 in Table 6.5) and the date of April 5 for soils to thaw. This run was also similar to run 6 except that the estimated initial depth of snow varied spatially and the rates assigned for steady state infiltration capacity (FC) were lower than for run 6 (soil 4 vs soil 3 in Table 6.5). This run produced estimates of initial pond volumes very close to those observed in the field. Larger ponds in lower landscape positions continued to grow until April 4 indicating continuing runoff from snow melt in excess of evaporation. All ponds diminished in volume after April 4 following a pattern similar to that observed in the field. Note the low rates assigned for FC resulted in the production of rainfall runoff and increases in volume of several ponds for the rainly period of June 1 to June 15, 1989.

6.6.10 Results from run 10

Objective of the run:	Investigate the effect of reducing infiltration to zero (0) for mean snow depth of 150 mm		
Estimated Depth of Snow Pack:	variable (mean depth is 150 mm)		
Method of estimating evaporation:	Penman equation estimates		
Maximum depth of surface retention:	20 mm		
Soil Store (Horizon):	**S1**	**S2**	**S3**
Maximum Infiltration Rate (FC):	0.0 mm hr^{-1}	0.0 mm hr^{-1}	0.0 mm hr^{-1}
Julian day soil temp goes above 0:	Apr 5 (95)	Apr 5 (95)	Apr 5 (95)

Table 6.16 Volume of ponds corresponding to field surveyed ponds as estimated by the model DISTHMOD for run 10

Pond Field Survey No.	Model Pond No.	March 31	April 4	April 12	April 19	April 26	May 3	May 10	May 17	May 24	June 1	June 15
7	4	37.5	36.4	33.2	27.1	23.6	17.9	13.0	10.9	24.0	17.0	33.6
182	13	761.9	761.0	730.4	659.8	618.8	551.7	472.1	418.4	606.0	531.7	727.1
8	14	32.5	31.6	27.9	20.4	15.9	8.8	4.1	3.4	20.5	11.8	28.2
184	19	545.0	540.6	501.9	433.8	380.0	308.3	243.3	204.6	354.4	279.0	498.3
6	23	187.5	187.5	168.0	130.5	107.2	71.4	41.8	26.9	187.1	143.3	170.1
3	34	10.0	9.9	8.8	7.8	8.0	7.3	6.1	5.4	9.5	9.2	9.0
185-EAST	35	987.2	1065.0	1067.2	920.4	853.9	735.8	579.2	473.3	735.1	591.0	1202.4
185-WEST	36	1460.2	1531.1	1474.9	1300.9	1203.9	1049.6	857.5	730.5	1022.5	831.1	1700.0
2	50	199.1	186.9	140.2	56.0	30.1	22.8	12.8	5.8	32.5	23.6	73.2
194	54	984.5	993.6	900.1	756.9	634.1	562.6	335.7	238.8	573.6	427.0	908.3
173	57	47.5	47.5	47.5	47.5	39.5	26.8	9.9	0.1	30.9	16.2	47.5
5	58	104.0	100.1	84.0	55.3	45.6	34.3	19.2	9.7	32.6	18.8	53.3
155	64	835.8	881.2	821.7	703.4	629.4	525.8	416.1	336.1	536.4	435.3	868.7
157	70	565.9	597.3	572.3	502.7	460.0	393.7	357.5	272.7	419.5	342.8	633.2
197	83	516.2	542.5	501.5	415.8	363.0	289.3	200.2	149.8	265.2	195.7	457.3
9-WEST	88	135.0	134.7	122.3	100.0	86.8	65.6	46.8	37.8	101.3	75.5	122.6
9-EAST	90	40.0	39.6	35.4	27.1	24.3	16.8	7.6	5.2	40.0	30.6	40.0
189	94	748.6	745.9	702.9	584.7	513.1	400.7	289.8	239.8	405.0	311.1	697.8

Discussion:

The intent of this run was to assess the relative importance of evaporation versus infiltration in simulating pond decay. Infiltration was set to zero and all other conditions were retained as defined for run 9. The effect was to ensure that any reduction in pond volumes following initial formation was attributable to losses by evaporation. The differences between runs 9 and 10 in rate of reduction of pond volume indicated the relative contribution of infiltration to the simulated decay of ponds. In all cases, the rates of reduction in pond volume simulated by run 10 were much lower than simulated by run 9. The clear conclusion is that infiltration accounted for the majority of the simulated reduction in pond volume following initial spring snowmelt. Evaporation would not account for the observed reductions in pond volume even if simulated rates of evaporation were doubled or tripled. Infiltration through the base of the pond must be permitted if simulations of pond decay are to be successful.

6.7 Summary and conclusions - model application

Application of the DISTHMOD model demonstrated both the strengths and weakness of the highly-distributed, physically-based modelling approach adopted for the study.

6.7.1 Highlights and positive contributions

The various runs of the model demonstrated that DISTHMOD was capable of simulating surface runoff and ponding successfully if the input data were correct and if error or omissions in the DEM did not prevent correct estimation of pond volume and connectivity. The model was successful in computing the effective contributing area explicitly for depressional watersheds at given times and under given sets of antecedent conditions. The ability to determine the effective contributing area explicitly represents a marked improvement on current lumped and distributed models for simulating runoff and ponding in landscapes with non-integrated drainage.

The basic framework of DISTHMOD proved to be its major attraction. The framework routed surface runoff and stored it in depressions at appropriate locations and to appropriate depths and volumes except for incompletely defined depressions at the edge of the data matrix. The concept of defining depressions as objects in a relational data base and of assigning each of these objects a maximum storage capacity and a set of pointers to indicate where water in excess of the maximum storage capacity would flow proved to be workable and successful.

The sub-models created to provide hourly estimates of potential evaporation and volume of snowmelt from a snowpack of varying thickness performed well. Estimates of total potential evaporation produced by the Penman equation corresponded quite closely to actual values for total pan evaporation recorded at approximately weekly intervals in the spring of 1989. Estimates of the timing and magnitude of snowmelt were in good agreement with the dates on which melting was observed in the field and with the observed growth and decay of ponds fed by runoff from snowmelt.

The very rapid runoff that created ponds at the site in early April required that infiltration into the soil be virtually zero and that all snowmelt be delivered directly to ponds as surface runoff. Simulation runs in which infiltration was permitted to occur at normal assigned rates for each soil resulted in complete infiltration of all snow melt and no runoff

or pond formation. These results are similar to those reported by Johnsson and Lundin (1991) in their application of the SOIL model. Since ponds were observed to form at the Lunty site, rates of infiltration into frozen soils during the main period of spring snowmelt were clearly lower than measured for unfrozen soils. Setting the rate of infiltration to zero for all soils for all dates on which the temperature of a soil store was below zero produced reasonable estimates for runoff and ponding. This deviates from observations of reduced, but still significant, infiltration into frozen soils reported by Woo and Rowsell (1993) and Johnsson and Lundin (1991).

The DISTHMOD model performed correctly in not simulating any runoff or ponding when infiltration was permitted into unfrozen soils at rates based on modal values of field measurements of saturated hydraulic conductivity. Infiltration rates based on field measurements were greater than any recorded rates of rainfall or simulated rates of snowmelt. The model should not have produced any infiltration excess runoff under these conditions and did not. When somewhat lower rates for steady state infiltration rate (FC) were assigned to all soils, the model was able to simulate infiltration excess runoff and re-growth of ponds during the rainy period from June 1 to June 15, 1989. The lower rates for FC corresponded to the lower range of values for saturated hydraulic conductivity measured in the field for each soil. Rates of rainfall or snowmelt encountered during the period of simulation were sufficient to generate infiltration excess overland flow when soils were assigned the lower values for FC.

6.7.2 Oversights and opportunities for improvement

A significant limitation of the model was its inability to continuously simulate soil temperature and to relate changes in soil temperature to changes in infiltration rate for each soil or grid cell. It was necessary to prescribe a value for soil temperature for each hourly time step of the model. The infiltration capacity of any soil store was set to zero for any time step when the soil temperature was below zero. This rather crude approach permitted the model to produce runoff for the periods of snowmelt in early spring 1989 when the soil was known to be frozen. Infiltration rates were reset to their normal assigned values after a specified date based on soil temperature measurements recorded at the site. Once the soil temperature was above zero the store was considered to be unfrozen and infiltration was permitted. This allowed the model to reduce pond volumes through both evaporation from the pond surface and infiltration into the pond floor. The model would benefit from an improved method for estimating soil temperature and its effect on infiltration rate such as that outlined by Johnsson and Lundin (1991).

The infiltration and drainage equations extracted from the ANSWERS model (Beasley and Huggins, 1981) did not reproduce observed patterns of soil moisture change well (data not reported). The ANSWERS equations are essentially designed to simulate runoff in instances where infiltration capacity is exceeded by rainfall. The critical determination in the ANSWERS infiltration equation is the time and amount of rainfall (or snowmelt) required to fill an infiltration store (S1). Water will pond on the surface and be available for runoff if the rate of rainfall or snowmelt input exceeds the steady state infiltration capacity of a saturated store or the base rate (FC) plus some additional increase for unsaturated conditions. The ANSWERS approach is best suited to short term event-oriented modelling. This is reflected in the approach to simulating drainage. Drainage is permitted to occur only to a minimum moisture content that approximates field capacity. Field capacity is a notional value taken to approximate the moisture content to which a soil will drain under gravity within 24 hours from an initial saturated state. This approach pre-supposes that the soil moisture content never falls below field capacity. It may be valid for short periods of time during and immediately following rainfall events but does not reflect the behaviour over longer periods of typical soils in semi-arid boreal climates. The moisture content of these soils more typically varies between a high not much greater than field capacity and a low just above wilting point.

The inability to simulate near-surface lateral flow (throughflow) was judged to be another limitation of the ANSWERS infiltration and drainage approach used in DISTHMOD. The ANSWERS equations were designed to simulate one dimensional downward flow in the soil. Field evidence indicated that soils in lower landscape positions remained wetter longer than those in upper landscape positions. Increases in moisture content in the top two horizons were observed from mid-April to mid-May during periods when snowmelt was complete and there was no significant rainfall. This supported the interpretation that moisture was moving laterally through the soil from higher to lower landscape positions. Such lateral movement would lead to a situation in which soils in lower landscape positions would be wetter and more likely to become saturated faster than soils in upper landscape positions. An ability to simulate lateral throughflow would have increased the ability of the model to simulate the expansion and contraction of variable contributing saturated areas.

The approach of passing runoff from higher to lower cells along flow paths did not prove to offer a significant advantage for the conditions in effect during the period of simulation. The intention in adopting this routing convention was to ensure that all

runoff from cells higher in the landscape was calculated and delivered to any given cell lower in the landscape before that cell was processed. It was expected that runoff from higher cells would infiltrate into the soils of lower cells and cause them to achieve saturation sooner and remain saturated longer than cells higher in the landscape. In practice, since the model seldom produced runoff, there were few instances where runoff from upslope cells contributed to saturation of downslope cells. The routing approach may still have value, but it can only be evaluated for a set of conditions in which the rate of rainfall input onto non-frozen soil is greater than the infiltration rate assigned to the soil. Such conditions were only simulated for short intervals during the present exercise.

CHAPTER 7

MODEL EVALUATION:

COMPARING SIMULATIONS OF POND VOLUME, DEPTH AND EXTENT WITH FIELD SURVEYS OF ACTUAL PONDING

7.1 Introduction

7.1.1 Overview

The purpose of this chapter is to evaluate the performance of the DISTHMOD model by comparing simulated results with field measurements. Estimates of the extent, volume and depth of ponding produced by the simulation model for specific dates are compared with the observed pattern of pond formation, growth and decay recorded at the Lunty study site at approximately weekly intervals during the spring of 1989. The model runs which most closely approximated observed field conditions are identified and discussed. For the most successful model run, grid maps illustrating the location, extent and depth of ponding simulated by the model are presented and compared with similar maps based on field records of pond location and extent.

7.1.2 Context

Comparison of simulated results to field measurements recognized the previously discussed need to link theoretical modelling with supporting field studies (Dunne, 1983; Dooge, 1988; Anderson and Rogers, 1987; Beven, 1989). Comparison of simulated ponding to actual field measurements provided a means of evaluating the performance of the DISTHMOD model for a particular set of conditions represented by the test data set. The comparison helped identify which aspects of the model were most sensitive to changes in input values. It also helped to identify which aspects of the model performed reliably and which were subject to considerable error. Analysis of the degree of similarity or difference between simulated and mapped pond extent provided a basis for improved understanding of the relative importance of processes contributing to the formation and decay of ephemeral ponds. Improved understanding

allowed the model to be revised and parameter values to be altered to more properly reflect conditions contributing to pond formation and decay.

7.2 Experimental design - model evaluation

The principal objective of model evaluation was to determine how well the DISTHMOD model was able to simulate the spatial and temporal patterns of formation, growth and decay of ephemeral ponds for a single period of spring snow melt and runoff. The specific sub-objectives of model evaluation were:

a) To compare the depth, area and volume of ponds estimated by the simulation model to actual field measurements of ponding recorded for the spring of 1989.

b) To analyse differences between simulated estimates and field determinations of ephemeral ponding to identify reasons for inaccuracies.

c) To identify the relative sensitivity of various components of the model to changes in input parameters.

d) To develop an improved understanding of the interactions among, and relative importance of, the various hydrological processes represented in the model as they affect spring runoff and ephemeral ponding.

e) To identify areas where the current model was deficient and could be improved.

The steps taken to compare simulated to actual ponding and to analyse the reasons for discrepancies may be summarized as follows (Figure 7.1).

Tables were constructed to detail the volume, area and depth of ponding simulated by each of 10 runs of the model for each of the 18 ponds observed on at least one of the 11 field survey dates. Also included in the table were the depth, volume and area of each of the depressions on each of the dates as determined by the field survey.

The data on pond depth, volume and area were reviewed to identify and analyse differences between the simulated and measured data. The reasons for discrepancies

were identified as were the relative sensitivities of the various sub-components of the model to variation in input data or assigned parameter values.

The relative success or failure of the model and its various sub-components at predicting actual field conditions was analysed to develop a better understanding of how the various hydrological processes interacted in the formation and decay of ephemeral ponds. The sensitivity of the model to changes in input data and parameter values provided an indication of the relative importance of various sub-processes in the generation and decay of ephemeral ponds.

The improved understanding of the reasons for model inaccuracies and the relative importance of various sub-processes was used to identify areas where the model could be improved and to suggest mechanisms for improvement.

7.3 Methods - model evaluation

The original intent was to conduct a rigourous statistical comparison of the degree of correspondence between the extent and depth of simulated ponding and actual pond extent as determined by field surveys. Once data from the various runs of the simulation model were available it became clear that statistical measures of difference or similarity were neither necessary nor useful. One the one hand, several of the simulations produced estimates for volume of ponding that were orders of magnitude different than the observed volume of ponding. Statistical measures of difference were unnecessary to confirm the obvious differences apparent in these data. On the other hand, the pond entities mapped by the field survey did not correspond exactly to the entities produced by the simulation model. This complicated efforts to automate statistical comparisons of the extent and depth of the various ponds and to provide explanations for differences.

For example, several of the ponds mapped by the field survey as a single entity were treated by the model as multiple entities. These multiple entities might coalesce to form a single entity if filled beyond a certain volume but might also never coalesce. It was difficult to compare the multiple entities defined by the model to the individual entities mapped by the field survey. Statistical comparison was further complicated by the fact that the field survey recorded pond depth to 3 decimal places (mm) while the vertical resolution of the DEM restricted estimates of pond depth by the model to 1 decimal place (10 cm). The procedure used to produce maps of surveyed pond extent

and depth computed the depth of ponding as the surveyed elevation of the pond minus the elevation of each grid cell lower than the surveyed elevation of ponding in all watersheds occupied by that pond. As a consequence, pond depths were permitted to extend above the overspill elevation (POUR ELEV) defined by the DEM and used in the model to define the maximum depth of ponding. Those ponds where the field survey recorded a maximum elevation of ponding greater than the DEM pour elevation were consistently larger than any pond simulated by the model. Finally, all ponds that overspilled at the edge of the DEM matrix were incompletely defined and any comparison with mapped ponds was unfair. The model predicted the development of several edge ponds in locations where no pond was observed (because topography outside the DEM did not constrain flow and create a pond). Similarly, the model failed to predict the development of several large edge ponds in which topography outside the known DEM constrained flow and caused several small first order ponds to coalesce to form a larger nested pond.

The decision was made to analyse differences between simulated and observed ponding subjectively so as to allow for consideration of the basic differences in the two data sets. It was not felt that statistical measures of similarity or difference would add significantly to any understanding of the reasons for model success or failure.

7.4 Results - model evaluation

7.4.1 Introduction

Tables 7.1 through 7.17 list the volume (m^3), area (m^2) and depth (m) simulated for the 10 simulation runs for each of 18 individual ponds identified on one or more of the 11 field survey dates. Also included are the volume, area and depth for each pond as computed from field survey data. No survey data were available for June 15, but since this was the final day for the simulation runs the simulated data were reported for this date and compared with data collected in the field for July 4, 1989. Table 7.18 summarises the degree of similarity between simulated pond volume and pond volume measured in the field for the simulation run(s) that most closely approximated the measured field conditions.

The DISTHMOD model produced estimates of pond volume in terms of metres per unit grid cell. These were multiplied by 25 m^2 (the area of one grid cell) to convert to

absolute volumes in m^3. The area and depth of each pond at each date were determined by reference to a lookup table which gave the volume and area of each pond at depth increments of 0.1 m. The lookup tables were based on data computed by the preprocessing program FLOODVOL. The program FLOODVOL computed the volume-to-first-flood and the number of cells affected by flooding (pond area) for each grid cell for each identified depression in the Lunty DEM. Since the vertical resolution of the DEM was degraded to 0.1 m, the depth-volume-area data calculated from the DEM were restricted to stepwise increments of 0.1 m. The area estimates therefore correspond to the number of grid cells in the Lunty DEM that would be flooded by the reported volume of water. The estimate of the areal extent of a pond did not increase continuously, but rather stepwise, as the pond had to rise 0.1 m, with a corresponding increase in volume, before a new area (or depth) was recognized. The depth reported in the tables corresponds to the minimum depth of the pond at the simulated volume. The actual depth may lie anywhere in the range from the reported depth to the next higher depth increment (i.e. 0.1 m depth corresponds to the range 0.1 - 0.2 m).

Each pond is identified by the number assigned to it for the field survey. These numbers were inherited from other research projects active at the Lunty site. Each field surveyed pond corresponded to one or more pond objects as defined by analysis of the Lunty site DEM (see chapter 4). Ponds recorded by the field survey as a single entity were sometimes treated by the simulation model as consisting of several distinct entities which amalgamated after a certain depth to form a single higher order pond. Data from the several distinct ponds defined by the DEM for use in the simulation model were summed for those cases where the field surveyed pond corresponded to a collection of individual pond entities in the simulation model. The field survey identified and numbered ponds in the early spring, when they first formed and were at their maximum extent. If they subsequently broke apart into two or more individual ponds separated only by a very low ridge of saturated soil, the field survey continued to treat them as a single pond. The field survey generally recorded a single pond elevation for each pond area even after the initial pond had broken up into two or more disaggregated ponds. The only exception to this practice was for ponds 173 and 2 which were initially surveyed as a single pond (pond 173) but separated into two such distinctly different ponds that a new pond centre was identified for pond 2 for the survey dates of April 4 and April 26, 1989.

The tables exclude data for volume, area and depth of ponds simulated by the model but not recorded by the field survey. These error ponds were mostly located at the

edge of the data matrix and estimated the extent and depth of ponding that would have occurred if flow away from the matrix had been constrained by topography outside the matrix. In cases where topography outside the matrix did not constrain flow, simulated ponds did not actually develop. Comparisons of simulated to actual ponding were not considered valid for these situations. The model also simulated the development of a number of very small ponds corresponding to pits in the DEM formed by one or two individual grid cells lower in elevation than all of their neighbours. Some of these pits may actually have existed. They may have even become inundated for a very short period in the spring. However they would have been overlooked by the field survey because they were considered too small and too shallow to be worthy of recognition. They would have appeared as simply small, wet or saturated areas in the field and would not have been recognized as true ponds. Lack of field data to verify whether these ponds actually existed precluded comparing simulated to actual conditions for these small ponds. Figures 7.2 through 7.6 illustrate the depth and extent of all simulated ponds (including error ponds) for one simulation run in comparison with the field surveyed ponds. Error ponds are identified and described in the discussion of these figures.

The order in which the ponds are listed in Table 7.18 and discussed below is intended to reflect the degree to which a pond was fully and completely defined by the DEM. Only results for completely defined ponds and watersheds can be considered relevant. Simulations for incompletely defined watersheds are expected to be incorrect since unknown areas contribute to defining the dimensions of the pond and of the watershed contributing runoff to it. The field survey data for each pond in Tables 7.1 through 7.17 appears as the first entry in each of the categories of volume, area and depth and is highlighted to improve readability. Also highlighted is the run (or runs) which produced estimates of pond volume, area or depth closest to the surveyed values. Each pond is discussed and reasons for differences or similarities between runs are identified.

7.4.2 Comparison of actual to simulated data for pond 185-East

Pond 185-East corresponded to the east half of the main central depression at the Lunty site. It, and the watersheds contributing flow to it, were fully defined by the available DEM data set. It contained the DEM watersheds 25, 27, 35 and 37 which coalesced to form the higher order ponds 116 and 118 (Figure 4.17 and Table 4.4). Since the DEM fully defined this depression and since it was expected to retain all

runoff it received (i.e. not overspill to any downslope watershed), this central depression was expected to provide one of the best tests of model performance.

The degree of correspondence between the observed volume of ponding for pond 185-East and that simulated by runs 6 and 9 was very high (Table 7.1). With no overspill from the pond, the simulated maximum pond volumes of 1065 m^3 (run 9) and 1118 m^3 (run 6) were very close to the observed maximum volume of 1032.5 m^3. This indicated that the model correctly estimated the total yield of runoff from snow melt between March 22 and April 4, 1989. In both runs 6 and 9, all snow melt in excess of the surface retention value assigned to each soil ran off. There were no losses to infiltration before April 4, 1989, only to evaporation. Thus, all snow present on the surface on March 22 was converted to runoff at a water equivalent of 220 kg m^3. A different combination of initial snow depth, evaporation losses and low infiltration rates might have simulated a similar result. It appeared, however, that the simplest case of virtually complete conversion of snow to runoff over the entire watershed produced a volume of ponding almost identical to that actually observed.

The critical factor in correctly simulating initial pond depth was the total depth of snow assigned to the watershed (see 3.4.7 for method and 3.5.7 for results of techniques used to estimate depth of snow). For example the mean depth of snow of 0.4 m assigned for run 5 produced estimates of initial pond volume that were an order of magnitude greater than produced for a snow depth of 0.13 m. Changing the snow depth from a single value of 0.13 m for all grid cells to a variable depth averaging 0.15 for all cells produced a negligible difference in simulated maximum volume of ponding. The variable depth of snow took longer to finish melting and so did not produce a peak pond volume until April 4, 1989. This was closer to the observed timing of the pond maximum than produced by run 6 for a fixed depth of snow.

The decay of pond 185-East simulated by both runs 6 and 9 was very similar to the observed pattern of pond reduction. The two runs assigned quite different values for steady state infiltration capacity for all soils and for dates on which the soil first thawed and permitted infiltration.

In run 6, all soils were assigned values for steady state infiltration rate (FC) based on field measurements of saturated hydraulic conductivity. The assigned rates were quite high and did not permit the development of any rainfall runoff once the soils thawed (note the continued reduction in pond volumes in the rainy period between June 1 and

June 15). Losses through infiltration in run 6 were restricted by staggering the date at which the soil first thawed and infiltration first became operative for each of the three soil stores. These dates were April 12, April 22 and May 2 for stores S1, S2 and S3 respectively. With no capacity for losses from the lowest store until after May 2, all pond losses in excess of evaporation simulated for run 6 represented uptake and storage of water by the upper soil stores S1, S2 and S3. Thus, storage of infiltrated pond water in the upper 1 meter of soil seems able to account for the observed reduction in pond volume in excess of that attributable to evaporation from the pond surface.

Losses attributable to infiltration in run 9 were restricted by assigning lower values of steady state infiltration rate (FC) to all soils than the rates used in run 6. The lower rates were based on the minimum values recorded by the field study for saturated hydraulic conductivity for each soil. All depths of all soils were assumed to thaw and permit infiltration at these slower rates after April 4, 1989. The results indicated that the model was not especially sensitive to either the steady state infiltration rate assigned to soils or to the date at which that rate was taken to become operative, as long as the rate was set to zero for the initial period of snow melt and runoff. After initial formation of ponds was complete, infiltration into the soil below the pond at any reasonable rate reduced the simulated volume of the pond in a pattern very similar to that observed. The one advantage of the lower rates for steady state infiltration rate used in run 9 was that they produced runoff from rainfall during the period June 1 to June 15. Since pond 185-East was observed to regain some of its lost volume between May 24 and July 4 it was clear that some runoff occurred during this rainy period and that the runoff replenished the pond. No similar runoff and increase in pond volume was simulated by run 6. For this reason, the conditions associated with run 9 were concluded to most closely reflect reality.

In both runs 6 and 9 pond 185-East was simulated to diminish in volume faster between May 10 and May 24 than recorded by field observations. This indicates that field conditions caused infiltration to proceed more slowly than simulated. The most likely explaination is that a rise in the watertable underlying pond 185-East counteracted and restricted infiltration. It may also be possible that the soil under the pond remained frozen within a metre of the surface, restricting infiltration into the sub-surface store (S3) until after May 24, 1989.

Overall, the results of both runs 6 and 9 were very close to the observed pattern of pond growth and decay. The model performed well when provided with any reasonable values for steady state infiltration rate and dates on which these rates became operational. The critical input value was the total depth of snow pack present in the watershed area. Quite unexpectedly, the mean depth of snow as computed for 44 snow sample sites provided the best estimate of snow depth and total volume of water released from the snow pack. Varying the depth of snow according to landscape position while maintaining a mean depth similar to measured mean snow depth produced a slight improvement in the estimated timing to peak pond volume but had a minimal effect on the simulated initial maximum pond volume (since all snow melt before April 4 ran off and accumulated anyway).

The results for pond 185-East supported the conclusion that the model could make accurate estimates of location, extent and volume of ponding if the depression and its associated watershed were completely and accurately defined and if the assigned depth of snow approximated the mean snow depth for the watershed.

7.4.2 Comparison of actual to simulated data for pond 185-West

Pond 185-West corresponded to the west half of the main central depression at the Lunty site. It, and the watersheds contributing flow to it, were fully defined by the available DEM data set. It contained the DEM watersheds 26, 29, 33, 36 and 39 which coalesced to form the higher order ponds 117 and 119 (Figure 4.17 and Table 4.4). It also received overflow from DEM ponds 23, 52, 55 and 64 once they were full to their maximum storage capacity. Since the DEM fully defined pond 185-West and since it was expected to retain all runoff it received (i.e. not overspill to any downslope watershed), this central depression was also expected to provide one of the best tests of model performance.

As with pond 185-East, the degree of correspondence between the observed volume of ponding for pond 185-West and that simulated by runs 6 and 9 was very high (Table 7.2). With no overspill from the pond, the simulated maximum pond volumes of 1532 m^3 (run 9) and 1534 m^3 (run 6) were remarkably close one another and to the maximum observed volume of 1560.5 m^3. This indicated that the model correctly estimated the total yield of runoff from snow melt from contributing watersheds between March 22 and April 4, 1989.

The discussion presented for pond 185-East applies equally to pond 185-West. Correct estimation of initial maximum pond volume was critical to proper simulation of subsequent pond decay. Effective estimates of initial maximum pond volume were obtained when the depth of snow was set to equal the mean measured depth of snow at the site. Varying the estimate of snow depth according to landscape position while maintaining the mean depth close to the measured mean produced a slight improvement in the estimated timing to peak pond volume. Assignment of relatively low rates for steady state infiltration with infiltration enabled for all soil stores after April 4, 1989 produced a reasonable estimate of pond decay and also permitted pond 185-West to recover in volume with runoff generated by rainfall in the period June 1 to June 15. The rate of pond decay simulated by run 9 was slightly faster than recorded by the field survey, especially for dates after April 26. This would support assigning even lower values for steady state infiltration rate to the soils underlying the pond.

The results for pond 185-West supported the conclusion that the model could make accurate estimates of location, extent and volume of ponding if the depression and its associated watershed were completely and accurately defined and if the assigned depth of snow approximated the mean snow depth for the watershed.

7.4.3 Comparison of actual to simulated data for pond 184

Pond 184 (Table 7.3) was fully defined by the DEM data set. The DEM defined two distinct ponds (19 & 21) which coalesced to form the larger pond recognized as pond 184 for purposes of the field survey. The DEM defined a maximum depth of ponding of 0.5 m and a maximum volume of 545 m^3. This compared well with the field observations of a maximum depth of 0.51 m and a maximum volume of 581.9 m^3.

Simulation runs 8 and 9 produced estimates for pond volume, area and depth that were very similar to the field measurements. The critical factor was the ability to simulate an initial maximum pond volume and depth for the April 4 field survey date. Both runs 8 and 9 filled the pond to its maximum storage capacity (545.0 m^3) by March 31. Run 9 maintained this maximum through April 4 because of continuing snow melt while run 9 simulated a slight reduction in volume between March 31 and April 4 due to an excess of evaporation over snow melt. The field data indicated the pond achieved a maximum volume of 581.9 m^3 by April 4 and experienced a continuous decay in volume after that date until refilling between June 1 and July 4. The match

between the observed maximum volumes and that predicted by runs 8 and 9 was very good. The difference may be explained as arising from rounding of the DEM elevation data. Snow drifting may also have filled the divide between pond 184 and its downstream outlet causing the initial pond to achieve a greater depth and volume than predicted from ground elevations.

The rate and pattern of decay of the pond was simulated very well by both runs 8 and 9. At every date, the volume of water simulated to remain in pond 184 was very close to the measured volume. Simulated pond area and depth were even more closely similar to the observed data. The model clearly simulated losses from the pond at a rate similar to actual pond losses. Run 10 represented a repeat of run 9 with infiltration set to zero. As such, it permitted evaluation of the relative contributions of infiltration and evaporation to pond losses between any two dates. Infiltration was a larger contributor to the reduction in pond volume than evaporation in any given period. Runs 8 and 9 used relatively low values for infiltration parameters but even run 6 which used higher values for maximum infiltration rates produced similar estimates for pond loss. The model was therefore not especially sensitive to the assigned rates of infiltration as long as they were reasonable (within an order of magnitude of one another) and as long as they permitted infiltration to occur.

It was encouraging to note that the model simulated runoff and the re-growth of ponds for the June 15 survey date. No field data were available for this date, but rain continued until July 4 and by July 4 the surveyed pond 184 had grown to a volume of 111.2 m^3. Growth of the simulated pond between June 1 and June 15 for both runs 8 and 9 suggested that had the simulation continued to July 4, the simulated ponds would have resembled the surveyed pond in volume and extent. No pond re-growth occurred for this period for run 6 which assigned more rapid infiltration rates to all soils. It was concluded that the lower steady state infiltration rates assigned to store S1 for runs 8, 9 and 10 more closely reflected actual field conditions than the more rapid rates used in run 6.

The difference in behaviour between runs 8 and 9 was attributed to the greater average depth of snow assigned to grid cells for run 8. The mean depth of snow for run 8 was 0.2 m in contrast with a mean depth of 0.15 m for run 9. Run 8 contained a greater number of grid cells assigned deeper thicknesses of initial snow pack. The deeper snow pack continued to melt and provide some runoff until at April 12. This runoff maintained the pond at its maximum depth and volume until at least April 4, 1989.

In both runs 8 and 9 pond 184 filled to its maximum storage capacity by March 31 and then overspilled delivering excess runoff to the downslope watershed (pond 185-East). Since the simulated maximum volume corresponded closely with the observed maximum volume, any amount of snow melt in excess of about 0.1 m would have filled the pond to capacity. The model was therefore only required to correctly estimate the rate at which the pond was reduced in size by infiltration and evaporation occurring after April 4. The model performed this task well, but this task represents only a partial test of the model's success. A complete test of the model requires that the estimate of initial pond depth and volume be correct for a pond that did not overspill but retained all received runoff.

7.4.4 Comparison of actual to simulated data for pond 155

Field survey pond 155 corresponded to a combination of two individually defined DEM depressions (55 & 64) which coalesced to form the higher order depression 129 (see Figure 4.17 and Table 4.4). Both of these watersheds and their associated depressions were completely contained with the DEM and did not receive overspill runoff from any incompletely defined watersheds. Under these conditions, pond 155 was expected to represent a valid test of model performance.

The results from simulation run 9 corresponded reasonably well with the pattern of ponding recorded in the field (Table 7.4). The maximum possible storage capacity of the pond before overflow had been computed from the DEM as 970 m^3. The field survey recorded a maximum pond volume of 847.8 m^3 on March 31. This was just less than the total storage capacity of the pond, indicating that the pond came close to overspilling but did not overspill. Simulation run 9 predicted a volume of 835.8 m^3 on March 31 which was almost identical to the field determined volume. Run 9 simulated continued growth of the pond to 881.2 m^3 on April 4 in contrast to the recorded decrease in volume to 652.2 m^3. As with pond 5, infiltration appeared to begin under pond 155 between March 31 and April 4 and to contribute to the observed reduction in pond volume. Since infiltration was set off in the model until April 4, the model did not simulate losses due to infiltration before that date.

The pattern of decay in pond volume and depth simulated by run 9 resembled that recorded by the field survey for the three dates of April 12, 19 and 26. The field survey did not record any volume in pond 155 from May 3 until the pond recovered to

a volume of 367.5 m^3 on July 4, 1989. It is hard to understand how the pond could have diminished from 200 m^3 on April 26 to nothing on May 3 given the rate of reduction in pond volume observed in the preceding two weeks (about 150 m^3 per week). There is some possibility that the field survey neglected to record data for this pond for the weeks from May 3 until July 4, 1989.

7.4.5 Comparison of actual to simulated data for pond 157

Field survey pond 157 corresponded to a combination of four individually defined DEM depressions (66, 67, 69, 70) which coalesced to form the higher order depressions 133 and 137 (see Figure 4.17 and Table 4.4). All of these watersheds and their associated depressions were completely contained with the DEM and did not receive overspill runoff from any incompletely defined watersheds. Under these conditions, pond 157 was expected to represent a valid test of model performance.

None of the simulation results (Table 7.5) corresponded well with the observed pattern of ponding. The most likely explanation for the poor match is that pond 157 lost volume to infiltration beginning as early as March 31. If infiltration had been allowed to begin as early as March 31, the results from simulation run 9 would have been much more similar to the recorded field data (shift all data for run 9 left one column). Another possible explanation is that the watersheds contributing flow to pond 157 contained a lower total volume of snow water equivalent than was assigned for the model runs. Less snow would have produced a lower initial volume of water in the depression and this volume would have diminished in a pattern similar to the observed pattern (see run 7). A third possible explanation is that the divide between the watersheds contributing flow to pond 157 and those contributing to the adjacent pond 197 was inaccurately defined by the DEM. Pond 197 received more runoff than simulated by any of the runs with snow depth set to less than .04 m. It is possible that some of the runoff directed into pond 157 was actually meant for pond 197.

The pattern of rapid reduction in pond volume recorded by the field survey for all dates from April 4 until May 3, 1989 could not be explained solely by evaporation (see run 10 results). In order for infiltration to begin, soils in the base of the pond must have thawed enough to permit infiltration into at least the uppermost store. The field data indicated a more rapid rate of pond loss to infiltration than simulated by any of the runs. Run 9 would have produced a more accurate portrait of the actual conditions if

rates of infiltration for the soils beneath pond 157 had been set to a larger value and if infiltration had been turned on earlier (by March 31).

The results indicated that the input data on snow depth, infiltration rates and date of initiation of infiltration into unfrozen soils were probably in error for the watersheds contributing to pond 157. None of the simulation runs produced a close correspondence with observed ponding for pond 157.

7.4.6 Comparison of actual to simulated data for pond 197

Field survey pond 197 corresponded to a combination of four individually defined DEM depressions (82, 83, 84, 86) which coalesced to form the higher order depression 139 (see Figure 4.18 and Table 4.4). All of these watersheds and their associated depressions were completely contained with the DEM and did not receive overspill runoff from any incompletely defined watersheds. Under these conditions, pond 197 was expected to represent a valid test of model performance.

None of the simulation results (Table 7.6) corresponded well with the observed pattern of ponding. All simulation runs in which mean initial snow depth was set to less than 0.4 m produced estimates for initial maximum pond volume considerably lower than recorded by the field survey. The simulation run most similar to surveyed ponding was run 8 in which initial snow depth averaged 0.2 m for the entire Lunty site.

The most likely explanation for the under estimate of initial maximum pond volume by most of the simulation runs is that the total volume of snow water equivalent in the watershed was under estimated by the procedures used to assign initial snow depth to each grid cell. For example, the initial mean depth of snow somewhere between that assigned for run 5 (0.4 m) and run 8 (0.2 m) would have produced an estimate for initial volume of ponding closer to the 997. m^3 recorded by the field survey. Pond 197 was surrounded by a dense ring of willows and brush which could have assisted in trapping snow and increasing the total snow available to contribute to runoff in the depression. If the estimate of initial pond volume had been closer to the field determined value, simulation of the subsequent decay in pond volume would have been closer to the truth.

A second explanation for the low estimates of initial maximum volume for pond 197 produced by most simulation runs might be that the total contributing area was under estimated. Results from simulation runs for pond 157 provided some support for this interpretation. Estimates of initial pond volume for pond 157 were consistently greater than determined by field survey. It is possible that the divide between watersheds contributing flow to pond 157 and those contributing flow to 197 was improperly defined and that some flow directed into pond 157 should actually have contributed to pond 197. Examination of perspective views of the catchments draped over topography suggested that, while portions of watershed 67 might have been able to deliver runoff to watershed 84 (pond 197) it was unlikely that this was the case.

A third, and more likely, explanation, for the larger volume of water in pond 197 than simulated by most runs is that the pond contained some initial volume of water remaining from a previous year. There was some field evidence to suggest that pond 197 was permanent and emerged from the winter with some small volume of water in place from the preceding year. The model assumed that all ponds were dry at the beginning of snow melt and all estimates would be in error if the pond contained some initial positive volume of water.

A final possible explanation for the noted discrepancy might be that the pond was in contact with and receiving recharge from the water table. This explanation is less likely than others since rapid movement of water from the saturated zone would be unlikely in March and early April when it would be required to provide the shortfall noted in Table 7.6.

The poor match between surveyed pond volumes and those simulated by most of the realistic simulation runs emphasised the importance of supplying a proper estimate of initial snow depth and snow water equivalent for each watershed. It also pointed out the need to know if any of the ponds were partially full with water from previous years so that the model could take account of any pre-existing pond volume.

7.4.7 Comparison of actual to simulated data for ponds 2 & 173

Ponds 2 and 173 were ephemeral upland ponds corresponding to the DEM defined depressions 46, 50, 51 and 46 (Figure 4.20 and Table 4.4). These individual depressions coalesced to form the higher order depression 143. The depressions were

fully defined by the DEM but the total contributing area of watershed 50 was unknown as it projected beyond the available DEM data set.

Comparison of simulated results to field mapping (Table 7.7) was difficult due to uncertainty about which DEM pond or combination of DEM ponds corresponded to pond 2 or pond 173 for any field survey date. For example, pond 2 was recorded by field mapping on only two dates, April 12 and April 26. It is not known if it disappeared between the two dates then reappeared of whether it was surveyed as part of pond 173 for the dates April 12 and April 19. The ponds were in close proximity and coalesced or broke apart with very small changes in volume and depth. When separate, the ponds were identified and surveyed individually. When coalesced, the field survey recognized a single pond and reported a single value for pond elevation and depth.

In order to permit a valid comparison, the simulated volume and depth of ponding for all of DEM ponds 46, 50, 51, 57 and 143 (if present) were summed and compared to the total volume recorded by the field survey for ponds 2 and 173 (Table 7.7). The only run of the model to come close to the observed pattern of pond development and decay was run 9. In this simulation, the maximum initial pond volume of 246.6 m^3 was recorded on March 31 in comparison with the field observed maximum of 445 m^3 on April 4, 1989. This indicated that, in the simulation, runoff from snow melt was exceeded by evaporation between March 31 and April 4. The field data indicated that runoff from snow melt exceeded losses from evaporation or infiltration for this period.

Several factors contributed to the inability of the model to correctly estimate total maximum pond volume. The first was that the maximum storage capacity computed for the combined ponds (pit 143) was 375.0 m^3. It was impossible for the model to achieve the observed maximum volume of 445.0 m^3 given that the maximum storage capacity was defined as 375.0 m^3. The difference in computed capacity versus field measured maximum volume was likely due to the effects of rounding of elevation values in the DEM. Rounding reduced the elevation of the divide cell representing the lowest pour point at which water could escape from DEM pond 143. This resulted in a lower computed estimate for maximum storage capacity than was in fact the case. Since run 9 never simulated a pond volume even as large as the computed storage capacity (375.0 m^3) this source or error was not active.

The inability of the model to fill the pond to even this underestimated maximum storage capacity was likely related to two conditions. One was that watershed number 50 was incompletely defined. Some portion of watershed 50 occurred outside the available DEM data set and contributed runoff to the combined DEM ponds 46, 50, 51 and 57. A larger contributing area would have resulted in more runoff and a larger estimate for initial pond volume.

The second reason for under estimating the initial maximum pond volume was likely an under estimate of snow depth for the cells of watersheds contributing flow to the combined depressions. The field data recorded that the combined ponds continued to grow between March 31 and April 4. This indicated that snow melt was continuing between these dates and was contributing runoff to increase the volume of the pond. In the simulation run 9, the combined volume of ponds 2 and 173 decreased between March 31 and April 4. This indicated that snow melt had ceased, or that runoff from snow melt was at least less than losses arising from evaporation. To maintain snow melt after March 30 ,1989 the initial depth of snow for at least some cells in the contributing watersheds would have had to be greater than 0.2 m (see Table 6.4). The procedure for estimating varying depths of snow for grid cells resulted in only 61 cells in the contributing watersheds having initial snow depths greater than 0.2 m. The reason is that watersheds 46, 50, 51 and 57 were upland catchments containing few cells with large upslope areas. Since snow depth was primarily related to upslope area count, few cells in upland catchments were estimated to have deep initial snow depths. The conclusion drawn from the results of simulation run 9 is that estimates of snow depth for grid cells in the contributing watersheds may have been too low. More cells with initial snow depths greater than 0.2 m would have resulted in more runoff and come closer to filling the combined depressions to their maximum storage capacity.

The results of simulation run 9 closely approximated the observed pattern of pond decay after April 4, 1989. It is interesting to note how rapidly the combined ponds diminished in volume and area after April 4, 1989. Ponds of comparable area and volume lower in the landscape (i.e. pond 6) did not decay nearly as rapidly based on either field observations or simulation results. The more rapid decay of this upland pond was mostly attributable to rapid infiltration into the soils underlying the pond. While some of the soils underlying the combined depressions 2 and 173 were similar to those mapped for depressions lower in the landscape (COR), a large portion of the area affected by ponding in these watersheds was occupied by much more rapidly permeable Elnora (EOR) soils. In addition to being more rapidly permeable, Elnora

soils had a lower initial water content than COR soils and hence a greater capacity to accept and store infiltrating water.

The results for simulation run 9 for the combined ponds 2 and 173 appeared to parallel the observed pattern of pond growth and decay. The field record of a volume of 102.5 m^3 for pond 2 on April 26 was not matched by any simulation. There was some rainfall between April 19 and 26 (3 mm) but this was insufficient to cause runoff or increase pond volumes for any other watersheds at the site. A transcription or recording error in the field data was suspected but could not be confirmed.

Pond 173 was recorded as empty by the field survey by April 26 whereas run 9 simulated a very small residual volume (0.8 m^3). This volume was so small that it could have represented a small muddy area or puddle that would not have been judged worthy of recording during the field survey. Ignoring this small residual volume, run 9 of the model quite accurately predicted the date at which the combined depressions 2 and 173 first became empty.

7.4.8 Comparison of actual to simulated data for pond 6

Pond 6 corresponded to the single watershed number 23 defined by the Lunty DEM. This watershed was fully contained within the available DEM data set and was expected to provide a legitimate test of the model results.

Correspondence between simulated and observed volumes and depths of ponding for pond 6 (Table 7.8) was not high. The root of the error was in the data for maximum depth and volume of ponding computed for this depression from the DEM. Determination of the maximum pond volume, area and depth for this depression (Table 4.4) yielded a maximum computed depth of 0.2 m and a maximum volume of 187.5 m^3. Field mapping recorded a maximum volume of ponding of 429.5 m^3 and a maximum depth of 0.31 m. The estimates of pond volume and depth computed from the DEM data were probably in error. The error might have resulted from rounding of the DEM elevation values to the nearest 0.1 m or from missing a higher elevation saddle elevation in the grid sample used to defined the DEM. Alternatively, ice damming from drifting snow may have created a temporary pour elevation in excess of that computed from terrain elevation data. In either case, the result was that the model was provided with input data (maximum pond volume) that precluded any possibility

of it correctly predicting the maximum volume and depth of ponding for this depression.

Any correspondence between simulated and observed pond statistics for pond 6 was purely fortuitous. Runs 3 and 10 provided the closest estimates of pond volume and depth but these were achieved by filling the pond to its maximum allowable volume (187.5 m^3) and then permitting losses at a very slow rate associated with evaporation only and zero infiltration. Differences between runs 3 and 10 were small and likely related to the variable snow depth assigned for run 10 which would have resulted in extending the period of runoff from snow melt past the April 4 date when all snow melt for run 3 was completed. Run 9 would likely have most closely reproduced the observed pattern of pond growth and decay if the available runoff in excess of 187.5 m^3 could have been retained up to the observed maximum volume of 429.5 m^3. Since the pond data statistics provided to the model did not permit this, none of the runs were able to fill pond 6 to its observed maximum depth. Water in excess of 187.5 m^3 was therefore added by the model to the downslope depression (185-West) and would be expected to contribute to an overestimate of the volume of water initially stored in pond 185-West.

7.4.9 Comparison of actual to simulated data for pond 8

Pond 8 (Table 7.9) was a small depression fully defined by the DEM (see Figure 4.20 and Table 4.4). It corresponded to DEM watershed 14 which drained into watershed 4 at a pour elevation of 724.9 m.

None of the simulation results for this pond compared well with the field survey data. The field survey data indicated that the initial pond volume (69.9 m^3) and depth (0.27 m) were significantly greater than estimated by any of the simulations. Two causes were evident. The first was that the DEM under estimated the total storage capacity of this depression. This was probably related to errors caused by rounding the elevation data to 0.1 m precision. The minimum elevation of the pit centre was probably lower and the maximum elevation of the pour point was probably greater than defined by the DEM. The second possibility is that the maximum elevation of ponding for pond 8 was defined by a snow dam rather than by terrain. This would explain the rapid decrease in volume between April 4 and April 12. The complete disappearance of the pond between April 12 and April 19 was not mimicked by any of the simulations. The closest approximations were runs 8 and 9 which stopped delivering runoff to the pond

by April 4 and simulated the pond to completely disappear by May 10. The model took much longer to remove the final small volumes of water from depressions than recorded by the field survey. Infiltration and evaporation must have been more rapid than simulated by any of the runs. It is, however, likely that the pond persisted as an area of wet soil beyond April 12 but was not recognized as an area of open water by the field survey.

7.4.10 Comparison of actual to simulated data for pond 194

Field pond 194 corresponded to a large and complex grouping of individually defined DEM watersheds and depressions (38, 28, 30, 32, 45, 48, 49, 53, 54, 60, 61, 56, 63, 59) located along the western edge of the study area (see Figure 4.19 and Table 4.4). Several of these watersheds and their associated depressions were incompletely defined as they extended outside the area defined by the available DEM data. It was not expected that the simulation model would correctly predict ponding for pond 194 given that the data set was incomplete.

Perhaps coincidentally, the results from run 9 (Table 7.10) were quite similar to the pattern of ponding and pond decay recorded by the field survey. The reasonably close correspondence between simulated and observed pond volume and depth for most dates suggests that the total storage capacity of all the depressions was adequately defined by the available DEM data and that most of the runoff feeding these depressions originated within the area defined by the DEM (i.e. little runoff originated from the area west of the depressions and outside the DEM). The run 9 simulation even predicted the re-growth of the pond during the rainy period in June which was substantiated by field data from July 4, 1989. The results indicate that in some cases even a partial data set can produce useful estimates of pond behaviour, if the area outside the data set does not make a substantial contribution to either runoff or control of maximum storage volume.

7.4.11 Comparison of actual to simulated data for pond 189

Field survey pond 189 corresponded to a large and complex grouping of individually defined DEM watersheds and depressions (81, 85, 89, 93, 94, 87, 96, 103, 105) located in the south west corner of the study area (see Figure 4.19 and Table 4.4). These ponds coalesced in stages to produce the higher order ponds 138, 140, 141,

and 142. Several of these watersheds were incompletely defined as they extended outside the area defined by the available DEM data. All of the depressions were reasonably well defined by the available DEM data set. It was not expected that the simulation model would correctly predict ponding for pond 189 given that the terrain data set was incomplete.

Results from all simulations with mean snow depth less than 0.2 m produced estimates for initial (and maximum) pond volume considerably lower than recorded by the field survey (Table 7.11). Run 8 (0.2 m initial snow depth) overestimated the initial pond volume and continued to overestimate pond volume for all subsequent dates. Runs 6 and 9 slightly underestimated the initial volume of pond 189 but produced quite close estimates for dates from April 19 to May 10. The under estimate was most likely related to not being able to compute runoff for areas outside the DEM that contributed flow to pond 189. It could also have been caused by a slight underestimate of initial depth of snow in the contributing watersheds. In both runs 6 and 9 simulation of pond losses by evaporation and infiltration closely paralleled the observed pattern of pond reduction.

The simulations demonstrated the relatively greater importance of infiltration over evaporation (see run 10) in achieving pond losses similar to those actually recorded. Even though both runs assigned quite different values for steady state infiltration rates to the various soils and permitted infiltration to begin at different dates for the various soil stores, the net results were similar. Overall the infiltration parameters set for run 9 were judged more correct as they permitted rainfall runoff to occur between June 1 and June 15. This runoff replenished pond 189 and increased its volume. This was in keeping with the recorded reappearance of pond 189 on July 4, 1989. As with other ponds, the model failed to remove the last vestiges of water from ponds as rapidly as indicated by field data. It is speculated that evaporation losses from very shallow ponds underlain by dark soils proceeded at a rate greater than predicted using the Penman equation for evaporation from open water.

7.4.12 Comparison of actual to simulated data for pond 5

Field survey pond 5 corresponded to the single DEM defined edge depression of watershed 58. This watershed extended outside the area defined by the DEM and so was incompletely defined.

None of the simulation results (Table 7.12) corresponded well with the observed pattern of ponding. The most likely explanation for the poor match is that pond 5 lost volume to infiltration beginning as early as March 31. The rapid reduction in pond volume recorded by the field survey between March 31 and April 4 could not be explained solely by evaporation (see run 10 results). In order for infiltration to begin, soils in the base of the pond must have thawed enough to permit infiltration into at least the uppermost store. In run 9, infiltration was turned off until after April 4 for all depths of soil by prescribing frozen soils conditions and zero infiltration rates until that date. If soil temperatures had been set to above zero and infiltration had been turned on by March 31, the results for run 9 would have approximated the recorded field results very closely (i.e. shift all results for run 9 left one column in Table 7.12). The model would still have simulated some very small residual volume of water for several weeks after the field data indicated the pond had dried up, but these were negligible volumes.

The most obvious explanation for the poor correspondence between field data and simulated results for pond 5 was the model choice to prevent infiltration until after April 4. This indicated a need to improve the model so that soil temperatures and infiltration rates tied to them could be predicted for the soils beneath individual depressions. The model assigned a single date for thawing of soil stores to all grid cells for any given soil depth. A more comprehensive approach would include a mechanism for simulating soil temperatures for individual cells or at least for individual soil types.

7.4.13 Comparison of actual to simulated data for pond 182

Pond 182 (Table 7.13) represents another incompletely defined edge pit. It does not represent a valid test of the model and is not discussed here in detail. The surveyed pond is much more shallow than the simulated ponds for most dates for most simulation runs. In reality, this was a large, semi-permanent pond that persisted well into May. A large portion of the depression was located outside the area defined by the DEM and so the total storage capacity of the depression at any given elevation was much greater than computed based on the available DEM data. The runoff computed for the various snow melt scenarios would have had to fill that larger storage volume and so would not have caused the pond to rise to the simulated elevations.

7.4.14 Comparison of actual to simulated data for pond 7

Pond 7 (Table 7.14) does not represent a good test of the model as neither the depression nor the watershed contributing flow to it are fully defined by the available DEM data.

Pond 7 corresponded to a single edge pit (pit 4) as defined by the Lunty DEM. Since edge pits are always incompletely defined it was expected that simulated ponds would not match the field surveyed volume and area for edge ponds. Runoff from areas outside the defined data matrix contributes to the formation of ponds in edge pits. The total extent and volume of edge pits cannot be determined accurately since some portion of the depression is defined by data outside the available matrix. Similarly, it is not possible to determine whether the topography outside the available DEM constrains flow and results in pond formation or allows water to escape away from the edge.

In the case of pond 7, topography outside the DEM did constrain flow and caused the formation of a true depression. Water accumulated in the depression to a greater depth and volume than predicted by the simulation model. The data supplied to the model predicted a maximum depth of ponding of 0.3 m whereas the maximum depth recorded by the field survey was 0.43 m. This discrepancy indicated that even the elevation data for the area encompassed by the DEM was in error. The surveyed elevation of the pit centre was 723.67 m whereas the minimum elevation in the DEM was 723.7. The maximum surveyed elevation was 724.13 whereas the maximum pour elevation computed from the DEM was 724.0. Rounding of elevations to the nearest 0.1 m resulted in under-estimation of the maximum storage capacity and maximum depth of this pond.

Under-estimation of the maximum storage capacity of pond 7 meant that the model could not possibly simulate pond volumes similar to those recorded by the field survey. Correspondence between simulated and field surveyed volumes of ponding required that simulated ponds achieve a maximum initial volume close to that recorded by the field survey. After achieving a maximum initial volume, most of the remaining activity consisted of simulating the decay of ponds due to evaporation and infiltration. If the initial simulated pond volume was similar to the surveyed volume, simulated pond decay approximated surveyed rates of change.

None of the simulated data for pond 7 matched the surveyed volume and area data closely. The maximum simulated pond volume was 37.5 m^3 compared to 83.5 m^3 and the maximum depth was 0.3 m compared to 0.43 m. Interestingly, none of the simulated ponds decayed as rapidly as the field surveyed pond, even though they all had a lower initial volume and depth. Two possible explanations are advanced. It is possible that the rate of infiltration into the soil beneath the pond was much greater than predicted by the model. A comparison of runs 3, 9 and 10 indicates the relative importance of evaporation and infiltration to the reduction in pond volume. Run 3 simulated no evaporation or infiltration, run 10 simulated evaporation but no infiltration and run 9 simulated both evaporation and infiltration. These data indicated that infiltration played a more significant role in decay of pond 7 than did evaporation. Infiltration at an even more rapid rate would be required for the simulated pond to have disappeared as rapidly as the field surveyed pond.

A second possible explanation exists for the significant difference in the rate of pond decay. Pond 7 formed along a fence line affected by drifting snow. It is possible that the pond was dammed by drifting snow and that all or some of the reduction in pond volume was caused by removal of the snow dam and rapid outflow of water to the level of the pour elevation defined by the ground surface. This explanation is distinctly possible.

7.4.15 Comparison of actual to simulated data for pond 9-West

Field survey pond 9-West corresponded to a combination of two small, individually defined DEM depressions (88, 97) which coalesced to form the higher order depression 136 (see Figure 4.18 and Table 4.4). Watershed 97 and pond 136 were incompletely defined as they abutted the edge of the data matrix and extended beyond the area for which elevation data were available. Under these conditions, pond 9-West was not expected to represent a valid test of model performance.

None of the simulation results (Table 7.15) corresponded well with the observed pattern of ponding for pond 9-West. All simulation runs under estimated the initial maximum pond volume as determined by field survey. The maximum pond volume as defined by geomorphological analysis (Chapter 4) was 135.0 m^3. Field surveys recorded a maximum volume of 208.5 m^3. Rounding of elevation data was likely responsible for the underestimate of maximum storage capacity for pond 9-West.

Snow damming might also have been responsible for temporarily raising the pour elevation above that computed from terrain data.

None of the simulation runs emptied pond 9-West precipitously between April 12 and April 19 as recorded by the field survey. The model always took longer to remove the final volumes of water in any given pond than recorded by field survey. It is likely that field surveys simply did not recognize very small ponds or small saturated areas with no discernible accumulations of free surface water. It is also possible that once a pond reached a critically low volume (and depth) evaporation occurred at a rate in excess of that predicted by the Penman equation. It would be reasonable to expect more rapid evaporation from a very shallow pond underlain by dark, warm soil than from a deeper pond of open surface water.

7.4.16 Comparison of actual to simulated data for pond 9-East

Field survey pond 9-West corresponded to a large and complex grouping of individually defined DEM watersheds and depressions (109, 107, 106, 99, 90, 91) located along the southern edge of the study area (see Figure 4.18 and Table 4.4). Most of these watersheds and their associated depressions were incompletely defined as they extended outside the area defined by the available DEM data. Topography outside the area defined by the DEM was known to constrain flow away from the edge of the DEM and to result in the formation of a larger and deeper pond than defined by the available DEM data. It was not expected that the simulation model would correctly predict ponding for pond 9-East given that the data set was incomplete.

None of the simulation results (Table 7.16) were anywhere close to the observed pattern of ponding for pond 9-East. All simulation runs under estimated the initial maximum pond volume as determined by field survey. The maximum pond volume as defined by geomorphological analysis (Chapter 4) was only 40 m^3. Field surveys recorded a maximum volume of 639.4 m^3 for pond 9-East. The underestimate of maximum storage capacity for pond 9-East was caused by ponding defined by topography outside of the available DEM. An artificial pond could have been defined for pond 9-East by imposing a barrier of infinite height at the edge of the data matrix. This was done for some other edge pits (i.e. 182) but was not attempted for pond 9-East.

The results for pond 9-East demonstrated the need to completely defined all terrain contributing to the definition of depressions or to the generation of runoff into depressions.

7.4.17 Comparison of actual to simulated data for pond 3

Pond 3 corresponded to the very small edge pit 34 incompletely defined by the DEM. It appeared for a single date (April 26) and was considerably larger and deeper than computed from the available DEM data Table 7.17. It is likely that this pond grew upwards into the study area from a depression located outside the area defined by the DEM. This pond did not provide a valid test of the model since data required to define its characteristics and to estimate the magnitude of runoff into it were lacking.

7.4.18 Discussion of the best fit simulation provided by run 9

The degree of correspondence between the extent and depth of ponding simulated by the best fit case (run 9) and that recorded by field survey is tabulated in Table 7.18 and illustrated in Figures 7.2 through 7.6. The maps of pond extent and depth illustrate how well the model predicted the locations and depth of ponding for most of the major depressions. The simulated location, extent and depth of ponding (Figure 7.7) is probably adequate for most analyses of on-farm water management options.

The location, extent and depth of ponding simulated by run 9 was sufficiently accurate to prove useful for most practical purposes. Ponds that were predicted but not observed to occur (Figure 7.7) were mostly located at the edge of the data matrix. These artificial ponds do not invalidate the model since the data required to fully defined then were missing.

The model predicted the formation of numerous very small ponds (1 or 2 grid cells) during the initial period of snow melt. Many of these small ponds were in upland catchments with a limited contributing area. They filled rapidly based on runoff from melt water but drained and evaporated just as rapidly. It was not possible to conclude, based on the field data, that these small ponds did not actually form. They may have been overlooked by the field survey because they were too small or because they were obscured by snow during the initial period of spring melt. Most of the small ponds simulated by the model, but not recorded by the field survey, had disappeared by April

12, 1989. The extent of ponding simulated by run 9 closely resembled that recorded by field surveys for dates after April 12, 1989.

7.5 Summary and conclusions - model evaluation

7.5.1 Highlights and positive contributions

Application of the DISTHMOD model to the Lunty site for the period March 22 to June 15, 1989 demonstrated that the model was capable of simulating the location, volume, area and depth of ponding with considerable accuracy when ponds and their associated catchment areas were completely and accurately defined and the model was provided with appropriate input data.

The accuracy and reliability of simulated pond extent, depth and volume is highly dependent on correct estimation of the depth of snow cover since runoff from snow melt is responsible for virtually all initial pond development. Simulation of the timing and pattern of pond decay is mostly dependent upon appropriate estimates of losses by infiltration below ponds, but also requires some estimate of losses by evaporation. The generation of runoff from snow melt requires that infiltration into the soil be set to zero for periods when the soil is still frozen. Reduction in volume of ponds by infiltration through pond bottoms requires the soil to thaw shortly after maximum volumes are achieved (early April) to permit infiltration at rates approximating measured values for saturated hydraulic conductivity.

The best overall correspondence between simulated and field measured pond volumes was obtained for simulation run 9. In this run, the initial depth of snow varied according to landscape position and the overall mean snow depth for all grid cells was 0.15 m. In model run 9, infiltration into all soil stores was prevented until after April 4, 1989. All soils were designated to be frozen at all depths until April 4 and to thaw completely after that date. Rates for steady state infiltration (FC) assigned to all soil stores (S1, S2, S3) were based on the lower range of field measurements of saturated hydraulic conductivity taken at the site. Evaporation estimates based on the Penman equation as implemented by the model SWATRE were similar to, but slightly lower than, weekly sums of pan evaporation recorded at the site.

The simulation results confirm previous findings (MacAlpine, 1992; MacAlpine, Cooper and Neilson, 1992; Hubbard and Linder, 1986; Richardson and Arndt, 1989; Woo and Rowsell, 1993; Woo and Winter, 1993; Fortin, van der Kamp and Cherry, 1991) that most spring ponding in prairie landscapes can be attributed to runoff of snow-melt on frozen soils. They further confirm findings (Johnsson and Lundin, 1991; Woo and Rowsell, 1993) that significant reductions in rates of infiltration for frozen soils are required in order to obtain the volumes of runoff observed to arise from spring snow melt. Evaluation of model results confirms that the concept of rapid infiltration of snow-melt runoff at a small number of sites of depression-focused recharge can account for the most of the observed losses of water from the system. Evaporation from open water at the pond surface accounted for a smaller portion of the computed water balance.

7.5.2 Oversights and opportunities for improvement

The ability of the model to make reasonable predictions of pond volumes was very sensitive to estimates of snow depth at the site. Estimates of pond volumes produced using an arbitrarily assigned uniform depth of snow of 0.4 m (not an especially thick snow cover) were an order of magnitude greater than recorded by the field survey. Estimates of pond volumes produced using a variable depth of snowpack predicted by a regression equation (mean depth 72 mm) were considerably lower than recorded volumes. Pond volumes estimated using an average of the depth of snow close to that recorded at 44 sites (130 mm) were closest to observed volumes.

Estimates of the initial depth of the snow pack were, therefore, the source of the greatest differences between simulated estimates and field determinations of ephemeral ponding. In this light, the procedure used to predict snow depth from terrain derivitives was not as successful as hoped. The predicted depth of snow averaged 72 mm for all 22400 grid cells. This did not compare well with the average depth of 130 mm computed from the 44 snow pack observation sites. The volume of runoff from the snowpack estimated from regression equations was insufficient to fill the major depressions to anything close to their observed volumes. Assigning the average depth of snow (130 mm) to all 22,400 grid cells produced volumes of runoff and ponding much closer to observed values. A revised regression equation produced estimates for snow depth averaging 150 mm for the 22400 grid cells and produced estimates of pond volume and extent much closer to observed ponding (run 9). Initial pond volumes were incorrectly estimated for watersheds in which the total accumulation of

snow was over- or under-estimated and for ponds which contained a residue of water from the previous year. Application of the model would benefit, therefore, from improved procedures for measuring or predicting the initial depth of snow and for checking if any ponds retained water from the previous fall..

Errors in estimation of the initial maximum volume of ponding (the volume after completion of snow melt) had a great impact on the subsequent success of the model to accurately predict pond decay and disappearance. Initial pond volumes were incorrectly estimated for depressions where geomorphological analysis of the DEM data set did not compute correct maximum storage capacity. Maximum storage capacity was under-estimated for several upland ponds which were computed to overspill at a lower elevation and lower volume than actually observed. The results indicate that geomorphological procedures for estimating the maximum storage capacity of depressions were sometimes in error and could benefit from increased precision.

Evaluation of model runs indicated that infiltration below ponds made a greater contribution to pond decay than did evaporation. Similar reductions in pond volume were achieved in run 6 when infiltration rates were set to relatively high values and run 9 when maximum rates for infiltration were set considerably lower. In run 6 the soil thawed and infiltration was enabled in a staged fashion with store S1 thawing on April 12, S2 on April 22 and S3 on May 2, 1989. This meant that all of the water lost to the pond through infiltration remained stored in the top one metre of the soil until at least May 2, 1989. It may be inferred that, for most ponds, the top one metre of soil was capable of absorbing and storing a volume of water equivalent to most of the simulated reduction in pond volume attributed to infiltration. This may explain why the reductions in pond volume simulated using markedly different values for steady state infiltration rate (runs 6 & 9) were so similar.

Reductions in pond volume attributed to infiltration did not necessarily have to contribute to net ground water recharge. The infiltrated water could be removed by evaporation later in the year, when the ponds were empty. Evaporation at the fringe around ponds might also draw water away from storage in the soils beneath the pond and lower the volumes of water available for deep recharge.

Evaporation was concluded to play a less significant role in pond reduction than infiltration. Rates of evaporation would have had to be 3-4 times as high as simulated

in order to account for all of the observed reduction in pond volumes. Since the simulated estimates of evaporation were in good agreement with total pan evaporation measured at the site, there was little reason to conclude that higher rates of evaporation were involved in reducing pond volumes.

Data for the test period of simulation did not produce significant amounts of runoff attributable to rainfall inputs onto non-frozen soils. Some rainfall runoff was generated when infiltration rates were set to the lowest values recorded in the field for each soil and horizon. Field surveys had shown that ponds increased in volume after heavy rainfall in late June and early July. Meteorological data required for input into the model were compiled only up to June 15, 1989. This prevented running the model for a period of heavy rainfall in late June and early July known to have resulted in pond growth. The test data set was therefore not adequate for evaluating the ability of the model to simulate rainfall runoff under conditions of non-frozen soils and normal infiltration rates. A meteorological data set extending beyond July 15 would have provided a better test of the ability of the model to correctly simulate runoff on non-frozen soils.

The results demonstrated that infiltration rates needed to be reduced below normal measured values in order to produce runoff. If soils were assigned steady state infiltration rates based on modal values from field measurements no runoff or ponding occurred. It was especially necessary to impose a reduction in infiltration rates during the period of spring snow melt in order to simulate runoff and ponding in amounts close to those observed. An additional opportunity for improving the model would therefore have been to include a procedure for simulating soil temperature changes with time and linking changes in soil temperature to changes in infiltration rate.

The large number of model inputs and parameter choices required for DISTHMOD meant that different combinations of input data and parameter selections could give rise to very similar results. The model therefore proved more useful for seeking understanding of how the various processes inter-acted to produce runoff and ponding than for actually predicting runoff and ponding given a single set of input data and measured parameter values. In this sense, the experience tended to confirm Beven's (1989) view that highly-distributed, deterministic hydrological models were more suited to improving understanding of hydrological processes than to producing reliable predictions of real world behaviour.

CHAPTER 8

SUMMARY AND CONCLUSIONS:

8.1 Introduction

8.1.1 Overview

This chapter has two main aims. The first is to synthesise the findings and conclusions presented in chapters 3 through 7 with reference to similar recent studies. The second is to suggest how the procedures developed and tested for the present research might be modified or applied to support operational decision making.

8.1.2 Context

Significant developments have occurred in the study of wetland depressions since the present study was initially conceived and executed. Many of these provide additional support for the validity and utility of the present study. Interest in depressional wetlands has been revitalised as researchers, politicians and the public have increasingly recognised the importance of wetlands as an environmental resource. This has been evident in shifts in government policy from previous support for wetland drainage to the present focus on preservation and enhancement of wetland habitats (AWRC, 1987). Similarly, while few recent studies of wetland depressions existed when the present research was initiated (1987), a number of significant field and modelling studies of wetland depressions have since been published (MacAlpine, 1992; MacAlpine, Cooper and Neilson, 1992; Hubbard and Linder, 1986; Richardson and Arndt, 1989; Woo and Rowsell, 1993, Fortin, van der Kamp and Cherry, 1991; Johnsson and Lundin, 1991; Woo and Winter, 1993).

Despite the increased interest in depressional wetlands, and the continued development of distributed hydrological simulation models by large teams of researchers (Abbott et al., 1986; Foster and Lane, 1987; Woo and Rowsell, 1993), existing distributed models show little evidence of incorporating procedures for recognising depressions explicitly or for accounting quantitatively for accumulation of runoff in depressions.

To the best knowledge of the author, none incorporate mechanisms for delineating and accounting for growth or decay of ponds in multiple nested depressions.

8.2 Main conclusion

The significant contribution of the present study is, therefore, the development and implementation of a set of procedures for computing depressional storage capacity explicitly and for routing water into, through and out of ponds located in depressions. The author is not aware of any established distributed hydrological simulation model that permits the explicit recognition of depressions and provides a mechanism for detailed accounting of the volume of water added to, stored in or lost from depressions. All existing models that propose to simulate runoff in prairie landscapes with low relief and non-integrated drainage would likely benefit from adoption of similar techniques for quantifying and simulating depressional storage.

8.3 Specific conclusions

The field study (Chapter 3) did not make any major original contributions to the scientific knowledge of surface runoff and ponding. Rather, it provided additional corroboration of previous studies that demonstrated the importance of snow-melt and reduced infiltration during the period of spring melt in generating surface runoff and in initially filling wetland depressions (c.f. MacAlpine, Cooper and Neilson, 1992; Hubbard and Linder, 1986; Richardson and Arndt, 1989; Woo and Rowsell, 1993, Johnsson and Lundin, 1991). The field study produced a locally relevant database of meteorological observations that might prove useful to other researchers in the region. The measured extent and volume of surface ponding provides a basis for calculating the amount of water held in storage in a typical agricultural landscape with non-integrated drainage in a manner similar to that adopted by Hubbard and Linder (1986). The model of topographically controlled distribution of soils provides local confirmation of similar models developed by Richardson and Arndt (1989) and Zebarth and deJong (1989a). The relative lack of success achieved by the field study in measuring the spatially and temporally variable attributes of hydraulic conductivity and moisture status points out the need for improved procedures in this area. As a first approximation, however, estimates of hydraulic properties stored in existing databases of Soil Series characteristics (Alberta Soil Layer File) proved to be a workable alternative.

The techniques of geomorphological analysis presented in Chapter 4 provide an effective means of calculating all of the data needed to define the location, depth, maximum volume and hydraulic connectivity for all potential locations of ponds. These techniques represent a unique and original contribution. They extend the limited amount of previous work concerned with delineation and quantification of depressions (Burrough, 1986; Jenson and Domingue, 1988; Jenson and Trautwein, 1987; Yuan and Vanderpool, 1986). They document procedures for coping with multiple nested depressions and for establishing hydrological connectivity between depressions. They respond effectively to a recognized need for better tools for defining depressional storage and represent an improvement over any existing techniques known to the author. Some of the geomorphological concepts developed to assist in subsequent modelling (i.e. volume-to-first-flood, mm-to-first-flood) are novel and may prove to be useful measures for relating topography to potential soil wetness.

The computational framework adopted for the DISTHMOD model (Chapter 5) demonstrated the feasibility and desireability of retaining an explicit representation of depressional storage in a hydrological simulation model for a landscape with low relief and non-integrated drainage. The concept of defining depressions as objects in a relational database and the algorithms written to traverse the database during addition or removal of water from ponds proved workable and effective. When supplied with appropriate input data, water was routed to the correct locations and accumulated to approximately correct levels. This framework is the essential feature of the DISTHMOD model. The model did not make any unique contributions in the area of representation of hydrological process since most processes were represented using equations or algorithms extracted from other models. These process equations could be replaced without significantly altering the utility of the model as long as the basic framework is maintained. The database indexing approach used by DISTHMOD to order the processing of cells in a hydrologically correct order is relatively unusual and might prove to be useful for application in other distributed hydrological models.

Application of the DISTHMOD model (Chapter 6) demonstrated both the advantages and the disadvantages of the model as designed, given the data provided. The highly distributed nature of the DISTHMOD model was not especially useful for simulating infiltration into the soil or surface runoff during the period of study. It was effective in computing and portraying the detailed spatial pattern of pond formation and decay at specific dates. Equally good estimates of initial pond volume and subsequent pond decay would likely have been achieved, however, using a semi-distributed model with

a simplified representation of process. Application of the model did confirm that reduced rates of infiltration for frozen soils were required in order to produce initial spring-time runoff and fill depressions. On the negative side, application of the model demonstrated the limitations imposed by not including mechanisms for simulating the effect of soil temperature on infiltration, for simulating upward and lateral flow of soil moisture and for accounting for time dalays in overland flow. Additional limitations were the large amount of input data required and the long time required to run the model to completion on a personal computer.

Despite the above reservations, evaluation of the DISTHMOD model results against field measurements of actual ponding (Chapter 7) confirmed that the model made reasonable estimates of pond volume when provided with appropriate input data. Accurate information on the depth and water equivalent of snow is the critical requirement for successful estimation of the initial (maximum) volume of ponds immediately following completion of snowmelt. For this reason, techniques used in the current study for estimating the spatial distribution of snow depth and for computing the relative extent of infiltration of snowmelt into frozen soils would benefit from improvement. Evaluation of the model indicated that infiltration of water into soils beneath the ponds was the primary agent of pond decay with evaporation playing a secondary role. The model was not especially sensitive to the rate of infiltration assigned to the pond soils. It appeared that most of the water entering the soil beneath ponds went into storage and was available for evaporative loss later in the season.

The overall conclusion drawn from the study is that there is considerable merit in geomorphological procedures and hydrological models such as DISTHMOD that can compute runoff into depressions in agricultural landscapes with low relief and non-integrated drainage and that can portray the spatial and temporal patterns of the resulting ponds. It is suggested that the procedures for geomorphological analysis might prove applicable immediately for quantifying the location, size and hydrological connectivity of depressional storage in agricultural landscapes in the Canadian prairies. The fundamentally new concept illustrated by development and application of the DISTHMOD model is one of recognising depressions as explicitly defined objects and accounting for flow into, through and out of depressions. This concept might prove to be attractive for use in more comprehensive distributed hydrological models such as WEPP (Foster and Lane, 1987) or SHE (Abbott et al., 1986) which, so far, lack such capabilities.

8.4 General conclusions

A synthesis of the results of the simulation modelling (Table 8.1) reveals that, in general, the model produces good results for large pits, more variable results for medium sized pits and poor results for small pits (observation and tabulation contributed by P. A. Burrough, 1994, personal communication). Consideration of the relative success of the simulations for various types of depressions (Table 8.1) leads to the following conclusions:

- relative errors are very large for the smaller pits
- relative error is not proportional to pit size; rather the reverse appears true.
- errors in correct simulation of pond volume are mostly caused by errors in the DEM or in estimation of snow depth, rate of infiltration, or pond linkages.
- incompletness or errors in the DEM result in incorrect estimates of pond volumes, contributing areas and pond linkages.
- success in estimating snow depth varies by watershed with better success for large watersheds.
- factors other than topography (wind, exposure, willow rings) influence the accumulation and depth of snow and result in error in estimating of snow depth.
- variation in rate of infiltration has a greater effect on the success of simulations for small pits than large ones.

8.5 Future developments and operational application of the research

A valid concern with the research described above is how the procedures and models might be best applied or modified for operational use.

The techniques for geomorphological analysis could be applied immediately and without modification for documenting the locations and the potential volume, area and depth of depressions in farm-scale landscapes. Such measurements of fixed depressional storage capacity are of interest to farmers planning drainage activities, government agencies charged with regulating on-farm water management (Alberta Agriculture, Alberta Environment) and environmental agencies involved with the preservation and conservation of wetland habitat (Duck's Unlimited).

Several minor and feasible modifications would, however, make the procedures for gemorphological analysis easier to use and more productive. The first is to fully

automate the procedures for pit identification and characterisation which are presently partially manual. This would greatly improve their utility but would be easier to accomplish automatically if the number of pits to characterise could be kept relatively small. The second proposed modification is therefore to restrict, on the basis of area or volume, the number of pits identified and characterised at any given site. The recommended approach is to remove automatically all pits of less than a specified minimum volume from the DEM data set using the pit removing procedures described in Chapter 4. This will reduce the pits requiring characterisation to an easily managed number of large and significant depressions. An argument defending this recommendation is developed below.

The third suggested modification is to maintain the DEM at its most detailed level of vertical resolution (i.e. not round elevations off to the nearest 10 cm as described in Chapter 4). This will improve the precision with which the terrain is described and minimize problems with inaccurate identification of pour elevations and subsequent pond volumes as discussed in Chapters 4 and 7. Retaining a high degree of precision in the vertical resolution of the elevation data is likely to result in identification of a large number of very small (first order) depressions when the techniques presented in Chapter 4 are applied. This reinforces the need to limit the number of pits by removing depressions of less than a given volume or area. This raises questions about the relative contribution of depressions of different size to the total storage capacity of a landscape and the relative significance, with respect to model utility, of depressions of different size and volume. The argument in support of removing small pits follows.

If depressions are ranked in decreasing order of volume and the rank is plotted against the cumulative volume of water stored in all depressions (Figure 8.1 a) it is apparent immediately that most of the water at the Lunty site is stored in a limited number of the largest depressions (observation and graph contributed by P. A. Burrough, 1994, personal communication). In fact, the 5 largest depressions at the site cumulatively store 85% of all the water retained on the landscape. Close to 99% of the total volume of water is accounted for by the 15 largest depressions. Consequently, the observation of poor performance by the model in simulating accumulation of water in small pits is concluded to be relatively unimportant given the minor contribution of small pits to the overall storage of water in the landscape. This evidence supports the suggestion that smaller depressions can be eliminated from the data set without any significant adverse affect on the utility of the data or the efficacy of the model.

A further concern is whether the procedures developed to characterise the geometry of depressional storage at the Lunty site are applicable to other areas and landscapes. It is difficult to recommend that the same procedures be applied to different areas without offering some evidence to suggest that these other areas can be expected to display a similar pattern of depressions. This is particularly true of the recommendation to remove all small pits, which is based on an assumption that small pits make only minor contributions to the total storage volume of a landscape.

An investigation of the frequency distribution of pits of different volume suggests that pit volumes follow a fractal distribution (Burrough, 1994, personal communication). Several plots (not shown) illustrate that pit volumes display neither normal nor log normal distributions. A plot (Figure 8.1 b) of the log of pit volume against the log of rank approximates a straight line (observation and graph contributed by P. A. Burrough, 1994, personal communication). The linearity of this plot indicates a hyperbolic distribution in which the pit volumes are fractal over three orders of magnitude in accordance with Zipf's law (see Burrough, 1993, pp. 102-106). The fractal pattern suggests that the pits are self similar and supports the assumption that they might all have been formed by a single, similar scaling process (glacial dead-ice melting). The evidence supports the expectation that other areas of similar glaciated landscape can be expected to display a similar distribution of depressions. The techniques of geomorphic characterisation detailed in Chapter 4 and the modifications proposed above for routine application are therefore expected to be applicable to a wider area of similar landscapes in Alberta and in many other locations characterised by glacial dead-ice moraine.

Practical application of the model would benefit from other modifications in addition to those proposed above. Each doubling of the effective grid size results in a four times reduction in the number of grid cells requiring processing. Selection of a grid size of 10 or even 20 metres would dramatically simplify the model by reducing the time and effort required to provide parameter data, compute topological structure, establish pond statistics and simply run the model. It is unlikely that the loss of spatial resolution would significantly reduce the utility of model results. In fact, an even more dramatic reduction in spatial resolution might be appropriate. It could be achieved by replacing the distributed processing of individual grid cells with a semi-distributed, conceptual model at the level of each watershed. This would require further work and development so it is not an easily implemented modification.

A further suggested enhancement of the present model is to provide tools and data sets to assist casual users to identify different soils in different landscape positions and to assign attribute values to each identified soil. This could be accomplished by including automated procedures for segmenting the landscape into landscape facets and then identifying a typical soil for each landscape facet. The appropriate soil for each landscape facet would be identified by choosing from a selection of soils in a database. The database would contain estimated values for all the soil parameters required to run the model for each of a variety of typical soils. Assisted selection and paramaterisation of soils data would facilitate operation of the model by casual users.

The model should be tested further in additional areas and landscapes. In particular, an effort should be made to test the capability of the model to simulate changes in drainage, in advance of physical changes, by redirecting pointers in the pit data table. This kind of testing of what-if scenareos would be invaluable if the model was demonstrated to be capable of it. Regulatory and conservation agencies have already expressed interest in trying to use DISTHMOD to predict the consequences of imposed changes in drainage in advance of undertaking the changes.

A final requirement for operational use of the model is the development and installation of a user-friendly interface for controlling input, model operation, output and display. All of these currently require the operator be able to operate a variety of subsidiary software packages and to be intimately familiar with the operation of the model, the data structures used and the links with subsidiary software. This is not acceptable for operational use.

9.1 References

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