CHAPTER ONE

1. INTRODUCTION

This thesis develops a soil moisture profile estimation algorithm, which can estimate the spatial distribution and temporal variation of soil moisture content over the soil profile from infrequent measurements of near-surface soil moisture. The methodology is developed for application to the types of data provided by current remote sensing platforms.

A series of numerical studies with this soil moisture profile estimation algorithm were carried out to demonstrate the methodology, to explore the effect of different satellite characteristics on soil moisture profile estimation, and to prove the effectiveness of the techniques used. This thesis concludes with a demonstration of the soil moisture profile estimation algorithm on a field site, using some of the collected data to simulate satellite observations, while other data were used to evaluate to soil moisture profile estimation.

1.1 IMPORTANCE OF SOIL MOISTURE

The role of soil moisture in the top one to two metres of the earth’s surface is widely recognised as a key parameter in numerous environmental studies, including meteorology, hydrology, agriculture and climate change. Although this thin layer of soil water may seem insignificant when compared to the total amount of water on the global scale, it is this thin layer of soil that controls the success of agriculture, and regulates partitioning of precipitation into runoff and ground water storage. Furthermore, soil moisture content is one of the few directly observable hydrological variables that plays an important part in the water and energy budgets necessary for climate studies (Jackson, 1993). However, as a result of the heterogeneity of soil properties, topography, land cover, evapotranspiration and precipitation, soil moisture is highly variable both spatially and temporally (Engman, 1991; Wood *et al.*, 1993).

An operational capability to predict the temporal variation and spatial distribution of the soil moisture profiles would have numerous benefits in the fields of meteorology, hydrology, agriculture, and the monitoring of global climate change. Some of the obvious benefits in these fields include:

- Improved estimates of evapotranspiration through the influence on partitioning of available energy at the ground surface into sensible and latent heat exchange (Entekhabi *et al.*, 1993, 1994; Jackson *et al.*, 1994; Giacomelli, 1995).

- Improved weather predictions through improved modelling of the interaction of land surface processes (Fast and McCorcle, 1991; Engman, 1992; Betts *et al.*, 1994; Su *et al.*, 1995).

- Improved flood forecasting through the influence on partitioning of precipitation between runoff and infiltration (Entekhabi *et al.*, 1993; Su *et al.*, 1995).

- Economical and water conservation benefits through rational irrigation scheduling (Jackson *et al.*, 1981; Jackson, 1982; Jackson *et al.*, 1987; Saha, 1995).

- Increased crop yield through optimal soil moisture conditions at pre-planting and during the growing season (Topp *et al.*, 1980; Jackson *et al.*, 1987; Saha, 1995).

- Economical and environmental benefits from selective application of pesticides for soil moisture dependent insects and diseases (Engman, 1990).

- Management of cultural practices, including trafficability in the fields (Wigneron *et al.*, 1998).

- Early drought prediction (Engman, 1990), drought monitoring (Jackson *et al.*, 1981; Jackson *et al.*, 1987) and evaluation of drought impact on agricultural production (Newton *et al.*, 1983) for management of rural subsidy schemes.

- Improved erosion prediction through improved hydrological modelling and the relationship between erosion and runoff producing zones (Beecham, 1995; Western *et al.*, 1997a).

- Monitoring of global climate change through persistence of high or low soil moisture content (Engman, 1992).
- Global heat balance as a result of soil de-nitrification (Axelsson *et al.,* 1990).

1.2 STATEMENT OF PROBLEM

In spite of its importance, there is no operational system for forecasting the soil moisture status. The reason for this is that most hydrologic, agricultural and meteorological applications which can benefit from soil moisture measurements have three general requirements: (i) frequent observations; (ii) an estimate of soil moisture content within the top one to two metres of the soil profile; and (iii) the spatial variation of soil moisture content over large areas (Schmugge *et al.,* 1980).

Soil moisture is difficult to measure over large areas in a cost effective and routine manner using conventional methods. Furthermore, traditional techniques for soil moisture estimation yield data for a point, which does not always represent the spatial distribution (Jackson *et al.*, 1981; Engman, 1990). However, the traditional techniques can provide an accurate measurement of soil moisture content in the soil profile at that point (Schmugge *et al.,* 1980). The problems associated with this type of acquisition are the limited area that can be satisfactorily monitored with an acceptable spatial and temporal resolution, as well as in trying to interpolate highly variable data that generally exhibits a very low spatial correlation (D’Urso *et al.,* 1994; Giacomelli, 1995). Thus, if the spatial distribution over a large area is required from point measurements, the costs can become prohibitive (Schmugge *et al*., 1980).

Given the difficulties associated with estimating the spatial distribution of soil moisture profiles from point measurements, soil moisture is often estimated from hydrological models (Mancini and Troch, 1995; Bolognani *et al.,* 1996). Soil moisture models provide predictions of the spatial distribution of soil moisture profiles. However, these models generally require large amounts of meteorological data, which can be difficult and costly to obtain (Ottlé and Vidal-Madjar, 1994). Furthermore, model parameters are difficult to determine, requiring calibration, often resulting in simulation errors (eg. Wood *et al.,* 1993).

In addition to point measurements and hydrological models, soil moisture content can be measured using remote sensing. Remote sensing methods can be used to rapidly collect spatial data over large areas on a routine basis, providing a *potential* capability to make frequent and spatially comprehensive measurements of the near-surface soil moisture content (Jackson *et al.*, 1987; Engman and Chauhan, 1995). Over the last two decades there has been a significant research effort to develop techniques for observing soil moisture content by remote sensing. Recent advances in remote sensing have demonstrated the ability to measure the spatial variation of soil moisture content in the near-surface layer under a variety of topographic and land cover conditions (Wood *et al.*, 1993).

However, a major problem with satellite data is the long satellite repeat time, which is the number of days between overpasses of the same point on the ground. All current active microwave remote sensing satellites have a standard repeat time in excess of 1 month (Wigneron *et al.*, 1998). Hence, current generation remote sensing platforms, while providing a good spatial coverage for any given image, have a poor resolution in time. Therefore, methods need to be developed for interpolation of the near-surface soil moisture observations with time, which account for the variations in atmospheric forcing.

In addition to the restrictions from a poor temporal resolution, remote sensing only measures the soil moisture content of the near-surface layer of soil, consisting of the top few centimetres at most. These upper few centimetres in the soil are the most exposed to the atmosphere, and vary rapidly in soil moisture content, on the order of hours (Raju *et al.*, 1995; Capehart and Carlson, 1997) in response to rainfall and evaporation. In fact, the soil surface may change from wet to dry within a period of 1 or 2 days (Jackson *et al.*, 1976), with deeper soil moisture content changing more slowly. Thus to be useful for many climatic, meteorologic, hydrologic and agricultural studies, remote sensing information must be related to the complete soil moisture profile in the unsaturated zone, as any individual image will largely reflect the climatic effects of the last few hours, rather than the average for the inter-observation period. Therefore, for remote sensing observations are to be valuable in applications, methods must be developed to estimate the *soil moisture profile* using the *near-surface layer* measurements of soil moisture content that these sensors provide.

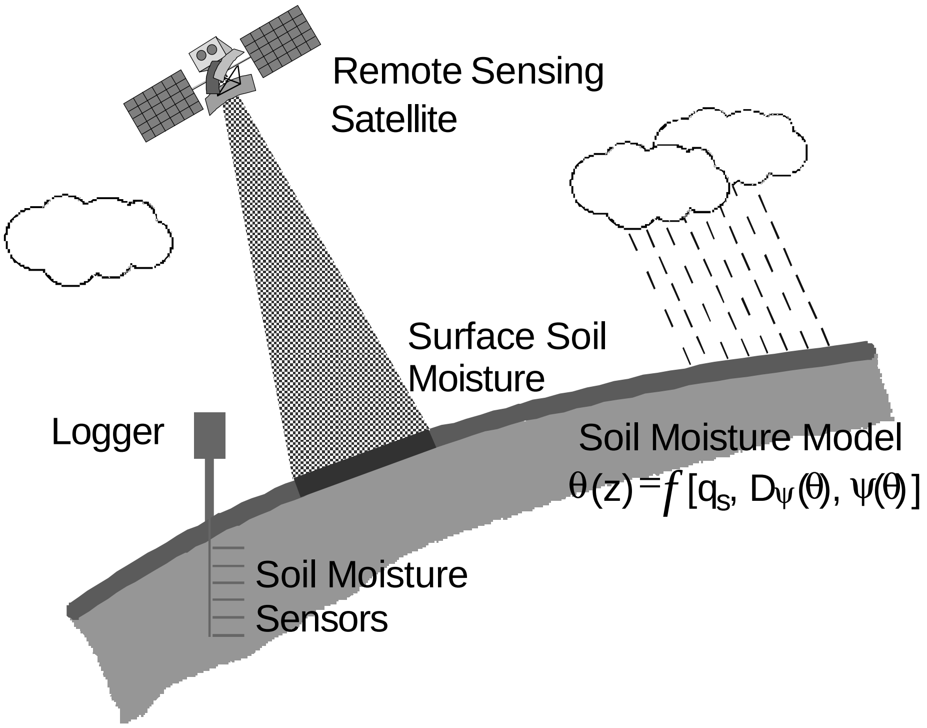

Figure 1.1: Schematic representation of the soil moisture estimation problem.

Given the inherent problems of the three separate approaches to determining the spatial distribution and temporal variation of soil moisture profiles, an effective soil moisture monitoring program must combine the three approaches; point measurements, hydrological modelling and remote sensing (see Figure 1.1). Point measurements, which are the most accurate, would be used sparingly for calibration and evaluation of the hydrologic model, which yields information on both the spatial (horizontal and vertical) distribution and temporal variation of soil moisture content. Remote sensing observations, which provide a measurement of the near-surface soil moisture content, would be used for updating of the hydrologic model by data assimilation, to minimise the effects of model input data (model parameters and atmospheric forcing) inadequacies. Using such an approach, the problems associated with collecting information on soil moisture status may be addressed, transforming soil moisture content from an internal to an external model variable. It is to develop this integrated estimation approach that this thesis is addressed.

Only a small number of studies have attempted to use remotely sensed near-surface soil moisture measurements as either input to a hydrologic model, or as verification data (Beven and Fisher, 1996). The reasons for this are: (i) that remote sensing data is just beginning to gain acceptance in the hydrologic community as an operational tool for measuring the near-surface soil moisture; and (ii) assimilation of remote sensing data requires the development of hydrological models that simulate soil moisture for a thin near-surface layer which is compatible with the nature of the remote sensing observations (Lakshmi and Susskind, 1997). In addition, techniques for updating the hydrologic model with remote sensing data require investigation, and the near-surface soil moisture observations must be proven useful when used with hydrologic models (Georgakakos and Baumer, 1996).

With the exception of only a few studies, all previous studies have assimilated near-surface soil moisture content into a hydrologic model, with the objective to improve predictions of evapotranspiration or runoff, or have only estimated the soil moisture profile for a one-dimensional soil column, often using synthetic data (eg. Entekhabi *et al.*, 1994). Furthermore, with the exception of a single study (Houser *et al.*, 1998), there has been no assessment of the assimilation schemes used for updating of the hydrologic model.

This thesis has investigated the ability to make improved estimates of the spatial distribution and temporal variation of soil moisture profiles from assimilation of near-surface soil moisture observations into a hydrologic model. Hence, the hydrologic model is forced with evapotranspiration and precipitation estimates from standard meteorological observations, and updated with near-surface soil moisture observations when they are available, to correct for model forecasting errors as a result of model calibration, initialisation and forcing errors. The following section describes more fully the objectives and scope of this thesis.

1.3 OBJECTIVES AND SCOPE

The principal objective of this research was to develop a methodology for making improved estimates of the spatial distribution and temporal variation of soil moisture profiles, by using a combination of the current approaches for soil moisture measurement and estimation, through the process of data assimilation. However, additional objectives included:

i) The development of a theoretical backscattering model for active microwave remote sensing observations that incorporates the effects of scattering within the near-surface soil layer (volume scattering).

ii) The development of a methodology for estimating the remote sensing observation depth for active microwave observations.

iii) The identification of an appropriate methodology for estimating the soil moisture profile from near-surface soil moisture measurements, and the establishment of this methodology (ie. the soil moisture profile estimation algorithm).

iv) The development of a one-dimensional model that is applicable for forecasting of soil moisture content in a manner that will allow the assimilation of near-surface soil moisture measurements.

v) A comparison of previously used techniques for assimilating near-surface soil moisture measurements into the hydrologic model, using the model developed in (iv).

vi) An assessment of the importance of observation depth in estimating soil moisture profiles, using the model developed in (iv).

vii) An assessment of the benefit of more frequent observations of the near-surface soil moisture content, using the model developed in (iv).

viii) Extending the hydrologic model in (iv) to forecast the *spatial* distribution of soil moisture profiles in a computationally efficient manner that is amenable to accepting the assimilation of near-surface soil moisture measurements.

ix) Development of a methodology for evolving the system state covariances in a computationally efficient manner for assimilation of the near-surface soil moisture measurements into the hydrologic model developed in (viii).

x) The collection of an appropriate data set for evaluation of the soil moisture estimation algorithm tested in this thesis.

xi) An assessment of the benefits from using spatially distributed measurements of near-surface soil moisture content to improve the estimate of spatial distribution and temporal variation in soil moisture profiles, from the data collected in (x), using the forecast model developed in (viii) and the system state covariance estimation methodology developed in (ix).

Actual remote sensing observations of the near-surface soil moisture content were not used for assimilation into the hydrologic model, as there are still some unresolved questions in the hydrologic community regarding the accuracy with which near-surface soil moisture content can be measured from remote sensing observations. Hence, to eliminate any of the influences from perhaps poor measurement of the near-surface soil moisture content on the conclusions of this thesis, ground measured near-surface soil moisture content with similar characteristics to ideal remote sensing data were used. In this way, the usefulness of near-surface soil moisture measurements, when assimilated into a hydrologic model has been proved.

Whilst no remote sensing data were used in the data assimilation component of this study, development of the methodology was focussed on direct application to remote sensing observations, and the potential of extending this methodology to an operational system for near-real-time estimation of soil moisture profiles on a large scale. Hence, in order to ensure applicability of the methodology to remote sensing observations, an intensive review of the current status and requirements of remote sensing models used for inferring the near-surface soil moisture from remote sensing observations was essential.

1.4 OUTLINE OF APPROACH

The philosophy taken towards achieving the objectives of this research was “you need to crawl before you can walk”. Hence, this work has investigated the ability to estimate the soil moisture profile for a one-dimensional soil column, before investigating the ability to estimate the spatial distribution of soil moisture profiles. The reason for this was that problems evident from a one-dimensional analysis, which still exist at the spatial scale, may be much more difficult to identify when modelling the spatial problem. Results from the one-dimensional modelling have provided insight into how to best undertake the estimation of soil moisture profiles over large areas. Furthermore, beginning with a complex one-dimensional hydrological model has yielded insight into the essential elements of a simplified hydrological model for the spatial problem. The use of synthetic data in this pilot study has separated out the effects of experimental errors and model error on soil moisture profile estimation from those of the soil moisture profile estimation algorithm itself.

The methodology proposed for making improved estimates of the spatial distribution and temporal variation of soil moisture profiles has been evaluated for the Nerrigundah experimental catchment. In this application, ground measurements of near-surface soil moisture content were used, to illustrate soil moisture profile estimation capabilities when using the most accurate near-surface soil moisture measurement capability currently available. This also illustrates the universal nature of the proposed methodology. The soil moisture profile estimation algorithm was evaluated using point measurements distributed throughout the experimental catchment.

1.5 ORGANISATION OF THESIS

The research embodied in this thesis is divided into twelve chapters. Chapter 2 gives the literature review of soil moisture measurement techniques (point measurements and remote sensing), while Chapter 3 gives the literature review of soil moisture profile estimation techniques (interpretation of point measurements, hydrological modelling, interpretation of near-surface measurements and their assimilation into hydrological models). Chapter 3 concludes with a detailed explanation of the soil moisture profile estimation algorithm investigated in this thesis.

A procedure for determining the radar observation depth and the soil moisture profile over that depth from radar observations is proposed in Chapter 4. A correct knowledge of the observation depth is essential for updating of the hydrologic model, while measurement of the soil moisture profile over the observation depth, rather than a single soil moisture value, may allow for improved updating of the hydrologic model. These procedures are evaluated with experimental data.

Chapter 5 develops the one-dimensional soil moisture profile model used in the synthetic soil moisture profile estimation study in Chapter 6, which investigates the feasibility of soil moisture profile estimation from near-surface soil moisture observations. In this synthetic study, a number of assimilation schemes are investigated. Their ability to improve soil moisture profile estimates from the soil moisture profile model is compared. The effects of observation depth, observation repeat time, and hydrologic model structure, are investigated. This synthetic study yielded invaluable insight into the most efficient data assimilation scheme for the spatial estimation problem and the essential requirements of the hydrologic model for forecasting of soil moisture profiles.

From the insights gained in Chapter 6, a computationally efficient hydrologic model is developed in Chapter 7 for forecasting of the spatial distribution and temporal variation of soil moisture profiles. In addition, the standard Kalman-filter assimilation scheme is too computationally intensive for large scale application. Hence, Chapter 8 develops a computationally efficient modification to the Kalman-filter assimilation scheme, which estimates the system state covariance matrix using a sub-optimal technique.

Chapter 9 presents the data collected in the Nerrigundah experimental catchment. This data is used in Chapter 10 for evaluation of a one-dimensional version of the simplified soil moisture model developed in Chapter 7, and its application to the soil moisture profile estimation algorithm with the Kalman-filter assimilation scheme. Chapter 11 applies the spatially distributed soil moisture forecasting model developed in Chapter 7 with the Modified Kalman-filter assimilation scheme developed in Chapter 8, to the estimation of soil moisture profiles in the Nerrigundah catchment.

The conclusions of this research and a discussion of future direction for estimating the temporal variation and spatial distribution of soil moisture profiles from point and near-surface soil moisture measurements are given in Chapter 12.