The Geomorphic and Hydrological Character, Behaviour and Function of an Intact Upland Swamp, Budderoo Plateau, New South Wales, Australia

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May 2010

This thesis is submitted as fulfilment for the Honours degree of Bachelor of Environmental Science from Macquarie University

Declaration

I certify that this thesis has not been submitted to any other university, or institution, for a higher degree. Except where otherwise acknowledged, this thesis comprises solely my own work.

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May 2010

Abstract

Upland swamps are a form of topogenous mire which occur on the plateaux areas of southeastern Australia. These systems are well recognised for their ecological value and their functional role in the hydrodynamics of the catchments in which they occur. However, little is known about the internal hydrological functioning of upland swamps and how this relates to their geomorphic structure and evolution. Upland swamps are currently vulnerable to widespread and ongoing degradation as a result of landuse change, longwall mining, dewatering, peat mining and urbanisation. With this in mind, the aims of this study are to supplement the current knowledge on the geomorphic evolution and physical characteristics of upland swamps of Eastern Australia, and to provide baseline data on their internal hydrological functioning. The sedimentological, geomorphic, hydraulic and hydrological properties of an intact upland swamp on the Budderoo Plateau NSW are investigated. The geomorphic structure of the swamp is simple, and is comprised of four distinct geomorphic zones: the central swamp, the headwater marginal swamp, the valley marginal swamp, and the hillslope zones.

The results of this study indicate that the development of the swamp was uniform and consisted of a sequence of mineral deposition (up to 1 m thick overlying bedrock) followed by a subsequent phase of organic accumulation up to 3.3 m thick. The organic accumulation has produced a layer of upper fibric organic fines and lower sapric organic fines. Each of these sedimentary units has different hydrological behaviours (rates of water transfer and discharge) that drive the overall function of the swamp in response to rainfall of various magnitudes and duration.

Three hydrological response regimes have been identified in the functioning of this swamp. These regimes are characterised by different peak and recession responses to rainfall. The form of the hydrograph produced is controlled by antecedent water table position (i.e. which sedimentary layers are saturated) and the amount, timing and duration of rainfall. Depending on antecedent moisture conditions, the swamp can be operating either as a store for water or as a rapid conduit for water throughflow and overland flow. It therefore has a dual function in terms of flow generation in response to rainfall. These findings are consistent with those established within the Australian literature on upland swamps and within the broader international peatland literature.

Acknowledgements

Firstly, I would like to acknowledge the indispensible and untiring support, encouragement and guidance provided by my principle internal academic supervisor, Dr. Kirstie Fryirs, throughout the completion of my thesis. I thank her for continually compelling me to achieve to my best ability, and for her valuable advice at times of doubt. I would especially like to thank her for drinking almost six litres of milk in less than a week so that I could use the empty bottles in my project. Thanks also to my secondary academic supervisor, Dr. Grant Hose, for his willing assistance wherever required, both in regards to the theory and in the field.

Secondly, I would like to thank my parents, Sue and Bob, for their generous and unceasing support in the field, in the lab, and at home. They shared in every moment of achievement, stress, fatigue, and pride that I experienced throughout the duration of my thesis project, and I am grateful for their patience and support.

Similarly, I acknowledge the kind support of my colleagues and friends, Erla Hafsteinsdottir and Supriya Mathew, and thank them for their contributions and positive encouragement. Thanks also to my field assistants, Nathan Cussen, John Bishton, and Jane Bailey who provided the much needed extra hands and muscle required to complete the field component of my research. Thanks to Russell Field, Scientific Officer, Department of Environment and Geography, for his technical advice and for helping to organise the extensive list of equipment required for the many field and lab components of my project.

Thanks to Jacqueline Devereaux and the staff at Fitzroy Falls NSW NPWS for their assistance and cooperation.

This thesis is part of a larger study on the geomorphological, hydrological, and biological functioning of upland swamps. Groundwater depth data was collected by myself and another Honours student, Jane Bailey. The raw groundwater data is therefore shared data.

This project was conducted in the Budderoo National Park under NSW NPWS Scientific Licence No. S13034.

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1 Introduction

Upland swamps are distinctive features of low-relief plateaux areas in southeastern Australia (Dodson, 1987; Young, 1982; Young, 1986a; Young, Young, 1988). They are a form of topogenous mire, restricted to the poorly-drained headwaters of low-order stream networks (Keith, Myerscough, 1993; Prosser, Slade, 1994; Young, 1982; Young, 1986a). While they are generally characterised by a lack of any persistent, continuous channel (Young, 1982; Young, 1986a), their geomorphic form is variable, and they can contain discontinuous pools, chains-of-ponds, and stable, narrow and deep channels (Eyles, 1977; Nanson, 2009a; Nanson *et al.*, 2010; Tomkins, Humphreys, 2006; Young, 1986a). This range of forms has led to some confusion regarding the terminology used to describe these landscape features (Mactaggart *et al.*, 2008), and they have variously been referred to as 'swampy meadows', 'dells', 'cut-and-fill landscapes', 'mires' and 'bogs' (Fryirs, Brierley, 1998; Prosser, Slade, 1994; Young, 1982; Young, 1986a; Young, Young, 1988). However, these upland swamp systems can be defined broadly as sediment-choked fluvial systems which are comprised at least in part of accumulations of highly organic deposits, and which actively function to store and transfer flows of water in alluvial fills on the valley floor.

A range of upland swamp types occur in various regions of southeastern Australia. On tablelands characterised by basic volcanic, fine-grained sedimentary or granitic lithologies, the '*Montane Peatlands and Swamps of the New England Tableland, NSW North Coast, Sydney Basin, South East Corner, South Eastern Highlands and Australian Alps Bioregions'* type occurs (DECC, 2008). Examples of this upland swamp type are found in the Barrington and Gloucester Tops (Dodson, 1987; Dodson *et al.*, 1994; Nanson, 2009a; Nanson *et al.*, 2010), the mountains of the ACT (Hope *et al.*, 2009), the Southern Highlands (Hope, 2003). On the sandstone plateaux of the Sydney Basin, the *'Temperate Highland Peat Swamps on Sandstone'* type are found (DECC, 2008). Examples of this type occur on the Woronora Plateau (Keith *et al.*, 2006; Tomkins, Humphreys, 2006; Young, 1982; Young, 1986a), on the Barren Grounds and Budderoo Plateaux (Burrough *et al.*, 1977; Prosser, Melville, 1988; Young, Young, 1988), in the Blue Mountains on the Newnes Plateau (Holland *et al.*, 1992), and on the Hornsby and Somersby Plateaux near Sydney (Bell *et al.*, 2005; Buchanan, 1979).

These upland swamp systems are well recognised for their high floristic biodiversity (Keith, Myerscough, 1993), and as habitat for endangered species of fauna including the Blue Mountains Water Skink, the Giant Burrowing Frog and the Giant Dragonfly (DEH, 2005). They are protected under Australian legislation as endangered ecological communities under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) due to their restricted distributions and ongoing threats from the impacts of agricultural landuse changes, longwall mining, dewatering, peat mining, and urbanisation. These factors have to date caused a significant degree of damage to many upland swamps, often inducing rapid, severe and irreversible erosion following knickpoint initiation brought about by physical and ecological changes such as sediment compaction and stripping, vegetation invasion, and water table drawdown.

In addition to the ecological values of upland swamps, they are widely cited as playing a functionally significant role in the maintenance and delivery of a potable water supply, and in catchment hydrodynamics (DECC, 2008; DEH, 2005; Hope, 2003; Keith *et al.*, 2006; Mitry, 2008). It is commonly upheld that upland swamps function to store rainwater falling within their sub-catchments, attenuating the storm hydrograph of the greater catchment in which they are found, and then release it slowly as base-flow in dry periods (Bell *et al.*, 2005; DECC, 2008; DEH, 2005; Hope, 2003; Hope *et al.*, 2009; Keith *et al.*, 2006; Mitry, 2008; Tomkins, Humphreys, 2006). However, within the Australian literature, there is a significant deficiency in quantified studies directly addressing these hydrological functions; to what degree the swamp affects the hydrograph (or whether it affects it at all), and by what internal mechanisms is this function determined. The resolution of these questions becomes imperative in the current Australian climate of water resources scarcity, and in the face of ongoing and expanding threats against the integrity of upland swamp systems.

The hydrology and geomorphology of upland swamps are tightly coupled. Since swamps largely act to store water in their sediment profile, and transfer it as subsurface flows through the sediment matrix, there is synergistic interaction between the physical properties of the swamp fill and the water which it contains (Kaufman *et al.*, 2005). In all peatlands, there is a reciprocal relationship between swamp hydrology and swamp geomorphology, such that the development of the geomorphic character and features of the swamp can be attributed, in part, to its historical hydrological regime. In turn, the geomorphic characteristics of the swamp influence its hydrological functioning within the greater catchment (Baird *et al.*, 2008; Balek, Perry, 1973; Belyea, Baird, 2006; Kaufman *et al.*, 2005; Romanov, 1968). The water flux through a swamp basin is affected by the antecedent conditions in groundwater position and soil moisture, as well as the character (magnitudes and duration) of the rainfall which occurs (Evans *et al.*, 1999; Kaufman *et al.*, 2005; Kvaerner, Klove, 2008; McCartney *et al.*, 1998; Rycroft *et al.*, 1975a; Worrall *et al.*, 2007). As such, the view that wetlands are water storage reservoirs and flood attenuators is subject to change under different hydrological boundary conditions. As such, it is imperative that for the management of downstream water resources, an understanding of the processes occurring within upland swamps must be considered.

1.1 Objectives of the Study

This study aims to supplement the current body of literature addressing the geomorphic evolution and physical characteristics of intact upland swamps, and provide baseline data on the hydrological behaviour and functioning of upland swamps in an Australian context (Figure 1.1, column 1).

The current study focuses on an example of *Temperate Highland Peat Swamps on Sandstone*, (henceforth termed upland swamp) located on the Budderoo Plateau in the Southern Tablelands of NSW, and addresses the aforementioned aims by resolving the following fundamental research questions (Figure 1.1, column 2):

- **Q1:** What is the geomorphic structure of the study swamp?
- **Q2:** What is the character and the structure of the sediments within the fill?
- **Q3:** How did the study swamp evolve, and what factors contributed to its development?
- **Q4:** What are the internal hydrological characteristics of the study swamp?
- **Q5:** What is the internal hydrological behaviour and function of the study swamp?

In Figure 1.1, Column 3 outlines the specific data analyses which will be used to answer these fundamental research questions. These methods are described in detail in Chapter 4.

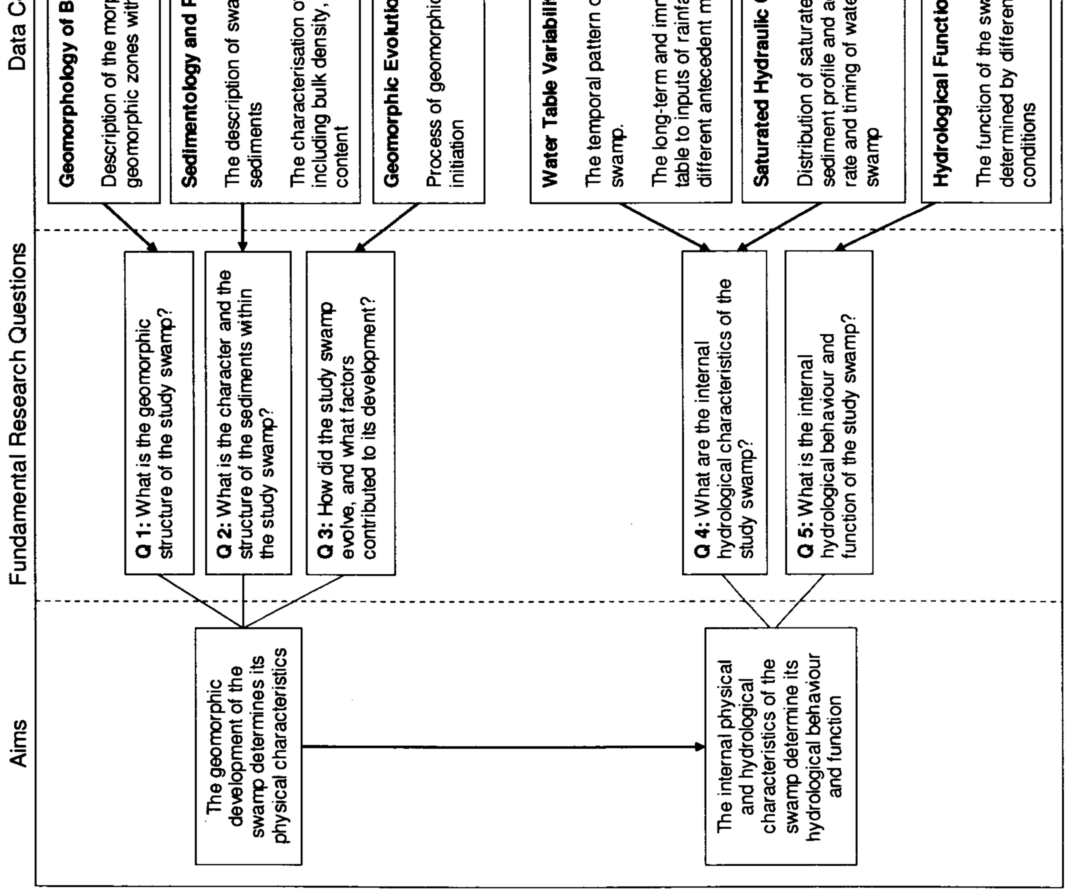


Figure 1.1: Conceptual diagram of project aims, fundamental research questions and specific

1.2 Structure of the thesis

Chapter 2 provides a literature review of domestic and international literature on the geomorphology, age structure and hydrological functioning of upland swamps and peatlands. Chapter 3 introduces the study site (Budderoo swamp) and its regional setting. Chapter 4 details the range of field and laboratory methods and experiments that were conducted in this project. Chapter 5 details the geomorphic structure of the study swamp, presenting the morphology and sedimentology of the swamp.

Chapter 6 presents the results from field and lab experiments to quantify the hydrological behaviour and hydraulic properties of the study swamp. Chapter 7 brings together the geomorphology and the hydrology for the study swamp to analyse the overall structure and function of the swamp. Chapter 8 places the current study in the context of the international literature and discusses the key scientific contributions from this research. Finally, Chapter 9 presents some summary conclusions, management implications and areas for further research.

2 Review of the Geomorphology, Evolution and Hydrology of Upland Swamps

This chapter reviews the current state of knowledge regarding the processes of formation, the geomorphic character, and the hydrological behaviour and functioning of upland swamps. First, the controls on upland swamp initiation and development in southeastern Australia are summarised, including dated examples from the Barrington Tops, Blue Mountains and Woronora plateaux. The evidence for specific swamp growth processes, such as phases of cut-and-fill and rates of peat accumulation and sedimentation, are reviewed. Next, the contemporary forms and geomorphology of upland swamps, as well as their proposed process-form origins, are described from the literature. The final sections of the review address the hydrological aspects of upland swamps, including hydrological zonation, water table behaviour, and the hydrophysical dynamics of peatlands. Throughout the review, attempts have been made to place the Australian literature in the context of international interests in peatland dynamics, to identify common concepts within the existing literature, and to critically assess its key limitations.

2.1 Initiation and Development of Upland Swamps

The literature addressing the development of upland swamps in southeastern Australia focuses on their age structure, the controls on swamp formation, and the history of geomorphic episodes such as increased sedimentation and cut-and-fill. While there are some significant insights into upland swamp development, there is still much to be resolved.

2.1.1 Controls on Swamp Initiation

While a wide range of basal dates record the start of swamp development in the late Pleistocene and early-mid Holocene, there is some agreement that a major phase of swamp development may have coincided with warmer, moister conditions occurring during the early- to mid-Holocene, around 8,000 – 5,000 years BP (Table 2.1) (Dodson, 1987; Dodson, Ono, 1997; Dodson, Thom, 1992; Johnston, Brierley, 2006; MacPhail, Hope, 1985; Singh, Luly, 1991). This timeframe is directly consistent with a Holocene peak in effective precipitation and low sediment yield (the hypsithermal) described by (Cohen, Nanson, 2007).

Table 2.1: Basal ages of upland swamps in southeastern NSW. 1. Stockton and Holland (1974); 2. Young, (1986a); 3. Dodson, (1987); 4. Kodela and Dodson (1988); 5. Sweller and Martin (2001); 6. Tomkins and Humphreys (2006)

Swamp	**Region**	**Elevation (m asl)**	**Basal Age (years BP)**	**Material**	**Reference**
Lawson Ck	Blue Mountains Plateau	685	4,110 ± 100	Sandy peat	1
North Katoomba Ck	Blue Mountains Plateau	975	7,350 ± 160	Sandy peat	1
Katoomba Ck	Blue Mountains Plateau	975	9,750 ± 150	Sandy peat	1
Leura Falls	Blue Mountains Plateau	940	17,050 ± 600	Sandy peat	1
Flying Fox Ck	Woronora Plateau	460	11,710 ± 280	Charcoal	2
Loddon River	Woronora Plateau	370	16,950 ± 140	Organic sand	2
Martins Swamp	Woronora Plateau	455	6,820 ± 90	Organic sand	2
O'Hares Swamp	Woronora Plateau	450	3,970 ± 70	Organic sand	2
Butchers Swamp	Barrington Tops Plateau	1260	11,280 ± 110	Carbon	3
Horse Swamp	Barrington Tops Plateau	1260	11,020 ± 180	Carbon	3
Boggy Swamp	Barrington Tops Plateau	1170	9,210 ± 230	Carbon	3
Black Swamp	Barrington Tops Plateau	1500	8,600 ± 130	Carbon	3
Top Swamp	Barrington Tops Plateau	1500	2,900 ± 100	Carbon	3
Polblue Swamp	Barrington Tops Plateau	1450	3,540 ± 70	Carbon	3
Killer Bog	Barrington Tops Plateau	1320	8,230 ± 130	Carbon	3
Sapphire Swamp	Gloucester Tops	1280	230 ± 90	Carbon	3
South Salvation Ck	Hornsby Plateau	130	5,150 ± 200	Peat	4
Burraga Swamp	Barrington Tops	985	38,050 ± 600	Carbon	5
Dahlia Swamp	Woronora Plateau	230	6,940 ± 140	Charcoal	5
Flat Rock Swamp	Woronora	150	1,974 ± 37	Charcoal	6

However, some authors disagree that a single major climatic shift on a regional scale was responsible for a synchronous landscape movement towards initial upland swamp formation throughout southeastern Australia (Dodson, 1987; Tomkins, Humphreys, 2006; Young, 1986b). These authors suggest that upland swamp initiation and development is related primarily to the influence of fundamental local controls. These may include topography, lithology and local hydrological balance (Buchanan, 1979; Burrough *et al.*, 1977; Holland *et al.*, 1992; Tomkins, Humphreys, 2006; Young, 1986a). On the Woronora and Hornsby Plateaux, Young (1982, 1986a) and Buchanan (1979) respectively, describe catchment slope as a significant indicator of swamp location and initiation. Young (1986a) states that 88% of swamps on the Woronora Plateau occur on slopes of less than 10°, while Buchanan (1979) reports that 85% of mapped swamps on the Lambert Peninsula section of the Hornsby Plateau occur on slopes of 5° or less. Similarly, longitudinal stream slope is recognised as contributing to swamp formation within the 'perched headwater valleys' of the Blue Mountains, albeit via a different mechanism than the simple topographic influence described by Young (1982, 1986a) and Buchanan (1979). Holland et al. (1992) notes that the occurrence of these systems in the Blue Mountains directly relates to the presence of resistant claystone outcrops which isolate the headwaters from lower reaches. This effects a low-gradient longitudinal profile in these upper reaches, which are fed by a reduced contributing area. These low longitudinal slopes, along with generally small catchment sizes, suggest inherently low-competence systems, which aids the gradual accumulation of sediment in these valleys.

The lithological character of the swamp catchment can act to create localised, perched water tables within the swamp basins. Buchanan (1979) describes a 'puggy' clay material underlying swamp sediments of the Lambert Peninsula, which not only acts as an aquiclude which impedes vertical drainage, but also contributes actively to the water balance by supplying inputs during low-flow conditions. Young (1982, 1986a) and Holland et al. (1992) also suggest that the Hawkesbury Sandstone lithology of the Woronora Plateau and Blue Mountains is likely to create an aquiclude due to very low vertical permeability. These conditions favour the development of a setting in which water is stored and swamps can develop. Young (1986a) emphasises the importance of lithology as a controlling factor by reporting that the upland swamps of the Woronora are restricted completely to valleys cut in the Hawkesbury sandstone, and that they do not occur where other lithologies (such as shale and igneous rocks,) which out crop on the plateau surface. All of these conditions serve to create a perched water table within the headwater area, and therefore contribute to the saturated conditions required for swamp formation.

Several authors note the importance of the local hydrological balance in determining the formation of upland swamps, and this is evidenced by the distribution of upland swamps on the sandstone plateaux of the Sydney Basin (Burrough *et al.*, 1977; Dodson, 1987; MacPhail, Hope, 1985; Young, 1982). While topographic and lithological controls similar to those described above may occur across the plateaux, these factors do not always lead to the development of upland (Burrough *et al.*, 1977; Young, 1986a). Instead, upland swamps are generally concentrated on the easternmost extensions of the plateaux, where orographic rainfall, high elevation and frequent fog serve to maintain high moisture inputs and relatively low evapotranspirative losses, creating a favourable climate for swamp formation (Burrough *et al.*, 1977; Young, 1982).

2.1.2 Processes of Swamp Development

The general theory of upland swamp formation involves the initial infilling of existing headwater stream reaches with mineral sediments, usually derived from the surrounding catchment (Dodson, 1987; Polach, Singh, 1980; Tomkins, Humphreys, 2006; Young, 1982). As these accumulate in the former headwater channels, stream power is reduced by lateral dispersion, decreasing the competence of the stream and resulting in intensified sedimentation in the funnel-shaped headwater valleys (Brierley, Fryirs, 2005; Fryirs, 2002). Low stream power then increases the residence time of water within the sediment filled valleys by directing flows to the subsurface sediment matrix, rather than an open channel. This leads to the persistence of waterlogged conditions within the valley fill (Brierley, Fryirs, 2005; Young, 1982). Consistently wet substrate conditions drive a successional change in vegetation towards hydrophilic graminoids, sedges and rushes, which subsequently reinforce the sediment and water holding function of these infilled headwater valleys by creating sediment traps and contributing to the formation of peat (Dodson, 1987; Young, 1982).

Based on the abovementioned studies (section 2.1.1) it is clear that, although there are common factors of control across different upland swamps, their development is greatly influenced by the specific local landscape context in which they occur. As such, swamps in different regions, and even individual swamps within regions, are likely to have a distinct history of evolution determined by the valley configuration and lithology of the catchment in which they are found. This is evidenced by the large variability in stratigraphy between different swamps, which can indicate periods of increased mineral sedimentation and peat accumulation, and also distinct erosion events within a swamp's history (Dodson, 1987; MacPhail, Hope, 1985; Tomkins, Humphreys, 2006). On the Woronora Plateau alone, a wide range of sedimentologies have been observed – from a relatively simple formation of organic fines accumulating above basal sands (Prosser, Melville, 1988; Tomkins, Humphreys, 2006; Young, 1982; Young, 1986a); to more complex compositions such as the bedrock blanketing basal peats, interspersed with sand wedges described by (Tomkins, Humphreys, 2006).

The distribution of sediments within the fill is indicative of the processes acting within the swamp at the time of their deposition. Complex stratigraphy indicates that the progression of swamp development is not necessarily linear, and that the swamps are responsive to intrinsic changes (and thresholds) within their catchments (Cohen, Nanson, 2007; Johnston, Brierley, 2006; Prosser, Slade, 1994; Schumm, 1979). For example, Young (198a) suggests that upland swamps on the Woronora Plateau have historically been affected by local fire and storm events. Within organic accumulations, channel-like structures which are infilled with clean, pebbly, coarse sands intermixed with charred vegetation fragments, are interpreted as evidence of cut-and-fill phases. These are likely to have occurred as a result of erosion during severe storm activity following the burning of the swamp surface and a reduction in surface resistance. This explanation is supported by Tomkins and Humphreys (2006), who report similar observations of cut-and-fill structures within Drillhole and Flat Rock swamps on the Woronora Plateau. Tomkins and Humphreys (2006) note that the timing of these cut-and-fill events is different in each swamp– ranging from 8,500 to 800 years BP – and that the timeframe over which the features are scoured and refilled suggests that these erosion episodes are very rapid. Similar asynchronous phases of swamp cut-and-fill are summarised for swamps of southeastern Australia by Prosser and Slade (1994) and Prosser and Winchester (1996).

Further evidence of the discontinuous nature of swamp evolution is provided where two or more basal dates are available for a single upland swamp. There is evidence that in these cases the downstream reaches are generally younger (Stockton, Holland, 1974; Young, 1986a). This implies that periodic flushing of swamp sediments occurs in downstream areas where contributing flows are larger and more concentrated (Young, 1986a). There is some recognition that these processes are not only important for historical swamp evolution, but that they are contemporary and observable in swamps today (Tomkins, Humphreys, 2006; Young, 1986a).

It has been noted that modern erosional events often lead to rapid and catastrophic peat and sediment stripping following knickpoint initiation (Brierley, Fryirs, 2005; Keith *et al.*, 2006; Tomkins, Humphreys, 2006). However, the preservation of historical cut-and-fill features within older sediments suggests that under natural conditions, while swamps are responsive to environmental forcers, they are also able to adjust and persist in the landscape. Understanding these cut-and-fill processes as natural stages in swamp evolution is becoming more important as erosion and gullying associated with anthropogenic activities, including agricultural expansion, urbanisation and mining, becomes more prevalent within swamp systems (Brierley, Fryirs, 2005; CGPtyLtd, 2004; NSWDepartmentofPlanning, 2008).

While this study does not directly address the task of developing a detailed reconstruction of the conditions leading to the development of the study swamp and the features observed within it, nor does it apply these historical reconstructions to modern degradational processes, it will contribute to these questions by providing further baseline data on the geomorphic form and development of an upland swamp.

2.2 Geomorphology of Upland Swamps

Many studies directly addressing the geomorphology of upland swamps either focus on broad-scale morphology, including swamp shape and boundary conditions, or on surface morphologies such as ephemeral drainage lines and meso-topographic features. Most of these studies were conducted more than 10 years ago. It is also surprising to note that, despite the clear importance of water in the history of all peatland systems, the link between internal geomorphic structure and sedimentology to the hydrology of these systems has been largely overlooked in an Australian context. Additionally, very little is known about form-process relationships within upland swamps, and unlike most other elements of the fluvial system, details of landscape (dis)connectivity, geomorphic thresholds and forcing factors are little explored.

2.2.1 Geomorphic Attributes of Upland Swamps

Given their location in first- and second-order valleys, upland swamps are generally small in size, with few extremely large exceptions such as Wingecarribee and Maddens Plains swamps (Young, 1982). The large-scale morphology of the upland swamps is dependent primarily on the underlying geology and characteristics of the valley in which they are found. As noted earlier, the slope of the swamps is controlled by the greater catchment slope and can be influenced by the presence of bedrock bars (Burrough *et al.*, 1977; Holland *et al.*, 1992). The shape of the swamps depends on bedrock controls on the width of the valley in which they occur, and also the distribution of seepage zones on the hillslope margins, in which areas the swamp may extend up slope out of the confines of the valley basin (Bell *et al.*, 2005; Holland *et al.*, 1992; Tomkins, Humphreys, 2006). Valley asymmetry between north-facing and south-facing slopes has been observed in upland swamps of the Blue Mountains and Sydney Basin (Buchanan, 1979; Holland *et al.*, 1992). Holland et al. (1992) presents evidence that soils are deeper, less compact, and dry out faster on north-facing slopes, and identifies solar radiation as the main factor responsible for this asymmetry.

As fluvial landforms, the primary geomorphic attribute of many upland swamps is a lack of any continuous, persistent and open channel within the fill (Keith *et al.*, 2006; Tomkins, Humphreys, 2006; Young, 1982). Apart from the stable, continuous peat-swamp channels of the Barrington Tops described by Nanson (2009a, 2009b, 2010), the majority of observed drainage structures within upland swamps are generally small-scale, discontinuous and non-permanent. While the lower reaches of a swamp may include a number of small outlet channels which drain into the open stream network, these rarely extend into the upper reaches of the fill unless significant disturbance of the system has occurred (Tomkins, Humphreys, 2006; Young, 1982; Young, 1986a). Vegetation controlled preferential flow-paths and surficial drainage lines may exist, but these are generally ephemeral, change with varying flow conditions, and often do not persist for long periods, becoming inactive when water table elevations are low (Tomkins, Humphreys, 2006). No detailed studies have been conducted to specifically characterise these structures, or to quantify their role in water transfers through the swamp.

Subsurface drainage structures have been similarly neglected within the Australian literature, except in recent work by Nanson (2009a, 2009b, 2010). Nanson (2009a) describes stable, steep-sided, narrow and deep channels occurring within the peat swamps of the Barrington Tops, and notes the presence of soil pipes within the sediment matrix, however, these features remain poorly characterised in the broader Australian literature. In the international peatland literature, the presence of soil pipes (diameters on the scale of tens of centimetres) and large macropores (pore diameters > 1 mm) as crucial conduits of water within the swamp peat matrix has been well recognised in the international arena, particularly in the raised bogs and blanket peatlands of the northern UK (Holden, Burt, 2002b; Holden *et al.*, 2002; Jones, 1971; Jones, 1997; Jones *et al.*, 1997). Importantly, Pearsall (1950) identified the collapse of the roofs of these pipes as the initial stage in gully erosion of a blanket bog in Scotland, a conclusion confirmed in a number of subsequent studies (Holden, Burt, 2002b; Taylor, Tucker, 1970).

Other hydrogeomorphic features which are also poorly understood are pools, such as those observed by (Tomkins, Humphreys, 2006) in swamps of the Woronora Plateau. They can be quite large (up to 100 m in length and 10 – 20 m in width in a swamp on the Woronora Plateau), and at various times they may be disconnected, discrete units, or connected by narrow drains, and have been known to change morphology, and appear and/or disappear over relatively short time-frames (Eyles, 1977; Tomkins, Humphreys, 2006; Young, 1986a). Although these features are relatively common within upland swamps, and despite their potential importance in the processes of infilling and erosion during swamp development, little is known about their formation and the role they play in the hydrological function of upland swamps.

Micro- and meso-topographic features observed within upland swamps in south eastern Australia include alluvial bulges with associated ridges and swales (Holland *et al.*, 1992), and patterned ground (Young, 1982). Holland et al. (1992) describe bulges in the swamp profile formed below abundant supplies of subsurface water from claystone bed outcrops. Here, it is suggested that the emerging water increases the plasticity of the soil, and over a long period adds sediment in suspension to supplement that transported from further upstream. The net result is a bulge in the profile, slumping downstream and ridges and swales normal to the ground slope. These ridges and swales are up to 0.5 m deep and are thought to be associated with the formation of large (up to 0.2 m) sediment traps, forming as a result of the accumulation of sheetwash debris, which are then reinforced by the colonisation of vegetation. Similarly, Young (1982) discusses the presence of linear 'patterned ground' in upland swamps of the Woronora Plateau. These features have only shallow surface expression of similar dimensions (no greater than 0.5 m in depth) to those observed by Holland et al. (1992), and are not related to variations in the subsolum. They are consistently associated with zones of seepage concentration and as such have been attributed to solifluction, rather than the formation of sediment traps.

Although the character of the sedimentary fill within Australian upland swamps may vary, a widely accepted, fundamental model of peat structure within peatland literature is the *diplotelmic model.* This concept denotes the vertical changes in peat properties resulting from progressive decomposition, which do not occur gradually with depth, but rather there is a sharp distinction between a relatively low-density upper layer and a much higher density lower layer. This configuration was first described by Russian peat researchers (Ivanov, 1953)and subsequently formalised in the English literature by Ingram (1978), in which the upper layer is termed the *acrotelm* and the lower layer the *catotelm.* Although the definition of these layers relates primarily to hydrology – the catotelm is confined beneath the long-term minimum water-table depth, while the upper acrotelm is subject to oscillating water table elevations – there are functionally important physical properties characteristic of each layer, as summarised in Table 2.3 (in section 2.3). It has been argued that this concept is fundamental to mire pedology (Ingram, 1978). Whether Australian swamps operate in the same way has not been examined in any detail. Given the climatic differences between the northern hemisphere regions where this model was first developed and extensively applied, and the Australian setting of upland swamps, there is an opportunity to investigate how Australian systems function and how this differs to those reported from overseas. There is the potential for wide disparities between the structure and composition of Australian upland swamp peats and those of the boreal regions, to such an extent that the diplotelmic model may not be applicable in a climate that experiences high flow variability and potentially large fluctuations in water table levels.

2.3 Hydrology of Upland Swamps

Beyond establishing the basic external influences of local hydrological balances on the initiation of upland swamp formation, there is little to be discovered in the Australian literature regarding the physical role of water in these systems (Nanson, 2009b). Available descriptions of swamp hydrology are for the most part restricted to basic studies on water table fluctuations and distributions, and geological groundwater investigations. Almost no studies address the mechanistic internal functioning of Australian upland swamps (Nanson, 2009b). As a result very little is known about upland swamp hydrological behaviour, or the relative contribution to gross water deliveries from overland flows, subsurface matrix drainage, macropore flow, or flow through soil pipes from upland swamps. However, there is a wide body of research from the peatlands of the northern hemisphere informing this area of study, which provides clear opportunities for investigation in the Australian context (e.g. (Baird, 1997; Baird *et al.*, 1997; Baird *et al.*, 2008; Boelter, 1964; Boelter, 1965; Daniels *et al.*, 2008; Dasberg, Neuman, 1977; Gnatowski *et al.*, 2010; Hemond, Goldman, 1985; Holden, 2009; Holden, Burt, 2002a; Holden, Burt, 2003a; Holden, Burt, 2003b; Ingram, 1983a; Ingram, 1978; Ivanov, Geogr, 1981; Rizutti *et al.*, 2004; Rycroft *et al.*, 1975a; Rycroft *et al.*, 1975b; Sobieraj *et al.*, 2004; Waine *et al.*, 1985)).

2.3.1 Hydrological Behaviour

In this study, the hydrological behaviour of a swamp is a description of the temporal and spatial variability of water storages and movements within the shallow aquifer. It refers to water table fluctuations on different time scales and with rainfall, and the spatial extent of saturation within the swamp sediment fill. Analysis of these factors in upland swamps has been limited, and most studies have been undertaken as industry investigations, focusing primarily on geological recharge/discharge and geochemical characteristics (CGPtyLtd, 2004; Tomkins, Humphreys, 2006). While there have been several theses produced which address the topic (for example (Mirlieb, 1978; Mitry, 2008; Prosser, 1983), the limited accessibility of these documents has restricted their influence within the scientific literature.

Within the few studies that could be attained, there have been some consistent trends noted. Young (1982), Young and Young (1988), and Holland et al. (1992)

describe three hydrological zones within the studied swamp catchments, which are defined by the behaviour of the water table. These are termed the 'lowland wet area', 'intermediate', and 'upland dry area', and the 'perennial', 'ephemeral', and 'woodland' zones by Young (1982) and Holland (1992), respectively. Young (1982) describes the position and distribution of water table elevations within Martin's Swamp on the Woronora Plateau, over a ten month period. It is reported that groundwater levels are consistently highest within the lowland swamp axis, generally lower in the intermediate swamp zones, and lowest in the upland dry forests. This pattern is also observed by Holland et al. (1992) in the perennial, ephemeral, and woodland zones of perched headwater valleys of the Blue Mountains, studied over a period of five years (Table 2.2).

Young (1982) also notes that after prolonged rainfall, within the swamp axis water remains close to the surface for over a week after rainfall cessation, whereas in adjacent forested areas no standing water persists. Holland et al. (1992) describe a similar trend: after swamps accumulate water during rainfall, they tend to dry out from the periphery and after a period of subsequent dry conditions, the woodland and ephemeral zones have zero water table depth. Holland et al. (1992) also gives details of an apparent asymmetry between north-facing and south-facing woodland slopes (section 2.2), in which more rapid drainage and greater evaporation (due to differences in compaction and solar radiation, respectively, as noted previously) on north-facing woodland slopes resulted in consistently lower water table conditions than were observed on south-facing slopes (Table 2.2). Additionally, an opposing

Table 2.2: Maximum height of groundwater table above bedrock (m) for swamp zones, March 1982 – December 1987. a) by season, for all sites; b) by season and aspect (woodland sites only). Holland et al. 1992

	Spring		**Summer**		**Autumn**		**Winter**	
(a)								
Woodland	0.6		0.5		0.5		0.6	
Ephemeral Swamp	1.9		1.6		1.9		1.9	
Perennial Swamp	2.6		2.6		2.6		2.6	
(b)	N	S	N	S	N	S	N	S
Woodland	0.4	0.6	0.2	0.5	0.4	0.5	0.4	0.6

trend in variability and mean groundwater elevations was observed along this aspect asymmetry. For north-facing woodlands sites, the general trend is that as the mean increases, the variability also increases. Alternatively, for south-facing perennial swamp sites, the general trend showed that as the mean increases, the range decreases. This gives some insight into variations of drainage efficiency between different hydrological zones. Mitry (2008), observes similar and additional patterns of storage in an upland swamp on the Woronora Plateau. He notes that water table elevations are consistently higher within the swamp axis, but also shows that elevations vary longitudinally down the swamp axis. Here, lower reaches display generally higher water tables with lower variability than upper reaches, and he attributes this to reduced drainage in the lower reaches due to proximity to a basal rock bar.

Only a few other general hydrological behaviours have been reported in the Australian literature. Holland et al. (1992) and Nanson (2009a) describe significant diurnal water table fluctuations correlating with temperature variations. In the Study by Holland et al. (1992), higher daytime temperatures were associated with lower water table levels, and vice versa. These daytime falls were greater in summer than in winter, and in areas where temperatures were higher within the swamp, the rate of fall was faster than in lower temperature areas. Both Young (1982) and Mitry (2008) report a close relationship between water table elevations and rainfall. Mitry (2008) describes the recession after 222 mm rainfall, which is relatively rapid until water levels drop below the upper 10 cm of the swamp profile, after which point the recession limb flattens out. He attributes this pattern to the greater drainage potential of the fibrous upper 10 cm compared to the more humified peat below.

2.3.2 *Hydrological Functioning*

In this study, hydrological functioning refers to the combined effect of the groundwater behaviour and the internal hydraulic properties and structure of the swamp sediments. The key hydraulic property used in this study is the hydraulic conductivity (K), which is controlled by the physical properties of the sediment (Boelter, 1965; Boelter, 1968; Dai, Sparling, 1973). The hydraulic conductivity of a soil represents the constant of proportionality in the Darcy function, which describes the linear relationship between volumetric flow rate and pressure gradient (Boelter, 1965). It refers to the soil's ability to transfer water under a given hydraulic gradient, thus determining the rate of transmission.

Physical factors which contribute to hydraulic conductivity are similar for all soil types, and generally relate to porosity. In rigid soils – soils with primarily mineral composition – porosity (pore geometry and connectivity) within a given stratum is generally stable and is usually assumed to be constant over specific spatial and temporal scales (Hillel, 1982). These assumptions underlie the Darcy function. However, they do not necessarily apply in peats, in which high organic contents confer distinctive dynamic characteristics to the soil which largely relate to the degree of decomposition of the organic materials (Beckwith *et al.*, 2003a; Beckwith *et al.*, 2003b; Boelter, 1965; Boelter, 1968; Evans, Warburton, 2007; Ingram, 1983b; Ivanov, Geogr, 1981). With increasing decomposition, the humification of peat increases and the particle sizes decreases, resulting in smaller pores and more dry material per unit volume bulk density (Boelter, 1968; Evans, Warburton, 2007; Richardson *et al.*, 2001). Correlated with decreasing porosity and increasing bulk density, are reductions in hydraulic conductivity. This relationship is illustrated in Figure 2.1.

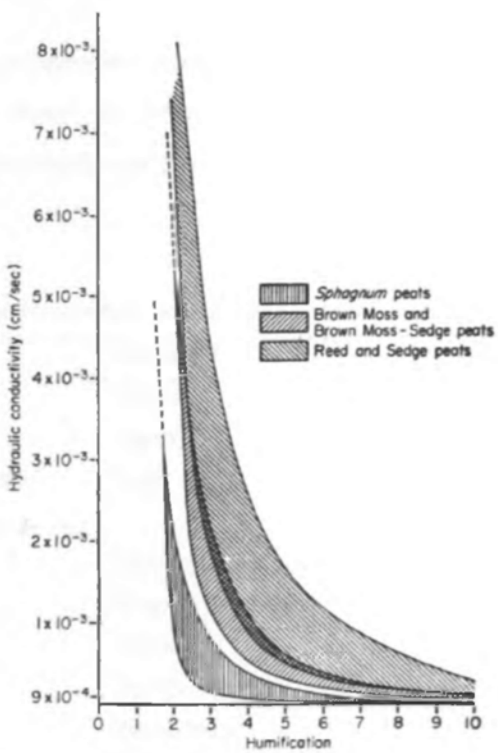


Figure 2.1: Summary diagram of 327 mean test results by the auger hole method, showing dependence of hydraulic conductivity on peat type and humification. *Rycroft et al. (1975a) after Baden and Egglesmann (1963)*

As previously discussed (section 2.2), in peatlands of the northern hemisphere, these changes in humification and bulk density do not occur gradually with depth, but rather sharply. This boundary distinguishes the upper acrotelm from the lower catotelm. These units have distinct physical and hydraulic properties, owing largely to differences in their degree of decomposition (Boelter, 1968; Evans, Warburton, 2007; Ingram, 1978; Ingram, 1983b; Richardson *et al.*, 2001). These are summarised in Table 2.3. The abundance of relatively undecomposed plant litter at the upper peat surface means that the density of the acrotelm is relatively low and hydraulic conductivity relatively high. However, because of rapid decomposition by aerobic bacteria in this zone, hydraulic conductivity declines and density increases quickly with increasing depth. According to Romanov (1968), the hydraulic conductivity may vary over as much as four orders of magnitude between the upper and lower boundaries of this layer. In the catotelm, however, peats are relatively uniform with depth, are more decomposed and therefore denser than in the acrotelm, and have been found to have hydraulic conductivities which can be 3-5 orders of magnitude lower than the acrotelm. Therefore these upper and lower layers differ significantly not only in physical structure, but also in their function.

However, the correlation between decomposition, porosity and consequent hydraulic conductivity is not as linear as these summaries suggest. Although the general pattern of decreasing hydraulic conductivity between the acrotelm and catotelm is

Table 2.3: Characteristics of the acrotelm and catotelm (Ingram, 1978)

Feature	Acrotelm	Catotelm
Exchange of energy	Rapid	Slow
Exchange of matter	Rapid	Slow
Activity of peat-forming aerobic microbes	High	Nil (general level of microbial activity low)
Macroflora	Matrix of living plant material	Dead, except for a few roots
Water table	Present (fluctuating)	Absent (constant)
Water content (vs time)	Variable	Constant
Permeability (vs depth)	Widely variable, highest at the surface	Relatively constant, low
Water transmission	Darcian	Non-Darcian
Aeration	Periodically aerated	Anaerobic
Upper surface	Upward limit of matric forces	Lower limit of rapidly variable characteristics

common across most studies, vertical changes in hydraulic conductivity in the catotelm appear to be more varied. Several studies show a log linear decrease in hydraulic conductivity with depth in the catotelm, while others report more variable results in which hydraulic conductivity cannot be directly related to depth (Beckwith *et al.*, 2003a; Clymo, 2004). These variations are thought to be attributable to heterogeneity in buried peat structure resulting from successional vegetation changes (Evans, Warburton, 2007). To further complicate these patterns, hydraulic conductivity commonly displays lateral heterogeneity and directional anisotropy across scales of metres within individual swamps, and as such wide variations in hydraulic conductivity values can be observed both within a single swamp and between different swamps (Beckwith *et al.*, 2003a; Rycroft *et al.*, 1975a; Surridge *et al.*, 2005). Table 2.4 summarises reported results of hydraulic conductivity tests, and illustrates the degree of this variability.

In addition, because peat soils are compressible, changes in porosity can also be produced by changes in the applied head of water (effectively changing the loading on the peat) (Dai, Sparling, 1973; Hemond, Goldman, 1985; Holden, Burt, 2003a). When water tables fall, compression occurs because the effective stress on the peat column is increased as water is removed, due to decreases in buoyancy provided by pore water pressure (Evans, Warburton, 2007). Price (2003) has demonstrated that the hydraulic conductivity of peats decreases as the water table drops, and suggests that this is due to the collapse of large pores. As a result, when addressing the transmission of water through peat it is somewhat misleading to refer to hydraulic conductivity, which, by definition in Darcy's Law, is constant for all hydraulic gradients (Ingram, 1983b).

There are numerous studies addressing the non-Darcian flow of water through humified peats (Baird *et al.*, 1997; Hemond, Goldman, 1985; Ingram *et al.*, 1974; Rycroft *et al.*, 1975a; Rycroft *et al.*, 1975b; Waine *et al.*, 1985), however these have not come to consistent conclusions. Ingram (1982, 1983) argues because of the saturated nature of lower peats, Darcy's law is still an appropriate model of water flow in peat. Alternatively, others (Hemond, Goldman, 1985; Rycroft *et al.*, 1975a; Rycroft *et al.*, 1975b; Waine *et al.*, 1985) have argued that, particularly at lower hydraulic conductivities, water flux through peat will be non-Darcian in nature, although Baird et al. (1997) argue that non-Darcian behaviour is only significant at high hydraulic conductivities which are unlikely to be found in natural systems.

Table 2.4: Range of reported values of saturated hydraulic conductivity for a variety of peatland types in the northern hemisphere

Location of Study	Type of Peat	Depth tested	K (m s^{-1})	Reference
Calcott Heath, Somerset UK	Drained agricultural fen peat	- 2.2 m	3.67×10^{-6}	Baird and Gaffney (2000)
Calcott Heath, Somerset UK	Drained agricultural fen peat	- 0.6 cm - 2.1 cm - 3 cm - 4.1 cm - 6.1 cm - 8.5cm	31.46×10^{-7} 17.06×10^{-7} 13.71×10^{-7} 9.82×10^{-7} 6.23×10^{-7} 4.04×10^{-7}	Baird (1997)
Somerset Levels, UK	Humified fen peat	- 120cm - 170cm - 200 cm	3.48×10^{-8} 0.79×10^{-8} 0.82×10^{-8}	Baird and Gaffney (1994)
Cors Fochno, West Wales	Estuarine raised bog, central area	- 200 cm - 400 cm	334.9×10^{-7} 9.6×10^{-7}	Baird et al. (2008)
Sutton Fen, Norfolk UK	Floodplain mire	- 45 cm (root mat)	4.84×10^{-5}	Baird et al. (2004)
Thorn Moore, South Yorkshire	Lowland raised mire	- 10 cm - 90cm	4.2×10^{-5} 0.1×10^{-5}	Bromley et al. (2004)
Ellergower Moss, Scotland	Raised bog	- 100 cm - 500 cm	5×10^{-8} 0.7×10^{-8}	Clymo (2004)
Hula Basin, Israel	Drained marshland	- 175 cm - 300 cm - 425 cm	1.67×10^{-6} 29.7×10^{-6} 29.7×10^{-6}	Dasberg et al. (1977)
Moore House NNR, north Pennines UK	Upland blanket bog	- 10 cm - 20 cm - 35 cm - 60 cm - 80 cm	34.9×10^{-8} 16.5×10^{-8} 0.6×10^{-8} 0.5×10^{-8} 7.6×10^{-8}	Holden and Burt (2003)
Lanoraie peatland complex, Quebec, Can.	Minerotrophic peat	- 50 cm -150 cm - 250 cm	69.4×10^{-8} 1.93×10^{-8} 6.42×10^{-8}	Rosa and Laroque (2008)
Lac Saint Jean, Quebec, Can.	Cutover peatland	Surface - 30 cm	1.5×10^{-5} 0.41×10^{-5}	Schlotzhauer and Price (1999)

Ingram et al. (1974) suggest that it may be necessary to divide peat into two categories in regards to the transmission of water, and that Darcy's law should only be applied to peats of low humification, such as those found in the acrotelm. Due to these uncertainties, Darcy's Law is still commonly employed in practical applications of peatland hydrology and is used in this study.

The hydraulic structure of the swamp sediments interacts with the behaviour of the water table, and together these factors determine the hydrological function of the swamp in terms of flow generation. In peatland systems, flow primarily occurs as near-surface flow through the fibrous sediment matrix of the acrotelm, or as overland flow. In the catotelm, lateral flow is negligible. The amount and timing of flow generation from peatlands systems is largely dependent on the antecedent water table position and soil moisture conditions (Branfireun, Roulet, 1998; Evans *et al.*, 1999; Kvaerner, Klove, 2008; McCartney *et al.*, 1998). In 'dry' conditions, where the water table is deep in the soil profile and the area of saturation within the swamp is reduced, significant storage of rainfall inputs can occur, attenuating the storm response in the downstream river network (Evans, Warburton, 2007). When rainfall occurs in 'wet' swamp conditions, the available storage within the swamp is minimal and downstream transfer from the swamp is more marked and immediate (McCartney *et al.*, 1998).

Under these wet antecedent conditions, the dominant mode of lateral transfer can switch from shallow subsurface flow to saturated overland flow. Although this process is poorly described within upland swamps, it is essentially the same in all peatland settings. Saturation-excess overland flow occurs where subsurface soil is saturated, the water table rises to the surface and water flows over the surface (Selby, 1993). This is referred to as 'saturation from below'. Once saturation from below occurs, all further surface water input becomes overland flow. This form of runoff occurs in two ways; by rain falling onto already saturated areas, or by return flow. Rain that falls onto already saturated areas will runoff immediately. However, the extent of the saturated area in a catchment varies both within individual storm events and between storms, resulting in expansion and contraction of the runoff zone as parts of the swamp become saturated and then dries out (Holland *et al.*, 1992; Prosser, Melville, 1988; Young, 1986a). Return flow occurs where throughflow is forced back to the soil surface (exfiltrated) at areas of saturation and becomes overland flow. Under these conditions the swamp ceases to function as a water storage feature and discharge into the lower catchment is generated.

The following chapter describes the study site and its regional setting on the Budderoo Plateau, NSW.

3 Regional Setting

This chapter provides details on the regional location of the study area, and outlines the landscape and environmental characteristics of the area in which it is found. A summary of the known physical characteristics of the study site, and a description of the study design are given.

3.1 Study Area

3.1.1 Budderoo Plateau

The study site is located within the plateau area of the Budderoo National Park, on the eastern edge of the Southern Highlands, about 30 km south west of Wollongong (approximately 34°37'S:150°40'E) (Figure 3.1) (NSWNPWS, 1998). The region is part of the southern section of the Sydney-Bowen Basin, and the plateau is capped by horizontally bedded Triassic quartz sandstone of the Hawkesbury Sandstone group. This lithology forms a gently undulating plateau of low relief (± 30 m) and low permeability, approximately 600 m above sea level (Figure 3.2). Some small, localised areas of basalt outcrop on the hills (Burrough *et al.*, 1977). The plateau is flanked to the east and south by sheer cliffs, overlooking Kiama and the northern tributary valleys of the Kangaroo Valley, respectively (Figure 3.2).

The predominate climate at the study site is temperate – cool and wet – and due to the elevation and proximity to the escarpment the area receives a high average annual rainfall as a result of orographic and fog precipitation patterns. There are no local climate data for Budderoo. At Robertson, approximately 10 km north-west of the study site, average annual rainfall is approximately 1560 mm yr^{-1}. Mean monthly totals range from 89 mm in March to 176 mm in February. However, Burrough et al. (1977) report a moisture gradient across the plateaux area from Barren Grounds to Fitzroy Falls in which the eastern scarplands receive the highest annual rainfall. They report that this drops off rapidly to the west and north-west at a rate of approximately 50 mm km^{-1}, and as such the rainfall received at the Budderoo study site is likely to be higher than these values for Robertson. Rainfall is dominant in summer as a result of summer subtropical depressions (Burrough *et al.*, 1977).

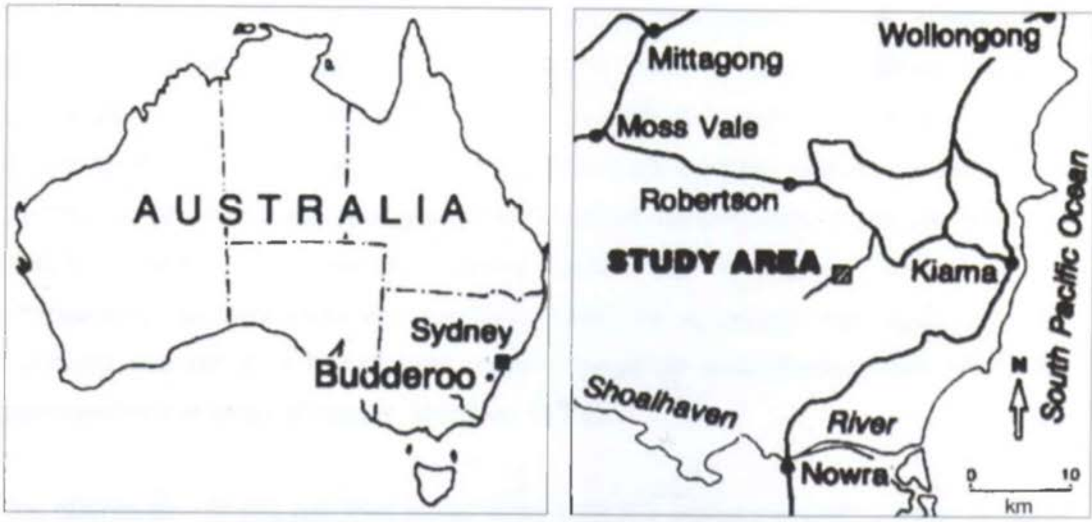


Figure 3.1: Location of study area, Budderoo Plateau, NSW, Australia

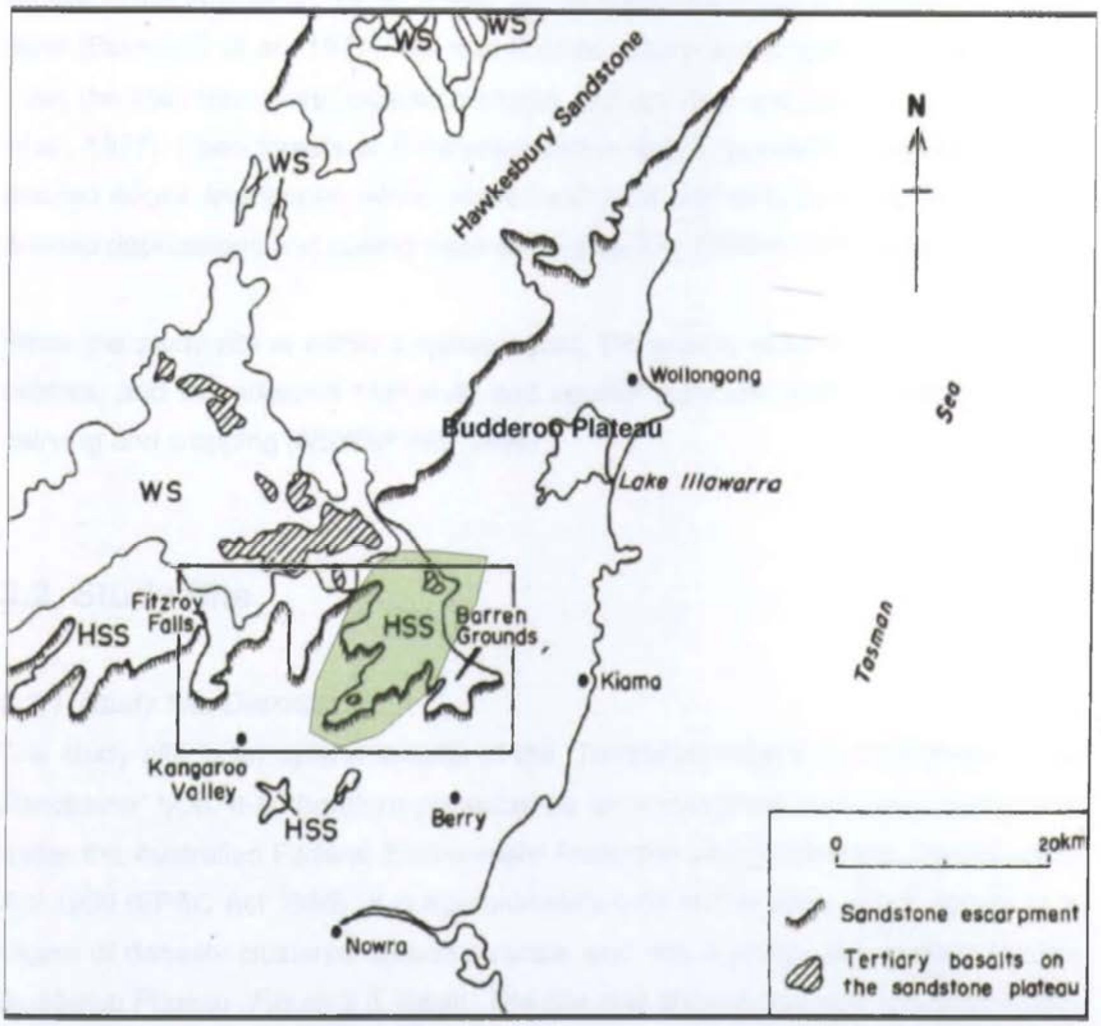


Figure 3.2: Geology of the Budderoo Plateau (in green) and Southern Highlands region. *Adapted from Burrough et al. (1977)*

Mean maximum temperatures at Moss Vale (approximately 31 km northwest of Budderoo) range from 28.5 °C in January to 10.7 °C in June. Mean minimum temperature range from just above freezing at 0.3 °C in July to 17 °C in February. Evaporation on the Budderoo Plateau is lower than mean annual rainfall inputs, creating a positive water budget which is most accentuated in winter (Prosser, Melville, 1988). This climatic regime, paired with the gentle relief and low permeability sandstone lithology results in a perched, localised water table within the overlying sediments of the plateau, with no regional groundwater table until great depth within the rocks (Prosser, Melville, 1988).

The distribution of this perched water table over the plateau creates a clear regional stratification of soil properties and vegetation communities (Burrough *et al.*, 1977)(Figure 3.3). In the extreme east and in poorly drained gullies and upland swamps, wet basin peats overly groundwater gleys and a thick, humus stained subsoil (Burrough *et al.*, 1977). These are generally underlain by a bleached sandy layer (Burrough *et al.*, 1977). On well-drained ridges and slopes, and towards the west, the soils have lower organic contents, and are drier and less dense (Burrough *et al.*, 1977). Open forests of *Eucalyptus sieberi* and *E. gummifera* occupy the well-drained ridges and slopes, while dense heathland and sedgelend dominate poorly drained depressions and upland swamps (Figure 3.4) (NSWNPWS, 1998).

While the study site is within a national park, the area is close to major population centres, and the adjacent highlands and coastal plain are used for cattle raising, dairying and cropping (NSWNPWS, 1998).

3.2 Study Site

3.2.1 Study Site Description

The study site is an upland swamp of the '*Temperate Highland Peat Swamps on Sandstone*' type. It is therefore protected as an endangered ecological community under the Australian Federal *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act 1999). It is approximately 0.02 km^2 in area, which occurs in a region of densely clustered upland swamps and wet drainage depressions on the Budderoo Plateau (Figure 3.5, inset). The site was chosen because it is in an intact geomorphic, vegetation and ecological condition, is isolated from off-site landuse

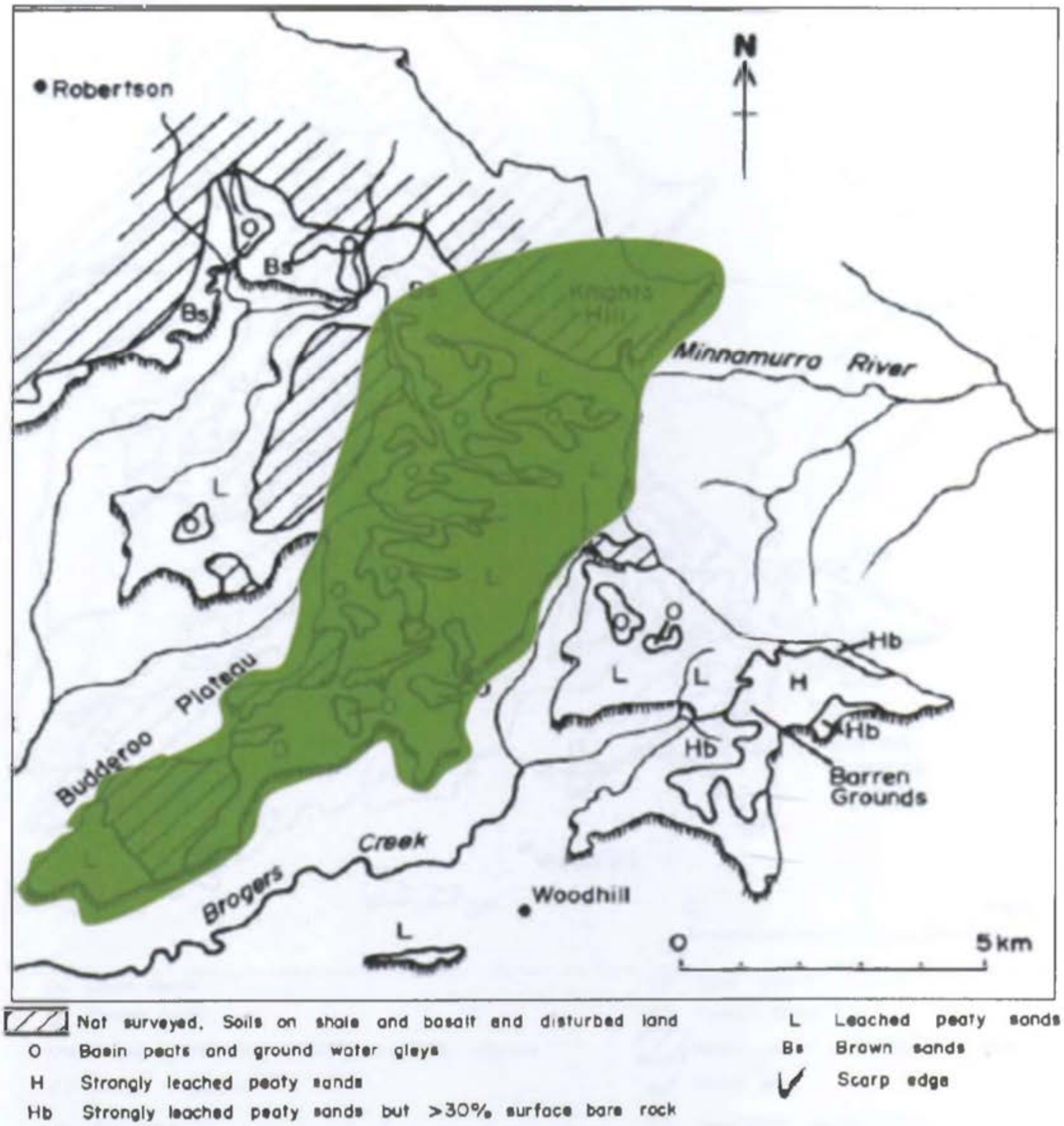


Figure 3.3: Soils of the Budderoo (in green) and Barren Grounds Plateaux. *Adapted from Burrough et al. (1977)*

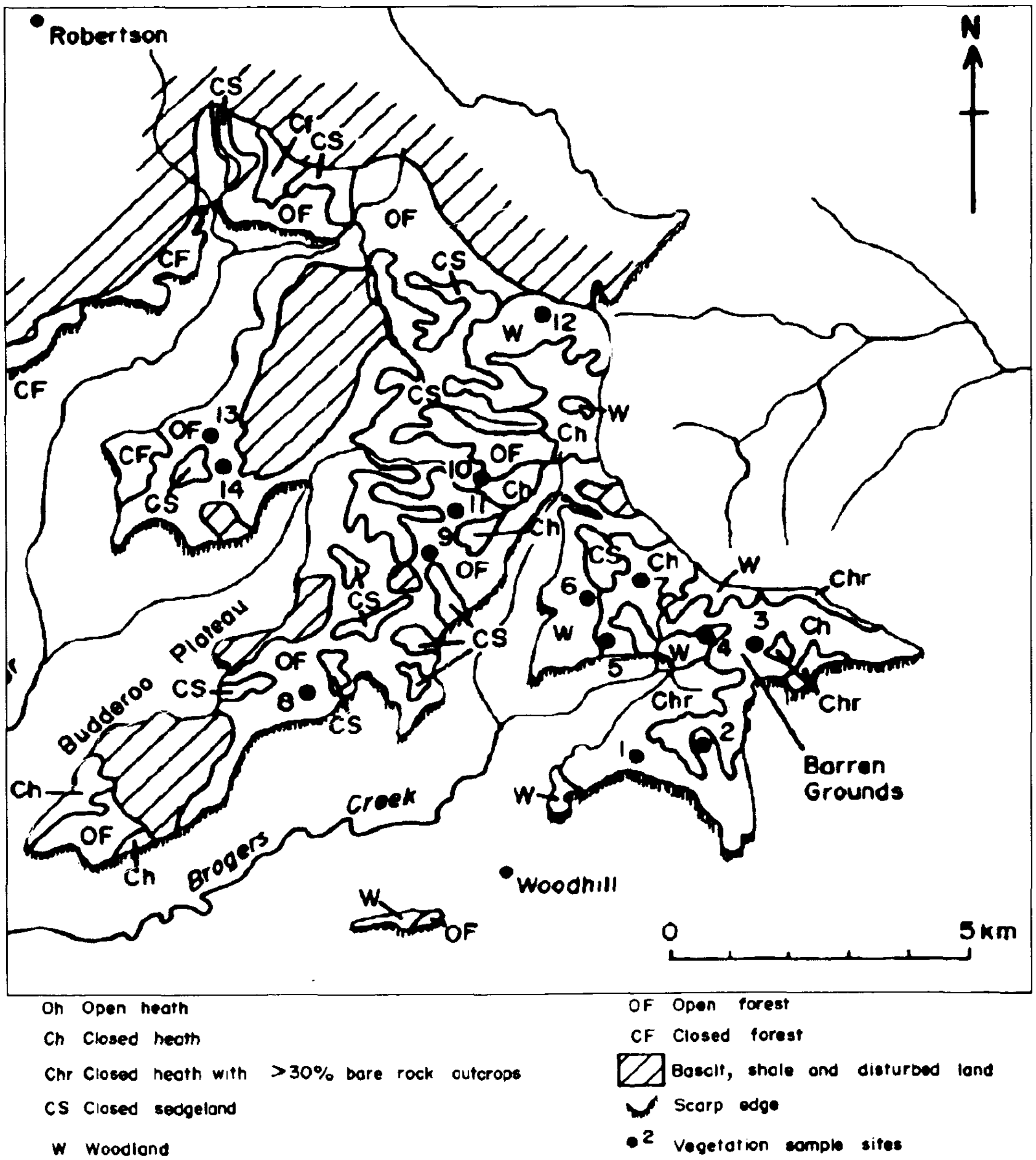


Figure 3.4: Vegetation communities of the Budderoo (in green) and Barren Grounds Plateaux. *Adapted from Burrough et al. (1977)*

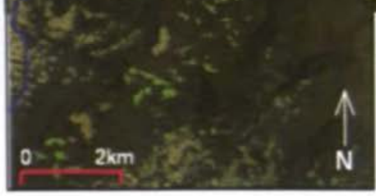


Figure 3.5: Location of Budderoo Swamp study site and relationship with Kangaroo River. Inset: Upland s
the Budderoo Plateau and study site (blue highlight) relationship with Kangaroo River (blue line)

and disturbance impacts, and is representative of upland swamps on the Budderoo Plateau. The swamp is accessible via a vehicular track. The swamp lies in the headwaters of a southern tributary of the Upper Kangaroo River, and drains to the west directly into this channel via a series of interconnected, discontinuous pools (Figure 3.5). The vegetation of the area is clearly delineated between drier, open shrublands and *Eucalyptus* forest on the hillslopes and ridges, to closed heath and sedgelands in the swamp basin where soils are wet for the majority of the year (Figure 3.6). The study swamp is dominated by *Gymnoschoenus sphaerocephalus* (button grass) and *Gleichenia dicarpa* (pouched coral fern), with *Leptospermum spp.* (tea tree species) occurring in the marginal zones. Where surface moisture is particularly high, localised concentrations of *Baumea articulata* (jointed twig rush) and *B. juncata* (bare twig rush) occur.

Figure 3.6: Vegetation of the study site. Area inside: solid line = closed sedgeland and wet heath; dotted line = marginal sedgeland and heath; dashed line = sandstone ridge *Eucalypt* forest; all other areas = hillslope open shrublands and heath

3.2.2 Study Site Design

An area encompassing the upper section of the swamp and relevant portions of the adjacent hillslopes was delineated as the area of study (Figure 3.7). The upstream limit is defined by the access road to the east of the swamp, and the north and south boundaries were arbitrarily selected. Although the swamp extends further than the chosen downstream limit, it was decided to concentrate this study on the intact area preceding the large pools located in the mid reaches, and as such, the downstream limit is located at a bedrock constriction where the first pools appear (Figure 3.7).

This reduces the complexity of the hydrological investigations of this study, and, by constraining the number of variables, enables a clearer interpretation of the hydrological behaviour of a basic swamp system. Further studies would be required to encompass the effect of pools and other common swamp features such as micro-topographic units on groundwater hydrology.

Six survey transects were chosen as sediment and water table study transects, from the upstream limit of the swamp to the bedrock constriction that marks the downstream boundary of the site (Figure 3.7). The placement of these transects is designed to encompass the range of geomorphic and hydrological units within the swamp and hillslope. Transect 1 is located in the upstream region of the swamp, while Transect 6 signifies the downstream extent of the study area. Along each transect, a number of sediment sample sites and groundwater monitoring piezometers were installed to form a grid pattern of sampling points (Figure 3.7).

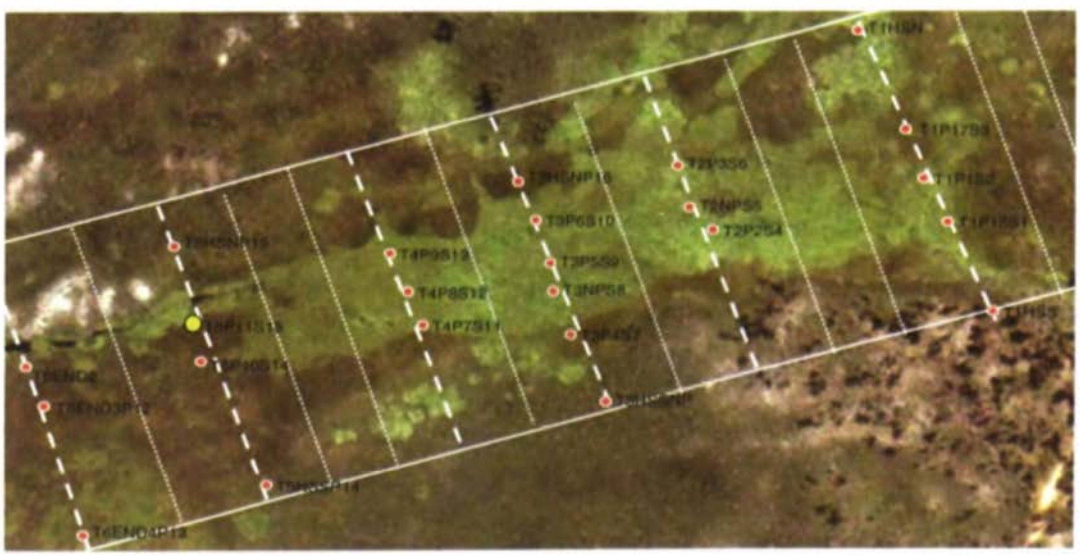


Figure 3.7: Map of study site design, showing survey and sample transects, sediment profile, location of water table monitoring piezometers, and digital data logger (yellow circle) (see Chapter 4 for details). In point codes, S = swamp sediment sample location; HSN/HSS = hillslope sediment sample location; P = monitoring piezometer location; NP = no piezometer

The following section details the methods used in sediment sampling and analyses, geomorphological characterisation, hydrological characterisation of the study swamp.

4 Methods

This chapter outlines the field, laboratory and desktop methods used to collect, analyse, and interpret physical data and measurements relevant to describing the internal hydrological functioning and behaviour of the swamp, and its evolutionary history. The first section outlines the field procedures used to survey the swamp area, extract sediment samples for physical characterisation, install the piezometer network, and monitor the water table. Following this account of the field methods, the laboratory methods used to analyse grainsize, degree of decomposition, organic matter content, and to delineate discrete sedimentary units within the swamp and adjacent hillslopes are described. The methods and analyses used to observe and interpret the hydrological behaviour of the swamp are then described. As the procedures used in the estimation of hydraulic conductivity require some discussion and special considerations, these are treated separately in the final section of this chapter.

4.1 Field Procedures

4.1.1 Survey of Swamp and Sediment Retrieval for Physical Characterisation

Using a total station (Leica TCR705), the target transects and additional sections perpendicular to the swamp axis were surveyed in order to capture the basin morphology and any meso-toppographic features of the swamp itself (see Figure 3.7 in Chapter 3). Geomorphic features which were easily identifiable by initial visual inspection (for example, pools and bedrock outcrops) were also surveyed in detail. To produce the 3D topographic block diagrams of the study site, Surfer® 8 was used. Cross-sections and a longitudinal profile were produced from this data.

Due to the waterlogged consistency of fine swamp sediments located below the water table, there was some difficulty in extracting sediment cores in some places. It was possible to manually remove upper, fibrous layers above the water table with a knife and trowel, and lower, coarser basal mineral layers with an auger. However, the removal of sediment from the intervening layer was somewhat more problematic. Several methods were trialled, including hand coring (with a PVC core lining, and also a flexible plastic tubing with fingered stopper diaphragm) however they were unsuccessful in holding a significant quantity of sample when removed from the pit. Ultimately, a combination of these techniques was used to extract samples from the fine, saturated sediment layers. Unfortunately, the integrity of these samples may have been compromised due to unavoidable mixing during core barrel retrieval. In these cases, additional replicate samples were taken to ensure that a representative range of samples was removed from depths below the water table. Where possible, sediment sampling holes extended to saprolite or bedrock. A total of 24 auger ~~pits~~ were sampled.

holes ?

4.1.2 Installation of Piezometers and Water Table Monitoring

Lengths of slotted (1 mm width) PVC piping (internal diameter 50 mm) were inserted into holes created during sediment sampling, and were concentrated within the main swamp body, with a number also located on the hillslope and in intermediary swamp areas. These were sealed at the bottom end with waterproof tape, which was perforated to allow water to flow into the pipe during insertion but prevent sediment intrusion at the base when the piezometer was in place. The tops of the piezometers were also sealed with waterproof tape to reduce evaporation from the free water surface and were labelled. In total 18 piezometers were installed across the study swamp.

Water table levels were measured by inserting a manual water level meter (dipper) into the piezometer tube and recording the depth below the soil surface. The water table at each piezometer was measured on a fortnightly basis for a period of 5 months from September 2009 to the end of January 2010. In order to observe finer scale fluctuations, an In-situ® Level TROLL® 500 non-vented (accuracy ± 0.1 % full scale), digital pressure/level/temperature data logger was inserted into one piezometer, T5P11S15, to continually monitor the water table at that point on an hourly basis throughout the same study period.

4.2 Laboratory Analyses of Sediment Characteristics

4.2.1 Grain Size Analysis

To estimate grain size trends, sediment samples were analysed visually using a hand lense. Sediments that were < 62 μm (silt and clay fractions) were characterised by field texturing, while sediments > 62 µm (sand fractions) were analysed using a grain size card. Sediment columns were constructed for each auger hole.

From each sediment type, several sub-samples were taken and the average sand size, as well as the largest and smallest sand sizes present (to indicate sorting) were recorded. At this stage, a basic note of the colour (black, grey, yellow, etc.) and sample features (for example, mottling) was taken as a general indication of organic matter content, as well as the hydrological conditions under which the sediments exist in the field. These parameters were used to separate samples into broad groups to be used in subsequent sediment analyses.

4.2.2 Organic Matter Content

The amount of organic matter in a soil physically affects the way it aggregates, and its ability to retain water (Collins, Kuehl, 2001). Both of these properties influence the amount and rate of water flow through the soil, and as such organic matter content is of interest for the hydrological section of this study. Soil organic matter can also be useful in interpreting the evolutionary history of the swamp. For example, interpreting the ratio of organic content to mineral content of different sediment layers can indicate periods of reduced or increased deposition of mineral particles, or of reduced or increased accumulation of organic materials. Organic matter content can be measured using standard Loss on Ignition (LOI) procedures (Hillel, 1982). Again, because it is the characteristics of the swamp deposits which are of concern for this study, only profiles from within the swamp area were processed for LOI. From each sediment type (identified in previous studies, section 4.2.1) within each swamp profile, three samples of approximately 20 g field moist weight were oven dried at 105 °C for 24 hours. Samples were then weighed for dry weight. Samples were placed in a furnace, and organics were burnt off at 500 °C for 24 hours. After cooling within a desiccator, samples were again weighed. The final weight of each sample was subtracted from its dry weight, and the result was expressed as a percentage of the dry weight to represent the organic matter content of the sediment samples.

4.2.3 Degree of Organic Matter Decomposition and Gravimetric Field Moisture Content

There are several ways to estimate the degree of decomposition of organic materials. Tests in the laboratory can determine either physical or chemical decomposition. In this study, the physical structure of the organic deposits is of interest, so determination of chemical decomposition is not necessary, and therefore estimation of bulk density can be used (Chason, Siegel, 1986). As discussed previously in section 2.3.2, bulk density can be related to the degree of decomposition of organic soils, which can be similarly related to hydraulic conductivity (Boelter, 1968; Chason, Siegel, 1986; Gnatowski *et al.*, 2010) Therefore, in highly organic mire deposits, it can also be used as an indicator of the boundaries between hydrologically significant layers (the acrotelm and the catotelm, as discussed in Chapter 2) (Holden, Burt, 2003b) and as such is a useful tool in designing hydrological studies such as those conducted here. Given that the purpose of this analysis is to characterise the decomposition of the organic swamp deposits, bulk density analyses were only conducted on samples from units located within the actual swamp area, and did not include estimates of bulk density for the mineral deposits of the surrounding hillslopes. As organic rich soils shrink considerably when dried, bulk density must be calculated on the basis of the wet bulk volume if it is to represent field conditions. If bulk densities are calculated on a reduced dry volume, they will be too high (Boelter, 1968). Nine samples from different locations (Table 4.2) were collected from depths representing each broad swamp sedimentary unit (identified in previous sediment analyses). At locations where it appeared that the characteristics of a particular sedimentary unit varied significantly with depth, two samples were collected for that unit (for example, T4P8S12 in Table 4.1). Samples were placed into sealable cylinders of known volume and weight, and were weighed while at field moisture. Each sample was oven dried at 105 °C for 48 hours, and weighed again for dry weight. Bulk densities were calculated as follows:

$$\rho = \frac{M_{dry}}{V_{wet}}$$

where ρ is the bulk density (g/cm^3), M_{dry} is the dry weight of the sample in grams, and V_{wet} is the wet volume in cubic centimetres. The greater the bulk density value, the greater the degree of decomposition (Bascomb *et al.*, 1977; Boelter, 1969; Boelter, 1968; Evans, Warburton, 2007). Once bulk densities were determined for each of the nine samples from each swamp unit, these were averaged to give a general indication of the differences in decomposition between the units. The field gravimetric moisture content for each sample was calculated as follows:

$$w = \frac{M_{wet} - M_{dry}}{M_{dry}} x100$$

where w is the gravimetric moisture content expressed as a percentage and M_{wet} is the wet weight of the soil sample. Similarly, field moisture percentages from the samples studied were averaged to provide an overall indication of the moisture contents of different sedimentary units within the swamp.

Table 4.1: Locations for bulk density and moisture content samples*

Location	Depth Sampled (cm)
T1P18S1	0 – 10
	90 – 100
T2P2S4	0 – 20
	100 – 110
T2P3S6	0 – 10
	100 – 110
T3P5S9	0 – 15
	100 – 110
T3P6S10	0 – 20
	100 – 110
T4P8S12	0 – 10
	20 – 30
	120 – 130
T4P9S13	0 – 10
	11 – 20
	90 – 100
T5P11S15	0 – 10
	30 – 40
T6END4P13	0 – 10
	30 – 40

* while samples were collected as near sediment retrieval sites as possible, areas compacted by previous field procedures were avoided.

4.3 Water Table Analyses

To characterise the water table behaviour of the swamp, the groundwater elevation data collected during the study period were graphed against time, and summarised by arithmetic mean, standard deviation, the range of maximum and minimum elevations and the modal elevation for each piezometer. Data from the in-situ data logger in T5P11S15 was used to observe fluctuations on a finer scale, including response to rainfall. Analysis of swamp response to rainfall involved isolating within the five month record periods during which significant rainfalls were recorded that were of various magnitude, and duration. Rainfall data for the five month period was from the Bureau of Meteorology weather station (068035) at "Jamberoo (the ridge)".

4.4 Saturated Hydraulic Conductivity

4.4.1 Experimental Design

The experimental design of the current study addresses the horizontal saturated hydraulic conductivity (K_{sat}) at different depths within the sediment profile which correspond to hydraulic layers identified in sediment analyses and water table monitoring. Ten locations within the swamp area (not including hillslopes) were tested (Table 4.2 and 4.4). In order to enable the association of hydraulic results with sediment character, these tests were conducted proximal to the areas where samples were removed for sediment analysis, but not within the area disturbed by compaction during the extraction process.

Despite the importance of properly defining the hydraulic properties of organic deposits for understanding swamp hydrology, there is no standard methodology that is systematically used to measure the hydraulic parameters of peats. Both laboratory and in-situ methods may be used to the factors used to estimate K_{sat}. As each approach has both advantages and limitations, often specifically relating to a particular study area, there is ongoing debate regarding which of these is the most suitable (Baird, Gaffney, 1994; Beckwith *et al.*, 2003a; Bouma, Decker, 1981; Rosa, Larocque, 2008; Surridge *et al.*, 2005). There is also disagreement about how flow-rate data, once it has been collected in the field or lab, should be analysed to estimate K_{sat}. Many authors are now suggesting that the theoretical basis behind in-situ piezometer and laboratory permeameter analyses, originally developed for rigid media (Hvorslev, 1951; Kirkham, 1945), may be invalid when applied to peat soils with the unique physical properties related to their high organic contents (see section 2.3.2) (Baird *et al.*, 2004; Beckwith *et al.*, 2003a; Holden, Burt, 2003a). Additionally, questions regarding the scale dependency of K within peats have been raised, suggesting that the use of measurements on the scale of a few centimetres in models of whole-of-swamp flow (on the scale of tens of metres) can lead to systematic underestimates (Bromley *et al.*, 2004). Studies dealing with these questions partly come to contradicting conclusions (Bromley *et al.*, 2004; Chason, Siegel, 1986; Clymo, 2004; Ingram *et al.*, 1974; Rizutti *et al.*, 2004; Rycroft *et al.*, 1975a; Rycroft *et al.*, 1975b), and given the lack of precedence for Australian upland swamp systems, it was somewhat difficult to assess the most appropriate approach.

For these reasons, several methods were first attempted in preliminary trials in order to establish the most effective approach for this study. As a result of difficulties encountered with removing intact samples from below the water table (see section 4.1.1 above), it was determined that field analyses would be most suitable for testing at these depths. However, as this study examines *saturated* hydraulic conductivity only, sediments located above the water table could not be correspondingly studied using the same methods.

Because it is hypothesised that the upper layers of swamp deposits contribute most significantly to water transfer (section 2.3.2), a detailed assessment of the hydraulic properties of this stratum could not be disregarded. Additionally, while basal sands are also considered units of hydraulic significance, they could not be assessed by the chosen field method as they could not be penetrated with the available instrument (see below for procedural details). Therefore, a combination of both field and laboratory methods was used. In-situ tests were carried out for organic swamp units at depths both above the water table and below, noting which depths were saturated and which were not. This data was supplemented with the collection of sediment samples from depths corresponding to those tested in field analyses, as well as augered basal sands, to be analysed in the lab using infiltration permeameters in which all samples could be tested at saturation.

Although it has been reported that laboratory tests often yield higher permeability values than field tests on the same peat, usually attributed to sample disturbance and leakage along the permeameter walls (Boelter, 1965; Ingram, 1983b), there is evidence that comprehensive assessment of peat hydraulic properties may be achieved successfully using complementary field and laboratory investigations. Rosa and Larocque (2008) demonstrated that the intrinsic variability associated with the different field and laboratory methods is small compared with the spatial variability of hydraulic parameters. The experimental design of this study is intended to provide data which represents field conditions where possible, but also provides results from the more well-controlled lab experiments in order to form a detailed baseline indication of the hydraulic functioning of the study swamp.

4.4.2 Field Methods

In the field, methods described by (Boelter, 1965; Chason, Siegel, 1986; Dai, Sparling, 1973) were used to conduct recovery tests at different depths within the soil column. Tests were only conducted for swamp sites and did not include piezometer sites at hillslope locations. Recovery tests were undertaken at depths which would provide indicative results for the target hydraulic layers identified during sediment analyses. For the lower layers, which are more uniform, one representative depth from the centre of the layer was used to simplify procedures. Because it is expected that the upper layers may have rapidly varying properties with depth, several depths were tested in the upper 50 cm, corresponding to physical changes noted in sediment analyses.

For the lower, saturated layers, the procedure involved inserting a pointed metal rod (32 mm external diameter) into the soil to the desired depth (*d*), which characterized a representative section of the target soil layer (Table 4.4.1 test sites and depths). The rod was then removed to create a hollow column in the soil. A PVC pipe of the same external diameter (32 mm) was then inserted into the hole to give a tight fit with the soil. The pipe was extended only to a depth 10 cm above (*d -10*) the base of soil column created by the steel rod in order to isolate inflow to a section of 10 cm length. This prevented inflow contribution from areas above the desired depth in the soil column and reduced the potential for confounding effects.

The piezometer was then developed by inserting a slug of water of known volume (V_i = volume slug insertion; proportional to the volume of water required to raise the water level in the column above the elevation of the surrounding water table) into the PVC

Table 4.2: Locations of piezometer recovery tests, depths of tests, and sedimentary unit tested

Location / Site No.	Depth (cm)	Unit	Method
T1P18S1	0 – 20	FOF	Falling head
	40 – 50	FOF	Falling head
	90 – 100	SOF	Falling head
	90 – 100	SOF	Rising head
T2P2S4	0 – 20	FOF	Falling head
	40 – 50	FOF	Falling head
	40 – 50	FOF	Rising head
	100 – 110	SOF	Falling head
	100 – 110	SOF	Rising head
T2P3S6	0 – 20	FOF	Falling head
	40 – 50	FOF	Falling head
	100 – 110	SOF	Falling head
	100 – 110	SOF	Rising head
T3P5S9	0 – 20	FOF	Falling head
	30 – 40	FOF	Falling head
	30 – 40	FOF	Rising head
	100 – 110	SOF	Falling head
	100 – 110	SOF	Falling head
T3P6S10	0 – 10	FOF	Falling head
	10 – 20	FOF	Falling head
	40 – 50	FOF	Falling head
	100 – 110	SOF	Falling head
	100 – 110	SOF	Rising head
T4P7S11	0 – 50	FOF	**
	50 – 60	SOF	Rising head
T4P8S12	0 – 20	FOF	Falling head
	40 – 50	FOF	Falling head
	40 – 50	FOF	Rising head
	80 – 90	SOF	Falling head
	80 – 90	SOF	***
T4P9S13	0 – 20	FOF	Falling head
	20 – 30	FOF	Falling head
	85 – 95	SOF	Falling head
	85 – 95	SOF	***
T5P11S15	0 – 20	FOF	Rising head*
T5P11S15	55 – 65	SOF	Rising head
T6END4P13	0 – 20	FOF	Rising head*
	55 – 65	SOF	Rising head
	55 – 65	SOF	Falling head

FOF = Fibric Organic Fines; SOF = Sapric Organic Fines (see chapter 5 for details)

* Rising head conducted on upper layers as water table present at soil surface in this location

** Could not be conducted due to excessively fast recoveries

*** Could not be conducted due to time restrictions

Table 4.3: Frequency of water level readings during recovery tests, modified from Brassington (2007)

Time since start timing / removal/addition of slug	Frequency of readings
0-10minutes	1 minute
10 – 120 minutes	2 minutes

pipe and allowing it to drain before slug removal and rising head tests were initiated. This was intended to clear pore blockages and smearing occurring in the test section during rod insertion, by creating a large head difference which should induce relatively rapid flows. The rate of the fall in head of this initial slug insertion was recorded in order to monitor flow development. Where the expected fall in head was exceptionally slow (or not detectable within the time frames available for this study), the falling head was allowed to proceed for 2 hours, at which time a slug of known volume (V_w = volume slug withdrawal; proportional to the volume of water required to lower the water level in the column below the elevation of the surrounding water table) was removed and rising head tests were initiated. The recovery within the pipe (water level *H* at time *t*) was recorded, in a method modified from Brassington (2007) (Table 4.3).

For the upper, unsaturated layers, a similar method was used to create test bores; however, for the uppermost layers (0 – 20 cm) the hole was not sealed with the PVC pipe as the depth of the column did not require this (there was no contributing area above these depths to confound results). In these layers, only falling-head tests were possible (the water table was below these levels). Water was added to the hole until levels reached the soil surface, and the volume of the slug and the time taken to drain the hole were recorded.

It is recognised that these methods may have some limitations, primarily related to sediment compaction and disturbance directly surrounding the test soil column as a result of rod insertion, however, these effects were unavoidable for this study. Ideally, the test bore would be created by removing a core of sediment, rather than by lateral compression with a rod. However, as previously discussed, difficulty in removing sediment cores without significant disruption to the surrounding soil structure prevented this method from being used at this site. While compaction of surrounding sediments may affect the rate of flows by reducing pore sizes and disturbing pore geometry in the immediate vicinity of the test hole, this effect is more favourable than the considerable disturbance created by available methods of soil removal. Additionally, this method has been used commonly in similar studies within peatlands of the Northern Hemisphere, with relatively reliable results (Boelter, 1968).

Flow-rate data from recovery tests within the saturated layers was then analysed following the methods of Hvorslev (1951), using the equation:

$$K_{sat} = \frac{A}{FT}$$

where K_{sat} is the saturated hydraulic conductivity in m s^{-1}, A is the cross-sectional area of the borehole at the test depth in m^2, T is the basic time lag in minutes, and F is the shape factor. The basic time lag T is determined graphically, as shown in Figure 4.1. Values of H/H_o are calculated by dividing the drawdown value H by the drawdown value at the start of the test H_o when t = 0. The data should plot on a straight line going through the origin (ie. when H/H_o = 1 and t = 0), although sometimes the early points may 'fall off the line'. A straight line is then drawn through as many points as possible. If this line does not pass through the origin, a parallel line that does should be drawn. The basic time lag T is the value of t when H/H_o = 0.37. This value for t on the graph is substituted into the equation.

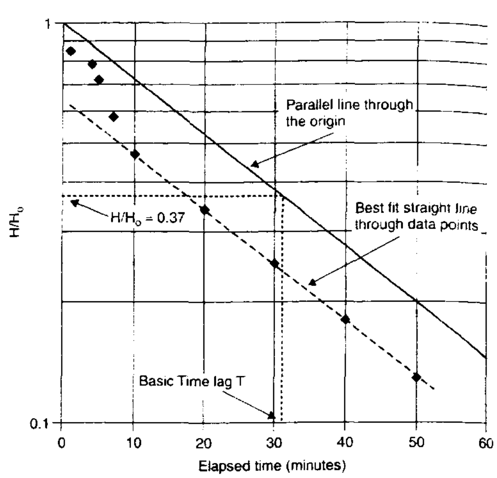


Figure 4.1: Method for determining the basic time lag T using Hvorslev's method. Reproduced from Brassington (2007)

Hvorslev (1951) recognised that the geometry of the test section will affect the calculation, and introduced the concept of the shape factor. Formulas for standard shape factors are available for most common test scenarios (see Brassington 2007).

For the methods used in this study, in which an open section of borehole extended beyond the casing within uniform soil, the shape factor is calculated as follows:

$$F = \frac{2\pi L}{In\left[(L/D)+\sqrt{\left(1+(L/D)^2\right)}\right]}$$

where L is the length of the isolated test inflow section of the borehole in cm, and D is the diameter of the borehole at the test section in cm.

As discussed in section 2.3.2, the use of the Hvorslev method, which is theoretically based on the behaviour of rigid media, may not be entirely valid when applied to studies of highly organic soils. This is primarily related to the fact that the K_{sat} of peaty soils may not behave independently of changing hydraulic gradient (that is, a greater hydraulic gradient may produce a different K_{sat} to that produced by a small hydraulic gradient), and so is not governed by the same physical laws as rigid media, and therefore should not be analysed using the same methods as for rigid media (Evans, Warburton, 2007; Ingram, 1983a). However, despite this, it is still commonly utilised in peatland hydrological studies, and it is considered to be adequate to enable the comparisons between different depths within single boreholes, and between corresponding depths in different boreholes which are required for this study. It does mean, however, that comparisons between in-situ head-recovery tests, which represent values of K_{sat} affected by a changing hydraulic gradient, cannot be directly compared to laboratory tests which represent K_{sat} at a constant hydraulic gradient. Nonetheless, a discussion of these collective results is still acceptable for the purposes of considering questions of experimental design, and for producing baseline data on the hydraulic properties of the sediments of Australian upland swamps. Subsequent studies should be undertaken in order to fine-tune these procedures within the Australian context.

For the unsaturated depths tested in-situ – all within the fibric organic fines unit – K_{sat} could not be estimated. Therefore, in place of K_{sat} values, gross flow rate data are presented. Although not directly comparable to the K_{sat} values obtained for this layer in laboratory tests (see below 4.3.3) or for other sedimentary units, these data provide good indications of variability in transfer capacity at different depths and locations within the fibric organic fines unit itself.

4.4.3 *Laboratory Methods*

As previously mentioned (Section 4.3.1), samples for laboratory permeameter analyses were collected from depths corresponding to the depths tested during field recovery tests, and therefore included a range of samples for each location, representing different sedimentary units. Samples of basal sands collected during initial sediment retrieval were also used for laboratory tests. Table 4.4 shows the samples used for permeameter analyses. Samples were placed directly into the permeameter apparatuses in the field. Permeameters were rectangular in shape (6.5 cm x 6.5 cm x 15 cm), and based loosely on the design of the cube- and modified-cube-methods described by (Surridge *et al.*, 2005). One end of the permeameter was covered with a permeable synthetic mesh to retain the sediment sample but allow free water discharge. Until lab analyses could be conducted, this end was sealed with water proof tape to prevent water loss from the sample, while the other end was plugged with wet newspaper to prevent evaporative losses. For the uppermost, unsaturated layers, a knife and a trowel were used to cut out samples and shape them to fit the permeameter with relatively little disturbance. These samples were orientated such that the direction of flow through the sample was horizontal, despite the permeameter having a vertical form. This allowed for the measurement of horizontal K_{sat} of interest for this study using simple infiltration permeameter methods. In the case of basal sands, which are mineral, massive, and compacted, the structure and orientation of the sample was not important, and samples were simply loaded into permeameters and pressed in order to simulate natural levels of compression.

For the lower layers located below the water table, sample retrieval was again problematic. Unfortunately, it was not possible to retain the structure of these samples during removal and placement into permeameter apparatuses. While this presents a considerable weakness for the laboratory studies of these layers, an investigation of matrix flow through these samples under controlled laboratory conditions was still considered useful for this study. Therefore, laboratory tests were still conducted on these disturbed sediment samples, and results will be interpreted with acknowledgement of the limitations of these particular experiments.

In the lab, infiltration experiments were performed on each permeameter sample, following the methods outlined in (Hillel, 1982). To reduce variability of consecutive measurements related to changes in the degree of saturation of the sediments, each

Table 4.4: Locations, depths, and units sampled for laboratory permeameter testing

Location / Site No.	Depth (cm)	Unit
T1P18S1	0 – 10	FOF
	90 – 100	SOF
T2P2S4	0 – 20	FOF
	100 – 110	SOF
T2P3S6	0 – 15	FOF
	100 – 110	SOF
	220 – 230	Grey sands
T3P5S9	0 – 15	FOF
	100 – 110	SOF
	240 – 250	Dark sands
	250 – 260	Grey sands
T3P6S10	0 – 10	FOF
	100 – 110	SOF
T4P7S11	*	*
T4P8S12	0 – 20	FOF
	20 – 30	FOF
	80 – 90	SOF
	150 – 170	Dark sands
	180 – 190	Grey sands
T4P9S13	0 – 10	FOF
	10-20	FOF
	85 – 95	SOF
	100 – 120	Dark sands
	170 – 180	Grey sands
T5P11S15	0 – 10	FOF
	100 – 120	Dark sands
T5P11S15	55 – 65	SOF
T6END4P13	0 – 10	FOF
	55 – 65	SOF

FOF = Fibric Organic Fines; SOF = Sapric Organic Fines (see Chapter 5 for details)

* sample could not be obtained

permeameter sample was submersed in water for 24 hours to fully saturate prior to experimentation. Once samples were saturated, a constant-head was applied and flow rates were monitored for consistency. After consistent flow rates were recorded for three consecutive runs for each permeameter, discharge rates (volume discharged *v* at time *t*) were recorded. These were used to calculate K_{sat} using a rearrangement of the Darcy equation:

$$K_{sat} = \frac{Q}{iA}$$

where K_{sat} is the saturated hydraulic conductivity in cm s^{-1} , Q is the flow rate in ml s^{-1} , i is the hydraulic gradient, and A is the cross-sectional area of flow in cm^2. Values of K_{sat} in cm s^{-1} were then converted to the standard measure of m s^{-1}

4.4.4 Desktop Analyses

After the determination of K_{sat} values for each in-situ test section and permeameter experiment, the results were grouped into their relevant sedimentary/hydraulic layers and averaged to provide a general indication of the hydraulic properties of each separate unit, for each type of analysis (in-situ or lab). These averages were used to broadly compare vertically distinct layers, and to assess the relative hydraulic effectiveness of these units. To investigate the spatial heterogeneity found within individual sedimentary units, values of K_{sat} for depths representing the corresponding layer in each borehole were compared. Also, considering that head recovery and permeameter tests were run for several depths within the uppermost layers, the results of these will be compared to investigate the change in hydraulic properties with depth within these layers.

Finally, the results of in-situ and laboratory analyses will be compared in order to evaluate the effect of the different experimental procedures. Because unsaturated layers could not be assessed for K_{sat} in-situ, a combination of field and laboratory results (with acknowledgement of the limitations of combining results from different methods, discussed in section 4.3.2) will be used to generate complete schematic cross-sectional, longitudinal and planform diagrams of hydraulic pathways and storages, governed by the distribution of varying values of K_{sat} throughout the swamp area: where areas of higher K_{sat} values represent zones of transfer, and areas of lower K_{sat} represent locales of high water retention (storage).

The following chapter, Chapter 5, presents the results of the physical analyses and Chapter 6 presents the results of the hydrological analyses.

5 Results I: Physical Characteristics

The results of sediment analyses and geomorphic investigations are presented in this chapter. Firstly, the primary geomorphic units comprising the swamp are identified and described in terms of their physical characteristics, geomorphic structure, vegetation associations, and distribution. Sediment analyses are then presented on a transect by transect basis, and compiled to create a longitudinal profile of sediment distributions. The results of bulk density and gravimetric water content analyses are then presented for the main sedimentary units within the swamp. Following the presentation of these results, cross-sectional and longitudinal patterns in the physical characteristics of the swamp are summarised.

5.1 Swamp Morphology

5.1.1 Basin Morphology

Within the study area, the slope of the swamp basin is approximately 6 ° from the upstream boundary (marked by a clear change in slope from the eastern hillslope) to the downstream limit of the study area at the bedrock outcrop. Along this gradient, the bedrock slope is not consistent, and a series of gradient changes occur in the downstream direction (Figure 5.1). The surface morphology approximately follows the shape of the bedrock, although at the upstream limit some bulging is apparent (Fig 5.1). Depth from the sediment surface to bedrock is greatest at Transect 2 on the long profile, reaching 3.3 m. In cross section, the bedrock morphology of the central swamp area is generally concave, with the inflection point roughly aligning with the swamp axis. There is some hillslope asymmetry, with greater slope gradients on the northern hillslopes than on southern hillslopes (Figures 5.2). The surface morphology vaguely reflects the bedrock concavity, although the gradient of the depression is not as severe (near flat). No significant meso-topographic features were observed within the swamp area. The shape of the swamp is approximately funnel-like: it is widest through Transects 2 and 3 (52.8 m and 58.8 m, respectively), and narrows in a downstream direction toward the point of greatest lateral bedrock confinement at Transect 6 (Figures 5.2 and 5.3). This is also the point of shallowest bedrock depth, and in this area a number of bedrock-based pools occur. However, this pattern of downstream swamp constriction pertains only to the central

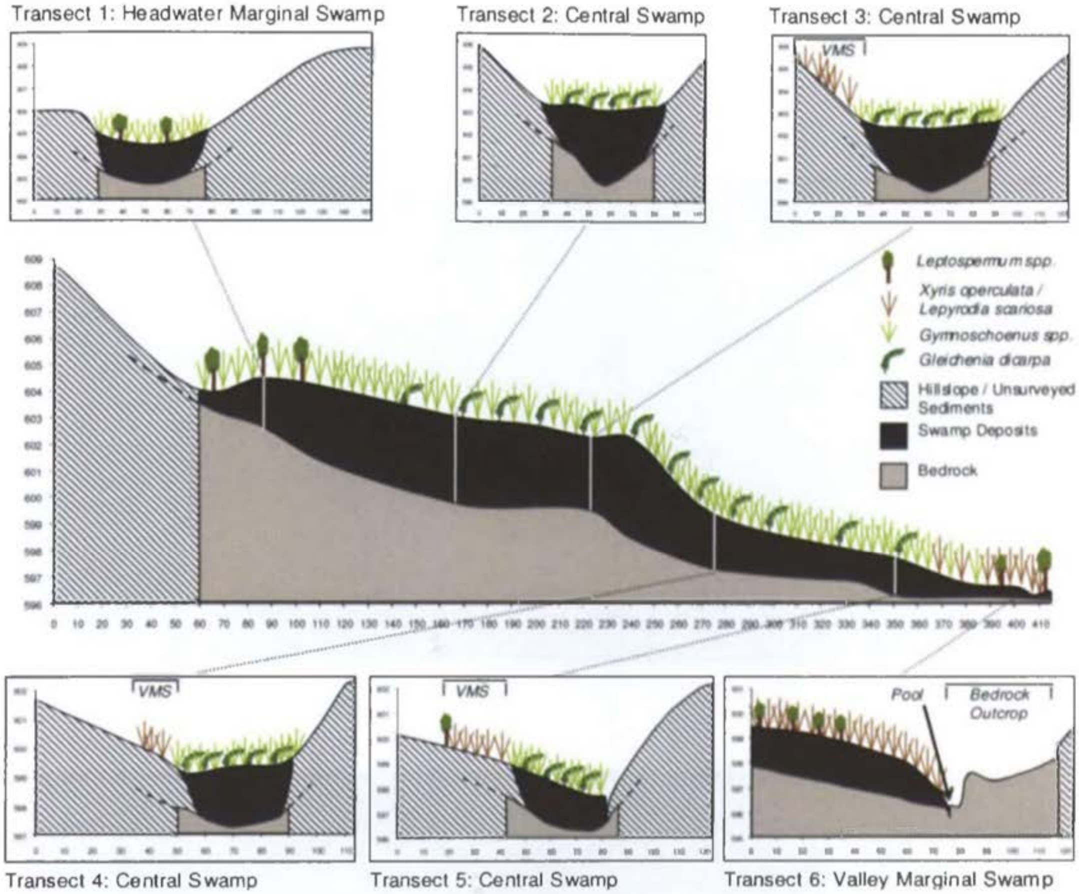


Figure 5.1: Summary schematic of swamp sediment distribution, geomorphic zones and features, and vegetation associations (VMS = valley marginal swamp)

swamp area, and if the marginal swamp areas are considered, the swamp actually broadens to > 76.4 m at Transect 6, and the depth to bedrock is no shallower (in the outer profiles T6END4P13 and T6END2P12) than observed in other swamp transects.

5.1.2 Swamp Geomorphic Zones and Units

Based on surface morphology, sediments and moisture, and vegetation structure, a number of geomorphic zones and units have been identified within the study area. The distribution of the geomorphic units is shown in Figures 5.2 and 5.3.

The study site can be classified into two broad divisions: the swamp areas and the bordering hillslope areas. The swamp areas are comprised of three different swamp zones, which are comprised of different geomorphic units (Figure 5.4). The zone

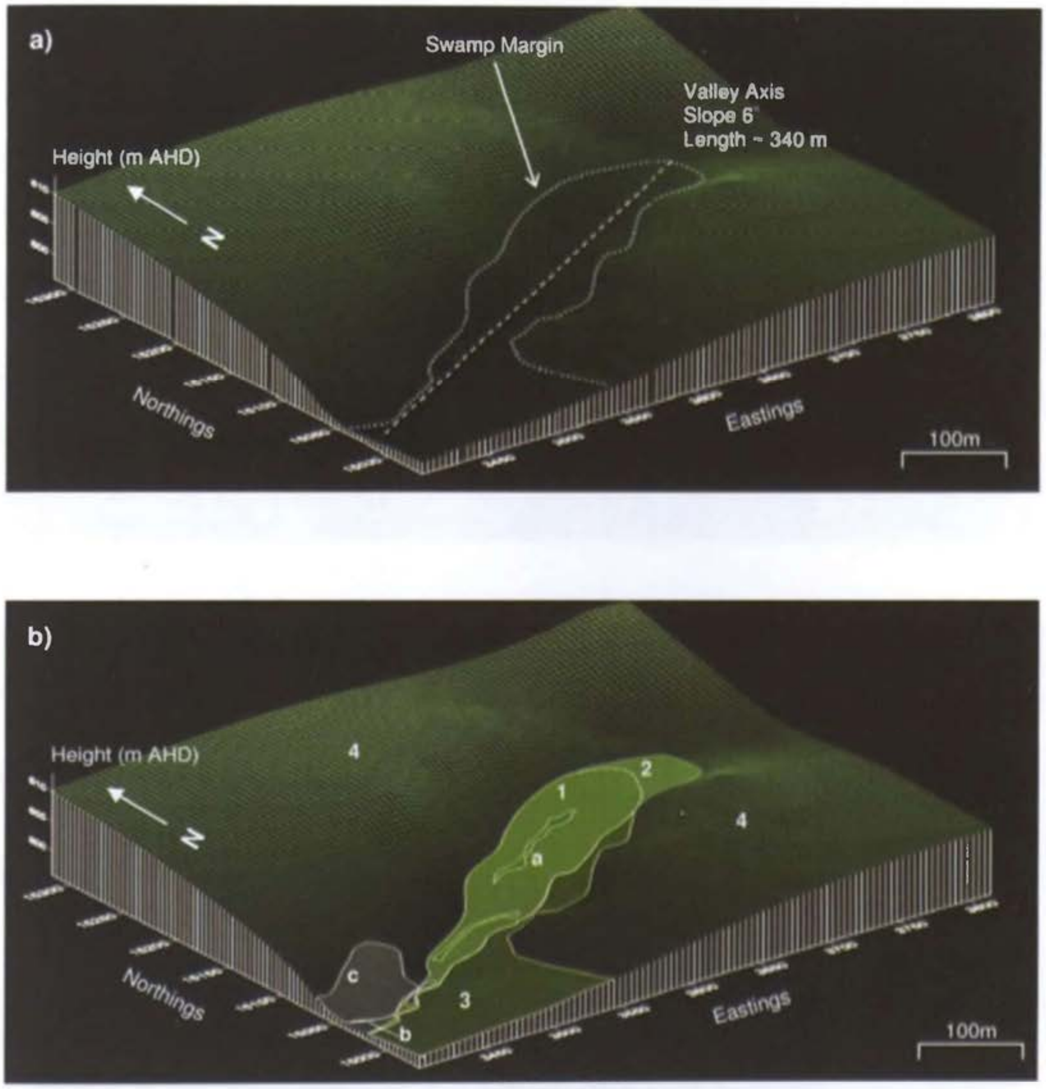


Figure 5.2: 3D topographic block diagrams of Budderoo Swamp study site. Produced from total station survey data using Surfer® 8.
a) broad swamp morphology showing valley margin and swamp axis
b) geomorphic zones and features: 1 = central swamp; 2 = headwater marginal swamp; 3 = valley marginal swamp; 4 = hillslopes; a = springlines; b = pools; c = bedrock outcrop

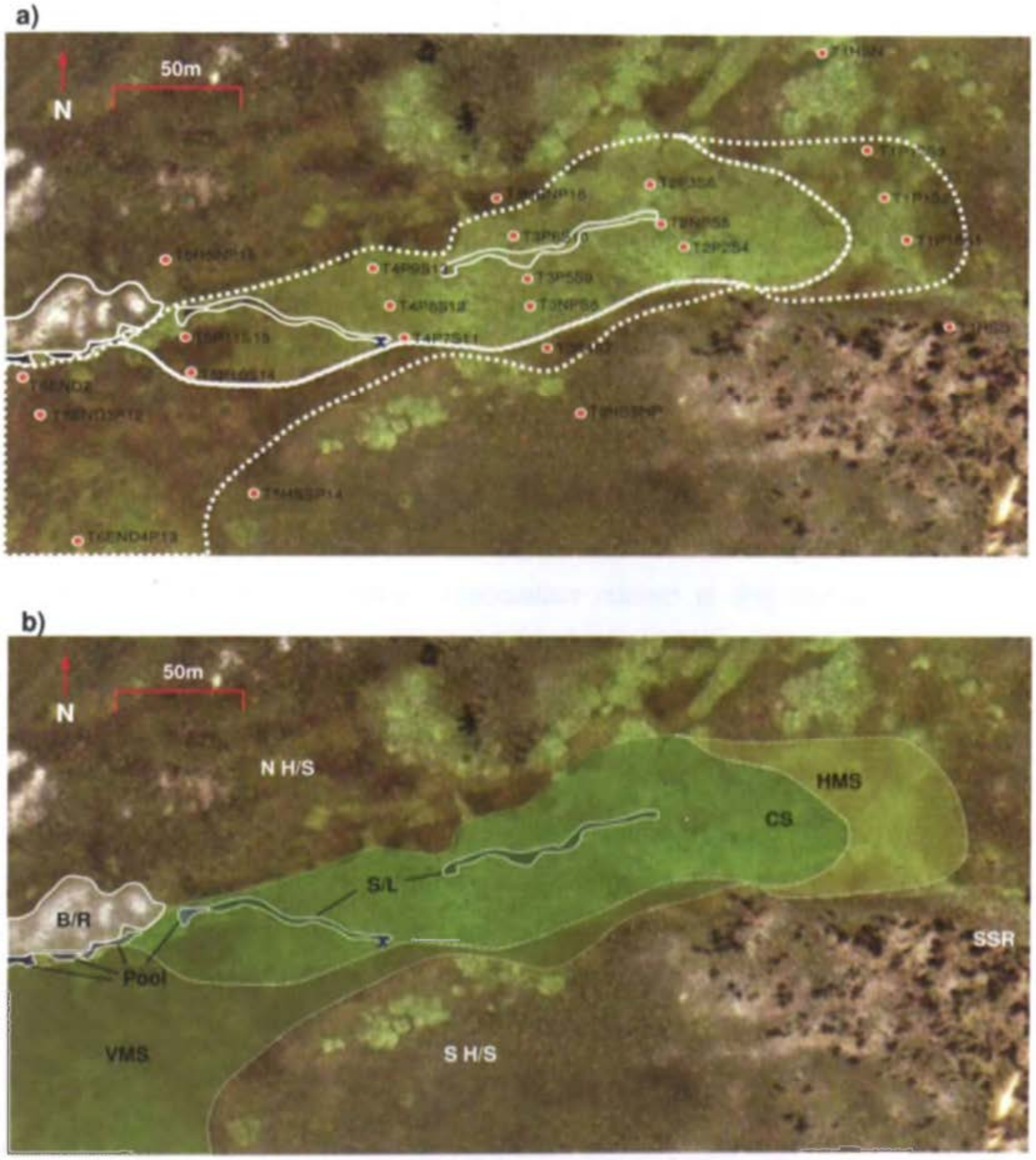


Figure 5.3: Planform geomorphic map. a) shows the boundaries of the geomorphic zones and units and the location of soil samples and water table monitoring piezometers; b) illustrates the geomorphic zones and units with labels: HMS = headwater marginal swamp; CS = central swamp; VMS = valley marginal swamp; N H/S = northern hillslope; S H/S = southern hillslope; B/R = bedrock outcrop; SSR = sandstone ridge; S/L = spring line; blue x represents location of possible spring.

which will subsequently be referred to as the 'central swamp' occurs along the primary axis of the total swamp area, roughly corresponding with the axis of bedrock concavity and the areas of lowest surface elevation between the two hillslopes. Table 5.1 presents a summary of the physical character of the central swamp zone, including primary vegetation associations and a description of the geomorphic unit structure. Sedimentary units and their physical characteristics, and the results of LOI, bulk density, and moisture content analyses are also contained in these tables but will be discussed in sections 5.2 – 5.3 below.

Three distinct geomorphic units can be found within the central swamp zone. It is hypothesized that a spring is located at T4P7S11. This feature is marked by persistent surface saturation, and observable flow generation in the region of the cavity created for piezometer placement at T4P7S11. Vegetation surrounding the area is dominated by the rush, *Baumea sp.*, rather than *Gleichenia dicarpa* and *Gymnoschoenus sp.*, which dominate the main area of the central swamp zone. Considering the clear vegetation association related to this spring unit, it was possible to identify other areas of potential spring contribution throughout the central swamp zone (Figure 5.4 and 5.5). Two spring lines were identified (Figure 5.3). These areas are comprised of basal sands, over which a thick, but relatively 'loose', accumulation of fine sediments occurs, supported by a dense rooting system. These areas were highly compressible at the surface, suggesting that the sediment matrix is loose in comparison to the structure of the organic fines dominating the central swamp zone. One spring line extends along the northern side of the central swamp, from near Transect 2 towards Transect 4. The second spring line originates close to T4P7S11, traverses the central swamp and terminates with a series of pools on the northern side adjacent to the bedrock outcrop.

The pools directly abut the northern hillslope, and are bedrock-based with relatively stable, steep boundaries comprised of organic fines (Figure 5.6). Similar to the spring lines, the perimeters are vegetated by *Baumea spp.*, which also dominates the connecting sediments between adjacent pools. Between two of these pools a relatively persistent 'cascade' of water was observed throughout the study period. This exchange appeared to occur through a subsurface soil pipe present within the sediment accumulation joining the two pools. Running water was clearly heard, and cascading flows were observed at the point of discharge from the upstream pool into the downstream pool, but no specific outflow point could be located at the perimeter of the upstream pool. As this flow was observed both at the beginning of the study

Table 5.1: Physical characteristics of the Central Swamp geomorphic zone

Dominant Vegetation	Geomorphic Units	Sediment Profiles	Sedimentary Unit	Physical Characteristics	Ave. Sand Size (Ø)
Button Grass - *Gymnoschoenus spp.* **Coral Fern -** *Gleichenia dicarpa*	**Spring -** Occurs at T4P7S11; marked by constant saturation at surface and consistent detectible upwelling and flow from piezometer cavity **Spring Lines -** Occur as areas dominated by dark green rush, *Baumea rubiginosa*; very loose sediment structure: mineral sediment and humus adhering loosely to roots in highly saturated matrix; underlain by sands **Pools -** Occur in downstream regions, related to spring lines and bedrock confinement; bedrock based; separated by loose organic accumulations (similar to spring lines described above); likely connected by underground piping as well as direct inflows from upstream pools	T2P2S4 T2NPS5 T2P3S6 T3NPS8 T3P5S9 T3P6S10 T4P7S11 T4P8S12 T4P9S13 T5P10S14 T5P11S15	Fibric Organic Fines	- high coarse organic matter content - matrix of organic fines - low clay content	*
			Sapric Organic Fines	- low coarse organic matter content - dense matrix of organic fines - low clay content	*
			Sandy Clay Loam	- predominantly mineral - moderate clay and sand content - low to nil coarse organic matter	2
			Dark Sands	- medium – coarse - poorly sorted, leached sands - includes organic fines - low to nil coarse organic matter	1
			Grey Sands	- medium – coarse - poorly sorted, leached sands - low fine and organic contents - some preserved organic materials - pebbles, mottling	1
			Saprolite	- white to yellow-grey - puggy - pebbles	*

u = upper fibric organic fines; *l* = lower fibric organic fines;
* denotes property not analysed for particular sedimentary unit

Figure 5.4: Downstream view of Budderoo Swamp showing swamp geomorphic zones and units, and bedrock outcrop (sold white line). Area inside: dashed line = central swamp; dash-dot line = headwater marginal swamp; dotted line = valley marginal swamp; blue area = pool; box = spring line

Figure 5.5: Photo of vegetation and sediment associated with potential spring and spring lines in Budderoo Swamp

Figure 5.6: Photo of bedrock-based pool found at the downstream constriction of the study area

period and at the end, it is believed that it may be fairly permanent. For the purposes of this study, these features will not be considered in terms of their hydrological implications, but are noted as distinct geomorphic features within the swamp.

The second swamp zone is the headwater marginal swamp, which occurs across Transect 1. It closely resembles the central swamp zone, but is differentiated from this zone, based on surface morphology and local vegetation associations. The surface is lobate, and vegetation in this unit is dominated by *Gymnoschoenus spp.* and *Leptospermum spp.* in a predominantly tall shrub habit that occurs in 'drier' conditions. The coral fern, *Gleichenia dicarpa*, although present, is much less abundant in this zone than in the central swamp zone. Table 5.2 summarises the characteristics of the headwater marginal swamp zone.

The third swamp geomorphic zone is the valley marginal swamp (Table 5. 3). This zone extends from T3P4S7, broadening across the southern hillslope towards Transect 6, and all profiles along Transect 6 occur within this zone. In the downstream region of the valley marginal zone, the central swamp zone pinches off into pools at the bedrock outcrop on the northern hillslope. Therefore, while not belonging to the central swamp zone, surface moisture and vegetational characteristics suggest that the valley marginal swamp zone is a form of swamp unit, rather than hillslope. The surface sediments are less compactable than in the central swamp zone and are drape-like over the underlying bedrock. The vegetation exhibits a clear distinction from both the central and headwater marginal swamps, and the southern hillslope. In the valley marginal swamp *Gymnoschoenus* becomes less dominant, and the herbs *Lepyrodia scariosa* and *Xyris operculata* become more abundant. Around T6END4P13, a cluster of tall *Leptospermum* shrubs also occurs. This zone, as marked by these vegetation associations, appears to continue beyond the boundaries of the study area, in both a southerly and westerly direction.

The final geomorphic zone in the study area is the hillslopes (Table 5. 4). Vegetation communities associated with this unit are comprised of heath species including *Hakea spp.*, *Leptospermum spp.*, *Epacris paludosa*, and *Platysace linearifolia*. The *Leptospermum spp.* occur in a smaller shrub habit than those occurring within the swamp zones. A sandstone ridge is found on the southeastern corner of the study area, comprised of loose clean sands, bedrock fragments and numerous bedrock outcrops, and supporting semi-open *Eucalypt* forest. The profile T1HSS is located on this ridge. At the north-western limit of the study area, a bedrock outcrop

Table 5.2: Physical characteristics of the Headwater Marginal Swamp geomorphic zone

Dominant Vegetation	Geomorphic Units	Sediment Profiles	Sedimentary Unit	Physical Characteristics	Ave. Sand Size (Ø)	Av LC
Tea Tree - *Leptospermum spp.*	N/A	T1P18S1 T1P2S2	Fibric Organic Fines	- high coarse organic matter content - matrix of organic fines - moderate clay content	*	45
Button Grass - *Gymnoschoenus spp.*			Sapric Organic Fines	- low coarse organic matter content - dense matrix of organic fines - moderate clay content	*	27
			Sandy Clay Loam	- predominantly mineral - moderate clay and sand content - low to nil coarse organic matter	2	15
			Dark Sands	- medium – coarse - poorly sorted, leached sands - includes organic fines - low to nil coarse organic matter	1	3.
			Grey Sands	- medium – coarse - poorly sorted, leached sands - low fine and organic contents - some preserved organic materials - pebbles, mottling	0.5	1.
			Saprolite	- white to yellow-grey - puggy - pebbles	*	*

u = upper fibric organic fines; *l* = lower fibric organic fines
* denotes property not analysed for particular sedimentary unit

Table 5.3: Physical characteristics of the Valley Marginal Swamp geomorphic zone

Dominant Vegetation	Geomorphic Units	Sediment Profiles	Sedimentary Unit	Physical Characteristics	Ave. Sand Size (Ø)	Av LC
Tea Tree - *Leptospermum spp.* **Tall Yellow Eye -** *Xyris Operculata* **Scale Rush** *Lepyrodia scariosa*	N/A	T3P4S7 T6END4P13 T6END3P12 T6END2	Fibric Organic Fines	- high coarse organic matter content - matrix of organic fines - moderate clay content	*	48
			Sapric Organic Fines	- low coarse organic matter content - dense matrix of organic fines - moderate clay content	*	44
			Clay Loam	- organic colouration - very low to zero sand - low to nil coarse organic matter	*	22
			Light Clay	- organic colouration - low content fine sand (<5%) - low to nil coarse organic matter	*	18
			Sandy Clay	- clay with medium-fine sand - low to nil coarse organic matter	2.5	6.
			Clayey Sand	- organic colouration - medium-coarse, poorly sorted - low to nil coarse organic matter	1.5	3.
			Dark Sands	- medium – coarse - poorly sorted, leached sands - includes organic fines - low to nil coarse organic matter	0.5	5.
			Grey Sands	- medium – coarse - poorly sorted, leached sands - low fine and organic contents - some preserved organic materials - pebbles, mottling	0.5	1.
			Saprolite	- white to yellow-grey - puggy - pebbles	*	*

u = upper fibric organic fines; *l* = lower fibric organic fines   * denotes property not analysed for particular sedimentary unit

Table 5.4: Physical characteristics of the Hillslope geomorphic zone

Dominant Vegetation	Geomorphic Units	Sediment Profiles	Sedimentary Unit	Physical Characteristics	Ave. Sand Size (Ø)	Av LC
Eucalyptus spp. *Hakea spp.*	**Sandstone Ridge** - Southern hillslope; loose sands;	T1HSS T1P17S3 T1HSN	Clay Loam	- organic colouration - very low to zero sand - minimal coarse organic matter content	*	*
Leptospermum spp.	bedrock fragments; bedrock outcrops;	T3HSS T3HSNP16	Fine Sandy Loam	- dark brown loam - fine, relatively well sorted sand	3	*
	semi-open eucalypt	T5HSSP14	Loamy Sand	- medium, poorly sorted sand	1	*
Epacris paludosa	forest	T5HSNP15	Sandy Clay Loam	- clay with medium-fine sand - low to nil coarse organic matter	2	*
Platysace linearifolia	**Bedrock Outcrop -** Northern hillslope; directly abuts		Clayey Sand	- coarse-fine poorly sorted sand with clay content - light grey or yellow	1.5	*
	swamp; location of		Light Clay	- clay with fine sand (<10%) - medium brown-grey	*	*
	bedrock-based pools, and end of		Sandy Clay	- Clay with fine sand - light grey – off-white	2.5	*
	study area		Sand	- medium – coarse - poorly sorted - leached - pebbles	1	*
			Saprolite	- bright yellow to dark orange - puggy - pebbles	*	*

* denotes property not analysed for particular sedimentary unit

appears, directly abutting the swamp and the bedrock-based pools at the terminus of the central swamp zone. As noted above (section 5.1.1 Basin Morphology), there is significant asymmetry between the northern and southern hillslopes, with the northern hillslope being steeper than the southern.

5.2 Sedimentary Analyses

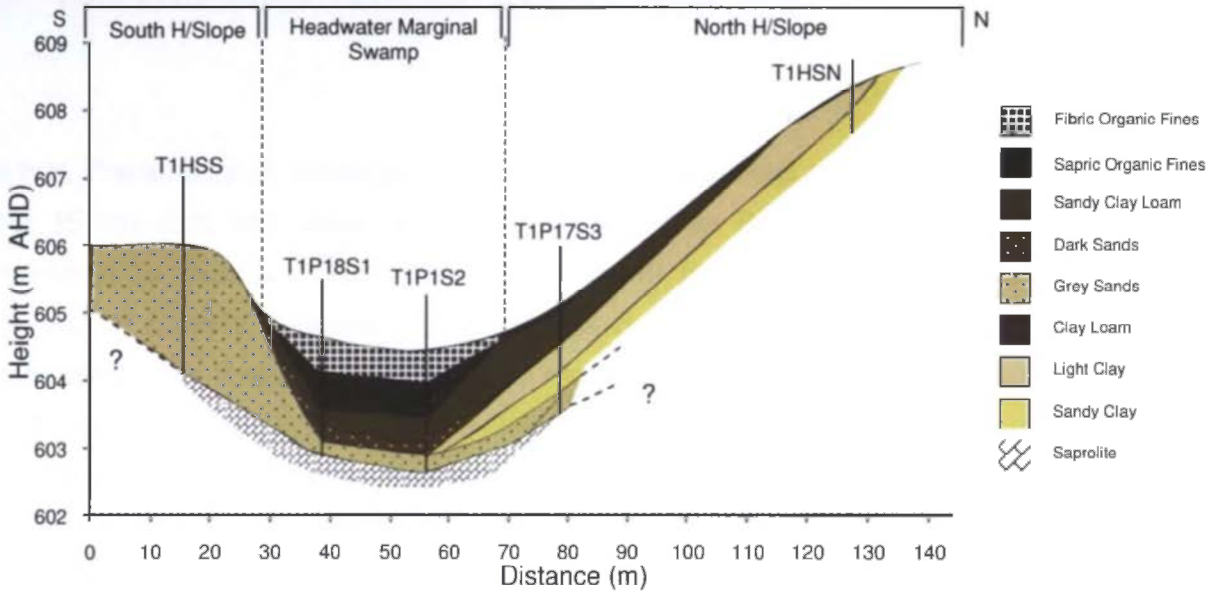
Using the sedimentological approaches outlined in Chapter4, the character of the sediments observed in each profile along each transect are described. Mean loss on ignition values for the swamp units are also presented. Sediments have been broadly separated into hillslope and swamp units based on their textural and grainsize character, as well as their organic matter content. Within these units, differences in textural, grainsize and LOI characteristics have been used to identify boundaries between different sedimentary units.

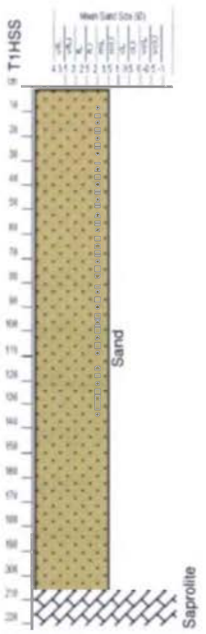
5.2.1 Transect 1

Transect 1 is the most upstream transect, along which five sediment profiles were analysed: T1HSS, on the sandstone ridge bordering the swamp to the south; T1P18S1 and T1P1S2 within the swamp area; T1P17S3 on the margin of the swamp and northern hillslope, and; T1HSN on the northern hillslope. Figure 5.7 shows the distribution of sediments along Transect 1, and the sedimentology of each profile.

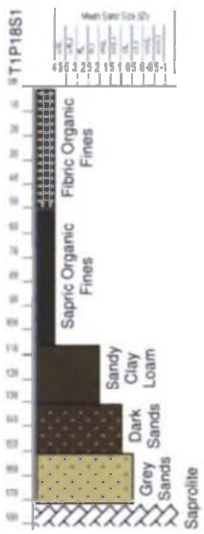
On the hillslopes, profile T1HSS is characterised by loose, massive, poorly sorted podsolised sands (mean sand size ~ 1.5 Ø) directly overlying the sandstone bedrock, while T1HSN is primarily clays and fine (mean sand size ~ 2.5 Ø) sandy clays. T1P17S3 bears most resemblance to T1HSN, but has a thin horizon of very dark brown, clayey organic fines and a clear development of sandy clay loam (mean sand size ~ 2 Ø) overlying the clays seen in the northern hillslope profile. The sedimentology of the swamp profiles T1P18S1 and T1P1S2 in Transect 1 consists of thicker accumulations of black clayey organic fines over a similar sandy clay loam layer (mean sand size ~ 2 Ø) as that observed in the profile T1P17S3. The upper horizon of the organic fines, extending down to 50 cm, is fibric (poorly or partially decomposed), containing a high proportion of coarse organic matter and vegetation

Figure 5.7: Transect 1 Sedimentology

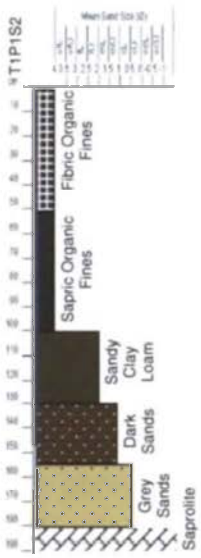




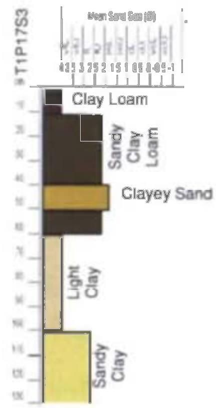
Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Sand	Hillslope sand; massive; poorly sorted, medium-coarse; podzolization – light grey grading down to dark orange base	1.5	*
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave 15mm b-axis); dark orange	*	*



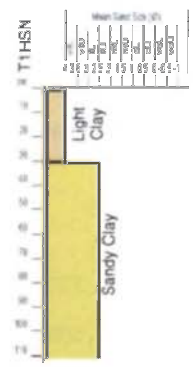
Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; coarse root mat and coarse detritus in sapric loamy-peat matrix; some clay content; very dark brown	*	48.0
Sapric Organic Fines	Sandy sapric peaty-loam; sand <10%; saturated; amorphous; sticky; filamentous roots and fine debris; some clay content; black	*	27.3
Sandy Clay Loam	Denser layer containing higher propotion of clay and coarse sand; few roots, little detritus; dark brown	2	9.6
Dark Sands	Medium-coarse, poorly sorted organic sands; clean sand grains; massive; medium brown	1	3.2
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 3mm b-axis); massive; wet; grading from light grey to yellow-grey;	0.5	1.5
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave.	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; some clay content; very dark brown	*	42.6
Sapric Org anic Fines	Sandy sapric peaty-loam; sand <10%; saturated; amorphous; sticky; filamentous roots and fine debris; some clay content; black	*	28.0
Sandy Clay Loam	Denser layer containing higher proportion of clay and coarse sand: sand increasing slightly with depth; few roots, little detritus; dark brown	2	20.4
Dark Sands	Medium-coarse, poorly sorted organic sands; clean sand grains; massive; medium brown	1	3.3
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 3mm b-axis); massive; light grey; dark organic mottles	0.5	1.3
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave.	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Clay Loam	Organic clay loam; very low to zero sand; few filamentous roots and fine detritus; dark brown	*	*
Sandy Clay Loam	Denser layer containing proportion of clay and coarse sand; few roots, little detritus; dark brown	2	*
Clayey Sand	Coarse-fine poorly sorted sand with clay content; medium brown	1.5	*
Light Clay	Clay with fine sand (<10%); medium brown-grey	*	*
Sandy Clay	Clay with fine sand (<50%); light grey – off-white (leached layer)	2.5	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Light Clay	Clay with fine sand (<10%); medium brown	*	*
Sandy Clay	Clay with fine sand (<50%); grades from brown-yellow to light grey (same as T1P17S3); bright yellow mottle from 90cm; sand content increasing slightly with depth	2.5	*

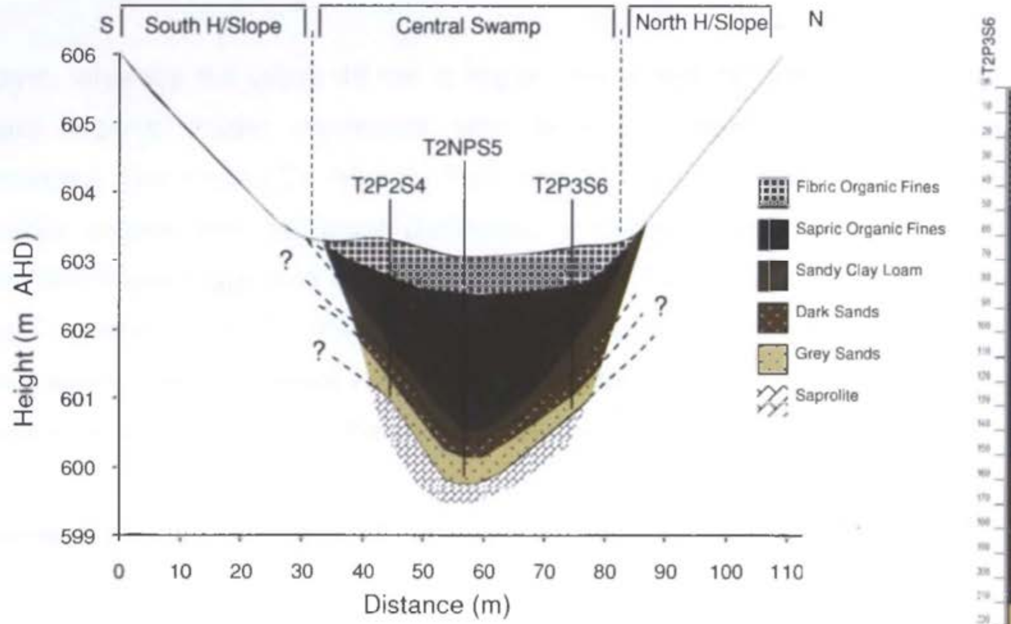
Mean sand size determined via visual assessment; LOI (at 500 °C) is percentage of dry (105 °C) weight root mat. The amount of coarse organic detritus in this stratum is greatest within the upper 15 cm, and decreases rapidly with depth. While thick roots continue to penetrate to the lower boundary of this layer (- 50 cm), from about 20 cm depth the proportion of partially decayed organic detritus decreases as it becomes more decomposed (less fibrous) with depth. The mean LOI value for the fibric organic fines in Transect 1 is 45.3 %. Below this fibric layer, the lower stratum of the organic fines is sapric (smooth, highly decomposed), and the organic content is primarily humic (mean LOI 27.6 %), with only sparse filamentous roots penetrating to these depths. The boundary between these organic layers is relatively gradual, with the depth of thick vegetation roots dictating the lower extent of the upper fibric layer. Beneath the organic fines is a layer of organic sandy clay loam, with mean LOI of 9.6 % in T1P18S1 and 20.4 % in T1P1S2. The boundary between the organic fines and the underlying sandy clay loam is diffuse.

In the swamp profiles the sandy clay loam overlies basal sands, that grade from dark organic sands to grey sands directly above saprolite. The boundary is sharp between the sandy clay loam and dark sands, but more diffuse between the basal sand units. These sands are comprised of poorly sorted, medium-coarse leached sands which resemble those seen in the upper horizons on the southern hillslope. Their mean LOI is low compared to the overlying layers, at less than 4 %. The dark sands are very dark brown in colour, and contain a slightly higher proportion of organic fines (mean LOI = 3.3 %) than the underlying grey sands (mean LOI = 1.4 %). In Transect 1 mean sand size is slightly finer in the dark sands (~ 1 Ø) than in the grey sands (~ 0.5 Ø). The grey sands grade from light grey to medium yellow-grey with depth, and contain patches of dark organic staining, usually containing preserved organic debris. They include a minor fraction of small quartz pebbles averaging 3 mm b-axis. Beneath both the southern hillslope sands and the basal swamp sands, quartz pebbles of 10 – 15 mm mean b-axis, and up to 25 mm b-axis are found within a thin puggy sandstone saprolite horizon.

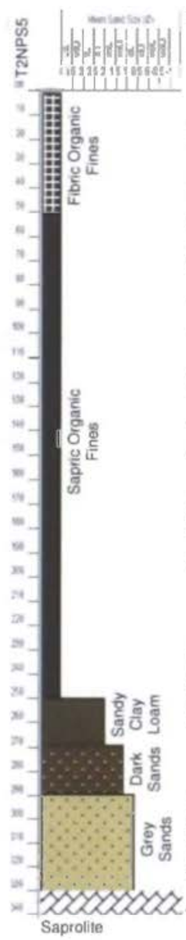
5.2.2 Transect 2

The sample profiles on Transect 2 are confined to the swamp area, and do not extend onto the hillslopes (Figure 5.8). Sedimentology is relatively uniform across these profiles and consists of the same sequence of sedimentary units as the swamp profiles in Transect 1. The fibric organic fines again extend to 50 cm, and appear to be related to the vegetation rooting depth. A similar stratification occurs in

Figure 5.8: Transect 2 Sedimentology



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; coarse root mat and coarse detritus in sapric peat matrix; some clay content; very dark brown	*	47.9
Sapric Organic Fines	Sapric peaty-loam; saturated; amorphous; sticky; sparse filamentous roots; some clay content; black	*	14.0
Sandy Clay Loam	Denser layer containing higher proportion of clay and sand; dark brown	2	6.6
Dark Sands	Medium-coarse, poorly sorted organic sands; clean sand grains; massive; medium brown	1	2.9
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 3mm b-axis); massive; light grey; dark organic mottles	0.5	1.2
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 10mm b-axis); yellow-grey	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; some clay content; very dark brown	*	53.0
Sapric Organic Fines	Sandy sapric peaty-loam; sand <10%; saturated; amorphous; sticky; filamentous roots; minimal clay content; black	*	29.0
Sandy Clay Loam	Denser layer containing higher proportion of clay and sand: dark brown	2	4.3
Dark Sands	Medium-coarse, poorly sorted organic sands; clean sand grains; massive; medium brown	1	4.1
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 4mm b-axis); massive; light grey; dark organic mottles	0.5	0.8
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 10mm b-axis); yellow-grey	*	*

Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; coarse root mat and coarse detritus in sapric peat matrix; some clay content; very dark brown	*	50.4
Sapric Organic Fines	Sandy sapric peaty-loam; sand <10%; saturated; amorphous; sticky; filamentous roots; minimal clay content: black	*	23.1
Sandy Clay Loam	Denser layer containing higher proportion of clay and sand: dark brown	2	7.4
Dark Sands	Medium-coarse, poorly sorted organic sands; clean sand grains; massive; medium brown	1.5	2.4
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 4mm b-axis); massive; light grey; dark organic mottles	1.5	0.9
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 10mm b-axis); yellow-grey	*	*

Mean sand size determined via visual assessment; LOI (at 500 °C) is percentage of dry (105 °C) weight

* denotes LOI not obtained for these profiles / sediment types

this layer, whereby the upper 15 cm is highly fibrous and the amount of partially decayed organic matter decreases with depth as organics become more decomposed. The mean LOI value for fibric organic fines in Transect 2 is 50.4 %. The sapric organic fines are again dominated by humic organic matter, with only sparse filamentous roots and fine detritus observed. The mean LOI for this layer across Transect 2 is 22 %. The texture of this unit is more amorphous, 'jelly-like', and less sticky than in Transect 1, and as such is likely to contain less clay. This unit thickens to around 2 m towards the centre of the swamp (at T2NPS5).

The average sand size of the sandy clay loam is ~ 2 Ø, and the mean LOI is 6.1 %. The basal units are again poorly sorted, medium to coarse dark sands and grey sands containing small pebbles (mean 4 mm b-axis), overlying puggy saprolite with pebbles (mean 10 mm b-axis). Again, these lower layers contain significantly less organic matter than the overlying loam and organic layers. The organic matter content of the dark sands (mean LOI = 3.1 %) is slightly greater than that of the grey sands (mean LOI = 1 %). In the dark sands of Transect 2, the mean sand size (~ 1 Ø) is again slightly finer than in the grey sands (~ 0.5 Ø).

5.2.3 Transect 3

Transect 3 contains profiles both on the hillslopes and within the central swamp area (Figure 5.9). The profile T3HSS on the southern hillslope consists of yellow earths, characterised by uniform, poorly sorted, clayey sand (mean sand size ~ 1.5 Ø) grading in colour from medium brown, through grey, to bright yellow with depth. In T3P4S7 there is a layer of fibric organic fines (mean LOI = 41. 6 %) overlying this clayey sand (mean LOI = 3.6 %). On the northern hillslope of Transect 3, textures in T3HSNP16 are sandier than those observed at a similar position on Transect 1 at T1HSN. In T3HSNP16 a thin horizon of fine sandy loam (mean sand size ~ 3 Ø) is underlain by sandy clay loam (mean sand size 2 Ø), grading into loamy sands and a base unit of sands (mean sand size 1.5 Ø and 1 Ø, respectively). The swamp profiles, T3NPS8, T3P5S9, and T3P6S10 are again similar to those seen in Transects 1 and 2. The organic fines are again structured into an upper horizon of fibric organic fines (mean LOI = 56.1 %) which grades in decomposition with depth and lies above the lower sapric deposits (mean LOI = 34.3 %). Based on textural characteristics, these have low clay contents similar to those in Transect 2. Again, this unit thickens to around 1.8 m in the centre of the swamp (T3P5S9).

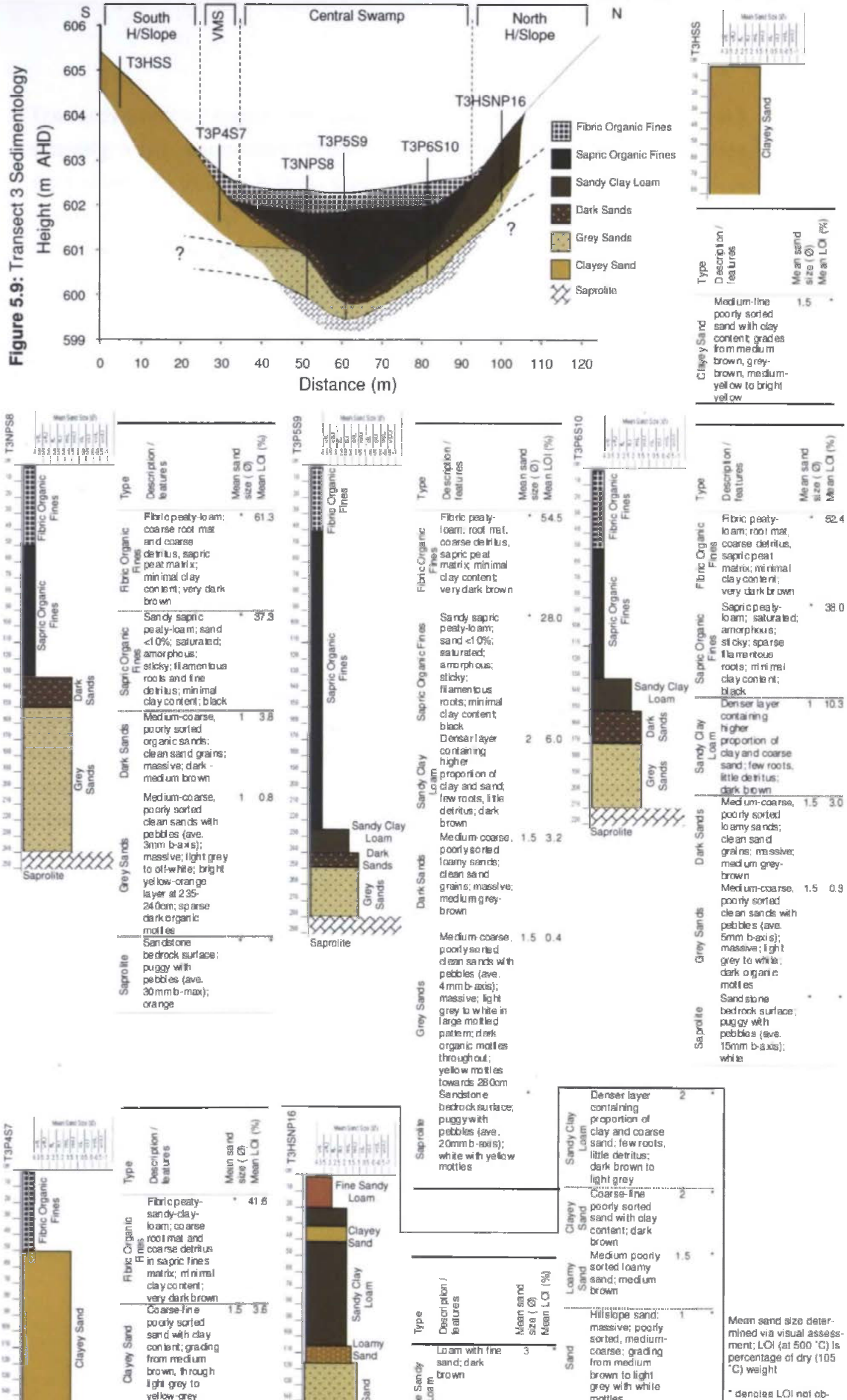


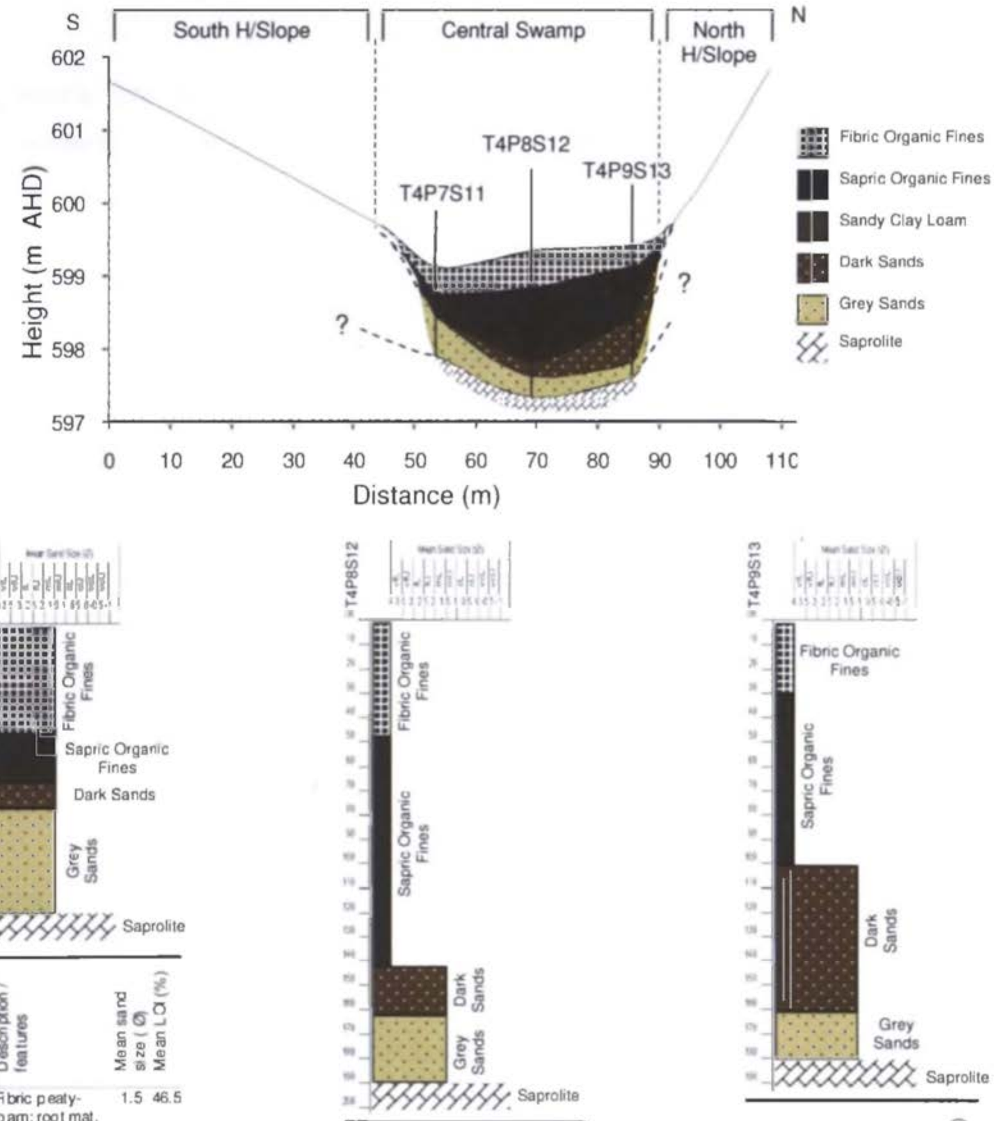
Figure 5.9: Transect 3 Sedimentology

The sandy clay loam horizon (mean sand size ~ 2 Ø) is discontinuous in Transect 3, extending only across profiles T3P5S9 and T3P6S10 (Figure 5.9). In these profiles, the average LOI value is 8.15 %. Dark sands and grey sands underlie all swamp profiles. Unlike Transect 1 and Transect 2, the average sand size for both dark and grey sands is observed (~ 1.5 Ø in T3P5S9 and T3PP6S10, and ~ 1 Ø in T3NPS8). The dark sands unit in Transect 3 is again characterised by poorly sorted, coarse to medium sands intermixed with a small percentage of dark organic fines (mean LOI = 3.3 %). Across the swamp profiles, the grey sands contain little organic fines (mean LOI = 0.5 %), and include dark organic mottles similar to those seen in Transect 2. In T3NPS8 and T3P5S9 these layers also contain yellow to orange mottles along the saprolite contact boundary. Pebbles found within the grey sands and along the saprolite surface average 4 mm and 22 mm b-axes, respectively.

5.2.4 Transect 4

All profiles on Transect 4 are within the central swamp zone (Figure 5.10). Their character is similar to those seen in the upstream transects, but differs slightly. While these profiles contain the dark fibric organic fines, the black sapric organic fines, and the basal sands of previous transects, the sandy clay loam layer is not present. The fibric organic fines are similar to those observed in Transect 2 and 3, exhibiting a less clayey texture than those in Transect 1, and extending to depths between 30 and 50 cm. They again grade towards a higher degree of decomposition with depth. The mean LOI value for this layer in Transect 4 is 40.1 %. On the outer profiles, T4P7S11 and T4P9S13, the sapric organic fines contain a greater proportion of sand than has been observed in previous profiles. In T4P9S13 this sand is fine to medium, and the proportion is estimated to be less than 5 %. In T4P7S11, however, the sands are medium to coarse, averaging 1.5 Ø, and comprise approximately 20 % of this unit. In T4P8S12, the sand content was negligible. There is also a distinct difference in organic matter content between T4P7S11, and the other two profiles on Transect 4. The average LOI values for T4P8S12 and T4P9S13 are 39.9 % and 28 %, respectively, while for T4P7S11 the average is 7.5 %. While this value for T4P7S11 more closely resembles values previously observed for the sandy clay loam layer in other profiles, the texture of this layer is distinctly jelly-like (indicating low clay content) and as such, has been classed within the sapric organic fines.

Figure 5.10: Transect 4 Sedimentology



T4P7S11

Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; minimal clay content; very dark brown	1.5	46.5
Sapric Organic Fines	Sapric peaty-loam; high coarse-medium, poorly sorted sand content; saturated; amorphous; filamentous roots and fine detritus; minimal clay content; black	1.5	7.5
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains massive; light grey with dark organic mottles – possibly intermediary between grey and dark sand	1.5	1.6
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 4mm b-axis); massive; light grey to white; dark organic mottles	1.5	1.8
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 15mm b-axis); white	1.5	*

T4P8S12

Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peay-loam; root mat, coarse detritus, sapric peat matrix; minimal clay content; very dark brown	*	44.2
Sapric Organic Fines	Sapric peat-loam; saturated; amorphous; sticky; sparse filamentous roots; minimal clay content; black	*	39.9
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains; massive; medium grey-brown	1.5	2.1
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 5mm b-axis); massive; light grey to white; dark organic mottles	1.5	0.8
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 20 mm b-axis); white	*	*

T4P9S13

Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; minimal clay content; very dark brown	*	31.3
Sapric Organic Fines	Sapric peaty-loams; saturated; amorphous; sticky; sparse filamentous roots; minimal clay content; sandy; black	*	28.0
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains; massive; medium grey-brown	1	3.5
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 4mm b-axis); massive; light grey to white; dark organic mottles	1	1.4
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 18mm b-axis); white	*	*

Mean sand size determined via visual assessment; LOI (at 500 °C) is percentage of dry (105 °C) weight

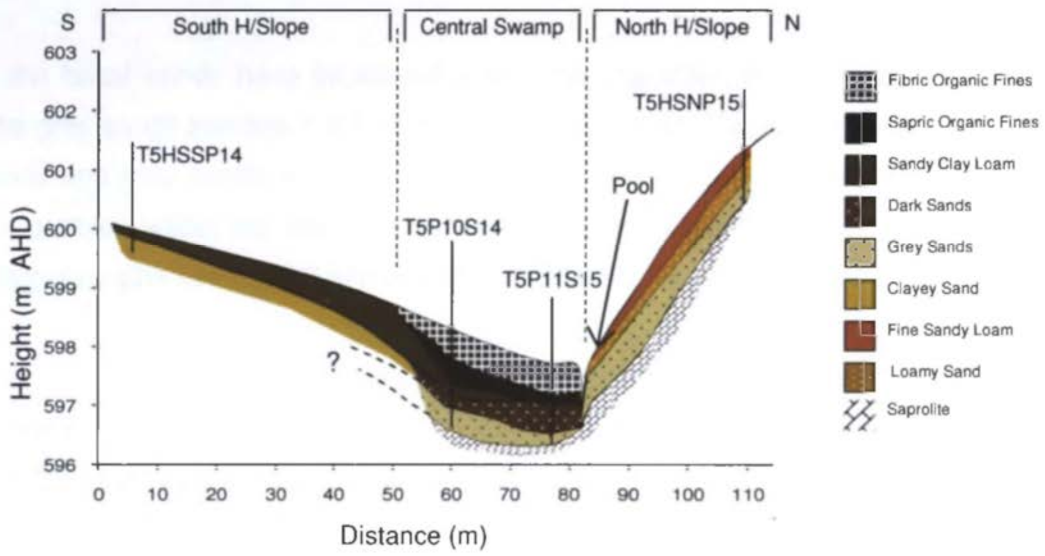
The dark sands are similar in T4P8S12 and T4P9S13 to those observed in upstream transects, but are slightly different in T4P7S11. At this location, the dark sands unit appears to be intermediary between the dark sands and the grey sands observed previously. The proportion of organic fines appears to be lower in the dark sands of T4P7S11 than in previous transects and the other profiles on Transect 4. This is confirmed by the mean LOI values for Transect 4, which are 2.1 % and 3.5 % for T4P8S12 and T4P9S13, respectively, and 1.6 % for T4P7S11. Also, the distribution of fines within the dark sands is not as uniform, and consists of dark organic mottles within a light grey matrix. Mean sand size is again uniform between dark sands and grey sands in Transect 4, averaging ~ 1.5 Ø for T4P7S11 and T4P8S12, and ~ 1 Ø for T4P9S13. The grey sands are similar to those observed in upstream transects, containing dark organic mottles (mean LOI = 1.3 %) in a light-grey to white matrix overlying white puggy saprolite. Pebbles within the grey sands average 5 mm b-axis, and along the saprolite boundary they average 18 mm b-axis.

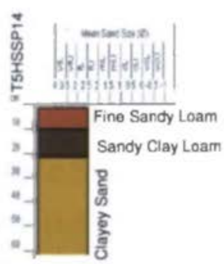
5.2.5 Transect 5

Transect 5 extends across the central swamp area and onto both hillslopes (Figure 5.11). The sedimentology of the northern hillslope resembles that observed on Transect 3, with T5HSNP15 consisting of fine sandy loam (mean sand size ~ 2.5 Ø) and loamy sands (mean sand size ~ 1 Ø) overlying a sand unit (mean sand size ~ 1 Ø). However, the clay content is lower in T5HSNP15 than in T3HSNP16. Similarly, on the southern hillslope, T5HSSP14 is similar to T3HSS on Transect 3. A main unit of clayey sand (mean sand size ~ 2.5 Ø) is overlain by a thin development of fine sandy loam (mean sand size ~ 2.5 Ø) and sandy clay loam (average sand size ~ 2.5 Ø) on T5HSSP14.

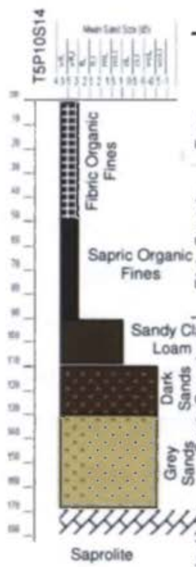
The swamp profiles, T5P10S14 and T5P11S15, are similar to those observed in other transects. The sedimentology of T5P10S14 consists of a 50 cm thick layer of fibric organic fines underlain by sapric organic fines, sandy clay loam, and the basal dark and grey sands units. This Sedimentology is consistent in profile T5P11S15, however the sandy clay loam layer is absent. Based on textural characteristics, the clay content of the organic fines in Transect 5 appears similar to that in Transect 2, 3 and 4, but less than in Transect 1. Mean LOI values for fibric organic fines and sapric organic fines in Transect 5 are 53.1 % and 26.1 %, respectively. The sandy clay loam layer returns at T5P10S14, and its mean LOI value is 4.75 %. The mean sand size of this sandy clay loam averages ~ 2 Ø. For both swamp profiles on

Figure 5.11: Transect 5 Sedimentology

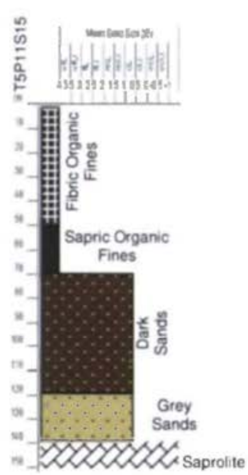




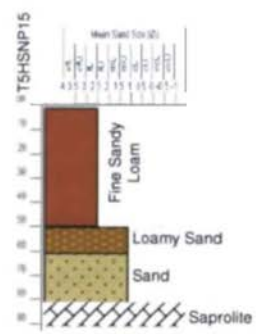
Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fine Sandy Loam	Loam with fine sand; dark brown	2.5	*
Sandy Clay Loam	Loam layer containing higher proportion of clay and sand; medium grey	2.5	*
Clayey Sand	Coarse-fine poorly sorted sand with clay content; light grey	2.5	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric pealy-loam; root mat, coarse detritus, sapric peat matrix; minimal clay content; very dark brown	*	63.4
Sapric Organic Fines	Sapric peaty-loam; saturated; amorphous; sticky; sparse filamentous roots; minimal clay content; black	*	26.1
Sandy Clay Loam	Denser layer containing higher proportion of clay and coarse sand; few roots, little detritus; dark brown	2	6.6
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains; massive; medium brown	0.5	2.6
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave 4mm b-axis); massive; light grey to white; dark organic mottles	0.5	0.8
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 18mm b-axis); white	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; minimal clay content; very dark brown	*	42.8
Sapric Organic Fines	Sapric peaty-loam; saturated; amorphous; sticky; sparse filamentous roots; minimal clay content; black	*	28.1
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains; massive; medium brown	0.5	2.9
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 4mm b-axis); massive; light grey with white creamy mottles; a few dark organic mottles	0.5	1.4
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 14mm b-axis); white	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fine Sandy Loam	Loam with fine sand; dark brown	2.5	*
Loamy Sand	Medium poorly sorted loamy sand; medium brown	1	*
Sand	Hillslope sand; massive; poorly sorted, medium-coarse; grades from medium brown (upper), medium grey (middle), to medium red-brown with grey mottles	1	*
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 16mm b-axis); orange	*	*

Mean sand size determined via visual assessment; LOI (at 500 °C) is percentage of dry (105 °C) weight

* denotes LOI not obtained for these profiles / sediment types

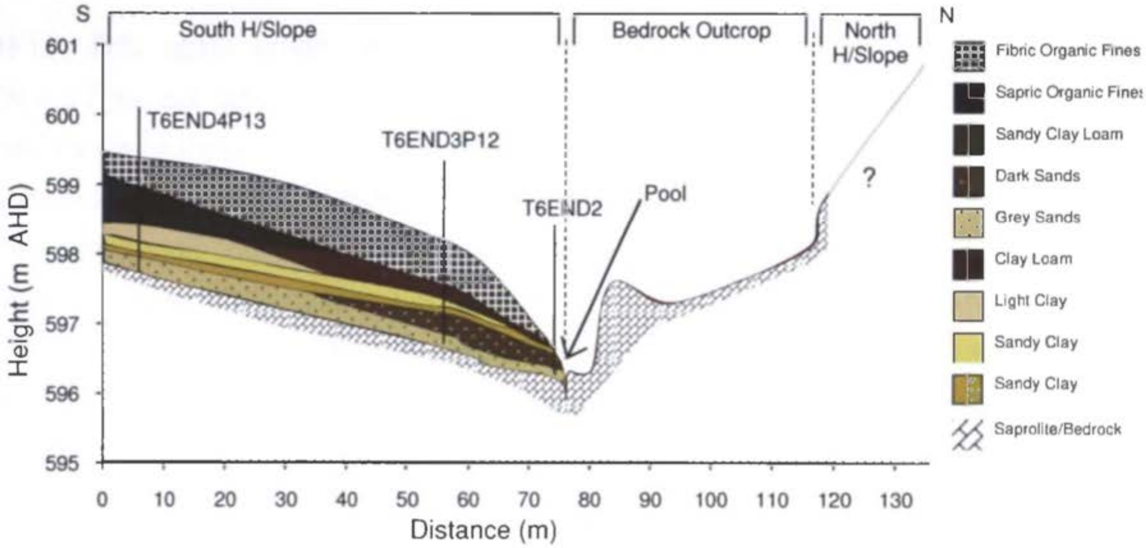
Transect 5, the basal sands have consistent grain size character. Both the dark sands and the grey sands average ~ 0.5 Ø, and are poorly sorted. Mean LOI values for darks sands and grey sands in Transect 5 are 2.8 % and 1.1 %, respectively. Clean quartz pebbles within the grey sands have average b-axes of 4 mm, and along the puggy saprolite average 16 mm across both T5P10S14 and T5P11S15.

5.2.6 *Transect 6*

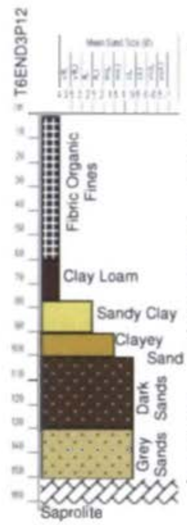
Transect 6 is the final transect for the study area, and it includes three profiles extending across the southern hillslope to the bedrock pool located in the central swamp (Figure 5.12). Due to the bedrock outcrop, no profile is located on the northern hillslope. The profiles on Transect 6 are different to those previously described, as they contain elements of both swamp profiles and hillslope profiles. The southernmost profile on Transect 6, T6END4P13, consists of the upper layers of fibric organic fines and sapric organic fines, similar in texture to the clayey swamp units described in Transect 1, but contain more clay than the swamp units in Transects 2, 3, 4, and 5. The mean LOI values of the fibric organic fines and sapric organic fines for T6END4P13 are 45.6 % and 44.8 %, respectively. Beneath these, however, rather than the sequence of sandy clay loam, dark sands and grey sands generally observed upstream profiles, the lower strata of T6END4P13 consists of sedimentology that resembles that observed in the northern hillslope profiles on Transect 1 (T1HSN and T1P17S3). The organic fines overlie a layer of light organic clay (average LOI = 18.9 %), which is darker in colour but similar in texture to the light clay observed in T1HSN and T1P17S3. Again, like profiles in Transect 1, the light clay is underlain by a fine sandy clay (mean sand size ~ 2.5 Ø; mean LOI = 4.9 %). This sandy clay grades into coarse, slightly clayey sand (mean sand size ~ 0.5 Ø; average LOI = 2.5 %), which is poorly sorted and resembles the grey sand unit observed at the base of swamp profiles. This sand unit overlies bedrock saprolite.

The sequence is similar for T6END3P12 in that the profile contains a combination of swamp and hillslope stratigraphy, but there are some key differences. The fibric organic fines (mean LOI = 59.1 %) are still present in the upper layer, but the sapric organic fines are absent. Instead, the upper fibric organics lie directly above a thin layer of organic clay loam (mean LOI = 22.7 %), which is underlain by fine sandy clay (mean sand size ~ 2.5 Ø; mean LOI = 7.8 %) similar to that observed in

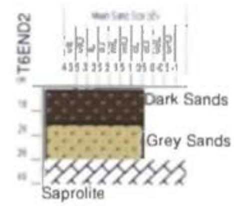
Figure 5.12: Transect 6 Sedimentology



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; some clay content; very dark brown	*	45.6
Sapric Organic Fines	Sapric peaty-loam; saturated; amorphous; sticky; sparse filamentous roots; loamy; very little sand; some clay content; black	*	44.8
Light Clay	Light organic clay; low content fine sand (<5%); sparse roots and detritus; dark brown	*	18.9
Sandy Clay	Clay with medium-fine sand (<50%); fine filamentous roots; dark brown	2.5	4.9
Clayey Sand	Coarse-fine poorly sorted organic sand with clay content; dark brown	1.5	2.5
Sand	Hillslope sand; massive; poorly sorted, medium-coarse; clean sand grains; yellow-grey to yellow	0.5	2.4
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 10 mm b-axis); dull yellow	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Fibric Organic Fines	Fibric peaty-loam; root mat, coarse detritus, sapric peat matrix; some clay content; very dark brown		*59.1
Clay Loam	Organic clay loam; very low to zero sand; few filamentous roots and fine detritus; dark brown		*22.7
Sandy Clay	Organic sandy clay; medium sands; fine filamentous roots; dark brown	2.5	7.8
Clayey Sand	Organic clayey sand; medium-coarse, poorly sorted; few filamentous roots and fine detritus; dark brown	1.5	3.7
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains; massive; medium brown	0.5	1.5
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 6mm b-axis); massive; light grey with white creamy mottles; a few dark organic mottles	0.5	1.2
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 16 mm b-axis); dull yellow	*	*



Type	Description / features	Mean sand size (Ø)	Mean LOI (%)
Dark Sands	Medium-coarse, poorly sorted loamy sands; clean sand grains; massive; medium brown	0.5	9.1
Grey Sands	Medium-coarse, poorly sorted clean sands with pebbles (ave. 5mm b-axis); massive; light grey with white creamy mottles; a few dark organic mottles	0.5	2.2
Saprolite	Sandstone bedrock surface; puggy with pebbles (ave. 18 mm b-axis); dull yellow	*	*

Mean sand size determined via visual assessment; LOI (at 500 °C) is percentage of dry (105 °C) weight

* denotes LOI not obtained for these profiles / sediment types

T6END4P13. This again grades to clayey sand (mean sand size ~ 1.5 Ø; mean LOI = 3.7 %), but rather than directly overlying grey sands as in T6END4P13, dark sands intercede these layers in T6END3P12. Like other swamp profiles, these basal sands are poorly sorted, medium to coarse sands, with average sand size of ~ 0.5 Ø. The dark sands contain a higher proportion of organic fines than the grey sands. However, mean LOI for this unit in Transect 6 (= 1.5 %) is slightly lower than observed in previous transects. The grey sands (mean LOI = 1.2 %) directly overlie sandstone saprolite, and the pebbles found in these strata average 6 mm b-axis and 15 mm b-axis, respectively.

The final profile on Transect 6, T6END2 consists solely of a thin deposit of basal sand units. The properties of the dark sands and grey sands at T6END2 are the same as observed at other swamp profiles, along Transect 6 and other transects through the central swamp zone. Mean sand size for both of these units at T6END2 is ~ 0.5 Ø. The mean organic content of the dark sands at T6END2 (LOI = 9.1 %) is slightly higher than observed in previous transects and the other profiles on Transect 6. Mean LOI for the grey sands in this profile (= 2.2%) resembles those of previously described profiles. The pebbles contained in the grey sands and along the saprolite boundary average 5 mm and 18 mm b-axes, respectively.

5.2.7 Degree of Organic Matter Decomposition and Gravimetric Moisture Content

The analysis of degree of decomposition (as represented by bulk density) and field gravimetric moisture content was dependent on the identification of major sediment units within the swamp profiles. As bulk density represents degree of decomposition in this study, only units which contain significantly high organic contents (as identified by LOI) were analysed. Similarly, since organic matter content is also the physical property largely responsible for the ability of sediments to retain high water contents, analysis of gravimetric field moisture content was conducted simultaneously with bulk density analyses. The results of these analyses are therefore presented separately as mean values for the major organic sedimentary units as a whole throughout the swamp area, rather than for each profile. In the swamp, the sedimentary units analysed were the fibric organic fines and the sapric organic fines of the swamp profiles. As discussed in Chapter 4, where clear changes in the structure of the upper fibric layer were observed, samples were also taken at different depths within this layer in order to characterise changes in this unit. The

Table 5.5: Average bulk density and field gravimetric moisture content for organic swamp sedimentary units

Sedimentary Unit	Ave. ρ (g/cm^3)	Ave. w (%)
Fibric Organic Fines	0.15 (upper)	85.4 (upper)
	0.37 (lower)	82.7 (lower)
Sapric Organic Fines	0.55	79.9

Ave. ρ is the average of the ratio of wet volume (cm^3) and dry weight (105 °C) (g); Ave w is percent mass change from wet weight (g) to dry weight (g) divided by wet weight (g).

average bulk density and moisture contents for the fibric layer are therefore presented as 'upper' and 'lower' components (Table 5.5).

The mean bulk density for the upper horizon of the fibric organic fines was 0.15 g/cm^3 (upper), and 0.37 g/cm^3 for the more decomposed lower horizon (lower). Mean bulk density for the sapric organic fines was 0.55 g/cm^3. The average gravimetric field moisture content for the upper layer of fibric organic fines was 85.4 %, and 82.7 % for the lower component of the fibric organic fines. For the sapric organic fines, average gravimetric moisture content was 79.9 %.

5.3 Patterns in Physical and Sedimentary Characteristics

5.3.1 Cross Sectional and Geomorphic Zone Trends

Within the central swamp zone, sedimentology and morphology are relatively consistent, and are very distinct from that of other geomorphological zones within the study site. In cross section, the swamp sediments infill the concavity within the central basin axis, and are comprised of a primary sequence of fibric organic fines, sapric organic fines, and a basal layer of dark and grey sands which directly overlie saprolite. A lobe of sandy clay loam extends from the headwaters to Transect 3, after which point it becomes sporadic or absent. This lobe is laterally consistent in Transects 1 and 2, but extends only part-way across Transect 3, from the northern hillslope to T3NPS8.

The sediments of the central swamp zone increase in thickness towards the centre of the swamp, where the bedrock concavity is greatest. The layer of fibric organic fines is consistently developed to around 50 cm depth throughout the swamp. The properties of this layer are gradational, and while the coarse organic matter content remains high with depth throughout the fibric layer due to live roots, the matrix of fines and organic detritus becomes denser with depth and bulk densities increase from 0.15 g/cm^3 in the uppermost portion of this layer, to 0.37 g/cm^3 in the lower portion. The inverse of this depth-density relationship occurs in gravimetric moisture content, which decreases from 85.4 % to 82.7 % as depth and density increase in the fibric layer. The thickness of the sapric organic fines varies with location across the swamp. It is thinnest at the margins and thickens towards the centre of the swamp. The character of the sediments within this layer is uniform both laterally and with depth. Average bulk density of this layer is much higher than the above fibric layer, at 0.55 g/cm^3. At 79.9 %, gravimetric moisture content is also lower in the sapric organic layer than at any depth within the upper fibric layer. The basal sands are uniform in character and thickness throughout the swamp and closely follow the bedrock morphology.

The basic constitution of sediments is the same in the headwater marginal swamp zone as in the central swamp zone, however, the organic fines are significantly more clayey in texture. The depth of the swamp sediments in the headwater marginal swamp zone is laterally consistent, with no central thickening as observed in the central swamp zone.

The valley marginal swamp is characterised by sedimentary sequences in which the upper layers resemble those of the central and marginal swamp units, but contain lower layers which are more similar to hillslope sedimentary units. In this unit, a series of clays intercede between the upper layers of organic fines and the basal sands units. The exception is T6END2 in which the only sedimentary units are the basal sands. Fibric organic fines are again relatively consistent across the valley marginal swamp zone, appearing at all profiles but T6END2. At T3P4S7, fibric organic fines are developed to 50 cm. The layer of sapric organic fines is absent, and the fibric organic fines directly overlie clayey sands. This pattern is similar for T6END3P12, in which fibric organic fines are developed to 60 cm, but then directly overlie clay loam. At T6END4P13, the fibric organic fines are somewhat thinner, and this unit doubles in thickness from 30 cm to 60 cm towards the central swamp axis. At this profile, sapric organic fines are again present and extend to 100 cm depth. The total thickness of sediments to saprolite thins towards the central swamp axis at the base of the bedrock outcrop on the northern hillslope.

In all swamp geomorphic zones, the fibric organic fines contain the highest organic matter contents, and average LOI values for this unit are relatively consistent for each swamp zone. Organic matter contents are also significantly high for sapric organic fines, and average LOI values were reasonably uniform between the central swamp and headwater marginal swamp zones, but were much higher for this unit in the valley marginal swamp zone. LOI values for both fibric and sapric units are substantially higher than those in underlying mineral units across all swamp geomorphic zones.

The hillslope areas are basically comprised of mineral sediments, including sands, clayey sands, and clays. Clays predominate in the upstream regions of the northern hillslope (as seen in T1P17S3 and T1HSN), but elsewhere sands and clayey sands dominate. In Transects 1 to 3, and also Transect 5, where sandy clay loam is present within swamp sediment sequences, sandy clay loam is also found on the hillslopes. Although different in colour, these swamp and hillslope sandy clay loam layers are texturally alike.

5.3.2 Longitudinal Profile Trends

The longitudinal profile was constructed by compiling sediment sample points along the central axis of the swamp. The long profile extends in the direction of flow from its headwaters at the eastern end of the swamp, downstream to the western sample boundary located at the point of bedrock confinement and crosses all geomorphic zones. It includes the profiles T1P1S2, T2NPS5, T3P5S9, T4P8S12, T5P11S15, and T6END2 (Figure 5.13). The longitudinal profile shows the distribution and thickness of distinct sedimentary units within the central swamp area. It shows that the distribution and character of the swamp sedimentary units are relatively uniform with distance along the swamp axis, until Transect 6. At the downstream end of the study site, the general sequence of swamp sedimentary units is truncated, and only the basal sand units are present at T6END2 where the depth of sediment accumulation above bedrock is at its lowest.

The swamp deposits roughly follow bedrock morphology in a blanket- or drape-like manner. Swamp sediments initially thicken downstream to 3.3 m and 2.8 m at T2NPS5 and T3P5S9, respectively, and subsequently thin towards Transect 6 to reach a minimum depth of less than 1 m at T6END2. While the fibric layer is consistently developed to around 50 cm depth along the entire profile, the thickness

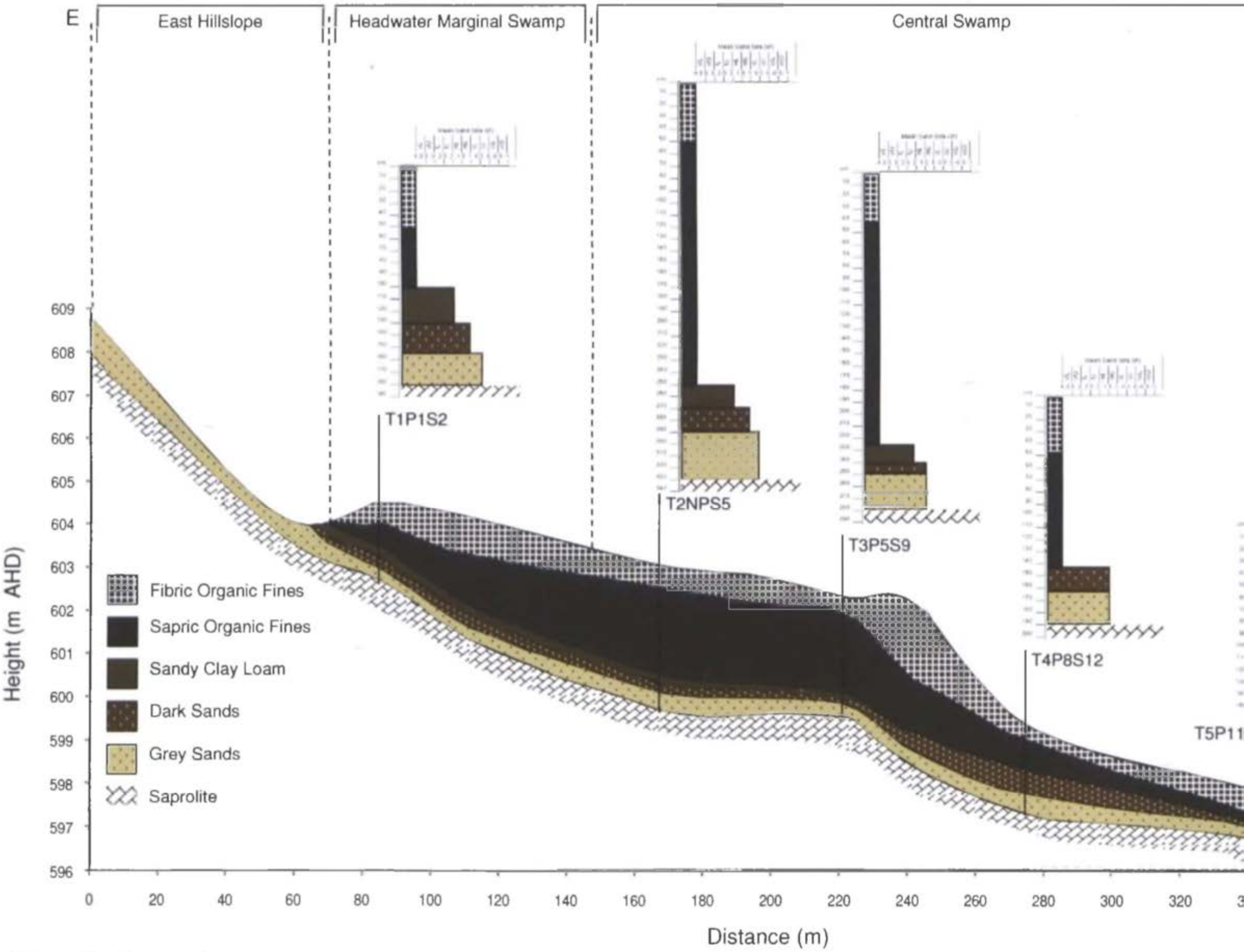


Figure 5.13: Long profile of sedimentology and geomorphic zones. *For details of sediment profiles, see Figures 5.2.1—5.2.6*

of the sapric layer increases longitudinally towards Transect 3, then thins towards Transect 4 before disappearing at T5P11S15 and T6END2. As previously mentioned, the sandy clay loam layer extends continuously to Transect 3, but then becomes sporadic towards Transect 6. Basal sands are continuous and maintain uniform thickness from the headwaters to the bedrock pools. In planview, (Figure 5.3) the swamp is roughly funnel-shaped with a wide central swamp zone that pinches at a valley confinement and bedrock step just downstream of Transect 6.

Chapter 6 will now examine the hydrological characteristics of the swamp and link this to the sedimentary structure of the swamp.

6 Results II: Hydrological Characteristics

Chapter 6 first presents the fortnightly and hourly groundwater elevation data collected during the study period between 1st September 2009 and 19th January 2010 using methods described in Section 4.1.2. These data are first analysed at a coarse scale, using the fortnightly measurements to investigate groundwater variations at individual piezometers to describe the water table behaviour over time at each site. These fortnightly water table elevation data are then compared to the rainfall record for the study period, and general relationships between water table fluctuations and rainfall variability are investigated. At a finer scale, the hourly data collected by the digital data logger at T5P11S15 is used to analyse the response of the water table to a sequence of individual rain events. This data is also used to analyse the character of the rise and recession of water table elevations at T5P11S15 during very brief periods of overland flow. The final section in Chapter 6 addresses the internal hydraulic properties of the swamp sediments, and presents the results of in-situ slug tests and laboratory permeameter tests to calculate saturated hydraulic conductivity and water throughflow rates of the swamp. Methods for conducting these tests were presented in Section 4.4.

6.1 Groundwater Behaviour

6.1.1 Broad-scale Water Table Variability and Response to Rainfall

The fortnightly water table elevation data, collected during a five month period from September 2009 to January 2010 (autumn to summer), provides an indication of the broad-scale temporal and spatial position and variability of groundwater within the swamp.

Overall, the water table is maintained at stable levels between successive recording dates and is persistently shallow within swamp zones (Figures 6.1 – 6.3). This contrasts with hillslope areas where the water table fluctuates more widely and reaches greater depths below the soil surface (Figures 6.1 – 6.3). When the swamp zones are examined in greater detail, however, some spatial trends do emerge.

Longitudinally, water table elevations display a positive downstream trend in which the headwater marginal swamp piezometers T1P18S1 and T1P1S2, and the most

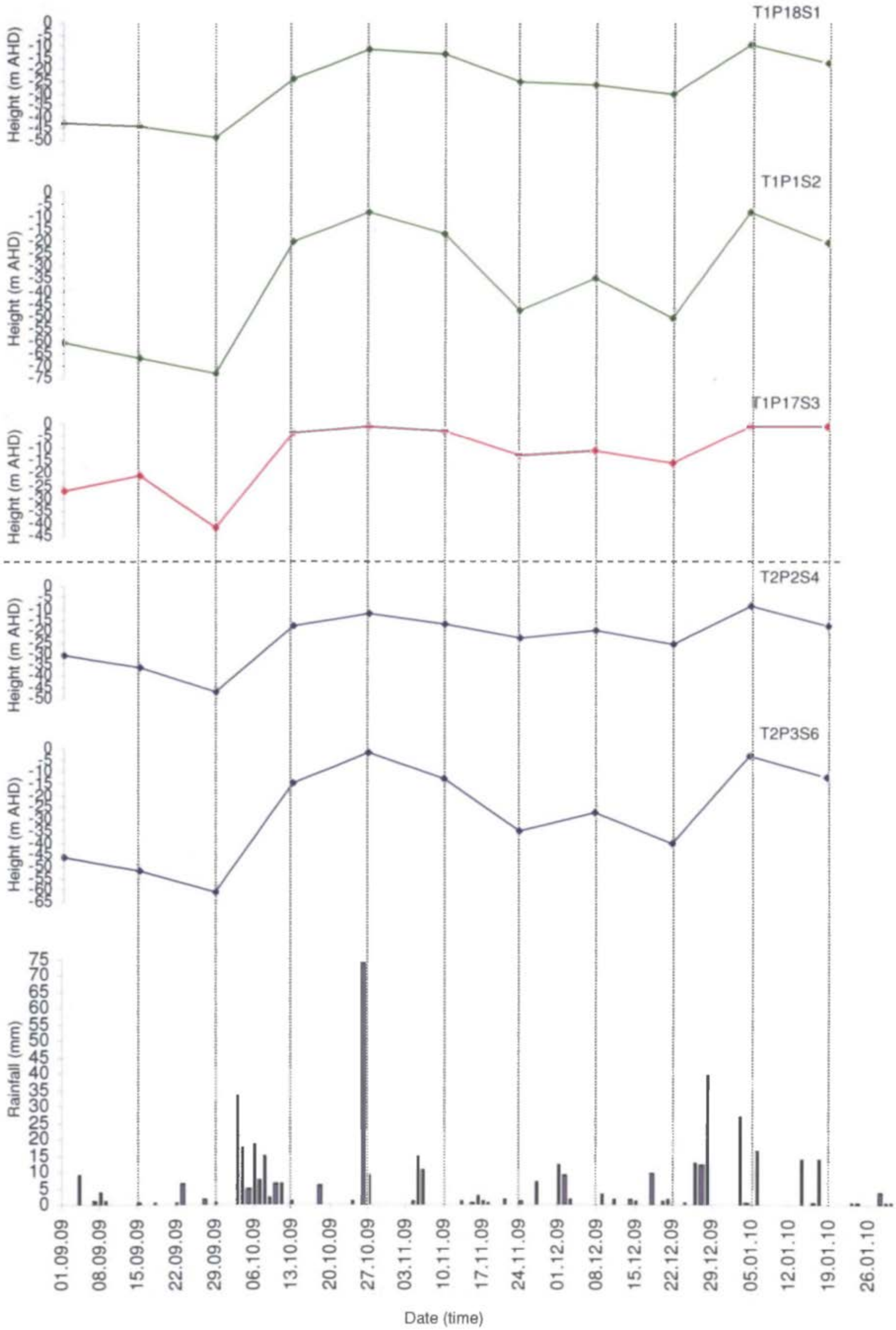


Figure 6.1: Fortnightly water table elevations, Transects 1 and 2
Green = headwater marginal swamp; Red = hillslope; Blue = central swamp
Vertical lines indicate fortnightly manual recording date; horizontal line delineates transects

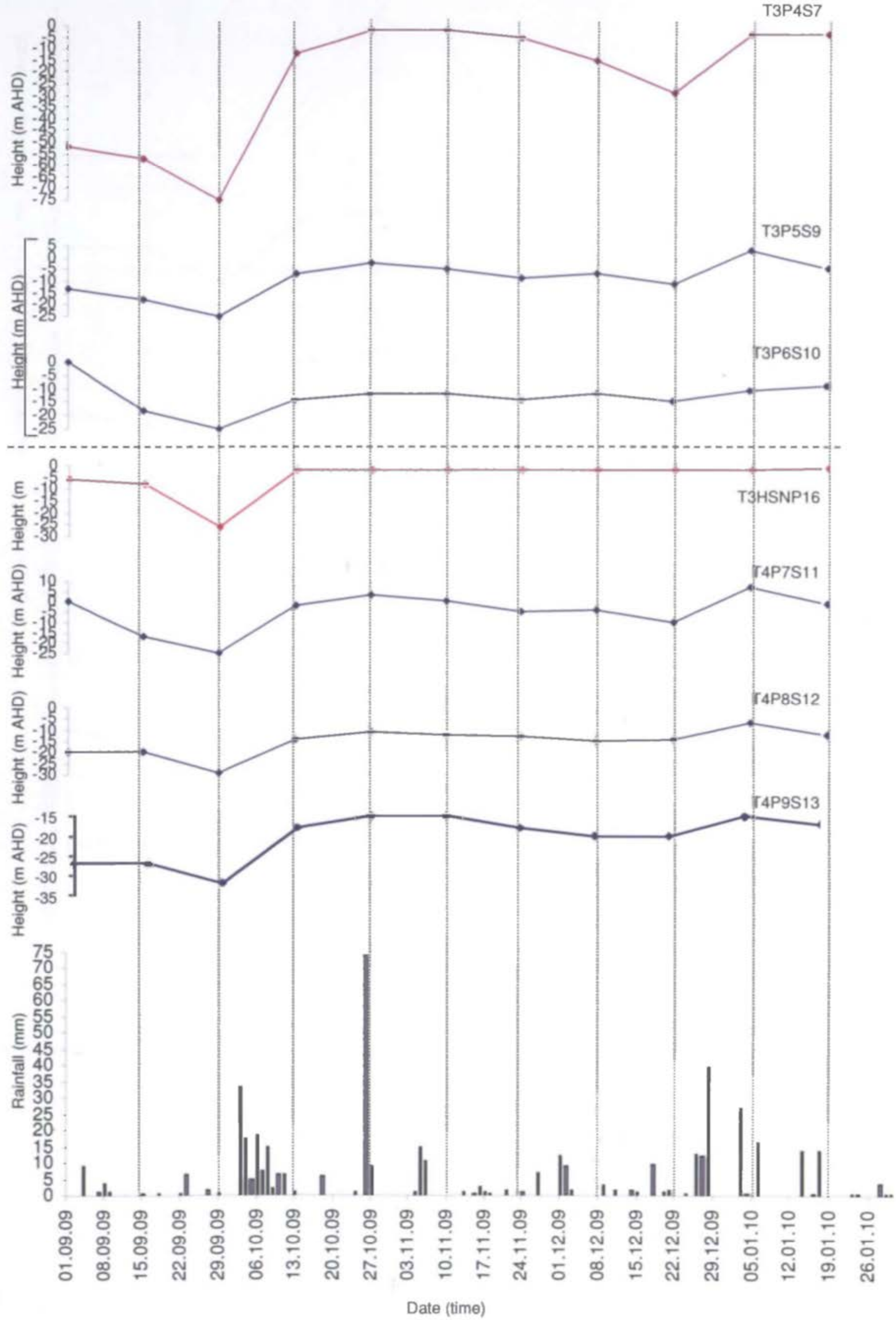


Figure 6.2: Fortnightly water table elevations, Transects 3 and 4
Purple = valley; marginal swamp; Red = hillslope; Blue = central swamp
Vertical lines indicate fortnightly manual recording date; horizontal line delineates transects

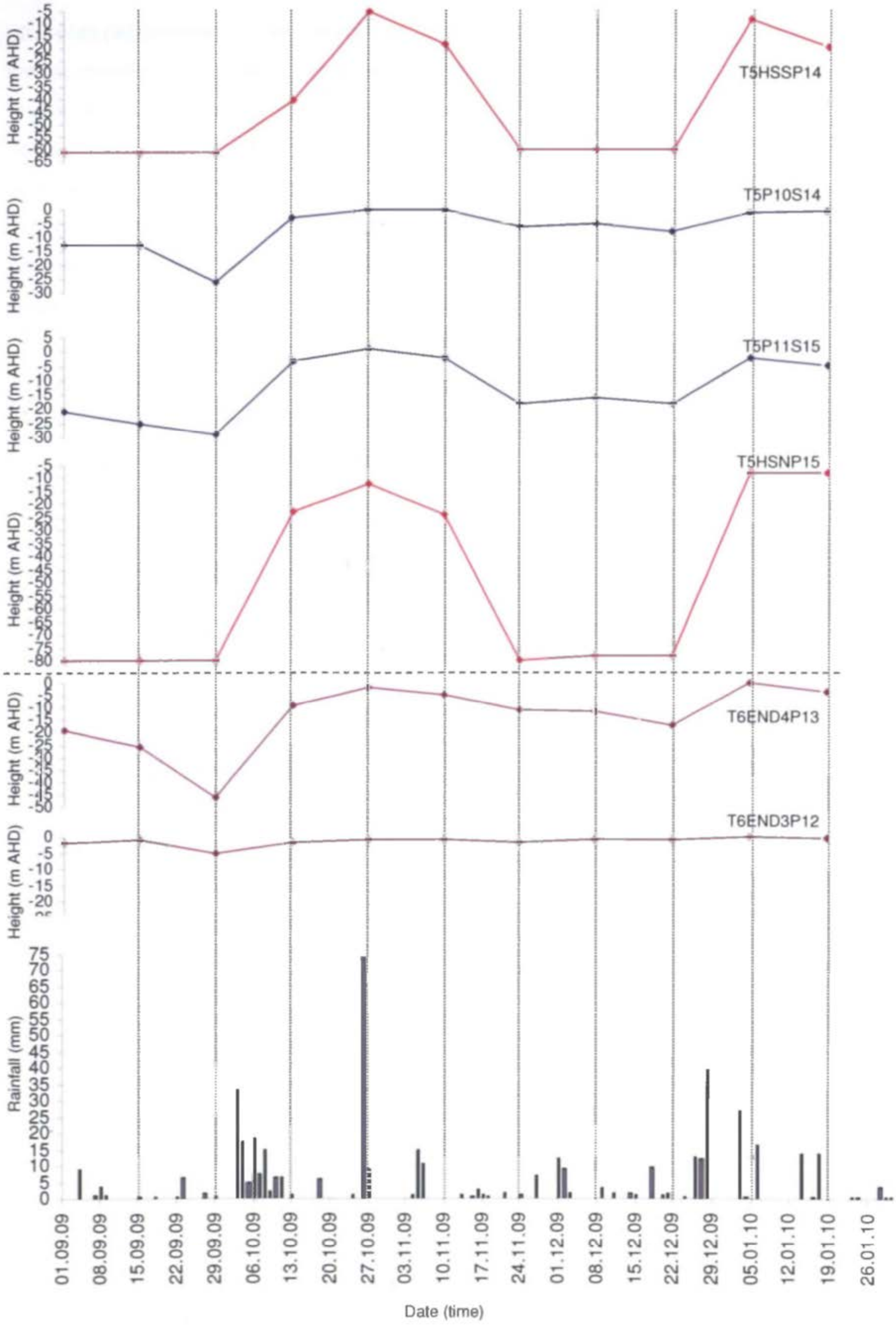


Figure 6.3: Fortnightly water table elevations, Transects 5 and 6
Purple = valley marginal swamp; Red = hillslope; Blue = central swamp
Vertical lines indicate fortnightly manual recording date; horizontal line delineates transects

upstream piezometers in the central swamp zone, T2P2S4 and T2P3S6, present the lowest minimum and lowest mean elevations within the swamp units (Table 6.1). These piezometers reach minimum water table depths of – 47 cm (T2P2S4) and below, and mean water table elevations of – 23 cm (T2P2S4) and below. Alternatively, piezometers downstream of these sites record much higher mean and minimum water table depths. In general, all piezometers occurring within swamp geomorphic zones downstream of Transect 2 retain water table elevations above or close to – 30 cm at their minimum (with the exception of T3P4S7, which behaves more similarly to upstream piezometers: minimum – 75 cm, mean – 23 cm; and T6END4P13 which has a minimum of – 46 cm). Mean water table elevations for these piezometers are also much higher than upstream swamp piezometers, and generally lie within 15 cm of the soil surface.

Table 6.1: Summary statistics for fortnightly water table elevation data

Geomorphic Zone	Location	Mean	St. Dev	Min	Max	Range	Mode
HMS	T1P18S1	-26	14	-49	-9	40	*
HMS	T1P1S2	-37	24	-73	-8	65	-8
H/S	T1P17S3	-13	13	-42	-1	41	-1
CS	T2P2S4	-23	11	-47	-9	38	-18
CS	T2P3S6	-28	20	-61	-2	59	*
VMS	T3P4S7	-23	26	-75	-2	73	-2
CS	T3P5S9	-9	8	-25	3	28	-7
CS	T3P6S10	-13	6	-25	0	25	-12
H/S	T3HSNP16	-5	7	-26	-2	25	-2
CS	T4P7S11	-5	9	-25	7	32	0
CS	T4P8S12	-15	6	-29	-7	22	-20
CS	T4P9S13	-20	6	-32	-15	17	-15
H/S	T5HSSP14	-39	24	-61	-5	56	-60
CS	T5P10S14	-7	8	-26	0	26	-13
CS	T5P11S15	-12	11	-29	2	31	-2
H/S	T5HSNP15	-50	34	-80	-8	72	-80
VMS	T6END4P13	-14	13	-46	0	46	*
VMS	T6END3P12	-2	1	-5	0	5	-1

HMS = headwater marginal swamp zone; H/S = hillslope; CS = central swamp zone; VMS = valley marginal swamp zone

* indicates mode not obtainable due to lack of repetition of any single depth on multiple recording dates

This pattern is less discernible when examining maximum water table depths. At all locations except for T4P9S13, maximum recorded depths reach elevations at or above – 9 cm (– 15 cm at T4P9S13). There is no clear longitudinal trend. However, positive water table elevations (above soil surface) were only recorded within central swamp piezometers occurring on or below Transect 3. These positive water table elevations were recorded at piezometers T3P5S9 (+ 3 cm), T4P7S11 (+ 3 cm and + 7 cm), and T5P11S15 (+ 1.5 cm). At T5P11S15, this depth was recorded on the 27th Oct following the second key rainfall event (see below), at T3P5S9 it was recorded following the third key rainfall event (5th Jan), and the two positive elevations recorded at T4P7S11 were recorded on each of those dates. These depths indicate periods of excess saturation at these locations, at which time the water table is exposed above the soil surface and a switch from subsurface to saturated overland flow occurs.

Trends in the degree of variability, as indicated by the range and standard deviation of recorded depths, appear to conform to the same patterns as those for average and minimum recorded water table depths. Both hillslope piezometers and swamp piezometers which lie furthest upstream and in marginal units display larger variabilities than downstream, central swamp units. However, the difference in these measures of variability between the hillslope piezometers and highly variable swamp piezometers is less marked than that seen in the previous analysis. The range of values recorded for T1P18S1, T1P1S2, T2P2S4, T2P3S6, T3P4S7 and T6END4P13 are comparable to those recorded at hillslope piezometers, and are in general above – 40 cm depth. The relatively high standard deviations at piezometers T1P1S2, T2P3S6, and T3P4S7 indicate that these ranges record variability in water level that is characteristic at these locations. At T1P18S1, T2P2S4 and T6END4P13, lower standard deviations indicate a lower degree of variability than suggested by the range alone. Both the range and standard deviations are lower for downstream, central swamp piezometers. The range of recorded values for these piezometers is mostly less than 26 cm (although it is 32 cm at T4P7S11, and 31 cm at T5P11S15). The standard deviations for all of these piezometers are low (generally below 9 cm), indicating that the water table usually sits within a relatively narrow range of elevations, and occasionally reaches 'extreme' values which lead to the larger gross range values observed.

The fortnightly data also reveals that the groundwater trend with time at each piezometer relates closely with the rainfall pattern throughout the study period.

Within the rainfall data, there are three key events which correspond to three major water table movements in all piezometers in the study area (Figures 6.1 – 6.3). These events began on the 3rd Oct (33.4 mm in 24 hrs), 26th Oct (74.2 mm in 24 hrs), and 28th Dec (39.6 mm n 24 hrs). A three-month period of very low rainfall (total 60.6 mm July – September (BOM, 2010) preceded the first key rainfall event.

The first rainfall event occurs four days after the recording date on which the lowest water table elevations observed in the study period were documented. In this event, moderate rainfall occurred over a period of 9 days, totalling 109.6 mm. A swamp-wide response was induced in relation to this event, in which the magnitude of the corresponding change in water table elevations is the greatest observed within the recording period at most piezometers (at the hillslope piezometers T5HSSP14 and T5HSNP15, the third event produced the greatest change) (Figures 6.1 – 6.3). The water table at all piezometers was raised to within 25 cm of the soil surface, but did not exceed elevations of – 2 cm. The size of the water table response at individual piezometers appears to be inversely related to the initial water table depth, such that the piezometers with the lowest groundwater elevations prior to the event; the hillslope piezometers and those in the upstream and marginal swamp regions (Figure 6.1 – 6.3: T1P18S1, T1P1S2, T1P17S3, T2P2S4, T2P3S6, T3P4S7, T5HSSP14, T5HSNP15), displayed the greatest magnitude rise in water table level (mean Δ 39.6 cm) as measured at the recording date directly following the event. At the downstream swamp piezometers (Figures 6.1 – 6.3: T3P5S9, T3P6S10, all Transect 4, T5P10S14, T5P11S15, Transect 6), the water level change was less significant but still averaged 18.9 cm.

A secondary trend is also apparent in the data for this event. Within the headwater marginal swamp piezometers and the piezometers on Transect 2, a north-south trend occurs in which the water table is shallower on the northern side of the swamp (T1P1S2, T1P3S6) than on the southern (T1P18S1, T2P2S4). This trend is reversed in Transects 3 and 4, and is not apparent in Transects 5 and 6.

While the second key rainfall event was smaller in total magnitude (83.2 mm) than the first event, and was restricted to two days in duration, the rate of precipitation was much greater, delivering 74.2 mm on the first day (26th Oct). The fortnightly data reveals, however, that across the swamp, the response to this rapid storm input had a much smaller effect on water table elevations than the first event. This is indicated by the reduced magnitude of the increase from the last depth recorded prior to this event ('start depth' for this event), and the one immediately following it ('end depth', recorded on the second day of this event). However, due to the temporal proximity of these events and the fortnightly resolution of measurement, the depth that serves as the 'start depth' for the second event, is actually also the 'end depth' for the previous event. There is therefore no water table elevation data representing the intervening period of significantly lower rainfall between the end of the first event and the initiation of the second. It is possible that within this period, actual water table levels dropped significantly, and that the real magnitude of water table rise has not been captured by this dataset. Additionally, as the 'end date' occurs on the second and last day within the rainfall event, it is possible that the water table continues to rise after the depth measurement on this date, and potentially the full response of the water table to this event was not recorded. As such, caution must be applied in the interpretation of relative response between these two events using coarse resolution data.

Nevertheless, it is interesting to note that despite the magnitude and rate of precipitation on the first day of the second event, the water table remained below the soil surface at most piezometers, and significantly so at some. Only at piezometers T4P7S11 and T5P11S15 did water rise slightly above the soil surface (+ 3 cm and + 1.5 cm, respectively), at T5P10S14 it occurred at the soil surface. For those piezometers at which the water table occurred below the surface, the previously observed spatial trends in which hillslope and marginal swamp piezometers respond similarly are not apparent following this event. However, there is a possibility that a time-lag exists which is not captured by the fortnightly measurements, and which may be obscuring this trend. The north-south trend in water table depth still occurs in Transects 1 to 4.

The third event occurs approximately two months after the second event, during which time relatively little rainfall occurred. From the data collected during this intervening period, it is possible to examine the response of the water table to decreases in rainfall input and a period of relatively dry conditions. While all piezometers fall to some extent during this period, only the hillslope piezometers T5HSSP14 and T5HSNP15 reach the minimum depths recorded prior to the first rainfall event demonstrating that this area drains more quickly than the swamp zones. At the remaining piezometers, the previously noted spatial trends continue. The greatest degree of water table decline is generally seen in headwater and marginal swamp piezometers at Transects 1 and 2, while the smallest decline is seen at the downstream, central swamp piezometers (T3P5S9, T3P6S10, T4P8S12, T4P9S13, T5P10S14, T5P11S15, and T6END3P12). These downstream swamp piezometers remain relatively fixed at or above depths of around – 20 cm for the remainder of the study period, and are little affected by the third rainfall event.

The third rainfall event started on the 26th Dec and lasted three days with a total rainfall of 64.8 mm. A small increase in water level occurred across all piezometers. However, the swamp piezometers which exhibit the greatest degree of decline in the intervening dry period (T1P18S1, T1P1S2, T2P2S4, T2P3S6, T3P4S7, and T6END4P13) also show a greater response to the third rainfall event. The response to this event is greatest at the hillslope piezometers T5HSSP14 and T5HSNP15. The previously described north-south trends on Transects 1 to 4 are also observed both consistently throughout the drier period, and following the third rainfall event.

6.1.2 Event-scale Variability and Response to Rainfall

The hourly data collected by the digital pressure/temperature gauge at T5P11S15 enables a finer scale analysis of water table variability and response to rainfall than that possible from fortnightly data. It provides a continuous record of water table elevation throughout the study period, and therefore a more detailed analysis of the rapid response and recession of groundwater to rainfall can be undertaken.

There are several significant features within the finer resolution hourly dataset. The first key feature is the rapid rate of response in water level to rainfall events. This is indicated by the direct correspondence between steep increases (mean rate 0.68 cm hr $^{-1}$) in water table elevations and daily rainfall data (Figure 6.4). Regardless of magnitude, for almost every rainfall event within the record, a corresponding peak which is roughly proportionate in magnitude can be seen in the hourly data.

The second key feature of this data is that although rapid water table response is a consistent occurrence, the character of the recession associated with the rapid rise varies considerably (Figure 6.4, recession type boxes). There are three principle forms of recession. The first type (recession type 1; mean rate 0.93 cm hr $^{-1}$) is equally as rapid and large as the rising limbs, occurring over a period of hours. Type 1 recessions directly correspond to cessation of, or decrease in, rainfall volume. The

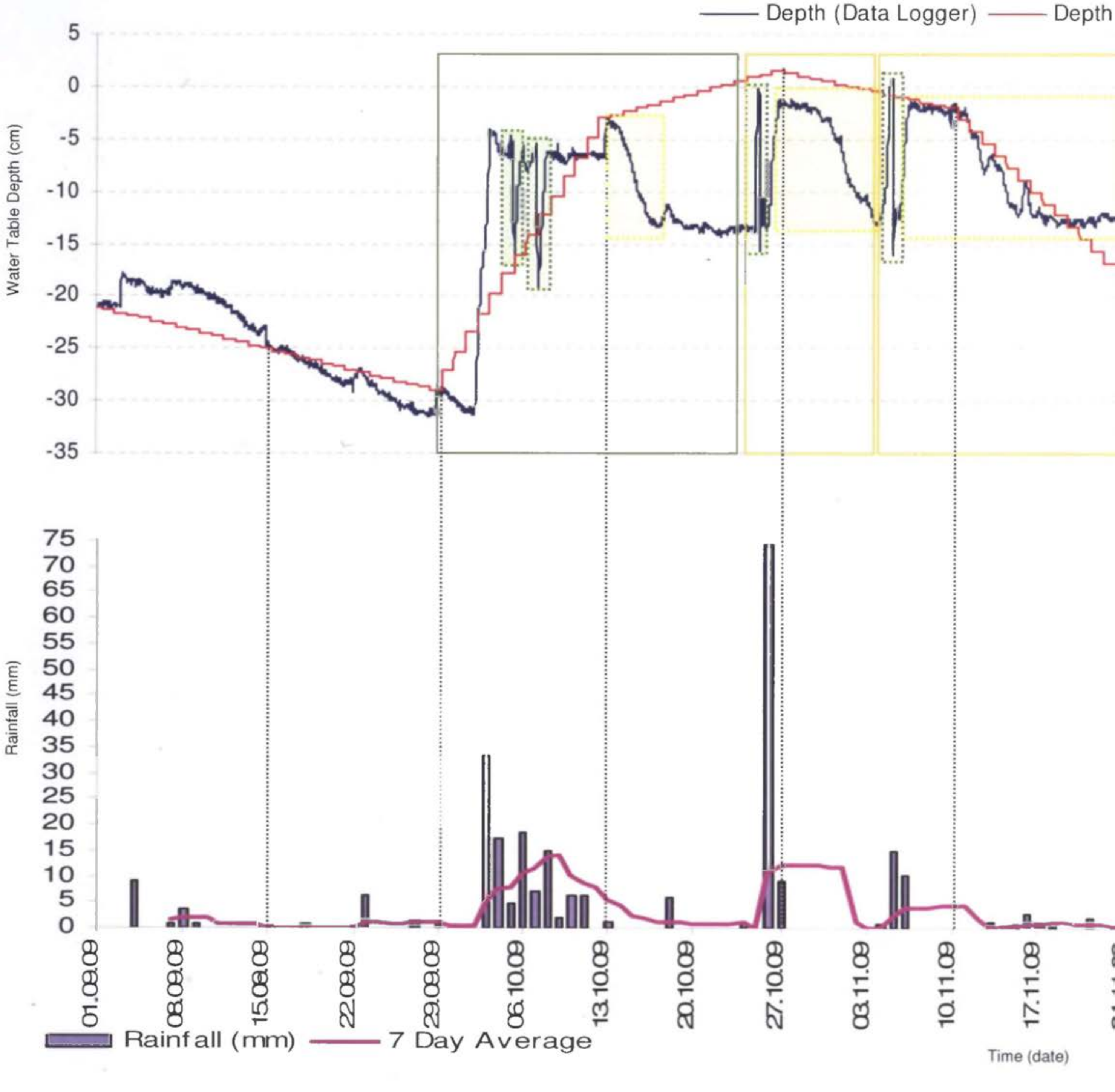


Figure 6.4: Hourly water table elevation data recorded at T5P11S15 vs daily rainfall record (BOM station 068035)

Vertical lines indicate fortnightly manual recording date
Green shaded box = recession type 1; yellow shaded box = recession type 2; purple shaded box = recession type 3
Green open box = response regime 1; yellow open box = response regime 2; purple open box = response regime 3

second type (recession type 2; mean rate 0.09 cm hr^{-1}) is a much slower, more gradual water table decline which occurs over a period of days after the cessation or reduction in rainfall (Figure 6.4, recession type boxes). The third type (recession type 3; mean rate 0.18 cm hr^{-1}) is intermediate between types 1 and 2 (Figure 6.4, recession type boxes).

Using this data, three different response regimes can be identified and related to certain water table and rainfall conditions (Figure 6.4, response regime boxes). An example of response regime 1 occurred during the first key rainfall event on the 3rd Oct. It is characterised by a rapid rising limb that directly corresponds with the onset of rainfall, followed by a series of rapid, flashy peaks (recession type 1) which directly correlate with consecutive decreases and increases in rainfall of small-moderate magnitude (Figure 6.4, green regime and response boxes, corresponding rainfall). By day 5 of this 9 day rain event, the water table stabilises at near surface depths (approximately – 6 cm to – 7 cm). Following another small peak associated with a low volume rainfall input on 13th Oct, the water table declines gradually over a period of four to five days (recession type 2), before again stabilising at around – 14 cm). A similar form of this regime is observed at the third key rainfall event occurring over three days from the 26th Dec where a series of small-moderate rain events initially result in rapid rises and falls in water level and then a gradual waning period when rain ceases. This regime response tends to occur after drier periods when the water level is low (– 20 cm to – 30 cm).

Response regime 2 is characterised by one initial rapid peak (recession type 1) in response to short-duration rainfall inputs, followed by a second rapid rise which stabilises close to the soil surface (approximately – 1 cm to – 2 cm) (Figure 6.4, yellow regime box). Following this stabilisation, a slow recession takes place over a period of about eight days (recession type 2). Regime response 2 has similar characteristics to regime response 1 but has a less flashy initial set of responses and tends to occur when the swamp is wetter and water levels are higher (- 5 cm to – 10 cm). Examples of this response regime occurred on 27th Oct and 5th Nov.

Response regime 3 consists of an individual, isolated groundwater peak of moderate magnitude (recession type 3) which occurs in response to small-scale, isolated rainfall (Figure 6.4, purple response box). A relatively rapid response occurs where the water level falls back to initial conditions within a period of about five days of the rain storm. Examples of this response regime occurred on 27th Nov and 2nd Dec. Unlike response regimes 1 and 2, response regime 3 does not include a period of stability and slow water table recession.

These response regimes appear to occur in a clearly defined sequence which is determined by the water table conditions at the onset of the corresponding rainfall event. Regime 1 results from rainfall inputs of moderate size and duration when initial water table levels are 'low' (– 20 cm and below). After accumulation of these rainfall inputs over several days, the base water table level rises and stabilises for a period at maximum depths of between – 10 cm and – 5 cm. At these higher groundwater elevations, further rainfall inputs lead to the occurrence of response regime 2. This regime occurs when the initial water level is 'high' (– 15 cm and above). It appears that the magnitude of associated rainfall is a less important factor than these antecedent water table conditions in determining the occurrence of response regime 2. The base water table levels again rise from initial conditions, and then stabilise at depths between the soil surface (0 cm) and – 5 cm. The third regime occurs during periods of relatively low rainfall and moderate initial water table conditions (between – 20 cm and – 25 cm) which coincide with the gradual decline in base water table levels following response regimes 1 and 2. Maximum depths reached in the peaks of regime 3 lie within – 7 cm and – 12 cm depths.

6.1.3 Occurrence of Saturated Overland Flow

During the recording period, three episodes of saturated overland flow conditions were observed in the hourly data. These occurred on the 5th Nov, the 5th Jan and the 16th Jan. The first two of these episodes occurred in the initial quick peak within periods of response regime 2. The third, on 16th Jan, occurred as a small response peak during a stable period of high (approximately – 2 cm) groundwater elevation. Each of these overland flow periods was short-lived and small in magnitude. The first had a duration of 6 hours, and reached + 0.68 cm above the soil surface. The second lasted for 2 hours, and reached + 0.15 cm in magnitude, and the third had a maximum magnitude of + 0.66 cm and lasted for 3 hours.

While caution must be applied to interpretation of these small magnitude events, given the error associated with the data logging instrument, the validity of these readings is supported by observations in the manual fortnightly data of positive water table elevations at several piezometers. If the details (duration and magnitude) of these events cannot be considered fully reliable, the more important factor to note is the timing of their occurrence in relation to the sequence of response regimes described above, and the associated water table and rainfall conditions.

6.1.4 Daily Variability in Groundwater Levels

The data logger data also reveals significant variability at the finest scale of resolution (hourly). Although the accuracy of the data logger is a significant limitation on the interpretation of this data, there appears to be a diurnal pattern in the water level of the swamp. This pattern is a function of changes in water pressure recorded at the data logger. During drier periods, in the absence of rainfall, up to 0.5 cm of diurnal variability can be detected. Examples of this phenomena occur between 10th and 22nd Sept, 28th Nov and 3rd Nov, 7th and 13th Dec and 30th Dec to 2nd Jan.

6.1.5 Spatial and Temporal Patterns in Hydrological Behaviour

The fortnightly and hourly water table data reveal several clear trends in groundwater distribution and behaviour throughout the swamp in response to different rainfall events. The water table appears to be highly responsive to rainfall throughout the swamp and hillslope zones. This response to rainfall is most variable at piezometers which experience the lowest average groundwater elevations: hillslope piezometers (T1P17S3, T3HSNP16, T5HSSP14, T5HSNP15), and at swamp piezometers which lie in upstream and marginal regions of the swamp. The swamp piezometers which fall into this category are T1P18S1, T1P1S2, T2P2S4, T2P3S6, T3P4S7, and T6END4P13. At piezometers which lie closer to the swamp axis and further downstream, the response is less marked. These piezometers are T3P5S9, T3P6S10, T4P7S11, T4P8S12, T4P9S13, T5P10S14, T5P11S15 and T6END3P12. These piezometers are recording cumulative responses to throughflow from upstream sites.

At all piezometers, the response is greatest when relatively continuous rainfall of moderate magnitude occurs after a period of low antecedent water table conditions. Where rainfall occurs during periods of shallower water table conditions, the response is suppressed, regardless of rainfall magnitude. Once the swamp has reached maximum water holding capacity (shallow water table), recession is rapid for hillslope piezometers, and slower for swamp piezometers. Of the swamp piezometers, water table fall (and swamp draining) is most marked in upstream and marginal swamp zones, and slowest in central piezometers in downstream sections of the swamp. At these piezometers, high groundwater elevations are maintained for weeks following a key rainfall event.

A secondary directional trend occurs in which a dip in water table elevations relative to the soil surface occurs towards the south in Transects 1 and 2, and is then reversed towards the north in Transects 3 and 4. While this is most likely due to topographic variations of the swamp surface rather than a real water table slope, these trends are significant for consideration of where overland flow occurs.

The nature of water table response to rainfall is primarily related to the antecedent water table conditions at the time of rainfall and the duration of the rainfall, rather than the absolute magnitude. Three water table response regimes were observed in the data. Where water table elevations are initially low, rainfall inputs generate a period of flashy peaks which correspond directly with changes in rainfall magnitude. Each of these rapid peaks achieve water table depths within the upper – 10 cm of substrate. Where rainfall is sustained for a period of several days, the base water table levels rise to within the range of these initial peaks, and remain stable at this level for a number of days after the cessation of rain. Further inputs at this time generate small response peaks regardless of magnitude. With no further rainfall, the water table begins to gradually recede over a number of days, at a rate much lower than the recessions associated with the series of intial response peaks.

Where rainfall occurs at shallower groundwater depths, only one initial flashy peak occurs before base water table levels rise. Again a period of relative stability at this heightened water table elevation occurs, and is followed by a slow recession occurring over a period of a week. Where isolated rainfall events of moderate magnitude occur at intermediate water table levels, single response peaks occur. The recession of these peaks is less rapid than the flashy peaks, but faster than the gradual recessions. Their magnitude relates to the magnitude and duration of the rainfall event.

6.2 Saturated Hydraulic Conductivity

6.2.1 Fibric Organic Fines

The upper sedimentary unit of the swamp zones, the fibric organic fines, was tested both in-situ and in the laboratory. However, due to unsaturated conditions within this layer in the field, the in-situ slug tests could not be used to estimate saturated hydraulic conductivity (K_{sat}). In this case, slug insertion tests were performed in order to observe gross flow rates within the fibric organic fines only. Laboratory permeameter tests on intact, saturated blocks from the fibric organic fines layer were performed in order to provide the K_{sat} values for these units.

Both flow rate and K_{sat} results are presented in Table 6.2 and Figure 6.5. The in-situ flow rate data, indicates a clear pattern of decreasing transfer capacity with depth in the fibric organic fines layer. Consistently, the upper 10 cm to 20 cm of the layer have the fastest flow-rates (mean 4.72 ml s^{-1}), which are generally several orders of magnitude greater than in the bottom 10 cm of this unit (mean 0.18 ml s^{-1}). Although it is not possible to determine whether these changes occur gradually or are related to distinct strata within the fibric organic fines, the data collected at T3P6S10 where this layer was tested at three depths: surface, base, and intermediate depths it appears that this is an inverse linear relationship, as flow rates continue to decrease with increasing depth.

Also clear in the flow rate data is the variability of flow rate within the fibric organic fines layer (standard deviation 2.34 ml s^{-1}; range 6.1 ml s^{-1}). Values for the upper 20 cm of the unit vary widely between locations (range + 4.37 ml s^{-1}). While the vertical trend is consistent, laterally there is no general conformity of the results, nor is there any discernable spatial trend. There is also no relationship between position on the longitudinal profile (upstream / downstream), or geomorphic zone. This variability is repeated in the flow rate data for lower depths, which differ by orders of magnitude between different sites (range 0.599 ml s^{-1}).

Due to difficulties in retrieving intact samples for permeameter tests, fewer samples from depths below surface were collected. As a result, the inverse linear trend seen in the field data is less clear in the laboratory data. Where deeper samples were collected and tested, the results are inconsistent. At T4P8S12, the pattern appears

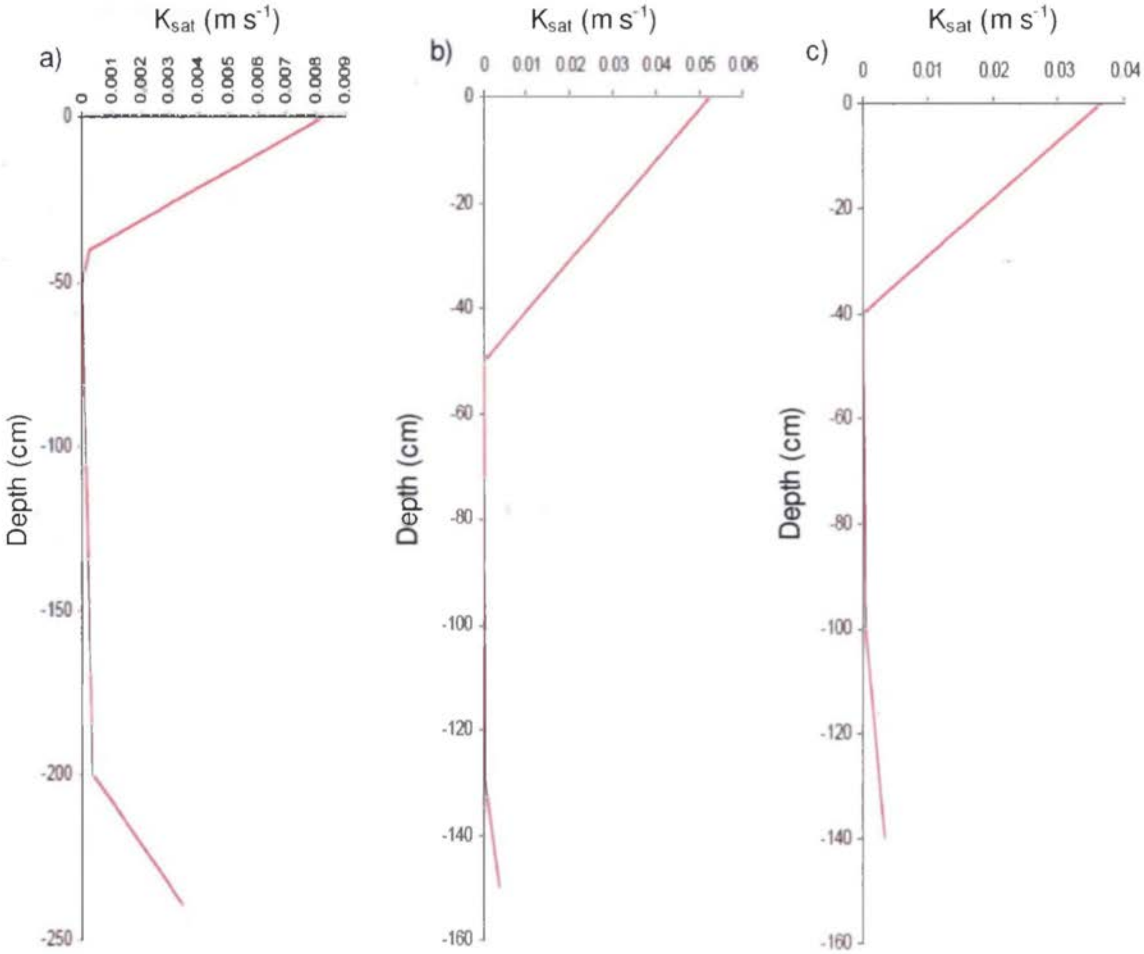


Figure 6.5: Average saturated hydraulic conductivity for profiles in each swamp geomorphic zone. a) central swamp zone; b) headwater marginal swamp zone; c) valley marginal swamp zone. Typical sedimentary unit depths: fibric organic fines = 50 cm; sapric organic fines = down to 200 cm in central swamp, approximately 120 cm in marginal swamp zones; dark sands = downs to 220 cm in central swamp; to 120 cm in marginal swamp; grey sands = lowest stratum

Table 6.2: Saturated hydraulic conductivity test results for fibric organic fines

Geomorphic Zone	Piezometer	Depth (cm)	In-situ[1] (ml s^{-1})	Depth (cm)	Laboratory[2] (m s^{-1})
Headwater Marginal Swamp	T1P18S1	0 – 20	5.16	0 – 10	5.28×10^{-4}
		40 – 50	0.001		
Central Swamp	T2P2S4	0 – 20	**	0 – 20	2.08×10^{-5}
		40 – 50	0.004		
	T2P3S6	0 – 20	4.16	0 – 15	1.01×10^{-4}
		40 – 50	0.001		
	T3P5S9	0 – 20	1.73	0 – 15	1.32×10^{-5}
		30 – 40	0.068		
	T3P6S10	0 – 10	6.10	0 – 10	2.16×10^{-4}
		10 – 20	0.84		
		40 – 50	0.009		
	T4P8S12	0 – 20	4.86	0 – 20	2.22×10^{-4}
		40 – 50	0.59	20 – 30	4.08×10^{-7}
	T4P9S13	0 – 20	**	0 – 10	2.25×10^{-6}
		20 – 30	0.60	10 – 20	4×10^{-6}
	T5P11S15	0 – 20	5.78	0 – 10	1.7×10^{-6}
Valley Marginal Swamp	T6END4P13	0 – 20	5.23	0 – 10	3.65×10^{-4}
		Mean (upper)	4.27		1.63×10^{-4}
		Mean (lower)	0.18		2.2×10^{-6}
		St. Dev	2.5		1.79×10^{-4}
		Range	6.1		5.27×10^{-4}

[1] values represent flow rates for unsaturated field conditions, rather than K_{sat} values

** indicates rate of recovery too rapid to record manually

[2] K_{sat} obtained in the laboratory from permeameter tests using the constant-head method

to be in agreement with that observed in-situ, with the K_{sat} decreasing with increasing depth. Conversely, at T4P9S13, the K_{sat} increases slightly with the depth of the sample. The wide degree of variability observed in the flow rate data is repeated in the permeameter results. For samples from the upper 20 cm of the fibric organic fines, values for K_{sat} vary by up to two orders of magnitude between locations (standard deviation 1.79×10^{-4} m s^{-1}; range 5.27×10^{-4} m s^{-1}). There again appears to be no spatial or geomorphic trend associated with this variability.

It is not possible to directly compare the differences in results between in-situ and laboratory methods because one reflects unsaturated conditions (field) and one saturated conditions (lab). Howevber, it is interesting to note that once saturated, flow rate tends to decrease by orders of magnitude. This may help to explain patterns of response to rainfall in these upper layers (see Chapter 7).

6.2.2 *Sapric Organic Fines*

The sapric organic fines layer was also tested in-situ and using laboratory permeameter tests. As all field measurement depths for sapric organic fines occurred below the water table, saturated hydraulic conductivity could be determined from the slug test recovery data. As such, values of K_{sat} are given for both field and laboratory tests for the sapric organic fines. The results of previous analyses (Chapter 5) revealed that the character of the sapric organic fines was largely uniform with depth, and therefore in-situ measurement of recovery or retrieval of permeameter samples were only undertaken at one representative depth in the centre of the layer at each test location.

The results of field and laboratory tests are shown in Table 6.3. The sapric organic fines have low saturated hydraulic conductivities in comparison to the upper fibric organic fines, and in general K_{sat} values for sapric organic fines are four to five (and up to six) orders of magnitude lower than those observed for the fibric organic fines. In-situ field K_{sat} values average 3.3×10^{-8} m s^{-1}, and laboratory values average 1.86×10^{-7} m s^{-1}. The variability between values of K_{sat} at different locations is also

Table 6.3: Saturated hydraulic conductivity test results for sapric organic fines

Geomorphic Zone	Piezometer	Depth (cm)	In-situ[1] (m s^{-1})	Laboratory[2] (m s^{-1})
Headwater Marginal Swamp	T1P18S1	90 – 100	3.26×10^{-9}	1.27×10^{-8}
Central Swamp	T2P2S4	100 – 110	1.32×10^{-8}	7.85×10^{-8}
	T2P3S6	100 – 110	6.86×10^{-10}	3.93×10^{-8}
	T3P5S9	100 – 110	1.62×10^{-9}	1.28×10^{-7}
	T3P6S10	100 – 110	4.39×10^{-9}	1.26×10^{-7}
	T4P7S11	50 – 60	7.04×10^{-8}	*
	T4P8S12	100 – 110	1.40×10^{-7}	3.44×10^{-8}
	T4P9S13	85 – 95	8.78×10^{-9}	7.54×10^{-8}
	T5P11S15	85 – 95	3.79×10^{-8}	1.03×10^{-6}
Valley Marginal Swamp	T6END4P13	55 – 65	5.01×10^{-8}	1.47×10^{-7}
		Mean	3.30×10^{-8}	1.86×10^{-7}
		St. Dev	4.46×10^{-8}	3.2×10^{-7}
		Range	1.9×10^{-7}	1.02×10^{-6}

* sample not tested by this method at this location

[1] in-situ K_{sat} obtained from slug test data using Hvorslev's equation

[2] Laboratory K_{sat} obtained from permeameter tests using the constant-head method

lower than observed for the fibric organic fines. The standard deviation of field tests is 4.46×10^{-8} m s^{-1}, and the range is 1.9×10^{-7} m s^{-1}. For laboratory results, the standard deviation is 3.2×10^{-7} m s^{-1}, and the range 1.02×10^{-6} m s^{-1}.

In general, permeameter tests resulted in higher K_{sat} values than obtained from field recovery tests (except at T4P8S12, where laboratory results were one order of magnitude higher than field results, and T2P2S4 where results were approximately comparable). The difference between the field test result and the corresponding laboratory permeameter result is up to two orders of magnitude. However, this difference is insignificant when compared to the degree of difference between sedimentary units. The degree of variability was also slightly lower (one order of magnitude) between samples in permeameter tests than between test locations in field recovery tests.

6.2.3 Basal Sands

As the instruments used in field slug tests for the organic layers were not able to penetrate the highly compacted mineral sands, K_{sat} values were obtained for basal sand units using permeameter tests only. The results of these tests are shown in Tables 6.4 and 6.5. The results from these tests show that the basal sands lie intermediate between the fibric organic fines and sapric organic fines in their K_{sat} values. The dark sands average slightly lower K_{sat} values (mean 3.44×10^{-6} m s^{-1}) than the grey sands (mean 3.48×10^{-5} m s^{-1}), which are only one order of magnitude slower than average fibric organic fines values for K_{sat}. Similarly, the variability in values of K_{sat} for both basal sands units is again intermediate between that of the fibric organic fines and sapric organic fines, and differs only slightly between dark sands and grey sands. The standard deviation for the dark sands is 6.58×10^{-6} m s^{-1} and is 2.45×10^{-5} m s^{-1} for the grey sands. Ranges are 1.32×10^{-5} m s^{-1} for the dark sands, and 4.43×10^{-5} m s^{-1} for grey sands.

Table 6.4: Saturated hydraulic conductivity test results for dark sands

Geomorphic Zone	Piezometer	Depth (cm)	Laboratory ($m\ s^{-1}$)
Central Swamp	T3P5S9	240 – 250	1.31×10^{-7}
	T4P8S12	150 – 170	7.68×10^{-8}
	T4P9S13	100 – 120	2.45×10^{-7}
	T5P11S15	100 – 120	1.33×10^{-5}
		Mean	3.44×10^{-6}
		St. Dev	6.58×10^{-6}
		Range	1.32×10^{-5}

K_{sat} obtained in the laboratory from permeameter tests using the constant-head method.

Table 6.5: Saturated hydraulic conductivity test results for grey sands

Geomorphic Zone	Piezometer	Depth (cm)	Laboratory ($m\ s^{-1}$)
Central Swamp	T2P3S6	220 – 230	5.61×10^{-5}
	T3P5S9	250 – 260	1.55×10^{-5}
	T4P8S12	180 – 190	1.18×10^{-5}
	T4P9S13	170 – 180	5.58×10^{-5}
		Mean	3.48×10^{-5}
		St. Dev	2.45×10^{-5}
		Range	4.43×10^{-5}

K_{sat} obtained in the laboratory from permeameter tests using the constant-head method.

6.2.4 Cross Sectional and Longitudinal Trends in Saturated Hydraulic Conductivity

The data obtained from in-situ slug tests and laboratory permeameter tests reveal a clear pattern of K_{sat} values between swamp sedimentary units (Figure 6.5). Saturated hydraulic conductivity is greatest within the fibric organic fines layer, which forms the upper 50 cm of sediment of the swamp. However, there is a clear and marked decrease in transfer capacity (as indicated by K_{sat} and flow rate data) with depth within this unit, in which the lower strata of the fibric organic fines are up to three orders of magnitude slower than the upper 20 cm (Figure 6.5). In field tests in unsaturated conditions, these upper strata exceeded measurable flow rates at a number of locations. Below the fibric organic fines unit, K_{sat} decreases dramatically (up to six orders of magnitude) within the sapric organic fines unit, but returns to intermediate values within the basal sand units. These trends in K_{sat} are illustrated schematically for each transect and the long profile in Figure 6.6.

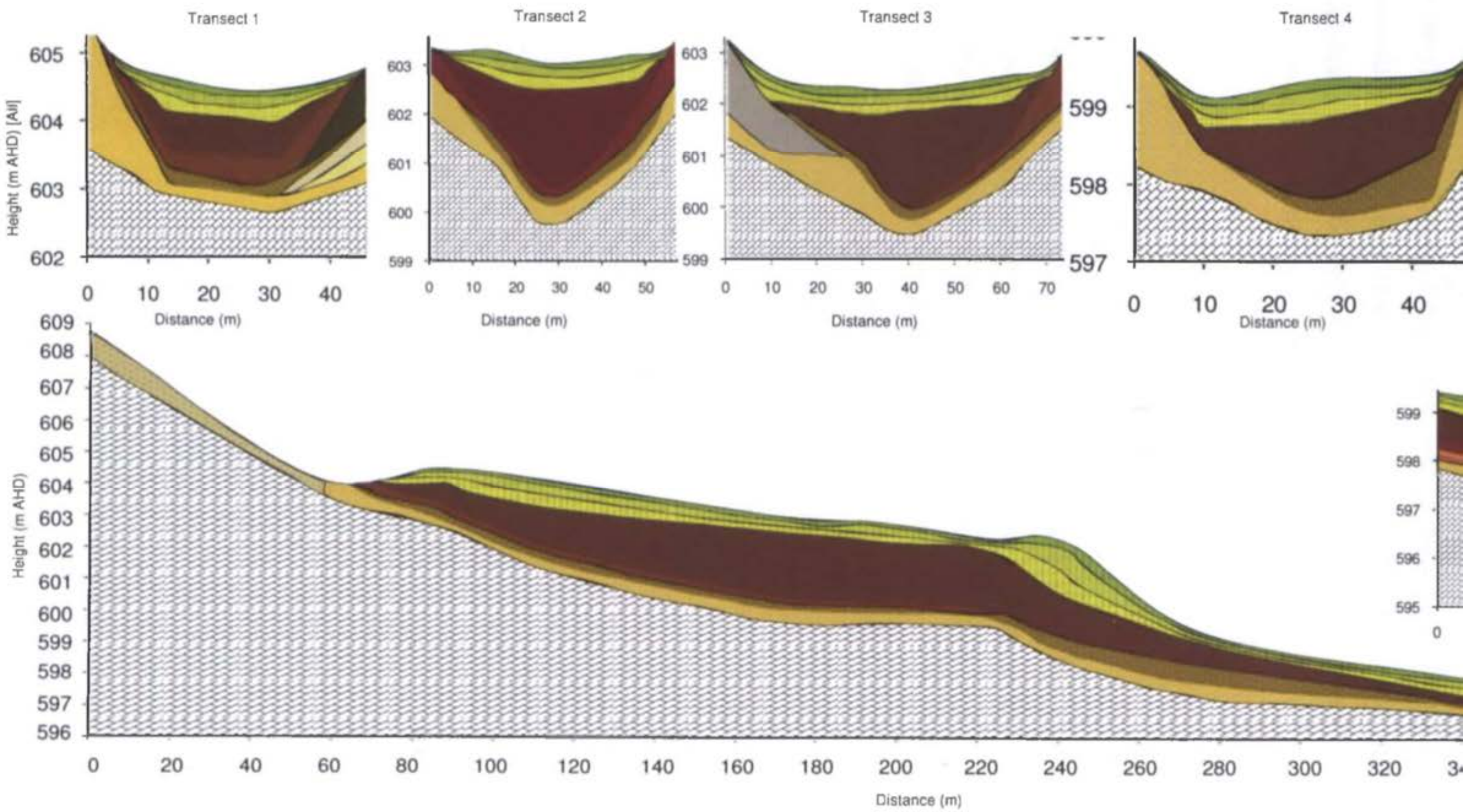


Figure 6.6: Schematic cross sections and long profile of saturated hydraulic conductivity.
Upper layer shows high K_{sat} in the upper fibric organic fines decreasing with depth (- 15 cm, - 30 cm, - 50 cm)
Red illustrates extremely low K_{sat} in the sapric organic fines
Orange indicates intermediate values of K_{sat} for the basal sands
* Grey/Brown areas represent untested hillslope sediments

Based on summary statistics – mean, standard deviation, range – there appears to be a linear relationship in which greater mean K_{sat} is associated with greater variability. This is clear in the parallel pattern of mean K_{sat} values with depth and sedimentary unit, and in measures of variability and depth. The fibric organic fines are spatially the most variable, and the sapric organic fines recorded the least spatial variability. The basal sands were intermediate in their variability.

The results show that ther e is a clear and singular relationship between K_{sat} and sedimentary unit. There does not appear to be any other spatial (lateral or longitudinal) trend in the data obtained for any of the sedimentary units. Geomorphic zone appear to have no bearing on the values of $K_{sat,}$

The following chapter pulls together the results from the geomorphology and hydrology and analyses the evolution and function of the swamp. Chapter 8 then places the Buderoo Swamp in the context of the structure and function of upland swamps documented in the international literature.

7 Analysis: the Physical Properties, Geomorphic Evolution and Hydrological Function of the Swamp

In this chapter, the results from physical and hydrological investigations will be synthesised and analysed. The physical structure and attributes of the swamp fill will first be fully described. Subsequently, the physical characteristics of the swamp basin and sediments will be used to determine the sequence of geomorphic development within the study swamp, and the landscape controls which influenced swamp initiation. Finally, the physical and hydrological data will be synthesised in order to interpret the functioning of the study swamp within the landscape.

7.1 Physical Properties of the Swamp Fill

The physical structure and characteristics of the sediments that comprise the swamp fill allow interpretation of the swamp's development and its natural range of historical and contemporary forms. These characteristics control both the internal hydrological functioning of the swamp and its role in the hydrology of the greater catchment. It is therefore important to adequately describe the physical properties of the swamp fill in order to address these questions.

The broad sedimentology of the swamp consists of a fairly simple, consistent sequence of colluvial mineral deposits, atop which have been deposited organics and fine mineral sediments. The basal layer consists of coarse-medium, poorly sorted, clean quartz sands which are massive, with no discernible bedding structures such as laminations or grainsize grading. There are two sub-units of the basal sands: the uppermost dark sands, and the lower grey sands. The darks sands differ from the grey sands in organic content and the inclusion of a very minor fraction of fines, and are therefore dark brown in colour as opposed to the dull off-white grey of the grey sands. However, they are texturally equivalent and consistently occur together, and as such can be considered a single unit. The differentiation of these units is most likely due to the surface position of the dark sands at the time of swamp initiation, which has imbued them with dark organic residues and a small amount of silts and clays. The basal sands directly overlie the sandstone bedrock and closely follow the bedrock morphology. The basal sands are continuous in extent and relatively uniform in depth throughout the entire swamp.

Above these basal sands are the organic accumulations, which taken as a whole, are relatively simple in structure, but when examined in more detail actually form a complex set of units with a number of significant features. The lower unit is the sapric organic fines. These are deposits of primarily silt/clay with only a very minor sand fraction (less than 10 %). They are black in colour, containing a high degree of humic residue, and very little coarse organic matter. This unit is variable in thickness depending on the bedrock morphology, but is thickest in the swamp axis (longitudinal and lateral centre) and thins towards the margins. The upper layer of the organic accumulation is the fibric organic fines. This unit is characterised by a high proportion of live and dead coarse organic matter but has the same matrix of fines of the sapric layer. The relative proportion of coarse organics increases towards the surface of the soil, where the active deposition of vegetation detritus is occurring. The vertical limit of this layer is the base of the primary rooting depth of the graminoid and sedge vegetation, and occurs uniformly at about – 50 cm across the swamp.

For these sedimentary units, the specific physical properties which were measured in this study included the mean grain size, loss on ignition (LOI), bulk density and gravimetric moisture content. Additionally, the saturated hydraulic conductivity (K_{sat}) was measured in the hydrological analyses. When examined together, some significant relationships become apparent. Figures 7.1 – 7.5 show average results for each of these analyses, plotted against the average depth of the fill and including the average depth of each sedimentary unit in order to provide a clear comparison (*nb*: while some of these values only extend to the limit of the organic accumulations it is the physical properties of the included units which are most significant for swamp functioning). These figures show that within the organic accumulations, mean grainsize is relatively constant until the basal sands, and LOI, moisture content and K_{sat} decrease with depth. In contrast, bulk density increases with depth. These trends occur rapidly within the fibric organic fines layer, creating the observed physical stratification within this layer in which the lowest horizons of this unit are denser and more decomposed than the upper horizons. There is therefore a significant degree of differentiation in physical properties with depth in this layer, which has important implications for the hydrological functioning of the swamp (see below 7.3).

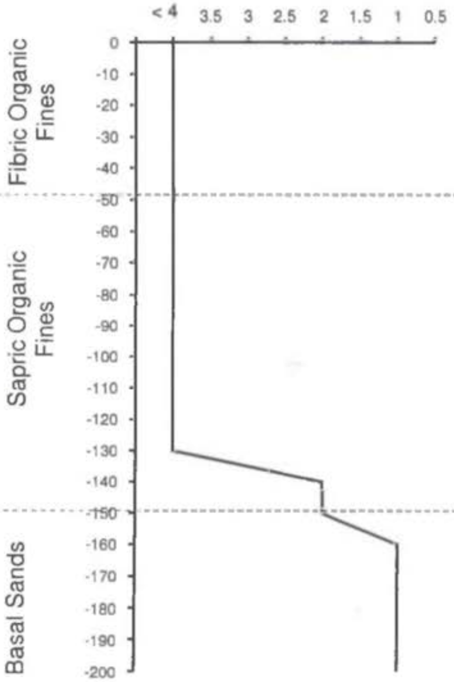


Figure 7.1: Mean grain size (Ø) with depth (cm)

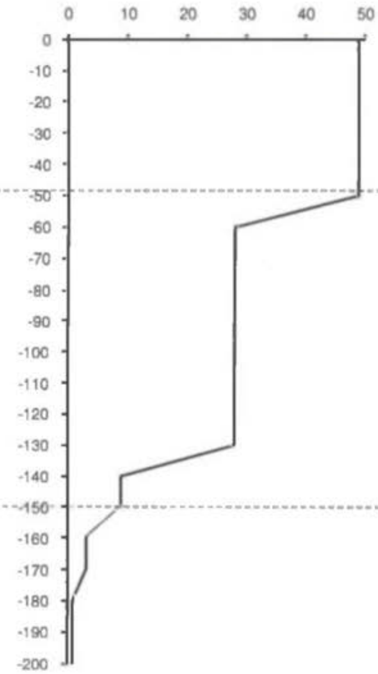


Figure 7.2: Mean LOI (%) with depth (cm)

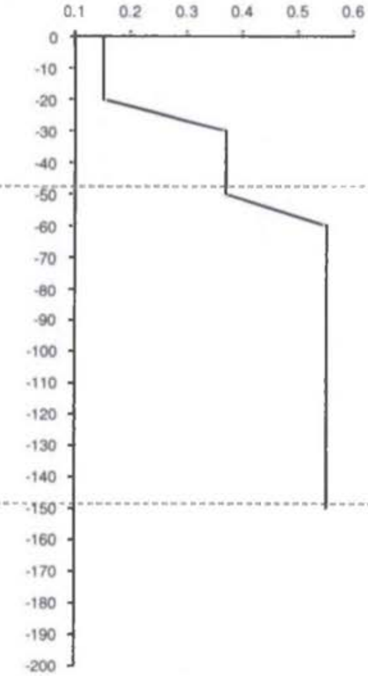


Figure 7.3: Mean bulk density (g cm $^{-1}$) with depth (cm)

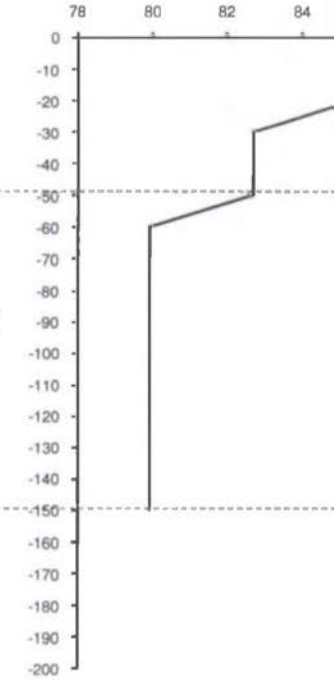


Figure 7.4: Mean moisture content (%) with Depth (cm)

These inverse relationships between bulk density and the other physical properties are primarily related to the degree of decomposition of the organics in the deposit. The surface layer, which is composed of relatively recent deposits of organic detritus, has had less time to decompose than the underlying layers. As a result the upper surface of the sediment is highly fibrous, and the undecomposed structure of the detritus promotes a high level or porosity in these layers. Below this, a gradually increasing degree of decomposition reduces the coarse fibres to humic residues, which decreases the porosity of the material and therefore increases the bulk density. The lowered porosity reduces the free volume in the sediment that is available to take on water, and therefore the absolute gravimetric water content also decreases with depth, but remains high in comparison to non-organic soils due to the high humic content – known to increase the water retention of sediments. The low porosity and high humic content serves to reduce the ability of the sediment to transfer water, thus K_{sat} decreases correspondingly.

7.2 Geomorphic Evolution of the Swamp

7.2.1 Sequence of Geomorphic Evolution

The stratigraphy of the study site provides insights into the process of the swamp's geomorphic development. As the swamp developed and evolved, physical adjustments within the alluvial valley fill were likely paralleled by transformations in the hydrological function of the swamp. The following section summarises the process of physical evolution of the swamp, and describes how this likely affected the hydrological function of the fill at each stage of development.

The sediments of the hillslopes surrounding the swamp are predominantly sands which are clayey and gradational and contain residual soils, weathered directly from the underlying Hawkesbury Sandstone surface. The sediments of the swamp are less clayey and show no clear pedogenic development, suggesting that they are depositional. As such, the swamp is an accumulation of alluvial sediment on the valley floor. Given its headwater location, the surrounding slopes are the primary source of sediments that make up the valley fill of the swamp.

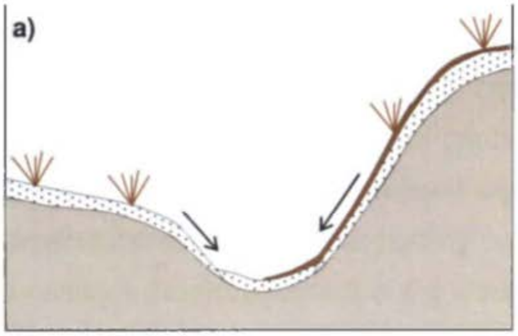
The stratigraphy of the swamp fill can be broadly broken into two depositional units: the basal sands, and the overlying organic fines. These two units represent two distinct phases within the evolutionary history of the swamp, each with very different hydrological function.

The first phase was initiated with the deposition of the basal sands units (Figure 7.6 a). This unit consists of the dark sands and the grey sands described in Chapter 5. Although the dark sands differ from the grey sands in organic content and therefore colour, they are texturally equivalent and as such can be considered a single depositional unit. Charcoal and woody organic debris are not significant components of these sands, and therefore it is unlikely that fire played a major role in their deposition. Instead, they are likely to have been deposited by sheetwash from the surrounding hillslopes, during a period when soil development was minimal and hillslope vegetation was sparse. Subsequent to the deposition of basal sands, a sandy clay loam lobe was deposited but only extends across the north-eastern section of the swamp (Transect 1 and 2, and northern side of Transect 3). This unit is only 15 – 20 cm thick. At this time the site is expected to be functioning in a similar manner to the wide, shallow sand-bed streams that dominate the sandstone valleys of the Sydney Basin.

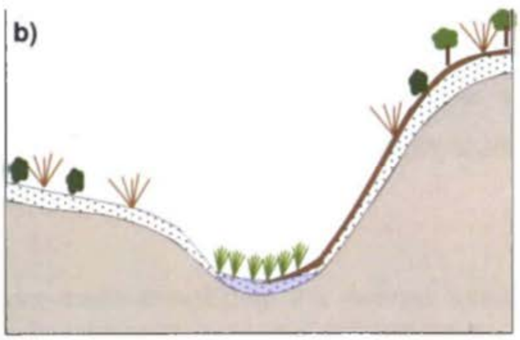
X 0.023 - 0.022

However, unlike other channelised systems this site has low slope, a headwater position and was likely competence-limited. As a result of the low stream competence and the tight bedrock constriction at the outflow of this headwater basin, the sand and sandy clay loam deposits were not flushed downstream. As a result the basin became choked with sediment, which was stored behind the bedrock step and valley constriction (Figure 7.6 b). With no efficient channel, this sediment mass acted to trap low-flow runoff, creating waterlogged conditions within the basin fill. At this stage, the fill is functioning to divert flows to the substratum where they are transferred out of the system at a much slower rate. The system acts as an unconsolidated water reservoir, creating a localised, perched water table within the basin. As a result of these conditions, the fill is then colonised by hydrophilic vegetation and a transition towards an unchannelised swamp is underway.

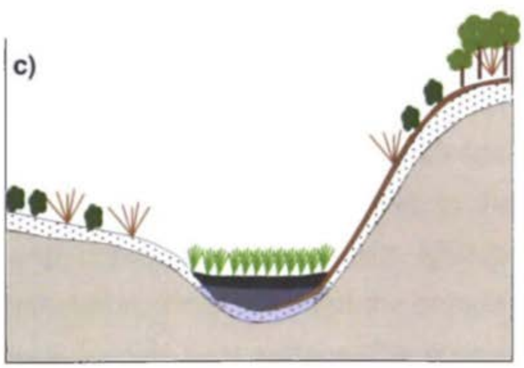
The next stage of development involves the gradual accretion of highly organic, fine sediments along the valley axis (Figure 7.6 c). This occurs as a result of increased organic input from the colonising sedge- and grass-dominated vegetation, and a concomitant decrease in the rate of organic decomposition due to the anaerobic soil conditions created by the shallow water table. Additionally, the dense vegetation



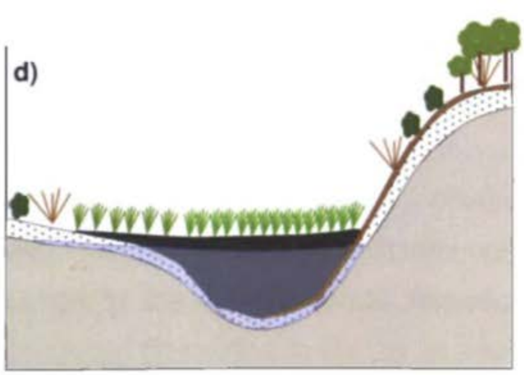
Stage 1: Basal sands deposited from sideslopes as sheet wash during period of sparse vegetation and minimal soil development. Sandy clay loam lobe also transported from slopes to north-eastern quadrant of swamp. Swamp functioning as a wide, shallow sand-bed stream



Stage 2: Transfer of sediment downstream impeded due to low competence of system and bedrock constriction, basin becomes sediment choked and low-flow runoff is diverted into the substratum where transfer is slowed. Sediment fill becomes waterlogged, and is colonised by early hydrophilic vegetation. The fill is now acting as an unconsolidated water reservoir, creating a localised, perched water table within the basin



Stage 3: Anaerobic soil conditions and dense swamp vegetation result in accumulation of fine sediments (trapped by the vegetation) with high organic matter content (due to slow decomposition in water). Highly organic deposits serve to retain water and actively maintains and enhances the shallow water table. The transition to a swamp has occurred and it is now acting as an active store for water.



Stage 4: Continuing accumulation of organic fines leads to vertical swamp growth and lateral swamp expansion. The structure of the swamp deposits are differentiated into a layer of actively decaying fibrous matter (fibric organic fines) at the surface, and an underlying layer of well-decomposed humic sediments (sapric organic fines). The swamp now functions in a complex pattern of water storage and transfer.

Figure 7.6: Stages in geomorphic evolution of Budderoo Swamp

further slows runoff and traps the fine sediment, which begins to accumulate above the basal sands. The incorporation of organic residues and a small portion of fine sediments within the upper layer of the basal sands (the dark sands) indicates the initiation of this stage. The increased organic content and the finer texture of the sediments increases the water holding capacity of the fill, which serves to maintain and enhance the development of the shallow water table. The transition to a swamp has occurred and it is now functioning as an active store for water. Water throughflow in the fill is slow and water release to the downstream catchment is attenuated. This function enables saturated conditions within the fill to persist even through dry periods, and therefore perpetuates the processes of organic accumulation by sustaining the physical and chemical relationships required for swamp development.

Under these conditions, the swamp continues to grow vertically within the confines of the basin hillslopes, and the water table rises to match the depth of the organic fill (Figure 7.6 d). As vertical accretion proceeds and the water table continue to rise, the area of saturation expands onto hillslopes where gradients are low and thus confinement is reduced. This results in lateral expansion of the hydrophilic vegetation communities, which then leads to swamp development on these low-lying hillslope areas. This is evidenced in the valley marginal swamp areas in which swamp deposits directly overlie hillslope sedimentologies. Also with increasing accumulation, the structure of the organic fines can be differentiated into the upper, actively forming peat surface (the fibric organic fines), and the underlying layer of more decomposed humic fines (the sapric organic fines). Once this structure has developed within the fill, the swamp is functionally hydrologically in a complex pattern of water storage and transfer (see Section 7.3 below).

The stratigraphy and sedimentary characteristics of the swamp indicate that its development has been predominantly uniform. There is no evidence of any major disruption to the developmental sequence associated with changes in sediment accumulation (in relation to fire, for example) or phases of cut-and-fill. It is therefore likely that this system has remained stable throughout its history, and has functioned as it does today for much of this time.

7.2.2 Controls on Swamp Initiation

The primary factors of control on the initiation of swamp development at the study site are geomorphic and climatic. Geomorphic controls include the size and shape of the valley basin, the low gradient slope, the sandstone lithology, and the bedrock constriction at the mouth of the basin. The small size of the swamp basin is naturally associated with a small contributing area for flows, and in combination with the gentle slope of the bedrock at the site, produces low stream powers in this valley. This produced competence-limited conditions such that the coarse-grained sediment derived from the adjoining sandstone hillslopes could not be transported downstream and remained stored in the basin. The transfer of these sediments has also been impeded by the bedrock constriction at the mouth of the swamp that acts to produce a funnel-shaped valley/basin within which sediments are trapped. The climatic conditions of the Budderoo Plateau contributed to the persistence of waterlogged conditions within this fill. Higher inputs of moisture from rain and fog precipitation relative to outputs as evapotranspiration created the positive water balance essential for the development of any swamp system.

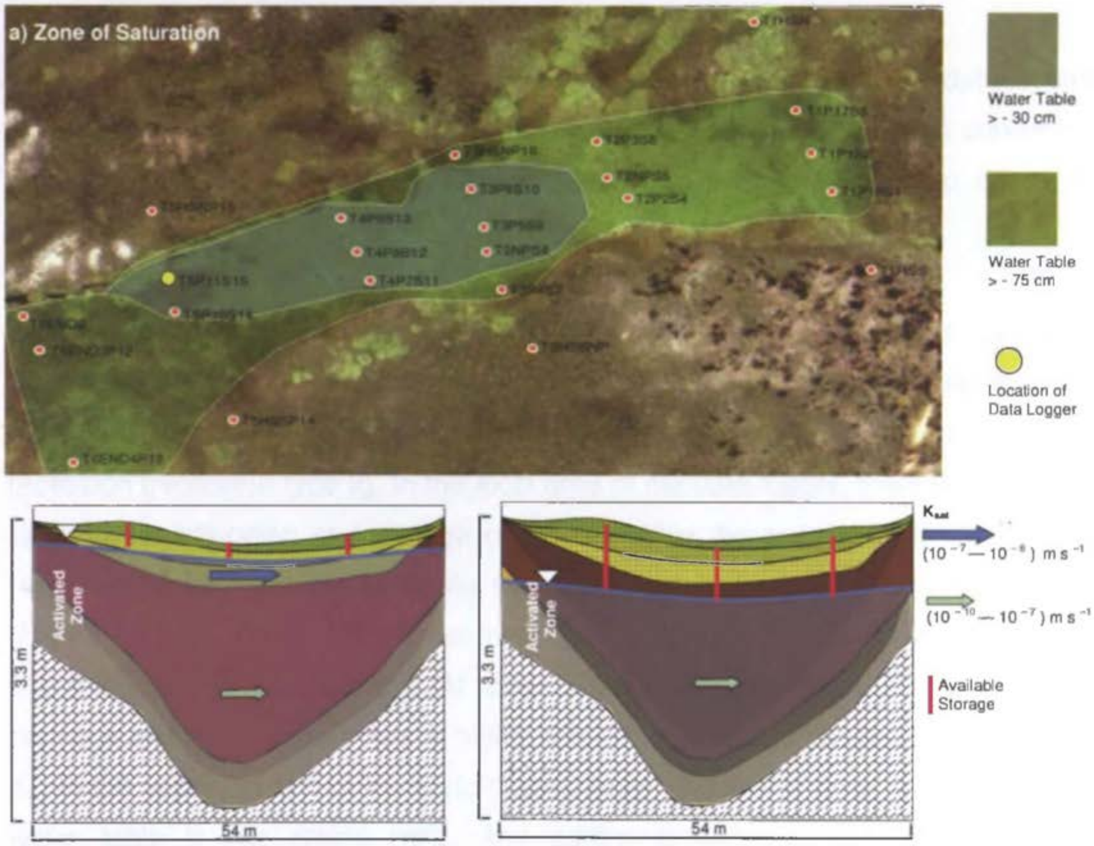
7.3 Hydrological Behaviour and Function

The interaction between the distribution and movement of the water table under different rainfall conditions and the physical structure of the swamp defines how the swamp functions to store and transfer water to the downstream catchment. Fluctuations in groundwater level control the zone of saturation across the swamp and within the sediment column. This zone of saturation defines the spatial limits of the area which actively contributes to the generation of flows, and therefore determines which geomorphic and sedimentary units play a functional role in the transfer of water through the swamp. The physical properties of these units determine the rates at which they contribute to water transfer. Therefore, using the physical and hydrological characteristics described in Chapters 5 and 6, it is possible to build a conceptual model of how the study swamp behaves hydrologically, and how it functions within the landscape.

7.3.1 Hydrological Response to Rainfall

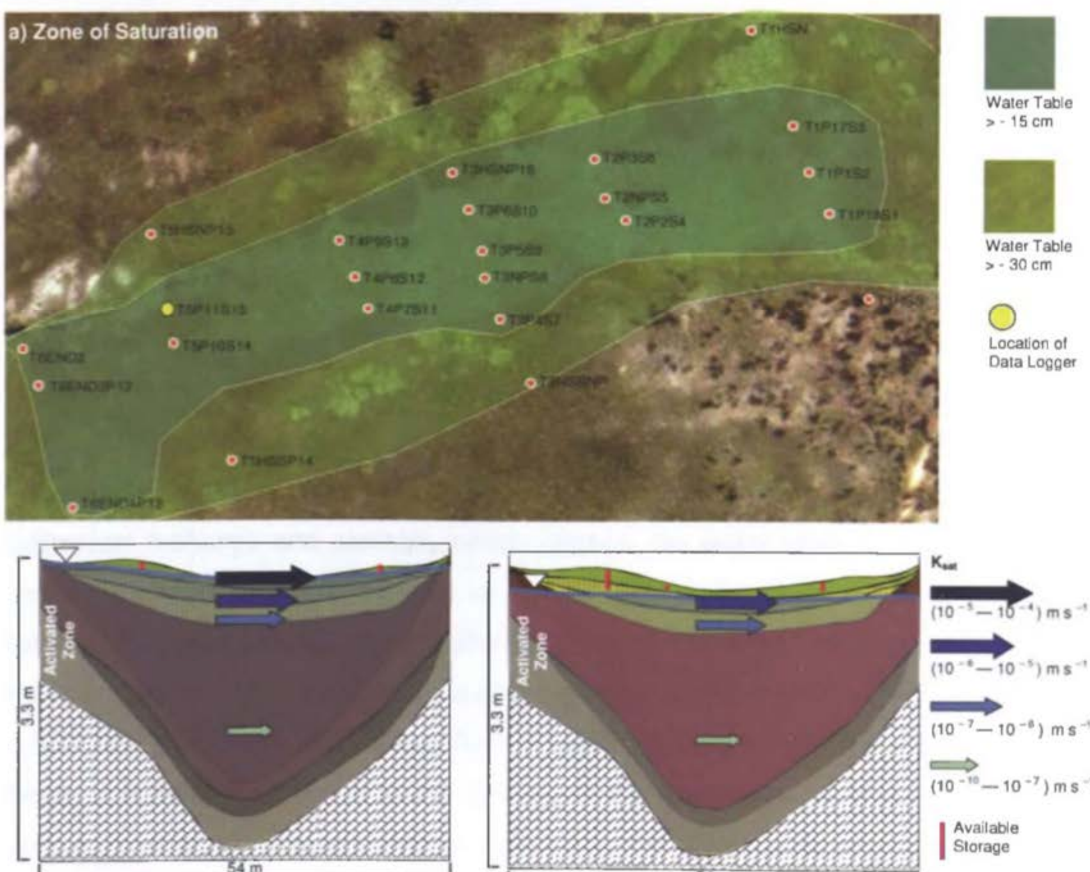
Even during dry periods, a significant proportion of the swamp sediments remain saturated or are at field capacity (i.e. moist/wet). However, the relative position of the water table in the sediment profile varies in space and time. After prolonged dry periods, such as those seen prior to the first key rainfall event in the study period, the zone of saturation (as indicated by water table distribution and depth) contracts and is concentrated within the central, downstream swamp areas where water tables remain stable at relatively shallow depths (within – 30 cm) (Figure # low period zone map, and inset b). The more marginal swamp areas have zones of saturation at depth (within – 75 cm) (Figure 7.7 a, c). This spatial differentiation in water table depth means that the degree of profile saturation, and therefore the potential storage, varies between different regions of the swamp (Figure 7.7 b, c). It also means that at different locations, a different set of sedimentary units are available for water uptake, storage and transfer prior to rainfall occurring (Figure 7.7 b, c). For example, in dry periods the marginal swamp zones are only saturated to the sapric organic fines. The unsaturated area above this is available for storage. Due to the extremely low K_{sat} of this layer, transfers are negligible under these conditions (Figure 7.7 c). Under the same conditions, the central swamp zone is saturated into the fibric organic fines and water transfer is activated through this layer (Figure 7.7 b). The available storage is minimal, and due to the greater K_{sat} of the fibric organic fines, transfers are therefore considerable relative to the marginal areas.

Following significant rainfall, the area of saturation expands to near-surface depths (within – 15 cm) in the central, downstream swamp regions, and to within the upper – 30 cm of the soil profile in the marginal swamp regions (Figure 7.8 a). The difference between zones in profile saturation and available storage is therefore reduced, and at all areas the upper sedimentary unit (fibric organic fines) is activated prior to subsequent rainfall (Figure 7.8 b, c). If the spatial distribution of water storage in the swamp varies under the same set of conditions, it can be expected that the response to rainfall will also differ between these regions of the swamp as various sedimentary layers are activated within the swamp. When rainfall occurs and the water table conditions are changes prior to the next rainfall, it can again be expected that the response to this subsequent rainfall will differ from the response to the first rainfall event. This variability in swamp function is captured in the hourly dataset (see Chapter 6).



b) Downstream / Central Region c) Upstream / Marginal Region

Figure 7.7: Low-stage hydrological conditions, prior to rainfall; a) zone of saturation; b) and c) schematic cross sections of water table and transfer characteristics



a) Downstream / Central Region b) Upstream / Marginal Region

Figure 7.8: High-stage hydrological conditions, following rainfall; a) zone of saturation; b) and c) schematic cross sections of water table and transfer characteristics

The different recession types and response regimes recorded within this dataset can be explained in terms of the spatial variability in antecedent water table conditions and the timing of local and cumulative responses of different swamp zones to rainfall.

The first response regime occurs following a period of low rainfall and low water table elevations across the swamp. After rain, a number of rapid peaks in water level (recession type 1) are followed by a period of relative stability and a final slow recession (recession type 2). In the local area of the data logger, there is little to no capacity for infiltration and storage of rainfall within the soil, and the water table responds rapidly, moving to within the upper soil horizon (–15 cm and above) (Figure 7.9 a, c). This occurs almost instantaneously (within hours) of significant rain falling on the swamp surface. At these water table depths, lateral subsurface drainage and water throughflow is highly efficient, as indicated by the high values of K_{sat} in the upper horizon of the fibric organic fines (Figure 7.9 a, c). As a result, the water table is not stable here. Any additional water is quickly throughput. Persistence of groundwater within this horizon relies on rates of input which equal or exceed rates of discharge. Therefore, when the rate of rainfall drops below this rate of discharge, a rapid, localised water table recession to depths of lower transfer efficiency (below – 15 cm) occurs (recession type 1). With fluctuations in rainfall intensity over the duration of a rainfall event, several of these localised, quickflow peaks may be recorded (Figure 7.9 d).

As indicated by the fortnightly data, however, in the drier areas upstream of the data logger, the initial water table lies deeper within the sediment profile than in the vicinity of the data logger (Figure 7.9 a). The transfer capacity (K_{sat}) of the sediment is extremely low at these depths, and the available storage in these marginal areas is considerable in comparison to downstream areas. As a result, it is likely that the water table response to rainfall in these areas is marked by an initial period of local infiltration recharge and storage, which causes the water table to rise within the sediment profile as lateral transfer at deeper depths is negligible. Given sufficient rainfall, the water table moves into the fibric organic fines, and subsurface horizontal transfer begins. There is therefore a time lag between the initiation of rainfall and the production of lateral water throughflow in these regions. When lateral transfer does begin, it is initially slow due to the low K_{sat} of the lower layer of fibric organic fines unit, and increases in speed and magnitude as the water table enters successively higher horizons of this unit (Figure 7.9 b). As these delayed flows are transferred

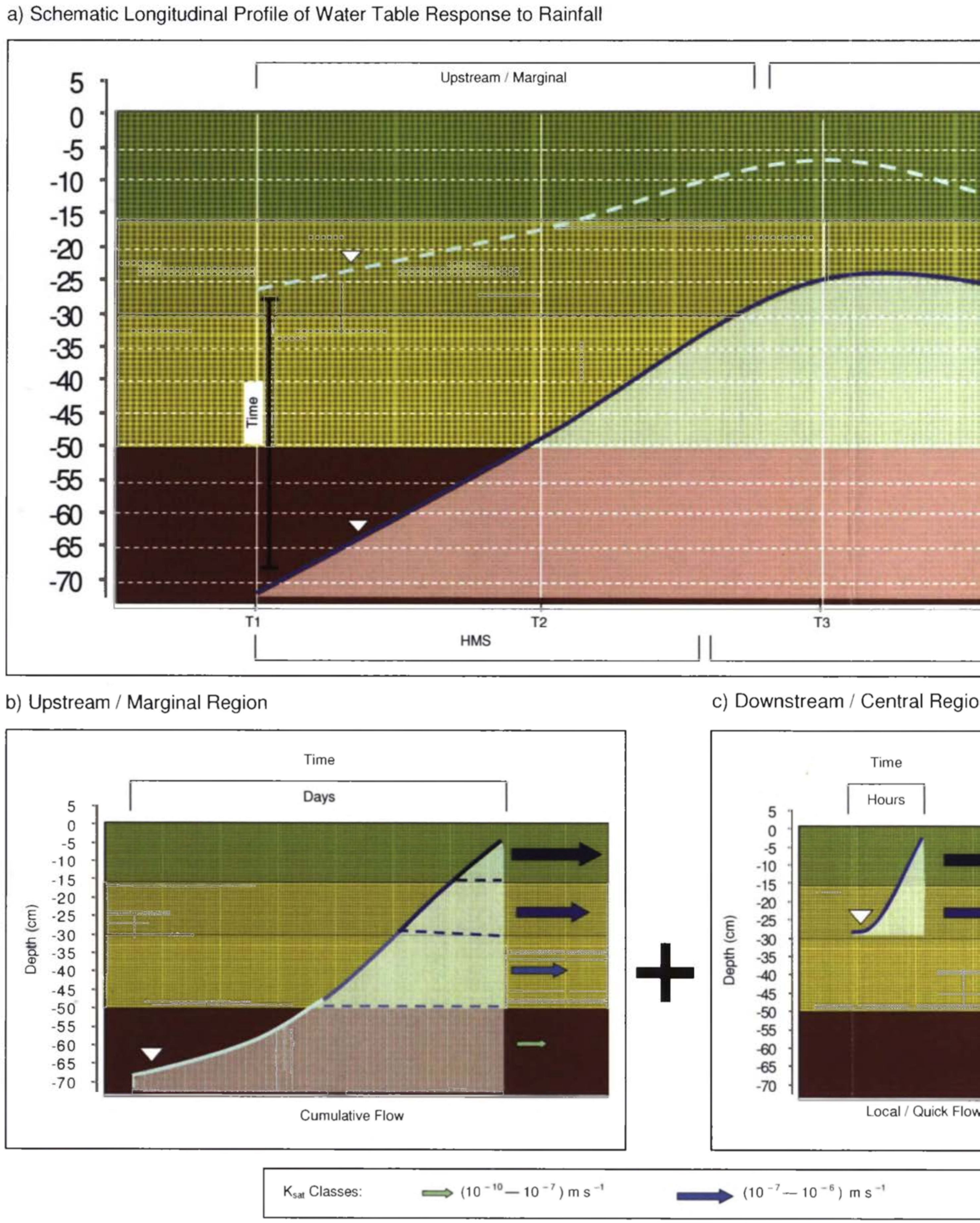


Figure 7.9: Water table response to rainfall and runoff regime

a) Schematic longitudinal profile of water table depth from soil surface, before rainfall (solid line) and after rainfall (dashed line); HMS = of central vs marginal regions

b) Schematic upstream / marginal zone water table response to rainfall; different colour sections represent response from different ante

c) Schematic downstream / central zone water table response to rainfall; initial water table is shallow, response time rapid, transfer rat

d) Schematic runoff response at downstream end of swamp; darker shading represents combined local and cumulative flows; number o downstream towards the central, saturated region where the data logger is located, they accumulate. When they meet the local water table at the data logger, the base water table level rises and stabilises within the upper horizons (Figure 7.9 d). The effect of these cumulative flows continues for a period after the cessation of rainfall, as indicated by a period of stability prior to the slow recession (recession type 2). With no further rainfall inputs, the contribution of the cumulative flows slowly wanes as the water table upstream falls and enters horizons of lower K_{sat}, and the downstream water table recedes slowly (recession type 2) (Figure 7.9 d).

The second response regime functions in the same way as regime 1, but the primary difference is the number of initial, local water table peaks prior to its stabilisation and gradual recession (Figure 7.9 d). This can be attributed to the higher antecedent water table conditions across the entire swamp at the initiation of this response regime. With higher initial water table conditions, the area of saturation is within the fibric organic fines unit in both upstream, marginal regions and downstream, central regions. Therefore, the storage capacity is uniformly low across the swamp, and lateral transfer is initiated in close association with rainfall inputs in the upstream regions. This means that while there is still a lag between local water table response and inflow from upstream regions, it is much shorter in duration than that which occurs in association with lower (drier) antecedent water table levels. A much higher percentage of the rainfall delivered to upstream regions is transferred directly to downstream areas (rather than taken into storage upstream), meaning that lower quantities of rainfall can produce a similar effect downstream to that observed in regime 1. As a result, the duration of the phase of rapid, localised water table fluctuations is truncated as cumulative flows from upstream reach the downstream area in a shorter time. This produces the sequence of a single initial flashy peak followed directly by the slow cumulative stabilisation and recession which is characteristic of response regime 2. The depth at which the water table stabilises before receding is higher in regime 2 (within – 5 cm) than in regime 1 (within – 15cm), suggesting that delivery of water from upstream is sufficient in quantity and duration to meet discharge rates in this layer, even with reduction or cessation of rainfall. A greater proportion of rainfall inputs is transferred directly downstream to support these water table levels. Additionally, it is only when even small magnitude rainfall occurs within these near-surface stable periods of regime 2 that saturation excess overland flow occurs. This indicates that at these times the system is fully saturated and is operating at close to its maximum transfer capacity. Because the sediments are saturated to the sediment surface, any additional inputs of rainfall cannot infiltrate and are transferred rapidly as saturation excess overland flow.

Response regime 3 is an intermediate form of response between regimes 1 and 2 (Figure 7.9 d). It occurs under conditions of moderate antecedent water table levels, and in response to moderate, isolated rainfall events. It most likely represents a localised response, as the recession is more rapid than that associated with cumulative water table inputs (recession type 3). This is probably because the quantity and duration of the rainfall associated with regime three is not sufficient to supply water from the upstream and marginal regions (where it is stored), as well as produce lateral transfers to the downstream region of the data logger.

7.3.2 Hydrological Function of Budderoo Swamp

The processes of groundwater response to rainfall and its interaction with the physical structure and sedimentary composition of the swamp produce a complex and dynamic set of swamp functions. Under various antecedent moisture conditions and with various patterns of rainfall, the swamp is acting as a 'sponge', sequestering water inputs, and as a conduit for the rapid transfer of flows. When continuous rainfall occurs at low antecedent water table conditions, the swamp can simultaneously act as a store for rainfall inputs in marginal regions where groundwater elevations are lowest, and can also immediately and rapidly transfer water to the downstream catchment from the central zone of saturation. With high levels of pre-event saturation, additional rainfall inputs result in a shift in function from water storage to water transfer and discharge. In periods of low rainfall input, the recession of the water table is drawn-out and attenuated suggesting that water is not readily released to the downstream catchment. In the absence of rainfall, the area of saturation within the swamp is reduced, but in central areas close to the swamp axis, water table levels are persistently shallow, even throughout the dry period. It can therefore be said that, in terms of flow generation, this swamp plays a dual role within the landscape by promoting water storage during periods below saturation, and, once saturated, by promoting the rapid transfer of water through the swamp.

In the next chapter the physical character, geomorphic evolution and hydrological function of the Budderoo swamp is placed in context of the international literature to discuss how these systems in eastern Australia differ to 'upland peatlands' found in other landscape settings.

8 Discussion

This chapter outlines the main findings of this study and places these in the context of the Australian upland swamp literature and the broader international peatland literature.

8.1 Geomorphology and Sedimentology

In the context of Australian upland swamps, the Budderoo swamp is relatively typical in physical structure. It occurs at high elevations (+600 m AHD) within a small drainage depression on the undulating topography of plateau area, similar to other upland swamp systems of south-eastern NSW, including those of the Barrington and Gloucester Tops (elevation 1500m above sea level, upon basalt plateaux) (Dodson, 1987; Nanson, 2009a) and the Woronora Plateau (300 – 550 m elevation, Hawkesbury Sandstone plateau) (Young, 1982). Its longitudinal slope of 6° corresponds with those observed in other upland swamps, including examples on the Woronora Plateau (of which 88 % have gradients below 10°) (Young, 1982; Young, 1986a) and the Lambert Peninsula (85 % have gradients less than 5°) (Buchanan, 1979). Although relatively small in area when taken alone (excluding the downstream extension not included in this study), the study site (0.02 km^2) is within the average size distribution reported in the literature. On the Barrington Tops, Polblue and Edwards swamps occupy an area of just 0.5 km^2 (Nanson, 2009a), and on the Woronora Plateau, (Young, 1986a) reported that of the 288 swamps identified, only 15 were greater than 0.25 km^2 in area. Only a few examples of extremely large upland swamps exist, including Wingecarribee swamp (originally covering 6.5 km^2) on the Southern Tablelands of NSW, Maddens Plains and Sublime Pt Moors (covering 7.3 km^2 in total) on the Woronora Plateau. The trend of downstream narrowing observed in the study swamp is also observed in the perched headwater valleys of the Blue Mountains (Holland *et al.*, 1992), but is not expressly noted in studies of other upland swamp systems.

The geomorphology of Budderoo swamp is somewhat simple, consisting of four geomorphic zones: the central swamp, the headwater marginal swamp, the valley marginal swamp and the hillslopes, and few other notable geomorphic units aside from pools and possible springlines. This configuration – related to vegetation, soils, and hydrology – resembles that observed in other upland swamps. In the perched headwater valleys of the Blue Mountains, Holland et al. (1992) report two distinct geomorphic zones: the *perennial swamp*, which is constantly wet and is characterised by a deeper fill and *Gymnoschoenus* dominated vegetation, and; the *ephemeral swamp* which is marginal and shallower, is irregularly saturated, and is dominated by *Lepyrodia* vegetation. Young (1982) describes a similar pattern of *lowland wet area*, *intermediate* and *upland dry* zones in swamps on the Woronora Plateau. These zones correspond closely with the characteristics of the central swamp zone (the perennial swamp / lowland wet area), the headwater and valley marginal swamp zones (ephemeral swamp / intermediate area), and the hillslopes (upland dry area). The pools in Budderoo Swamp occur downstream at the bedrock constriction, and are small, steep-sided and discontinuous. These are similar in location and character to pools observed in the upland swamps of the Woronora (Tomkins, Humphreys, 2006; Young, 1986a) and Barrington Tops (Nanson, 2009a). The continuous peat-swamp channels of Barrington Tops swamps, described by Nanson (2009a), did not occur within the study swamp. The meso-topographic features observed in upland swamps of the Blue Mountains and Woronora Plateau, including alluvial bulges, ridges and swales, or patterned ground (Holland *et al.*, 1992), were also not observed in the study swamp.

In Budderoo Swamp, the depth of the valley fill reaches 3.3 m in the centre of the swamp, which is consistent with other upland swamp systems (Buchanan, 1979; Dodson, 1987; Hope, 2003; Tomkins, Humphreys, 2006; Young, 1982). This fill is composed of a basal unit of mineral deposits (up to 1 m thick) which underlie a thick (up to 2.5 m), uniform accumulation of black, humic organic fines and a surface layer of fibric organic fines (50 cm thick). This sedimentary sequence is consistent with the findings of a previous study conducted by Prosser and Melville (1988) in a nearby swamp on the Budderoo Plateau. The sediments are depositional in origin, and are derived from the adjacent hillslopes and the accretion of organic matter from the swamp vegetation. This basic structure is similar for many upland swamps in south eastern Australia, although the basal sediments vary according to the lithology of the swamp (for example, the clay- and basalt cobble-based swamps of the Barrington and Gloucester Tops (Dodson, 1987; Dodson, Myers, 1986; Nanson, 2009a), and the 'puggy' clays of the Lambert Peninsula (Buchanan, 1979). In some cases the organic deposits (peat) directly overlie bedrock (Tomkins, Humphreys, 2006). In Budderoo Swamp, the basal units are massive, coarse-grained sands, which consist of dark (organic stained) and grey sands that bear close resemblance to the *organic sands* and *grey-brown sands* units described by Young (1982, 1986a) and Thomkins and Humphreys (2006) in swamps on the nearby Woronora Plateau. These findings at the study swamp are consistent with the findings of a previous study of soils covering the entire plateau area from Barren grounds (east of Budderoo Plateau) to Fitzroy Falls (west of Budderoo Plateau), conducted by Burrough et al. (1977).

Within the organic accumulations, the black, sapric fines are uniform throughout their entire depth. In several other swamps, however, the stratigraphy of the humic layer is more complex, and can consist of a series of interbedded mineral-dominated horizons and organic layers with varying degrees of fibrous organic matter. For example the sand horizons described by Tomkins and Humphreys (2006) at Drillhole and Flat Rock swamps on the Woronora Plateau, and the interbedded fibric and humic peats of Brown Marsh, Tasmania, described by MacPhail and Hope (1985). In contrast to the uniform sapric organic fines in Budderoo Swamp, the character of the upper layer of fibric organic fines changes significantly over short depths (within 50 cm). Coarse organic matter content, LOI, and moisture content decrease with depth as bulk density (and its proxy, decomposition) increase with depth. This is a well-established feature of the upper layer of peat accumulations (Boelter, 1969; Chason, Siegel, 1986; Collins, Kuehl, 2001; Ingram, 1978; Ingram, 1983b; Young, 1982), and has been documented throughout Australian upland swamps (Buchanan, 1979; Dodson, 1987; Hope *et al.*, 2009; Keith *et al.*, 2006; MacPhail, Hope, 1985; Nanson, 2009a; Tomkins, Humphreys, 2006).

In the international peatland literature, this structure of the organic accumulations is termed the *diplotelmic* structure. The upper layer is known as the *acrotelm*, and is the zone of active organic deposition. Due to its surface position it is exposed to fluctuating water table levels. The lower layer, the *catotelm*, is defined by the long-term minimum water table depth, and is therefore persistently saturated and anaerobic. The physical structure, and therefore the function, of these layers varies widely (see section 2.3.2). In the Australian literature, the importance of this model has not been extensively investigated. Given the functional (and ecological) significance of the diplotelmic structure, it is important to confirm its application in Australian upland swamps. The results of this study suggest that this model can be applied in upland swamps which exhibit the physical structure of the study swamp. However, the potentially wide fluctuations in water table depth in Australian swamp systems may result in very deep acrotelm horizons (Hope *et al.*, 2009), and as such disparities between the physical and hydrological definitions (See section 2.3.2) of these layers may occur within Australian swamps.

The current study provides some evidence of this disparity. The physical characteristics of the fibric organic fines and sapric organic fines correspond with those of the acrotelm and catotelm, respectively. The rapidly changing characteristics of the fibric organic fines and the uniformity of the sapric organic fines are consistent with physical descriptions of the acrotelm and catotelm, respectively, in studies from the northern hemisphere (Holden, Burt, 2003b; Ingram, 1978; Ingram, 1983b; Ivanov, Geogr, 1981; Romanov, 1968). In this study, however, it has been found that minimum water table depths can reach – 75 cm within the swamp fill. At these depths, the water table lies within the sapric organic fines unit. If the sapric organic fines are to be taken as a physical analogue for the catotelm, the hydrological definition – that the catotelm is constantly beneath the water table, saturated and anaerobic – cannot be applied. Since the relationship between the hydrological and physical definitions of these layers has functional significance (related to hydraulic conductivity and rates of throughflow), it is important to recognise this inconsistency in an Australian setting. The results of this study suggest the functional boundary between these layers may be less clear than is described in the international literature (Ingram, 1978; Ivanov, Geogr, 1981; Romanov, 1968). Spatial differences in average water table depths within the swamp may further complicate the application of the diplotelmic model in Australian upland swamps. As the extent of the fibric organic fines is relatively consistent (to about 50 cm depth) throughout the swamp, but minimum water table elevations vary spatially, additional functional complexity associated with this model is likely.

8.2 Geomorphic Evolution

As indicated by the consistent stratigraphy of the fill, the geomorphic evolution of Budderoo Swamp is likely to have been relatively uniform. It was marked by an initial phase of mineral deposition, followed by vertical accretion of organic deposits within the valley axis, and more recently lateral expansion onto the low-lying southern hillslopes. Tomkins and Humphreys (2006) report a similar sequence of geomorphic development at Swamp 18 on the nearby Woronora Plateau. Young (1982) also describes this basic sequence in her study of dells on the Woronora

Plateau. The phase of organic accumulation is a fundamental growth and development sequence observed for all peatland systems (Belyea, Baird, 2006; Clymo, 1984; Romanov, 1968). However, the progression of development within this organic accumulation can be irregular, and can be punctuated by periods of increased erosional or depositional processes within the swamp catchment. Several authors describe complex stratigraphy in upland swamps, including evidence of recurrent episodes of cut-and-fill, the development of inset floodplains associated with swamp channels, and alternating periods of increased organic / mineral accumulation (Dodson, 1987; Fryirs, Brierley, 1998; Hope *et al.*, 2009; Nanson, 2009a; Tomkins, Humphreys, 2006; Young, 1982; Young, 1986b). No such stratigraphic evidence was recovered from Budderoo Swamp, suggesting that during its development, the swamp (including surrounding hillslopes) has been stable and has not been subject to irregular depositional or erosional events. Given the proximity of the study swamp to the Woronora Plateau, however, it can be expected that it was subject to a similar set of climatic and environmental boundary conditions as the swamps which occur there. That the study swamp has recorded no significant episodes of erosion or differential sedimentation similar to those observed in swamps on the Woronora, points to the importance of localised and swamp-specific intrinsic geomorphic thresholds as a primary factor in the occurrence of such erosional/depositional events (Prosser and Slade, 1994; Prosser and Winchester, 1996).

Similar to the dells described by Young (1982, 1986a), the controls on swamp initiation at the study site have been identified as geomorphic, relating primarily to the morphology of the swamp basin and the character of the valley sediments. Like most upland swamps, valley slope is considered to have been a major factor in the initial accumulation of mineral sediments within the basin (Buchanan, 1979; Young, 1982; Young, 1986a). Additionally, the small size of the basin catchment contributed to the low-competence of the pre-swamp drainage system and the grainsize of the hillslope derived sands prevented downstream flushing. This process was also described by Young (1982) for dells on the Woronora Plateau. The final geomorphic attribute of the swamp basin which is likely to have played a role in preventing downstream transfer of the mineral sediment sheet is the bedrock constriction at the downstream end of Budderoo Swamp. This is likely to have caused a physical barrier to the transfer of sediments. Similar controls occur as a bedrock step in the perched headwater valleys of the Blue Mountains (Holland et al), in base of escarpment settings (Fryirs, 2002), and as large woody debris blockages on the Woronora Plateau (Tomkins, Humphreys, 2006).

Although the sediments of Budderoo Swamp have not been dated, given the proximity and physical and developmental resemblance to swamps on the Woronora Plateau, it can be surmised that the timing of its initiation roughly coincides with swamp initiation on the Woronora. Young (1986a, 1986b) and Tomkins and Humphreys (2006) place the basal ages of swamps on the Woronora within the late Pleistocene and Early Holocene (see table 2.1, section 2.1.1).

8.3 Hydrological Behaviour and Function

Although there are few accessible studies in the Australian scientific literature which examine the internal hydrological behaviour and functioning of upland swamps, those that are available describe several trends which are consistent with the findings of this study. In the Budderoo Swamp, several basic groundwater table trends have been observed. Firstly, an inverse trend of increasing mean water table elevations and decreasing groundwater variability occurs in which the central, downstream areas are stable at shallow groundwater depths, while the upstream, marginal and hillslope areas are more variable and have lower mean elevations. This relationship between mean groundwater elevation and degree of variability is also described by Holland et al. (1992), in the north-facing perennial swamp areas of the perched headwater valleys of the Blue Mountains, and Buchanan (1979) for the swamps on the Lambert Peninsula. Mitry (2008) notes a longitudinal trend in water table elevation in which the downstream areas have consistently higher water tables than upstream regions in a swamp on the Woronora Plateau. This is consistent with the longitudinal trends observed in this study.

These patterns in water table distribution and variability delineate distinct hydrological zones within the swamp area. The behaviour of the downstream, central region identified in this study is consistent with the behaviour of the 'perennial swamp' and 'lowland wet area' zones described by Holland et al. (1992) and Young (1982), respectively. These zones are permanently wet, and remain highly saturated to near surface depths for long periods following recharge from rainfall. In contrast, the behaviour of Holland et al.'s (1992) 'ephemeral' zone, Young's (1982) 'intermediate' zone, and the upstream / marginal region identified in this study is more variable with changing rainfall. In these zones, the water table rises rapidly and significantly in response to rainfall, but also falls more markedly after its cessation. In the studies of both Holland et al. (1992) and Young (1986), and also in this study, the hillslope areas are dry for a significant percentage of time throughout the recording periods, and while they also fill significantly in response to rainfall, they are dry within days following its cessation. The findings of Prosser and Melville (1988) for a nearby swamp on the Budderoo Plateau are in agreement with the behaviours described in these studies, and those found in the present study.

The similitude between the behaviours of these individual swamps in different regions suggests that there is a characteristic hydrological structure common across upland swamps with similar physical structure in southeastern Australia. Saturation is stable and concentrated downstream and within the swamp axes, is more variable at its perimeter, and is most variable in the surrounding hillslopes. While somewhat obvious, this structural concord between swamps in different regions has not previously been formally acknowledged within the Australian literature. Further studies are clearly required to confirm this as the typical hydrological form for intact, unchannelised upland swamps, however in doing so it may provide a baseline against which to compare other types of upland swamps, such as those containing pools, chains-of-ponds, and channels.

The hourly data collected at T5P11S15 records the fine resolution water table response to rainfall within the central, downstream region of the swamp. The pattern of this response, which is generally characterised by a number of rapid initial peaks (determined by the antecedent moisture conditions of the swamp), followed by a later slow recession, has not previously been described in the Australian literature. As such, this data forms a baseline on which to build further studies to expand the current knowledge of the fine-scale behaviour of the groundwater table in response to rainfall within the upland swamps of southeastern Australia. In addition, a small diurnal oscillation of 0.5 cm has been observed during dry periods in the current study. A similar small diurnal fluctuation has been noted by Nanson (2006) in the stage height of the narrow and deep peat-swamp channels of the Barrington Tops. Few other studies have examined upland swamp water table behaviour at similar resolutions, and as such there is the opportunity to further elucidate these patterns in future investigations.

The internal hydraulic structure of the study swamp is complex. In the upper layer of fibric organic fines, the hydraulic conductivity decreases sharply with depth. At the base of this layer (– 40 cm to – 50 cm), the hydraulic conductivity is up to three orders of magnitude lower than at near-surface depths. These findings are consistent with the values reported in studies conducted in peatlands of the northern hemisphere (Table 2.4, section 2.3.2) (Baird, 1997; Holden, Burt, 2003a; Schlotzhauer, Price, 1999). In the context of typical hydraulic conductivities for mineral sediment types (Table 8.1), the mean value for the upper fibric organic fines (1.63×10^{-4}) is similar to that of clean sands and gravels, and is considered high. In contrast, the mean hydraulic conductivity for the lower fibric organic fines (2.2×10^{-6}) is within the 'moderate' range, similar to the conductivity of fine sands. Lower still is the mean hydraulic conductivity of the sapric organic fines (1.86×10^{-7}), which is on a similar scale to fine-grained sediments such as silts and clays. At some locations, the hydraulic conductivity of this layer reached the very low rates associated with massive clays. These values for the sapric organic fines are also consistent with reported values of hydraulic conductivity from studies in the northern hemisphere (Table 2.4, Section 23.2) (Baird, Gaffney, 1994; Clymo, 2004; Dasberg, Neuman, 1977; Rosa, Larocque, 2008). Below the sapric organic fines, the mean hydraulic conductivities of the basal sands sit within the 'moderate' range.

To the author's knowledge, there are no quantitative Australian studies with which to compare these results. These data again form a baseline with which to compare subsequent studies on the hydraulic structure of the upland swamps of southeastern Australia. Considering that the physical structure of the Budderoo Swamp is simple in comparison to that observed at other locations (see above section 8.1), it can be expected that the hydraulic structure of other upland swamps may be even more

Table 8.1: Typical hydraulic conductivities in metres/second for various sediment types. *Adapted from Brassington (2007)*

	Hydraulic Conductivity (m s^{-1})				
	$10^{-10} - 10^{-9}$	$10^{-8} - 10^{-7}$	$10^{-6} - 10^{-5}$	$10^{-4} - 10^{-3}$	$10^{-2} - 10^{-1}$
Relative Hydraulic Conductivity	Very Low	Low	Moderate	High	Very High
Representative Materials	Massive clay	Silt, clay and mixtures of sand, silt and clay	Fine Sand	Clean sand and sand and gravel	Clean gravel

complex than observed in this study. Further studies to establish the hydraulic structure of unchannelised upland swamps are necessary for developing a better, quantified understanding of how they act to store water and to transfer flows to the downstream catchment.

The interaction between the groundwater behaviour and the hydraulic properties of the swamp determines how the swamp functions in terms of generating flows in response to different rainfall events. Although direct runoff measurements were not a part of this study, the runoff behaviour of the swamp can be inferred from the position of the water table, and the physical and hydraulic properties of the sediments at the corresponding depth. It can therefore be said that this study found that the Budderoo Swamp has a dual function in which it both stores and rapidly transfers flows, depending on the antecedent moisture conditions of the swamp sediments. When water table elevations are low following a period of dry weather, the upstream, marginal region of the swamp serve to store rainfall within the sediment profile where lateral transfers are negligible, and only begins to release significant flow downstream as the water table rises to more conductive sediment layers. In contrast, due to the persistently high saturation of the downstream, central regions of Budderoo Swamp, a rapid water table response in which near-surface elevations are attained – and therefore shallow subsurface flow through highly conductive fibric layers – occurs within these areas. This low flow condition may well be a unique characteristic of Australian upland swamps that occur in regions with significant rainfall and flow variability (McMahon et al. 1992). Long periods of drought followed by relatively short periods of intense rainfall mean that these swamps are functioning in this way for the majority of the time.

At periods of high initial water table elevations, the available storage in even upstream, marginal areas of the swamp is minimal, and initiation of downstream water transfer from these areas is less lagged. Under these conditions, throughout the swamp the water table sits within the transfer efficient fibric organic fines, and the swamp functions primarily as a conduit for the rapid downstream transfer of flows via near-surface matrix flow or saturation excess overland flow. While it is recognised that the water table levels recorded in the hourly data, on which much of this interpretation is based, may not directly represent the total discharges from the swamp (for example, there is the potential that significant discharge through the basal sands or soil pipes also occurs (Hope *et al.*, 2009; Nanson, 2009a), for the purposes of this study it is taken that the differential functioning of the swamp is dependent primarily on the relative storages or transfers generated within the organic sediments.

While not expressly interpreted as swamp function, Young (1986a) describes a similar hydrologic system for the dells of the Woronora Plateau. She explains that as a result of the high level of saturation within the swamp axes, there is little to no storage available for rainfall and as such these areas yield runoff almost immediately. However, the sediments of the marginal sideslopes of the dells act as intermediate areas which become saturated and store water after rainfall, and which may yield flow directly if fully saturated, or over longer periods by lateral throughflow into the saturated zones. Young (1986a) is therefore also describing a dually functioning swamp system. Few other Australian studies make mention of the implications for flow generation of the hydrological behavioural zones described above, however, provided systems which share this hydrological structure have similar physical and hydraulic structures, they can be expected to function in a similar way.

In the international literature, this dual functioning of swamp systems in association with different antecedent moisture conditions has been well recognised (Bay, 1969; Evans, Warburton, 2007; Kaufman *et al.*, 2005; Kvaerner, Klove, 2008; McCartney *et al.*, 1998). Evans et al. (1999) describe the response of a blanket peatland in the UK to rainfall, and report that while significant stream runoff from the system was generated through saturation excess overland flow when rainfall occurred at surface or above surface water table elevations, immediate runoff was not produced and streamflow was delayed by groundwater recharge when rainfall occurred when the water table was depressed. This suggests at least some level of storage within the peat in response to rainfall under low antecedent moisture conditions. Similarly, Kvaerner and Klove (2008) emphasise the importance of antecedent water table position, and report that in a boreal flat fen, streamflow was attenuated as a result of storage within the peat when rainfall occurred at low initial conditions. Branfireun and Roulet (1998) detail the correspondence between water table elevations and streamflow in a Precambrian Shield peatland in Canada, and state that under 'dry' antecedent conditions when the water table was deep in the peat profile, rainfall generated significant increases in water table elevation (8 – 10 cm), but corresponding increases in discharge were small. However, under 'wet' conditions, streamflow increased rapidly with only a small water table increase as its initial position was already at- or near-surface. They also expressly note the relationship between the increasing hydraulic conductivity towards the peat surface and the increasing discharge as water tables enter these upper horizons, in comparison with the low discharges observed when the water table lies within the poorly conductive lower strata. These studies confirm the likelihood of a dual functioning in which storage is occurring at unsaturated conditions and discharge to downstream catchments is lagged, but rapid transfer occurs when wide-spread swamp saturation is reached. This occurs within the Budderoo Swamp.

The following chapter presents some concluding remarks and a summary of the key findings of this research.

9 Summary and Conclusions

This chapter summarises the main findings of this study, and makes concluding remarks about their significance for future research and management of upland swamps in southeastern Australia.

9.1 Summary of Findings

With the aim of providing additional and baseline information on the physical, evolutionary and hydrological characteristics of upland swamps, the present study investigated the geomorphology, sedimentology, and hydrology of an intact upland swamp on the Budderoo Plateau. The results of these investigations were analysed to describe the swamp's physical structure, and interpret its geomorphic evolution and hydrological behaviour and functioning.

The geomorphic structure of Budderoo Swamp is relatively simple, consisting of four geomorphic zones: the central swamp, the headwater marginal swamp, the valley marginal swamp and the hillslope zones. These are characterised by changes in dominant vegetation, sediment characteristics, and hydrology. The central swamp zone is persistently saturated, even in dry periods, while the marginal and hillslope zones vary in their degree of saturation. These findings are consistent with others cited in the Australian upland swamp literature.

The geomorphic evolution of Budderoo Swamp was relatively uniform, and consisted of a sequence of mineral deposition onto the valley floor, followed by a period of organic accumulation under waterlogged conditions. No significant erosional or depositional events (cut-and-fill), such as those observed in upland swamps on the Woronora Plateau, occurred during its development. The organic accumulation has produced a layer of upper fibric organic fines and lower sapric organic fines. Each of these sedimentary units has different hydrological behaviours (rates of water transfer and discharge) that drive the overall function of the swamp in response to rainfall of various magnitudes and duration.

Three hydrological response regimes have been identified in the functioning of this swamp. These regimes are characterised by different peak and recession responses to rainfall. The form of the hydrograph produced is controlled by antecedent water table position (i.e. which sedimentary layers are saturated) and the amount, timing and duration of rainfall. Depending on antecedent moisture conditions, the swamp can be operating either as a store for water or as a rapid conduit for water throughflow and overland flow. It therefore has a dual function in terms of flow generation in response to rainfall. These findings are consistent with those established within the Australian literature on upland swamps and within the broader international peatland literature.

9.2 Conclusions

9.2.1 Implications for Management

This study helps to inform management by providing additional insights into the range of natural forms, physical characteristics and hydrological behaviour and functioning of upland swamps. By building baseline data in these areas, it is possible to adequately assess the extent of degradation occurring within upland swamps currently under threat, and to help protect and mitigate against future damage. Understanding of the hydrological function of these systems is particularly crucial in an environment of worsening water resources scarcity.

9.2.2 Future Research

Although there has been a recent swell in interest in upland swamps systems, both from a hydrological and an ecological perspective, the science is still relatively sparse in regards to many facets of upland swamps, particularly when taken in the context of the broader international peatland hydrology. Further research into the natural range of processes, behaviours and thresholds within upland swamps is both an intellectual priority in order to fully characterise these unique Australian systems, and is also critical in predicting their response to changing environmental conditions. In particular, further work focusing on the distinctive hydraulic and hydrological functioning of these systems is necessary, and much guidance can be sought from the international peatland literature.

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