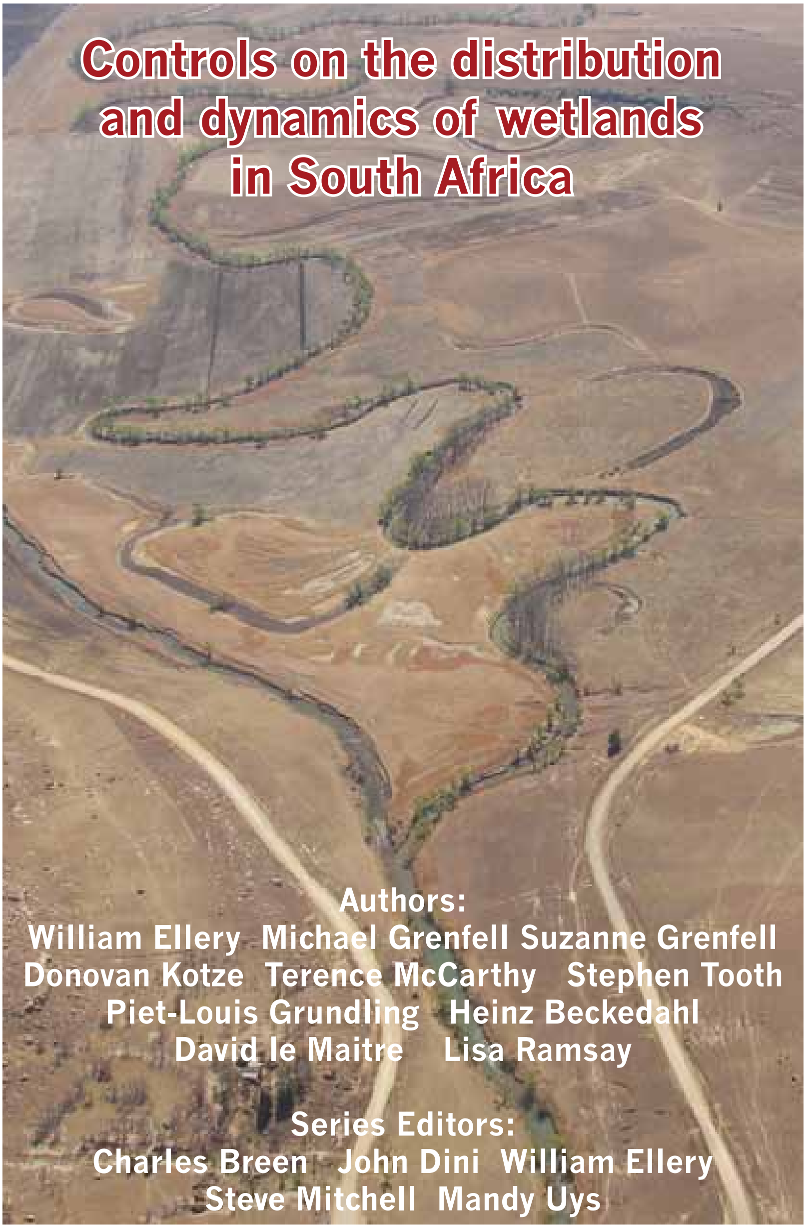
Wetland Management Series

WET-Origins



Controls on the distribution and dynamics of wetlands in South Africa

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Environmental Affairs and Tourism
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Working for Wetlands

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Water Research Commission

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WRC Report TT 334/09
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Front cover: The lowermost portion of the Upper Mzimvubu River wetland west of Matatiele in the Eastern Cape. A meandering stream with oxbow lakes occurs in a broad valley underlain by Karoo sedimentary rocks, downstream of which a dolerite dyke confines the stream to a straight, narrow valley. An artificial drain enters the Mzimvubu River immediately upstream of the dolerite dyke.
Photograph: Japie Buckle

Inside front cover: Boneberg's frog (*Natalobatrachus bonebergi*), commonly known as Ngoye frog, is a threatened endemic species along the coastal region of KZN.
Photograph: Errol Douwes

Preface: Background to the ***WET-Management*** Series

The need for wetland rehabilitation in South Africa is compelling: loss and degradation of wetlands have been great and national policy and legislation provide clear direction and support for rehabilitation. However, rehabilitating wetlands is often complex because wetlands and their links with people are complex (e.g. through the ways that people use wetlands and the different benefits that people receive from the ecosystem services that wetlands supply). Thus a series of tools has been developed to assist those wishing to undertake wetland rehabilitation in a well-informed and effective way (Box 1P).

These tools were developed as part of a comprehensive nine-year research programme on wetland management which was initiated in 2003 by the Water Research Commission (WRC) and a range of partners that examines wetland rehabilitation, wetland health and integrity and the sustainable use of wetlands. The rehabilitation component, which was co-funded by the WRC and the Department of Environmental Affairs and Tourism, through the Working for Wetlands (WfWetlands) programme, was prioritised to take place first because of the need to provide a firm, scientific and technical foundation for the extensive rehabilitation work already under way.

The Working for Wetlands programme is a national initiative that seeks to promote the protection, rehabilitation and wise use of wetlands in South Africa. As part of this initiative, WfWetlands has a national programme for the rehabilitation of wetlands, including a structured process of prioritising rehabilitation sites and supporting their rehabilitation. At the same time, however, it is acknowledged that sustainable use of wetlands in the long term can be achieved only through the dedicated participation of civil society, whose wetland interests may have a strong local focus. Thus the tools have been developed in such a way that they can be applied outside of the Working for Wetlands programme, and without having to engage the process of national or provincial prioritisation should the user not desire to do so. Even so, the tools encourage local wetland rehabilitation efforts to strengthen links with the national initiative and the opportunity these provide for fruitful partnerships.

The series consists of a roadmap, two background documents, eight tools and an evaluation of the success of six individual projects (Box 1P). From Table 1P it can be seen that some of the tools (e.g. *WET-RehabMethods*) are designed to be used by those dealing specifically with wetland rehabilitation and its technical requirements. Other tools (e.g. *WET-Health*) have much wider application such as assessing impacts associated with current and future human activities in Environmental Impact Assessments (EIAs) or assessing the Present Ecological State (PES) of a wetland in an Ecological Reserve Determination (ERD).

One can locate the tools in terms of some basic 'who', 'what', 'where' and 'how' questions that any team undertaking wetland rehabilitation should be asking (Table 2P). Furthermore, each of the tools can be used individually, but there are close links between them (Figure 1P).

Box 1P: Overview of the *WET-Management* Series

The series includes documents that provide background information about wetlands and natural resource management, tools that can be used to guide decisions around wetland management, and an evaluation of rehabilitation outcomes in a number of case studies.

WET-Roadmap

WET-Roadmap provides an introduction to the *WET-Management* tools and includes:

- a brief outline of the documents and tools in the *WET-Management* series and how they inter-relate
- an index of wetland rehabilitation related terms
- reference to specific sections in the relevant tools.

WET-Origins

WET-Origins describes the remarkable geological and geomorphological processes that give rise to wetlands in South Africa, and provides a background description of:

- the geology, geomorphology, climate and drainage of southern Africa
- an introduction to wetland hydrology and hydraulics
- geomorphic controls on different wetland types
- wetland dynamics due to sedimentation and erosion.

It incorporates this understanding into a methodology that can be used to help develop insight into the hydrological and geomorphological factors that govern why a wetland occurs where it does, which is useful when planning rehabilitation.

WET-ManagementReview

WET-ManagementReview has four parts:

1. An assessment of effectiveness at programme level, including:
   - a national overview of land-uses affecting the status of wetlands and the institutional environment that affects wetlands.
   - an overview of five natural resource management programmes affecting wetlands and their impact in different land-use sectors; Working for Wetlands, Working for Water, LandCare, the Crane Conservation Programme of the Endangered Wildlife Trust, and the Mondi Wetlands Programme.
2. An assessment, using the *WET-EffectiveManage* tool, of the management effectiveness of 21 wetland sites in a variety of different land-use and land-tenure contexts.
3. An assessment of stakeholder participation in wetland rehabilitation at six wetland sites.
4. A framework for assessing the effectiveness of collaboration between partners, described and applied to a site where a rehabilitation project has been under way for several years.

WET-OutcomeEvaluate

WET-OutcomeEvaluate is an evaluation of the rehabilitation outcomes at six wetland sites in South Africa, including an evaluation of the economic value of rehabilitation. The six sites are:

1. Killarney Wetland
2. Manalana Wetland
3. Kromme River Wetland
4. Dartmoor Vlei
5. Kruisfontein Wetland
6. Wakkerstroom Vlei.

WET-RehabPlan

WET-RehabPlan offers a process that can be followed to develop comprehensive wetland rehabilitation plans. It has three main elements:

- Introduction to rehabilitation, planning and stakeholder involvement.
- General principles to follow in planning wetland rehabilitation.
- Step-by-step guidelines for undertaking the planning and implementation of wetland rehabilitation at a range of scales from national/provincial to catchment to local. It directs the user to the right tools and sections at appropriate points in the rehabilitation process.

Good planning ensures a rational and structured approach towards rehabilitation as well as a clear understanding of the reasons for rehabilitation, the actions and interventions required, and the benefits and beneficiaries.

WET-Prioritise

WET-Prioritise helps to identify where rehabilitation should take place once the objectives of rehabilitation are identified. It works at three spatial levels. At national and provincial level an interactive GIS modelling tool assists in identifying priority catchments by evaluating a range of scenarios, based on different combinations of 13 socio-economic and bio-physical criteria (e.g. Biodiversity Priority Areas, High Poverty Areas). Once a catchment is selected, the tool helps to identify areas for rehabilitation within that catchment. Finally, individual wetlands are selected based on the predicted cost-effectiveness and sustainability of rehabilitation.

WET-Prioritise provides step-by-step guidelines applicable at all three spatial scales, including:

- identifying objectives and an appropriate scale.
- developing prioritisation criteria.
- applying the criteria, usually in a two step process of rapidly screening all candidate sites to arrive at a preliminary set of sites, from which individual priority sites are selected.

Three case examples of prioritisation are described.

WET-Legal

WET-Legal presents South African legislation that is relevant to wetland rehabilitation, including the Conservation of Agricultural Resources Act (CARA), National Environmental Management Act (NEMA), and National Water Act (NWA), as well as relevant international agreements such as the Ramsar Convention on Wetlands. *WET-Legal* lists the environmental impacts potentially associated with typical wetland interventions and the legislative provisions that apply to each of these impacts. It also covers laws compelling rehabilitation and the legal responsibilities of different parties involved in rehabilitation.

TOOLS

WET-EcoServices

WET-EcoServices is used to assess the goods and services that individual wetlands provide, thereby aiding informed planning and decision-making. It is designed for a class of wetlands known as palustrine wetlands (i.e. marshes, floodplains, vleis or seeps). The tool provides guidelines for scoring the importance of a wetland in delivering each of 15 different ecosystem services (including flood attenuation, sediment trapping and provision of livestock grazing). The first step is to characterise wetlands according to their hydro-geomorphic setting (e.g. floodplain). Ecosystem service delivery is then assessed either at Level 1, based on existing knowledge, or at Level 2, based on a field assessment of key descriptors (e.g. flow pattern through the wetland).

WET-Health

WET-Health assists in assessing the health of wetlands using indicators based on geomorphology, hydrology and vegetation. For the purposes of rehabilitation planning and assessment, *WET-Health* helps users understand the condition of the wetland in order to determine whether it is beyond repair, whether it requires rehabilitation intervention, or whether, despite damage, it is perhaps healthy enough not to require intervention. It also helps diagnose the cause of wetland degradation so that rehabilitation workers can design appropriate interventions that treat both the symptoms and causes of degradation. *WET-Health* is tailored specifically for South African conditions and has wide application, including assessing the Present Ecological State of a wetland for purposes of Ecological Reserve Determination in terms of the National Water Act, and for environmental impact assessments. There are two levels of complexity: Level 1 is used for assessment at a broad catchment level and Level 2 provides detail and confidence for individual wetlands based on field assessment of indicators of degradation (e.g. presence of alien plants). A basic tertiary education in agriculture and/or environmental sciences is required to use it effectively.

WET-EffectiveManage

WET-EffectiveManage provides a framework that can be used to assess management effectiveness at individual wetlands based on 15 key criteria (e.g. the extent to which a regularly reviewed management plan is in place for the wetland). A scoring system is provided for rapidly assessing the criteria. This tool is Chapter 2 in the *WET-ManagementReview* manual.

WET-RehabMethods

WET-RehabMethods is used to guide the selection and implementation of rehabilitation methods that are appropriate for the particular problem being addressed and for the wetland and its catchment context. It provides detailed practical rehabilitation guidelines for inland palustrine wetlands and their catchments, and focuses particularly on wetlands associated with natural drainage networks. It can be adapted to meet specific needs. Some aspects of the tool require high levels of civil engineering expertise, but it is designed primarily for rehabilitation workers who have completed training in soil conservation, life sciences or engineering at a diploma level or higher, and who have practical field experience.

WET-RehabMethods includes the following:

- Key concepts relating to wetland degradation, particularly those resulting from erosion.

- Guidelines for the selection of an appropriate type of rehabilitation intervention (including both 'soft' and 'hard' engineering options).
- Detailed guidance, provided for designing a wide variety of intervention types (e.g. determining an adequate spillway to account for runoff intensity).
- Detailed guidance provided for the implementation of the different intervention types.

WET-RehabEvaluate

WET-RehabEvaluate is used to evaluate the success of rehabilitation projects, and is designed with the understanding that monitoring and evaluation are closely tied to planning, which, in turn, should accommodate monitoring and evaluation elements. *WET-RehabEvaluate* provides the following :

- Background to the importance of evaluation of wetland rehabilitation projects.
- Step-by-step guidelines for monitoring and evaluation of rehabilitation projects, both in terms of project outputs and outcomes. The outcomes are based on system integrity and the delivery of ecosystem services, and results from *WET-Health* and *WET-EcoServices* are therefore included. The guidelines include review project objectives, identify performance indicators and standards, develop and implement a monitoring and evaluation plan, and evaluate and report on performance.

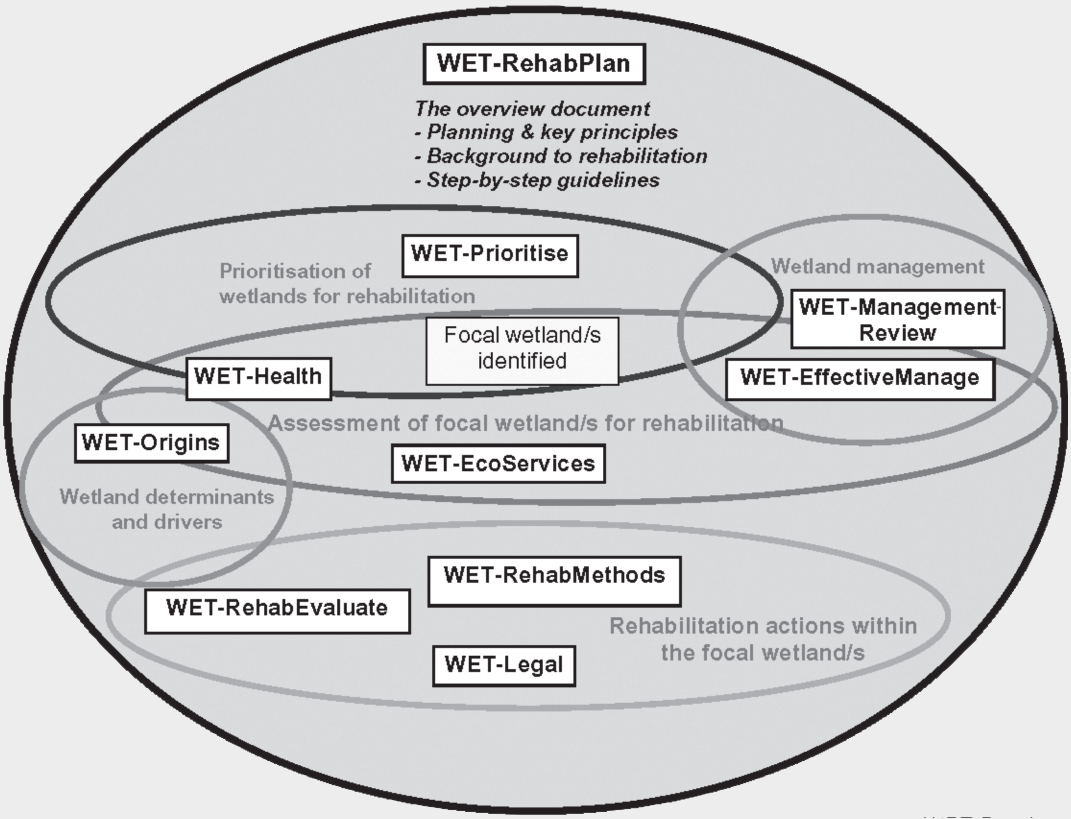

Figure 1P: How do the *WET-Management* tools relate to each other in a rehabilitation context?

Table 1P: Likely relevance of the background reading and tools in the ***WET-Management*** series to a variety of different potential uses

Potential users	*WET-Origins*	*WET-Management - Review*	*WET-RehabPlan*	*WET-Prioritise*	*WET-Effective-Manage*	*WET-Legal*	*WET-Rehab-Methods*	*WET-Eco-Services*[1]	*WET-Health*[2]	*WET-Rehab-Evaluate*
Rehabilitation planning - wetland specialist	High	Some	Some	Some	Some	Some	Some	High	High	High
Rehabilitation planning - engineer	Some	Part 1 (Some)	Step 5 (Some)			Some	High			
Rehabilitation programme coordination - *national*	Some	High	High	High	Some	High	Some	Some	Some	Some
Rehabilitation programme coordination - *provincial*	Some	High	High	Some	High	High	Some	Some	Some	Some
Rehabilitation implementation			Step 5 (Some)		Some	Some	High			High
Impact assessment	Some	Part 1 (Some)				Some		Level 1 (High)	Level 2 (High)	
Wetland management	Some	Some	Some		High	Some				
Ecological Reserve Determination - DWAF officials & consultants	High	Part 1 (Some)		Some		Some		Level 1 (High)	Level 2 (High)	
Catchment planners - CMAs and others	Some	Part 1 (Some)		High		Some		Some	Some	
Broad-scale biodiversity conservation planning	Some	Part 1 (Some)		High		Some		Some	Some	

Some: The tool is likely to have some relevance

High: The tool is likely to have a very high level of relevance

[1] *WET-EcoServices* is of particular relevance in determining the Ecological Importance and Sensitivity (EIS) of a wetland.

[2] *WET-Health* is of particular relevance ino determining the Present Ecological State (PES) of a wetland.

CMA = Catchment Management Agency
DWAF= Department of Water Affairs and Forestry

Table 2P: Rehabilitation-related questions typically posed at different spatial levels, and the tools most relevant to assisting the user in answering each question

Common questions	Tool/s likely to be relevant in addressing the question
Questions that might typically be asked at the national or regional level	
What is causing the degradation of wetlands?	*WET-Health* (Level 1) & *WET-ManagementReview*
Which are the most important wetlands?	*WET-Prioritise* & *WET-EcoServices* (Level 1)
Which wetlands should we rehabilitate?	*WET-Prioritise*
How should wetland rehabilitation be integrated within broad-scale catchment management?	*WET-Prioritise* & Dickens *et al*. (2003)
Questions that might typically be asked at the local level	
How effectively is the wetland being managed?	*WET-EffectiveManage*
What is causing the degradation of the wetland?	*WET-Health* (Level 2)
Is the wetland in need of rehabilitation?	*WET-Health* (Level 2) & *WET-Origins*
How do I decide what rehabilitation interventions will be appropriate for meeting my rehabilitation objectives?	*WET-RehabPlan* (Step 5F) & *WET-RehabMethods*
What are specific technical considerations I must make when designing a rehabilitation intervention?	*WET-RehabMethods*
Will the planned project be legally compliant?	*WET-Legal*
How do I evaluate my rehabilitation project?	*WET-RehabEvaluate*
Who should be involved in the rehabilitation project?	*WET-RehabPlan*
How do I align my rehabilitation project with catchment-, regional- or national-level programme/s?	*WET-RehabPlan* & WfWetlands Strategy (Working for Wetlands, 2005)

The National Water Act defines wetlands as:

'....land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which in normal circumstances supports or would support vegetation typically adapted to life in saturated soils.'

This is the definition used by the *WET-Management* Series.

Summary of ***WET-Origins***

This document is a review of material that is the product of research in wetlands in southern Africa over many decades, with a focus on work over the last 20 years. South Africa has a wealth of expertise in wetland science that is both globally innovative and extremely relevant to global wetland conservation and management. We hope that this document will inspire those involved in wetland rehabilitation to integrate what they do with natural and anthropogenic factors to make a difference for wetlands. It should also inspire young researchers to consider wetlands in new and holistic ways.

Many of the ideas presented in this document are novel and are the outcome of research from several sites. The ideas have been published in good journals, but they have not necessarily been widely accepted. This does not mean they have been rejected, but in most cases they contrast strongly with what applies in northern temperate wetland systems. Our view is that southern African wetland systems cannot easily be compared with their northern temperate counterparts, and we therefore need to develop appropriate ways of studying and understanding our systems. The African landscape is ancient and has not undergone recent tectonic and mountain-building processes in the same way as have many parts of the northern continents. The mean annual rainfall of Southern Africa is less than half of the global average for continental areas. The potential evapotranspiration is generally greater than rainfall. Thus we should have few wetlands, and these should be connected to the open drainage network of streams. Southern Africa is also situated at a much higher mean altitude than other continents, with the southern African interior greatly elevated relative to the coast. As a consequence, our rivers are in a long term state of active incision, which should reduce the likelihood of wetland formation. Yet South Africa has a diversity of wetland types, the existence, characteristics and processes of which are determined regionally by variation in climatic conditions, and locally by variation in geomorphological setting and other factors.

The strong linkage of our wetland systems with the drainage network makes it necessary for us to understand forms and processes of fluvial systems. Thus there is a strong focus here on fluvial geomorphology. It is argued that wetlands are likely to occur in depositional settings, and that wetland morphology is linked to interactions between clastic, organic and chemical sedimentation. These are also novel insights that may not always be appropriate in temperate settings.

So, there are many novelties that are introduced here. Our work has also been the product of genuinely interdisciplinary interactions that enable insights far beyond those that can be generated by the sum of individual disciplines working on their own. However, we have studied relatively few systems, and many of the ideas need to be tested thoroughly. As such, this document is very current and forms the framework for ongoing research.

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Feedback

In South Africa the rehabilitation of wetland ecosystems is still in its infancy. In order to promote the growth of this activity, this manual needs to be revised by including the experiences of those individuals involved in wetland rehabilitation within South Africa. Any comments or advice can be sent to:

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TABLE OF CONTENTS

1 INTRODUCTION

Wetlands form at the interfaces between terrestrial and aquatic environments, and between groundwater and surface-water systems. They vary from small seeps on steep slopes in headwater settings to massive low-gradient floodplain wetlands that may be thousands or tens of thousands of hectares in extent. Is there a set of unifying factors that contribute to their formation? If so, what are the key ingredients of their formation? Unless we understand the factors contributing to wetland formation and dynamics, management may intervene in ways that work against Nature rather than with her. In a context of limited resources, this may lead to unexpected outcomes that are ultimately detrimental to wetland ecosystem well-being.

Because wetlands occur at interfaces they have been largely overlooked scientifically since they are neither terrestrial nor aquatic, nor are they determined solely by groundwater or surface water (fluvial) processes. The occurrence of wetlands at these interfaces means that they are products of a diverse range of processes, and understanding these systems requires that they be examined and understood from an equally wide range of perspectives. Wetland specialists need broad understanding of the biophysical environment if they are to conserve and manage wetlands wisely, and this is the mandate that we have to live up to given this role. This handbook attempts to give readers the broad perspective that is required of wetland scientists and managers.

The formation, size and persistence of wetlands are controlled ultimately by hydrological factors. For a wetland to form, one needs a surplus water supply at or close to the soil surface for a sufficiently prolonged period to cause anaerobic conditions in the rooting zone of herbaceous plants. Rivers and lakes also have excess water supply that leads to the creation of anaerobic conditions in the soil, but they either have fast flowing water (rivers) or are flooded to too great a depth (perennial rivers and lakes) to permit the colonisation of macrophytic plants. Thus, for a wetland to form, saturation needs to be prolonged and shallow. Luckily, processes of landscape change that arise as a consequence of geological, geomorphological and climatic processes, and shape the landscape in ways that promote prolonged shallow flooding of soils. So in order to understand wetland origin, one needs to understand the immediate (hydrological) circumstances that lead to such prolonged and shallow flooding, as well as the longer-term geological processes that promote flooding by limiting rapid loss of surface water from a site via streamflow. It is the intention of this manuscript to investigate these issues in some depth, drawing on the work and experience of a diverse group of researchers in the region, and on the literature in general.

The subject of why wetlands occur where they do, and a consideration of wetland evolution, is important. It should become clear that wetlands are transient features of the landscape over geologically long time scales, and that they are dynamic over relatively short ecological periods. Wetland 'managers' generally treat them as permanent features that are static or stable. There may thus be a contradiction between what managers aim to achieve in wetlands through management, and what would happen naturally in the absence of substantial human intervention. Unless these sorts of contradictions are understood, wetland management - including rehabilitation - may achieve quite the opposite of what is intended,

2 WETLAND DISTRIBUTION AND CLASSIFICATION IN SOUTHERN AFRICA

Wetlands occur widely in this region of Africa. They occur in diverse settings ranging from the broad, flat coastal plain of northern KwaZulu-Natal to the highlands of the eastern escarpment of southern Africa, and from the hyper-arid to arid Namib Desert and arid to semi-arid Kalahari and Karoo regions to the cool, wet southern coast of Africa. They occur at the heads of streams, on floodplains along rivers, and in the downstream reaches of most rivers, particularly larger rivers such as the Zambezi and Orange/Vaal systems. They may be associated with lakes or dams, they may occur as shallow, closed drainage systems ('pans'), and they may vary from fresh to brackish. They vary in size from 15 000 km2 in the case of the Okavango Delta to less than tens of m2 in the case of many wetlands that lead into headwater streams. The variety of wetlands in the region is primarily attributable to differences in geology, drainage and climate, and to a lesser extent to human-induced disturbance.

It is not the intention here to provide a detailed description of the distribution of southern Africa's wetlands, or to present a system of classification. There have been many attempts to do this in the region, and for a comprehensive discussion of these systems, readers are referred to Rogers (1997), Dini *et al*. (1998) and Ewart-Smith *et al*. (2006). A problem with these, as discussed by Rogers (1997), is that they only serve as general descriptions of the range of wetland types that occur in the region. However, as pointed out by McCarthy and Hancox (2000), these classification systems offer little insight into the fundamental processes that determine their occurrence or their future evolution. As such, they do not provide an adequate framework for the conceptual understanding of wetlands from the perspective of why they occur where they do, or how they evolve as a consequence of natural processes such as sedimentation, erosion or climate change, or in response to human interventions of different kinds. This is the kind of understanding that managers need if they are to develop sustainable management protocols, particularly in the field of wetland rehabilitation where one wants to work with rather than against Nature.

We are also of the view that southern African wetlands differ from those in northern temperate regions in ways that are very fundamental. The southern African landscape is ancient, with insignificant current or recent tectonic activity or mountain-building episodes, but it is a continent situated at an unusually high mean elevation. Recent glaciation has not been a significant feature shaping our modern landscape. Southern Africa also has a mean annual rainfall that is about one-half of the global average for continental areas, and potential evapotranspiration is high due to relatively high average annual temperatures. This combination of factors means that this region should not contain many wetlands and that peatlands should not occur at all. It also means that the majority of the wetlands in this region are linked in some way to streams. Recognition of broad differences between our wetlands and those of their better studied counterparts in the northern hemisphere makes it imperative that we develop deep insights into wetland origin and its relationship with wetland structure and function through basic research. Such understanding will undoubtedly contribute to wise management of wetland systems in our region.

3 AN INTRODUCTION TO THE GEOLOGY OF SOUTHERN AFRICA

Southern Africa has a long geological history, the oldest rocks dating back 3600 million years. Geological activity in the region has been ongoing since that time, and rocks are still forming today in the interior in the Kalahari Basin, a great depression in which substantial deposition of sediment (that will in time become sedimentary rock) is occurring. For the sake of simplicity and convenience, the complex geological history of South Africa will be discussed in terms of geographic distribution and age of the rock formations, with reference to the simplified geological map in Figure 1 (see also McCarthy and Rubidge, 2005).

Amongst the oldest rocks in South Africa are granites and related igneous rocks, which intruded into pre-existing volcanic island chains ('island arcs'), making them larger, stronger and more rigid. The remains of island arc terrains host large fragments of metamorphosed volcanic rocks and are known as Greenstone Belts, excellent examples of which form the Barberton and Murchison Mountains in Mpumalanga and Limpopo provinces. They formed between 3 600 and 3 100 million years ago and constitute part of one of the oldest continents on Earth (the Kaapvaal Craton). These rocks are collectively known as the Archaean Basement Complex (ABC) and underlie much of South Africa and south eastern Botswana, but are exposed on surface only in the north eastern portions of the country, with isolated occurrences scattered elsewhere. The ABC formed a floor upon which several important sedimentary and igneous rock sequences were subsequently deposited.

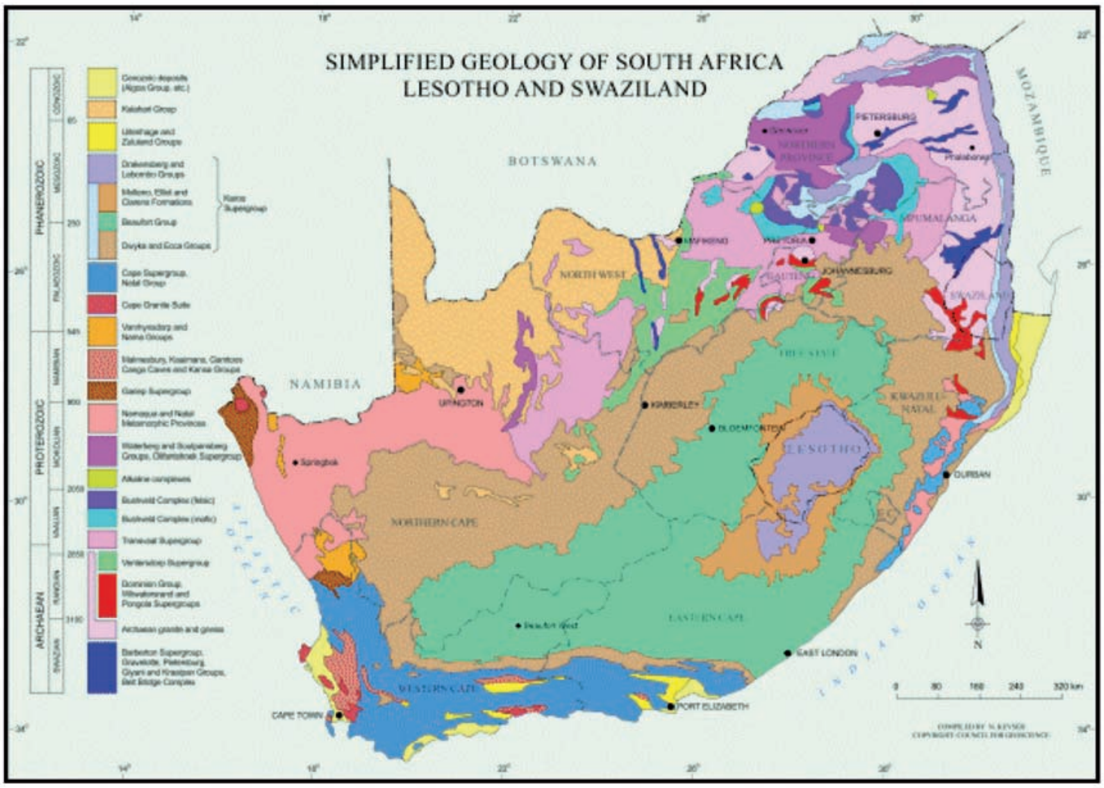

Figure 1: Simplified geological map of South Africa, Lesotho and Swaziland (after McCarthy & Rubidge, 2005).

The Witwatersrand Supergroup was the first of the sedimentary sequences laid down on the ABC (Figure 1) and consisted of mudstones and sandstones, which were later metamorphosed to slates and quartzites. Although fairly extensively developed, these rocks are mainly buried beneath younger rocks and only crop out along the Witwatersrand escarpment, in the Vredefort Mountain Land, and in the Heidelberg area, where the quartzites form locally prominent topography because they are resistant to erosion. The overlying, predominantly igneous (volcanic) Ventersdorp Supergroup (Figure 1) is somewhat more extensively exposed in outcrop and forms prominent ridges in the Vredefort area, around Heidelberg (Suikerbosrand) and the Witwatersrand (Klipriviersberg). Elsewhere, and especially in the Northwest Province, these rocks form gently undulating terrain. Overlying the Ventersdorp is the Transvaal Supergroup (including the rocks of the Transvaal and Griqualand West sequences) and the Olifantshoek Supergroup (Figure 1). These consisted of mudstones and sandstones, now metamorphosed to slates and quartzites, as well as dolomite and resistant iron formations, particularly in the Griqualand West area. The resistant quartzites are responsible for spectacular mountain scenery along the eastern escarpment in Mpumalanga and Limpopo provinces, and also form the Magaliesberg and Daspoort Ranges, whilst iron formations and quartzites form the Asbesberge and Langeberge in the Northern Cape. The dolomites underlie the Ghaap Plateau and extensive areas in Northwest, Gauteng and Mpumalanga provinces. The dolomites host large volumes of groundwater in sub-surface caverns, which are the source of numerous perennial springs such as the Eye of Kuruman and Maloni's Eye.

The Transvaal Supergroup forms a broad, basin-shaped structure, and the rock layers dip inwards towards its centre. This dip imparts the characteristic asymmetry to mountain ranges formed by its more resistant strata, such as the Magaliesberg and the eastern escarpment in Limpopo and Mpumalanga. In the interior of this basin lies the Bushveld Complex (Figure 1), a vast mass of layered igneous rocks of various types. The lower layers, consisting mainly of gabbro, weather to produce black turf soils, whilst the upper layers, consisting of granites and rhyolites, form higher ground such as the Sekhukuni Plateau in Mpumalanga and parts of the Waterberg (e.g. west of Mokopane/Potgietersrust). The youngest of the Proterozoic sedimentary deposits on the ABC are the quartzites of the Waterberg and Soutpansberg Groups. These resistant rocks form the high ground of the Waterberg and Soutpansberg, and somewhat less elevated ground in the area north of Middelburg.

The Kaapvaal Craton is surrounded by metamorphic rocks of a variety of ages, which formed in the past during collisions between the Craton and other continental masses due to continental drift. The oldest is the Limpopo Belt, situated north of the Soutpansberg, which formed about 2 700 million years ago during collision of the Zimbabwe Craton with the Kaapvaal Craton. The 1 800 million year old Kheis (or Ubendian) Belt extends from the Northern Cape Province along the western margin of the Kaapvaal Craton through central Botswana, which formed during the collision of the Angolan-Congo Craton with the Kaapvaal Craton. Rifting, which is a consequence of tension in the earth's crust that signifies the break-up of continents as a consequence of continental drift, subsequently occurred along this zone, followed by collision about 1100 million years ago, forming another metamorphic belt at this time, the Kibaran Belt. Kibaran belt rocks also formed along the southern margin of the Craton, and today constitute the

Namaqua-Natal Belt of Namaqualand and northern KwaZulu-Natal. The rocks in these belts consist mainly of granites and gneisses, together with lesser highly metamorphosed sedimentary rocks. The Kibaran event is believed to mark the formation of a supercontinent known as Rodinia. Rifting occurred along the Kibaran belts during the subsequent break-up of Rodinia and sedimentary rocks accumulated in the rifts. Further collisions occurred along these rifted margins around 500 million years ago, producing metamorphosed sedimentary rocks and associated granite intrusions of the Damara belt, which extends across Namibia into northern Botswana, and in the southern Cape (Malmesbury and Nama Groups and the Cape Granites). These rocks are collectively known as the Pan-African belts, and their formation marks the assembly of Gondwana, a supercontinent incorporating all of the present-day continents of the southern hemisphere, plus India.

About 450 million years ago, rifting occurred along the southern Cape and extended north eastwards into KwaZulu-Natal, and mudstones and sandstones of the Cape Supergroup (Figure 1) were deposited in the resulting rift valley basin. Closure of this rift commenced about 300 million years ago, and the rocks of the Cape Supergroup began to fold, forming the embryonic Cape Fold Belt. At this time, Gondwana lay over the South Pole, and the region incorporating southern Africa experienced extensive glaciation, initiating deposition of the Karoo Supergroup (Dwyka Group; Figure 1). As Gondwana moved northwards from beneath the icecap, a seaway formed across the southern Cape in which sandstones and especially mudstones accumulated on top of older Dwyka glacial deposits (Ecca Group). These deposits included extensive coal deposits. The seaway gradually filled with sediment, and marine and deltaic deposits gave way to river deposits (mudstone and sandstone) of the Beaufort Group. Conditions became more arid as Gondwana moved north, and desert wind-blown deposits (mainly sandstone) of the Stormberg Group were deposited. Commencing around 180 million years ago, the southern African region of Gondwana experienced a major volcanic event, apparently initiated by a plume of hot material rising from deep in the mantle below, and the desert sands of the Stormberg Group were buried beneath a vast sheet of basaltic lava (Drakensberg Group), preserved today in the Maluti Mountains of Lesotho, in the Springbok Flats and the Lebombo Mountains. The Drakensberg Group in the Lebombo Mountains also includes rhyolite, reflecting incipient rifting in that area that would culminate in the break-up of Gondwana.

Break-up of Gondwanaland began with the opening of the Mozambique Channel, and by 140 million years ago oceanic crust had formed beneath what is today central Mozambique. Sediments eroded from the interior began to accumulate in this newly formed ocean basin, and today these form the coastal plain of northern KwaZulu-Natal and Mozambique. The Atlantic Ocean began to open 120 million years ago as South America split from Africa, and a rift valley formed along the west coast. Separation here may also have been initiated by a hot plume rising from the mantle, which produced vast basalt eruptions in Namibia and Argentina (Parana and Etendeka lavas). The Falkland Islands and their surrounding sub-marine plateau originally lay off the southern Cape and KwaZulu-Natal, and as the Atlantic opened, the plateau remained attached to South America and separated from Africa by sliding westwards, along a major fracture extending along the south-east African coastline. The plateau had fully separated from the Cape and started on its westward journey by 90 million years ago.

Around 60 million years ago, the interior of the sub-continent began to experience warping and a depression formed in its centre to produce the Kalahari Basin. The climate at the time was relatively moist, and the depression contained several large lakes, but gradually conditions became more arid (see below), and the lakes desiccated and semi-desert conditions began to prevail. Sand began to accumulate in the depression, forming the Kalahari sands of the Northern Cape and Botswana. Sand accumulation continues at the present time.

4 BROAD-SCALE GEOMORPHOLOGY AND DRAINAGE OF SOUTHERN AFRICA

The break-up of Gondwana left southern Africa with three major river systems (Karoo, Kalahari and Limpopo River Systems) and several smaller ones (Partridge and Maud, 2000). Two major systems arose as a result of high ground created by the plumes of volcanic rock that initiated the break-up of this portion of Gondwana, namely the Drakensberg and Etendeka plumes. The headwaters of the major, southern drainage basin lay in the Maluti Mountains, and this river system, known as the Karoo River system, discharged into the Atlantic Ocean near the present mouth of the Olifants river. Further north lay the Kalahari River system, of intermediate catchment size, that drained southern Botswana and the northern Cape, entering the Atlantic at the present Orange River mouth. The other major river system flowed east, and included the present-day Okavango, Kwando, Upper Zambezi, Kafui and Luangwa Rivers, which formed tributaries of the Limpopo River (Moore and Larkin, 2001). This drainage system may also have included the rivers that now drain from the north into the Etosha Basin. Sediment from this vast catchment was deposited in the Mozambique Channel, forming a large delta between Maputo and Beira. Elsewhere around the newly formed coastline, the rivers were short and relatively steep. Many still exhibit this character today, particularly the rivers along the KwaZulu-Natal and southern Cape coastline.

The elevation of southern Africa at the time of break-up is uncertain and may have been as high as 2000m above mean sea level (amsl) in the east in the headwaters of the Karoo River. Erosion by the river systems of the region removed mainly the Karoo Supergroup rocks (the harder, underlying strata were less affected). The extent of erosion was very variable, with the area most severely affected being a tract extending north-eastwards across southern Africa from Namaqualand to south-eastern Zimbabwe, along which the Karoo rocks were almost completely removed. This region had formed high ground prior to the Dwyka glaciation. Much of the topography of this region is exhumed pre-Dwyka topography, and most of its mountain ranges (e.g. Magaliesberg, Waterberg, Soutpansberg etc.) were shaped by glacial erosion 300 million years ago. North-west and south-east of this zone, Karoo rocks are still preserved. By about 60 million years ago smaller coastal rivers had cut the proto-escarpment back to virtually its present position, and had produced an extensive low-relief plain (peneplain) across southern Africa known as the African Erosion Surface. The climate at the time was moist and warm, and thick, highly leached tropical soils developed across southern Africa.

About 60 million years ago the interior of southern Africa began to experience warping and subsidence that profoundly influenced the drainage patterns in the region. The headwaters of the Limpopo system were cut off by faulting and subsidence in the Kalahari Basin and large lakes formed in the interior (e.g. Lake Palaeo-Makgadikgadi). The Kalahari River captured the Karoo River (Figure 2), forming the present Orange River system. Local uplift also isolated the Etosha drainages, and a large inland lake formed in the Etosha Basin as well. About 20 million years ago the East African Rift began to propagate into southern Africa. The lower Zambezi, which until that time had been a minor coastal river, began to cut headwards into the interior. Aided by faulting associated with the rifting, it proceeded to progressively capture rivers draining into the Kalahari Basin. Over the next 20 million years, major rivers that once formed part of the Limpopo system were progressively captured by the lower Zambezi. Only the Okavango River remains to be captured. The course of the Okavango River has been disrupted by rift-related faults, creating the Okavango Delta, and the area is still seismically active. Capture of the Okavango River is currently in progress via the Selinda Spillway.

The climate of southern Africa also experienced profound change, commencing around 35 million years ago, when the land link between Antarctica and South America was severed, opening the Drake Passage. This event allowed circum-polar ocean circulation to commence, thermally isolating Antarctica. The Southern Ocean began to cool, and the Antarctic icecap began to grow, reaching the ocean by about 23 million years ago. Southern Africa became cooler, and a strong, semi-permanent high pressure system became established over the South Atlantic Ocean. Resulting trade wind circulation gave rise to the Benguela upwelling system along the west coast about 14 million years ago, as persistent strong winds blowing from the land to the sea (offshore) forced surface water away from the coast, to be replaced by colder waters from the deep. This isolated the south-western interior of the continent from moisture from the Atlantic Ocean, establishing the (cool, dry) west to (warm, moist) east rainfall gradient across southern Africa.

The climate of the region was also profoundly affected by uplift of southern

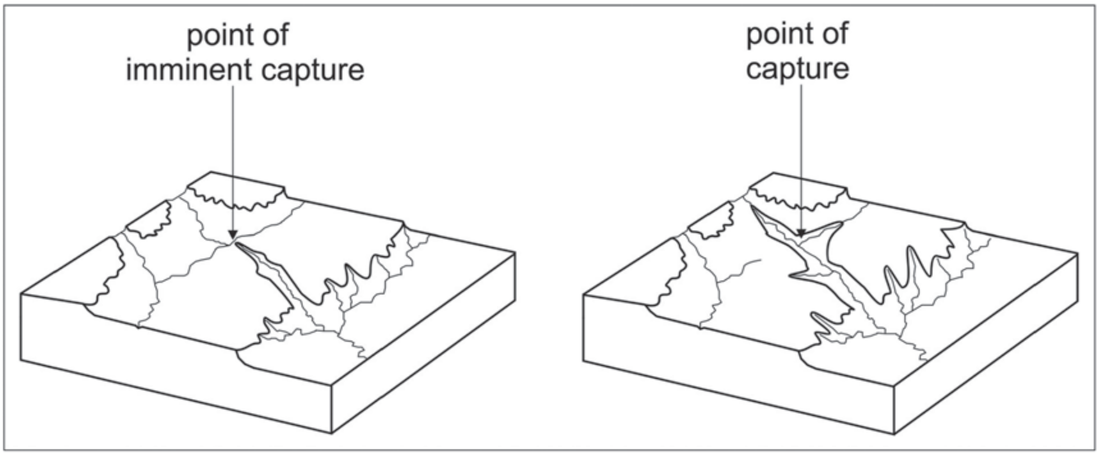

Figure 2: Schematic illustration of the process of river capture (adapted from Hamblin, 1992).

Africa, which seems to have occurred in two pulses. Around 20 million years ago the eastern portion of the subcontinent rose by about 250m and the west by about 150m. Further uplift occurred about five million years ago, when the eastern subcontinent rose by about 900m, and the west by about 100m. Rise of the eastern escarpment further reduced rainfall in the interior and strengthened the west to east rainfall gradient because air masses originating over the Indian Ocean lost much of their moisture as they rose against the now very elevated eastern escarpment. Desert sands began to accumulate in the aridifying Kalahari Basin. These periods of uplift resulted in pulses of erosion in the interior, driven mainly by the increased river gradients arising from tilting of the African Erosion Surface. These pulses of erosion were responsible for removing most of the deep weathering mantle of the older African Surface, leading to the formation of new erosional plains at lower elevations (Post-African Erosion Surfaces). The effects of post-African erosion were particularly dramatic along the coastal rivers, and renewed erosion produced striking topography such as the Valley of a Thousand Hills in KwaZulu-Natal and the deep river gorges of the southern Cape such as along the Storms River. Local subsidence occurred in the Bushveld Basin, which subsided by up to 400m. This movement appears to have been essentially a northwards tilt bounded by large faults (e.g. Zebediela Fault). This subsidence resulted in the preservation of Karoo strata in the Springbok Flats, and the flats may represent a remnant of the ancient African Erosion Surface. There are some indications suggesting that subsidence may still be occurring along these faults, albeit slowly, and thermal springs abound along the lengths of the faults.

These uplifts of southern Africa and the associated erosion cycles have resulted in the present-day topography of southern Africa, which consists of a broad plateau in the interior that is tilted gently to the west, lying at an average elevation above 1250m amsl (Figure 3). The plateau is separated from the coastal regions by a conspicuous escarpment, which becomes particularly steep where resistant rocks overlie more easily weathered types, such as along the Natal Drakensberg (Drakensberg lavas overlying Karoo mudstones and sandstones) and in Mpumalanga (quartzites of the Transvaal Supergroup overlying granite of the ABC).

The southern Africa plateau constitutes a topographic anomaly of global significance and interest. Its high average elevation contrasts sharply with that of areas of comparable geology such as Western Australia and northern Canada, which lie only a few hundred metres above sea level. This topographic anomaly has been termed the African Super Swell, and its origin is still the subject of active research.

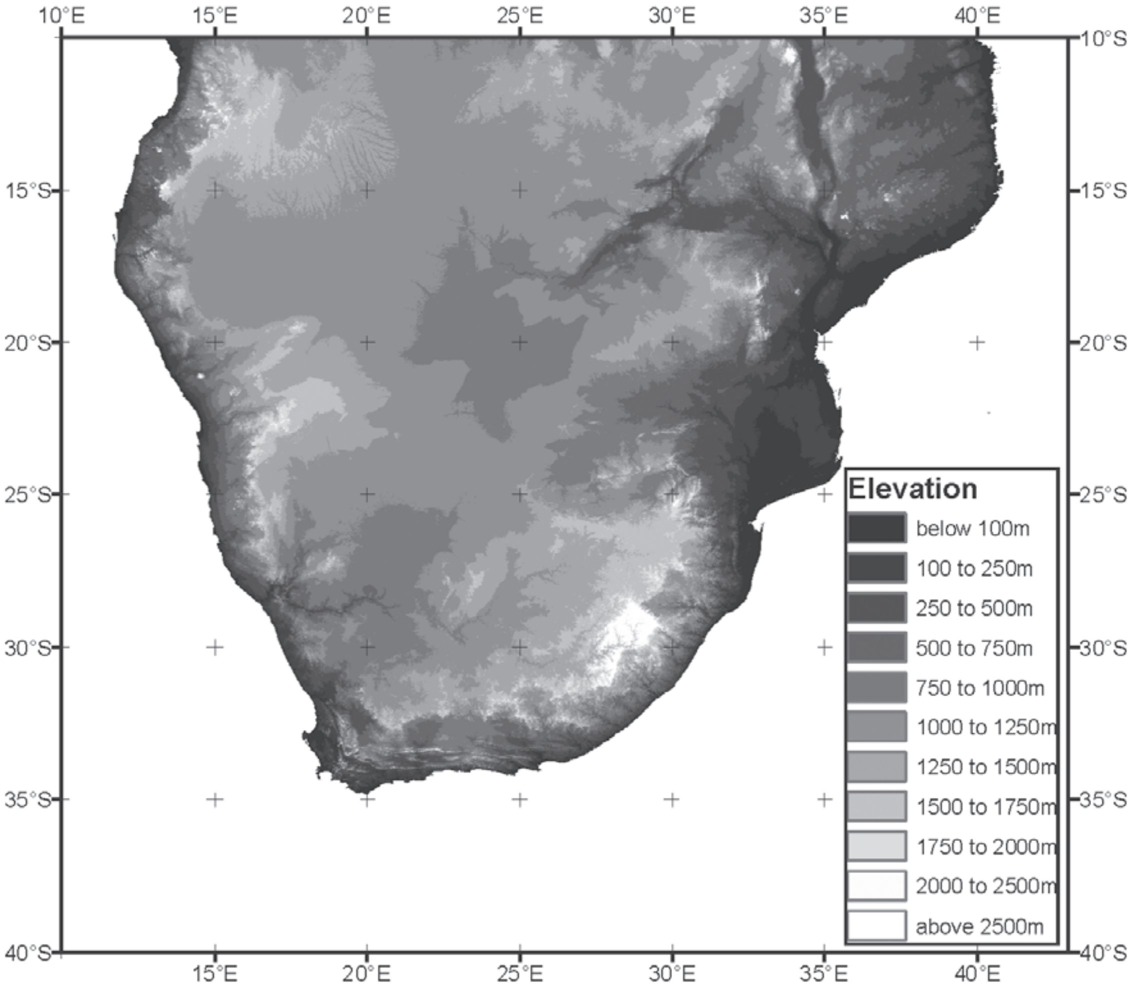

Figure 3: Digital elevation model of southern Africa.

5 SOUTHERN AFRICAN CLIMATE AND CLIMATE CHANGE

5.1 Present climate

Inland wetlands rely on rainfall for their water supply, either because rainfall becomes runoff (surface flow or river flow), or contributes to groundwater recharge that enters a wetland (subsurface flow), or because it falls directly on the wetland. The pattern of rainfall in the region is generally well understood (Tyson & Preston-Whyte, 2000). In general there is a relationship between rising air masses and rainfall since rising air cools, causing water vapour present to condense and thus produce rainfall. Conversely, subsiding air is dry since air warms as it descends. Broad circulation cells of rising and subsiding air (known as Hadley and Ferrel Cells; Figure 4) arise at various latitudes, due to differential heating of the earth's surface by the sun. Air rises at the equator when the sun is directly overhead, drawing surface and near-surface air from north and south in a region known as the inter-tropical convergence zone (ITCZ). The ITCZ moves southwards during the southern summer, drawing in moisture-laden tropical air that results in high rainfall in the summer in the northern part of the southern African subcontinent that exceeds 800mm per annum (northern Namibia, Zimbabwe and Mozambique; Figure 5a). Low pressure systems occasionally develop in the interior of South Africa during summer, drawing in moist tropical air that leads to summer rainfall.

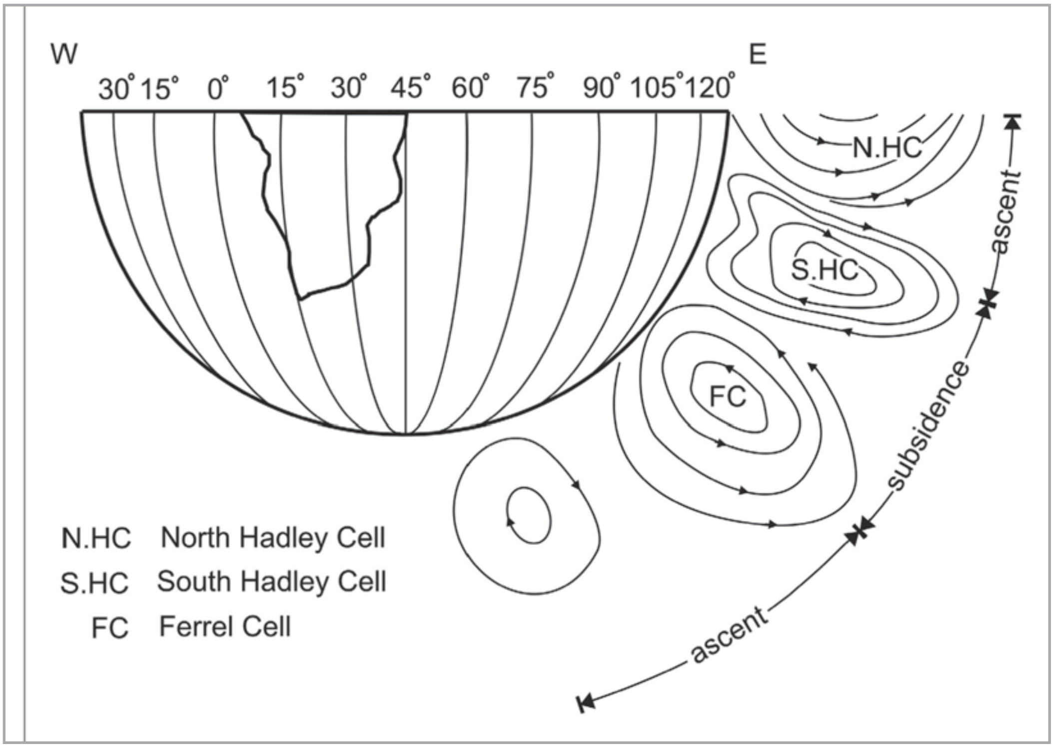

Figure 4: Large-scale circulation of air over the southern hemisphere in summer (after Tyson and Preston-Whyte, 2000).

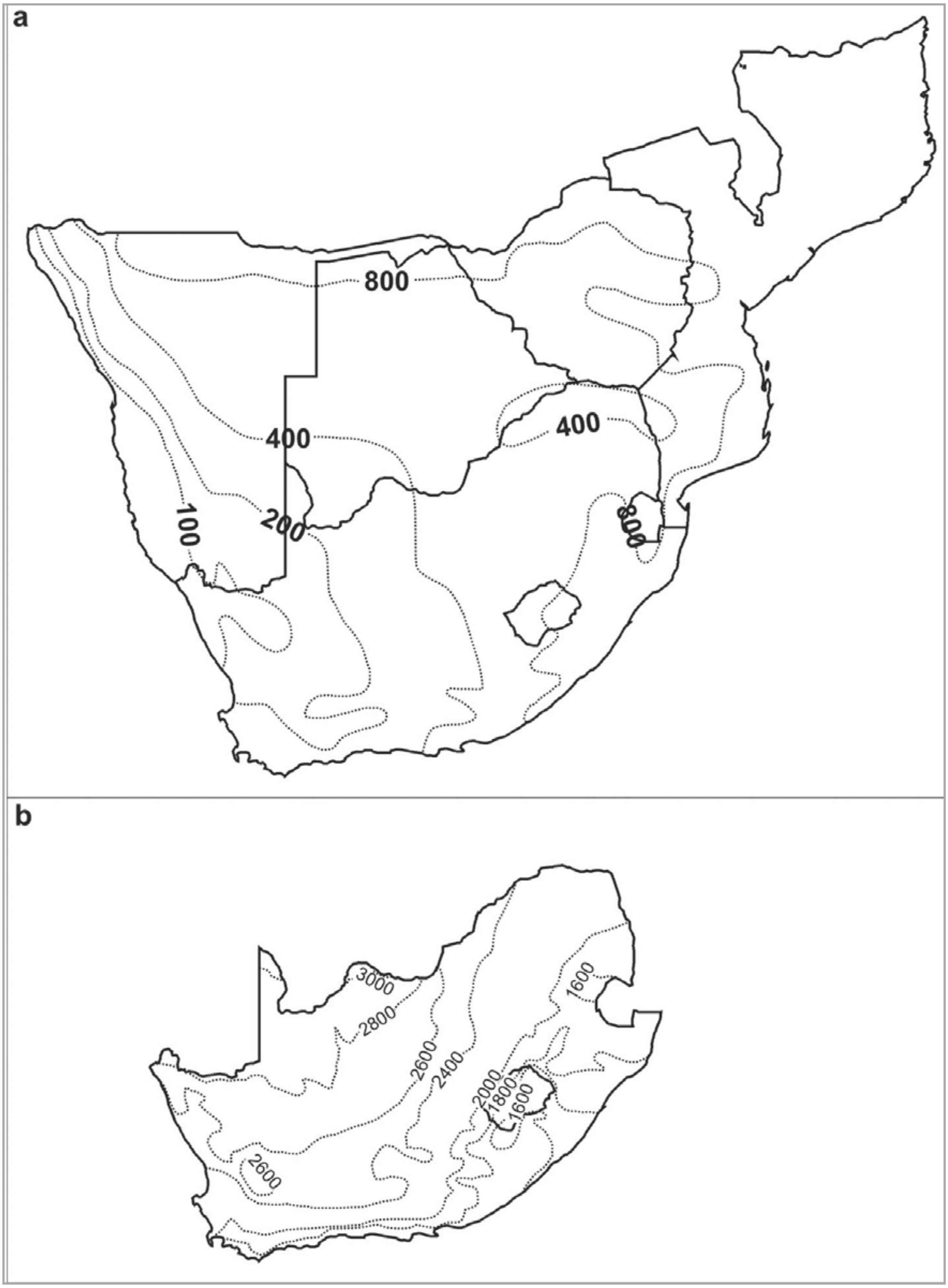

Figure 5: Distribution of mean annual rainfall (mm) over southern Africa (a) and mean annual potential evapotranspiration (mm) over South Africa (b). Both maps are plotted at the same scale: 1cm = 200km.

The descending limbs of the southern Hadley and Ferrel Cells (Figure 4) produce a zone of high pressure at about 30°S, creating anticyclonic conditions that dominate southern African climate. Moisture in this region originates mainly over the Indian Ocean. As this moisture-laden air starts to move westwards over the subcontinent, the presence of the great escarpment in the east promotes precipitation, and moisture content declines progressively towards the west, resulting in increased aridity westwards.

Upwelling of the cold Benguela current along the southwestern coast ensures that air masses originating over the Atlantic Ocean carry little moisture. The west coast is therefore arid. Cold fronts originating over the south Atlantic Ocean, however, move eastwards onto the subcontinent in the wintertime, bringing rain to the southern and south-western coast.

Water availability in wetlands is determined not just by inputs from rainfall and its contribution to runoff and groundwater, but also by atmospheric demand. Thus it is important to consider the water balance, with potential evapotranspiration being a useful indicator of atmospheric demand for water. Solar radiation provides the energy that drives evapotranspiration. It follows that potential evapotranspiration increases westwards in the region due to the presence of clear skies and high levels of solar radiation (Figure 4b). Given this combination of climatic circumstances where rainfall is greatest in the eastern and northern part of the subcontinent, and where potential evapotranspiration is greatest in the western part, the greatest abundance of wetlands should be expected in the eastern and northern parts of the subcontinent.

5.2 Climate change

From approximately 120 million years ago, as Gondwanaland fragmented during the Cretaceous, southern African climate altered with the changing position of the subcontinent, the development of the proto-Atlantic and proto-Indian Oceans, and the formation of the Antarctic Ice Sheet. Early Agulhus and Benguela Current systems formed around the southern African landmass, which had reached approximately its present position by the late Miocene (approximately 4 million years before present; Shannon, 1985). More recently, tectonic uplift further influenced the climate, as discussed above.

The more recent part of the southern hemisphere climatic record is well-known from the Vostok ice core from Antarctica, which extends back 420 000 years. The recently announced DOME C core will extend the record back to almost 800 000 years. These records are illustrated in Figure 6, and indicate that generally colder conditions than present have characterized the past several hundred thousand years, interspersed with brief warmer periods at intervals of about 100 000 years.

During numerous glacial periods of the last 1.5 Ma, southern Africa became extremely arid and a vast sand-sea developed across the continent, extending from the Northern Cape Province of South Africa almost to the equator (Tyson and Partridge, 2000). The more arid conditions prevailing during glacial maxima are also suggested by high dust concentrations in the Dome C core (Figure 6) reflecting enhanced fall out of atmospheric dust derived from poorly vegetated land surfaces. The last major cooling (Last Glacial Maximum) occurred about 22 000 years ago when temperatures were as much as 8°C lower than today in parts of the subcontinent (Tyson, 1986) and conditions were more arid. The climate has become increasing warm and wet since the Last Glacial Maximum, although this trend was interrupted by a short

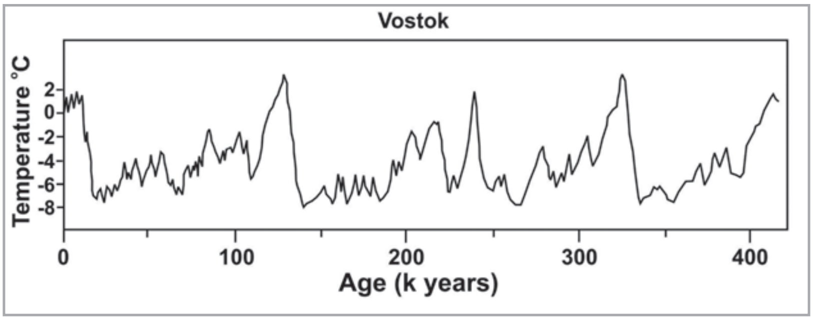

Figure 6: Reconstruction of climate from the Vostok Ice Core from Antarctica (Jouzel et al., 1987) that indicates surface temperature relative to current temperature.

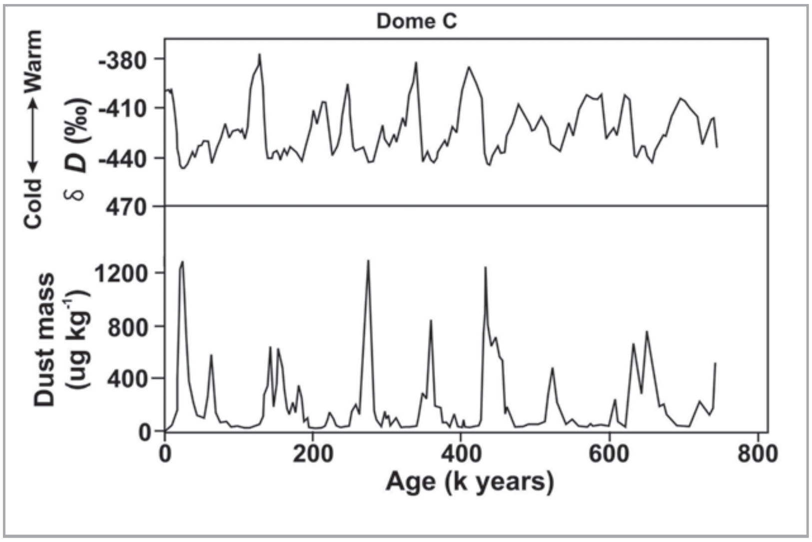

Figure 7: Reconstruction of temperature from the Dome C Ice Core from Antarctica (EPICA 2004), including the dust concentration, which is inversely related to rainfall in continents of the southern hemisphere.

period of cooler, dryer climate c. 13 – 11 Ka (the 'Younger Dryas'). Warming from approximately 11 000 years ago brought higher temperatures and rainfall to the region, and only during the early Holocene, and the Medieval Warm Period (c. 900 – 1300 AD), was the climate warmer and wetter than it is today. Fluctuations in climate have occurred and have been documented particularly over the past 3000 years (Holmgren *et al*., 1999; Tyson *et al*., 2002). These records suggest quasi-cyclical oscillations in rainfall, with periods of about 1 500, 600, 80 and 18 years.

Contemporary climate change is associated with global warming and is a result of human activities. During the last century, climate change has proven to be a dramatic environmental problem and the majority of the world's scientists no longer debate this reality. As wetland scientists, it is essential to recognise that rising temperatures and changing rainfall patterns may affect marginal and transitional wetland systems, decreasing their extent and modifying their species diversity. Climate change may result in the loss of habitat, increased toxic contamination, increases in invasive plants, increased eutrophication, accelerated atmospheric deposition, and increased septic runoff into waterways, thereby amplifying many current stresses.

6 AN INTRODUCTION TO HYDROLOGY

6.1 The hydrological cycle

The hydrological cycle is a complex cycle that involves the net movement of water from the oceans to the atmosphere to continental areas and back to the ocean again. It operates as a closed system globally, and different components act at different spatial and temporal scales. The most rapid turnover of water is within the atmosphere, such that water entering the atmosphere can be expected to leave the atmosphere again in less than 2 weeks (Table 1). In contrast, water in the oceans is turned over in approximately 3 100 years, and in the ice caps in approximately a half of that time.

Of the water in the atmosphere at any point in time, 84% is from the oceans and 16% is from continental areas. Of this, 77% falls into the oceans while 23% falls on continental areas. The surplus 7% of water in continental settings is transferred back to the oceans as runoff via rivers and streams.

It is the water in continental settings that sustains life on the continents, including wetlands. It is this same water (or lack of it) that confronts us daily through its limited availability ('droughts' and 'water shortages' are familiar to every South African) or its excessive delivery as stream-flow ('floods' are also familiar to all of us). Readers are well aware of the ways in which this water impinges on our daily lives. However, it is the silent work of this water that most appreciably shapes the world in which we live. Water in the hydrological system weathers, transports and deposits rock and soil material in continental settings or coastal areas, shaping the landscape in fundamental ways.

6.2 Surface flow: Some important hydrological and hydraulic concepts

In view of the fact that large areas of South Africa are semi-arid, average runoff constitutes only approximately 9% of the total volume of water falling on the country (Schulze, 1997). Thus approximately 91% evaporates again. The amount of runoff and the percentage of runoff as a proportion of rainfall tends to increase with rainfall such that while runoff in the north-west of the country is less than 5mm per annum, there is a fairly systematic increase in run-off southwards and eastwards in the country. The eastern escarpment of Limpopo, Mpumalanga and the Drakensberg in KwaZulu-Natal and the Eastern Cape, and the coastal areas of KwaZulu-Natal and the Eastern and Western Cape are areas of particularly high runoff at greater than 200mm per annum. KwaZulu-Natal is by far the wettest province in South Africa in terms of its mean annual runoff (over 800mm per annum).

Table 1: Size and turnover periods of the major components of the hydrological cycle.

Component	% global supply	Turnover period
Oceans	97.5	3 500 years
Atmosphere	0.0001	9-12 days
Land: • Ice caps • Groundwater • Lakes • Rivers and streams	20.0050.60.0001	 1 500 years 300 – 4 500 years 10-100 years 12–120 days

Runoff patterns reflect a combination of precipitation characteristics such as the amount of rainfall, its intensity, concentration of the rainfall season, and persistence of consecutive rain days (Schulze, 1997). It is also dependent upon features of the surface onto which it falls, such as soils and geological substrate, levels of vegetation cover, and the extent to which surfaces have been hardened.

Moving water and the sediment it carries play a very important role in shaping the earth's surface, and a rudimentary understanding of how they work will provide some insight into the occurrence, morphology and dynamics of wetlands. Where the ability of the stream to transport sediment is greater than its sediment load, erosion should occur, but where sediment load exceeds the ability of the stream to transport sediment, deposition occurs. Where the two are roughly equal, rivers act as conduits of water and sediment, with no erosion or deposition. The ability of running water to erode and transport sediment is largely dependent upon stream velocity (Figure 8). The velocity at which a grain of a given size is picked up from the bed and moved downstream is shown by the broad upper curve (entrainment velocity). It has an unexpected shape as it describes the work required to lift a particle off the bed over which the water flows. It is a broad curve, as the exact velocity at which erosion occurs depends upon characteristics of the water, such as water density, as well as upon characteristics of the grains being lifted, such as shape and density. It shows that high velocities are required to lift large particles, that lower velocities are required to move smaller particles, and, surprisingly, that high velocities are required to lift very small particles (silt and clay). This is because they tend to adhere to each other owing to strong electrostatic forces, and this cohesion restricts movement as individual grains. The lower curve shows settling velocity, the velocity at which a particle settles out of suspension. It reveals that once a particle is in suspension, the velocity at which particles settle is dependent upon particle size alone, being higher for larger grains and lower for smaller particles.

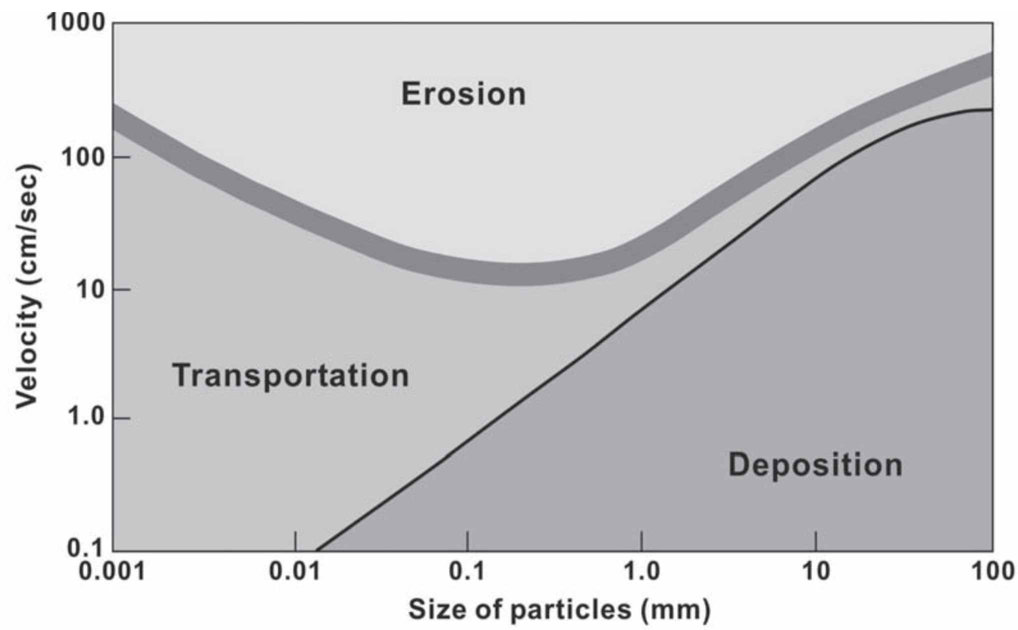

Figure 8: Erosion, transportation and deposition of sediment in relation to grain size and current velocity

Velocity of surface water can be described by Manning's Equation, which is useful to grasp. The energy available to erode sediment is defined by the stream power, which is primarily a function of discharge and channel gradient. Discharge in turn is simply the mean velocity multiplied by stream cross-sectional area, and is related to channel gradient and hydraulic radius, and is inversely related to the roughness of the channel bed as follows:

$$V = \frac{R^{2/3}.S^{1/2}}{n}$$

where:

- V = mean velocity
- R = hydraulic radius = cross-sectional area / wetted perimeter
- S = gradient of the channel
- n = Manning's roughness coefficient

Thus, for all other variables constant, velocity is:

- proportional to hydraulic radius such that for a given roughness and slope, wide, shallow channels have a lower velocity than channels with a narrower, deeper cross-section (Figure 9a),
- proportional to slope such that for a given hydraulic radius and roughness, channels with a steep slope have a higher velocity than channels with a shallow slope (Figure 9b), and,
- inversely proportional to bed roughness, such that for a given hydraulic radius and slope, streams with boulder strewn or vegetated beds have lower velocity than unobstructed sandy or unvegetated beds (Figure 9c).

It is also useful to remember that because the hydraulic radius is the stream cross-sectional area (width multiplied by depth) divided by the wetted perimeter (crudely approximated by width in most settings), it can be approximated by the mean depth of the channel. It is interesting to consider that velocity increases with depth for constant slope and bed roughness. This is because relative roughness is greater in the case of a shallow channel than for a deep channel with constant slope and roughness.

Examples of roughness coefficients are provided in Table 2. These coefficients have generally not been determined from wetland studies, but they can be applied to stream flow into and out of wetlands.

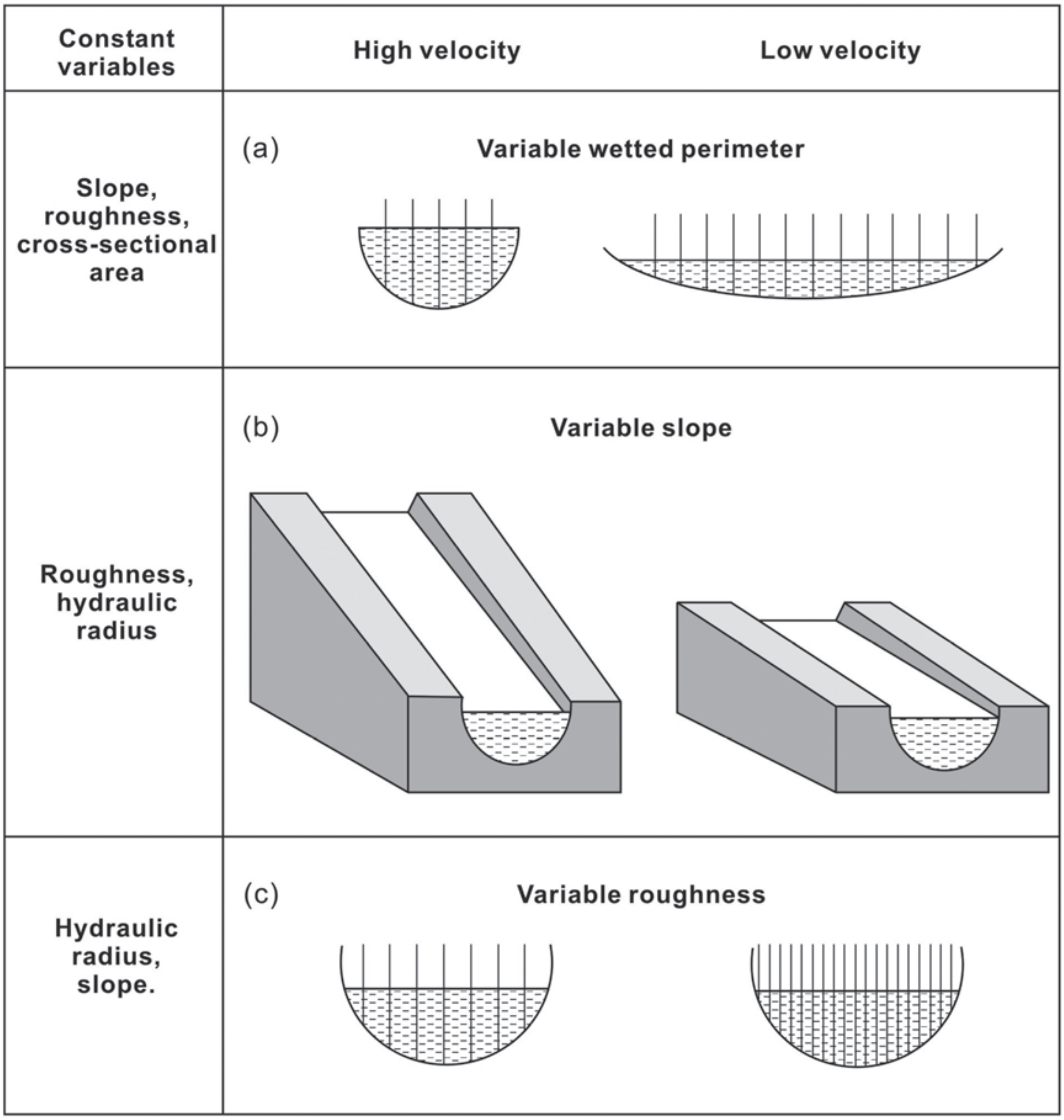

Figure 9: Relationship between current velocity and the variables hydraulic radius (a), slope (b) and bed roughness (c), vertical lines within channels represent obstructions such as stems of emergent vegetation.

Table 2: Roughness coefficients for Manning's Equation in different environmental settings

Stream Conditions	**Manning coefficient**
Straightened earth canal	0.02
Winding natural stream with some plant growth	0.035
Mountain stream with rocky streambed	0.04-0.05
Winding stream with abundant plant growth	0.04-0.05
Sluggish stream with very abundant plant growth	0.065
Very sluggish stream with extremely abundant plant growth	0.112

6.3 Groundwater flow

The extent to which groundwater is a significant component of a wetland water budget varies considerably, and indeed the prevailing opinion is that there is insufficient experience with site specific studies to infer general principles. Nevertheless, for the purpose of generating a general understanding of wetland–groundwater relationships, it is useful to understand Darcy's Law, which describes the velocity of groundwater flow (and potentially the discharge, since discharge is simply calculated as the product of velocity and cross-sectional area) as follows:

$$V=ks$$

where:

- V = velocity
- k = hydraulic conductivity (permeability of the substratum)
- s = slope on the groundwater surface.

Thus, in the case of groundwater, velocity is proportional to the permeability of the substratum and the slope of the surface of the water table. Therefore, for a given permeability, velocity increases in proportion to the slope of the water table. Conversely, for a given slope, the velocity of water flow will be proportional to the permeability of the material through which it is moving.

Where the slope of the water table is oriented away from the wetland, the wetland is referred to as a recharge wetland as the groundwater is supplied by water in the wetland. In contrast, where the water table slopes towards the wetland, the wetland is referred to as a discharge wetland, since the groundwater discharges water to the wetland. In general, wetlands are assumed to be groundwater discharge features, but this is a very poor assumption as wetlands typically have both zones of groundwater recharge and of groundwater discharge, as will be pointed out later (Section 8.3).

It is important to note that both slope and hydraulic conductivity need to be considered simultaneously in considering the rate of water supply or loss from a wetland to or from groundwater, as the presence of a steep water surface may simply be a consequence of low hydraulic conductivity, and it does not necessarily indicate rapid flow of water through the soil. Conversely, if the slope of the water table is gentle, substantial quantities of water may still be exchanged between surface and groundwater if the permeability of the material is high. A different perspective adds further insight. Highly permeable materials will enable rapid water movement, and therefore they will tend to be associated with gentle slopes on the water table surface. Conversely, material with low permeability will tend to develop greater slopes due to the extremely low rates of water flow in such material.

6.4 Hillslope hydrology

When rainfall reaches the soil surface it may follow a number of paths en route to a wetland or river. These hillslope runoff processes, illustrated in Figure 10, are termed:

1. infiltration-excess overland flow (path 1)
2. saturation-excess overland flow (path 2)
3. groundwater flow (path 3)
4. shallow subsurface flow (path 4).

As precipitation reaches the soil surface it infiltrates into the soil profile. This process continues until the soil becomes saturated (maximum infiltration capacity of the soil is reached). As a rainfall event progresses and infiltration capacity is exceeded, water will accumulate on the soil surface and fill small depressions. Once this depression storage is exhausted, water begins to run downslope as infiltration-excess overland flow (also known as Horton overland flow;

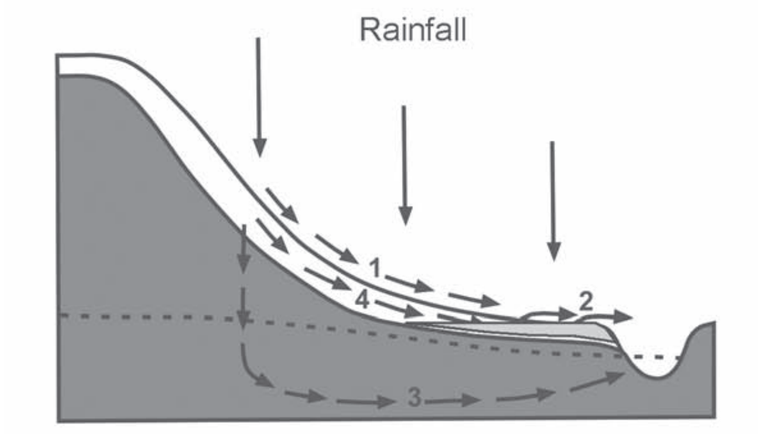

Figure 10: Hillslope runoff processes showing infiltration-excess surface flow (1), saturation-excess surface flow (2), groundwater flow (3) and throughflow (4) (after Dunne and Leopold, 1978).

path 1, Figure 10). This flow increases in depth and velocity as more rainfall is added on its path downslope (Dunne and Leopold, 1978). Infiltration-excess overland flow occurs most readily in areas with thin soils and/or sparse vegetation. It is, however, most obvious in built-up urban areas where the soil infiltration capacity is reduced to zero by impervious surfaces.

In most humid regions rainfall intensities generally do not exceed infiltration capacities because vegetation promotes open, well- developed soil profiles. As rainfall infiltrates, surface water is displaced downwards towards the water table by gravitational forces. When a wetland is situated at the base of a hill slope, the level of the water table coincides with the surface water level of the wetland, thus the area adjacent to the wetland has a shallow water table. Prolonged infiltration will cause the water table to rise adjacent to the wetland, resulting in an expanding saturated zone surrounding the wetland. Rain falling directly onto this zone will result in saturation-excess overland flow (path 2, Figure 10).

Under the upper slope positions of the catchment the distance to the water table is greater, and a large proportion of infiltrating water will initially go into storage in an unsaturated zone and then slowly recharge the water table over a number of days after the rainfall event. During prolonged rainfall the water table will slowly rise and the resultant increase in the gradient of the water table will, according to Darcy's Law, increase the flow of groundwater from upper to lower catchment positions (path 3, Figure 10, Dunne and Leopold, 1993).

When surface soil horizons are underlain by a layer of lower permeability, infiltrating water will not reach the water table. Rather, it accumulates above the impermeable layer and flows downslope, through the soil along a shallow subsurface flow (path 4, Figure 10). Under prolonged rainfall conditions shallow subsurface flow will also contribute to saturated overland flow. Saturated overland flow often moves at very rapid velocities, usually between those of Horton overland flow and shallow subsurface flow (Burt, 1992).

The flow of water into wetlands from local catchments ('microcatchments') is thus a complex combination of infiltration-excess overland flow, Darcian flow, throughflow and saturation-excess overland flow. The strong climatic seasonality of large parts of southern Africa results in a dynamic situation whereby infiltration-excess flow dominates early in the wet season, true groundwater flow occurs throughout and beyond the wet season with outflow into channels, and saturation-excess overland flow occurs during the peak wet season.

It needs to be borne in mind that flow rate is seldom uniform within a soil due to the presence of zones within the soil where flow is preferential (percolines). Therefore, within a sequence of sediments of alternating sand, silt and clay layers that might occupy a valley, water will move preferentially along sand layers. A further complication is that with a saturated regolith, water will tend to concentrate at the soil–regolith boundary, resulting in a positive pore water pressure. This will have two potential consequences. The first is preferential water movement along this boundary. The second, which is of particular importance to considerations of degradation and rehabilitation, is that the increased pore water pressure will decrease the friction of soil particles with each other and with underlying weathering rock (regolith) along that boundary and therefore increase the likelihood of slumping and landslides. Where the soil-regolith boundary is exposed in a stream bank, the bank is prone to being unstable and may collapse into the channel, disrupting the wetland vegetation mat but also contributing a pulse of sediment into the channel. This debris will then be redistributed downstream and can either be trapped elsewhere within the wetland, or flushed out of the system altogether.

6.5 Some important concepts regarding groundwater

A component of rainwater seeps into the ground, as discussed above, filling up the available pore spaces in the soil and other subsurface materials, where it becomes groundwater. The surface below which all of the pore spaces are filled is called the water table. The zone below the water table contains groundwater and is termed the phreatic zone, while that above the water table is the vadose zone. The pore spaces occupied by groundwater may be intergranular spaces in, say, an alluvial sand deposit, or decomposed material in a soil profile, but in South Africa the most common host for groundwater is cracks, joints and fractures in the solid rock mass (so-called fractured rock aquifers).

Immediately above the water table is the capillary fringe, a zone in which groundwater is drawn up by capillary action. The thickness of this zone is inversely proportional to the grain size of the host material, being thicker in fine-grained than coarse-grained sediments or soils. The capillary fringe can be several metres thick in fine-grained material, and may reach the surface if the water table is shallow, producing moist conditions in the soil.

The water table generally fluctuates seasonally, rising during the rainy season, and falling in the dry season, as it responds to recharge by rainfall. In general the water table lies more or less parallel to the land surface, but with generally shallower gradients.

7 RIVERS AND STREAMS IN THE LANDSCAPE

7.1 Water, streams and sediment as factors that shape the landscape

In South Africa, most wetlands form an integral part of the drainage network comprising rivers. Rivers arise as a consequence of runoff that is generated by rainfall. They occur in valleys that have been shaped by the power of running water, and they are more than just conduits of water. Flowing water carries sediment, and the combination of water and sediment determines the characteristics of rivers and their associated wetlands.

The word 'sediment' typically is associated with the silt and mud that turns water grey or brown, but we need to recognise that several types of sediment are transported by rivers (Figure 11). Clastic sediments are the particles of clay, silt, sand, cobbles and boulders that typically spring to mind when the word 'sediment' is mentioned. It is important to distinguish suspended sediment that is transported in suspension in the water column, typically comprising silt- and clay-sized particles, and bedload sediment that is transported by being rolled or bounced along the bed of the stream, usually being anything from sand to boulders. Dissolved sediment comprises all of the dissolved material present in flowing water, including solutes such as nitrogen and phosphorus that are usually present in such low concentrations that they limit the growth of plant life, including algae, in rivers and wetlands. Such solutes would typically lead to an increase in primary productivity if their concentration increased for some reason. These are conveniently referred to as nutrient solutes. However, less commonly considered are those solutes present in concentrations that do not limit plant growth, such as potassium, sodium, chlorine and silica. An increase in the concentration of such solutes either has no effect on rates of growth of plants and algae, or it may in fact be detrimental to such growth. These solutes are therefore referred to as detrimental solutes. A third type of sediment needs to be distinguished for the purposes of this discussion, organic sediment (partially to highly decomposed plant matter), which tends to accumulate in a benign way in low energy environments such as wetlands, but is uncommon in rivers.

Characteristics of rivers are shaped by their interactions with rock and sediment. Bedrock river characteristics are shaped primarily by properties of the rock over which they flow, including the location of more and less resistant features of the rock such as joints, faults or dykes. In contrast, alluvial rivers flow on beds made by deposition of sediment, such that there is very little contact between bedrock and the river. The characteristics of alluvial rivers are determined mainly by the dominant sediment type transported by the stream, and also by the nature of the discharge (episodic or regular), and the stream gradient. For instance, braided streams, where areas of flowing water repeatedly divide and rejoin, occur where stream sediment load is dominated by bedload sediment, discharge is very episodic (i.e. flashy) and gradient relatively steep. In contrast, meandering rivers, where the channel meanders across a floodplain such that deposition takes place on convex banks and erosion on concave banks, and the channel migrates, tend to occur where suspended sediment is predominant, where discharge is more regular and where gradient is relatively shallow.

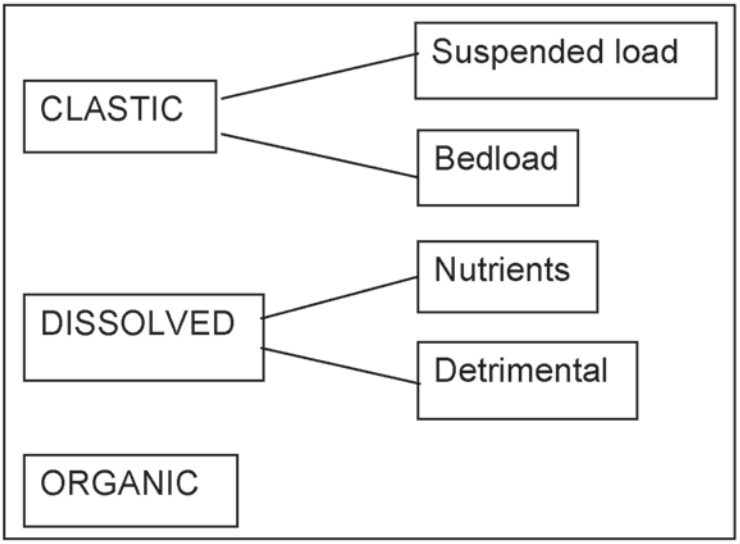

Figure 11: Types of sediment that are useful to distinguish in respect of wetland sedimentation

7.2 Longitudinal characteristics of river systems

Drainage basins are typically characterised by headwaters where the downstream gradient is steep and streams are fast flowing. Here streams are deeply incised and valleys are steep sided with a narrow 'V' shaped cross-section (Figure 12). This gives way downstream to a region of the drainage basin where river gradient and current velocity decrease, and where the valley flattens out to a broad 'V' shaped cross-section. The lower reaches of rivers typically have a shallow gradient, low current velocity, and valleys are typically very shallow in cross-section. Thus rivers typically have a concave upward longitudinal profile from their headwaters to the sea.

This concave-upward longitudinal profile is accompanied by a number of systematic changes in the characteristics of the river and its bed from the headwaters to the ocean, the most important of which are:

- an increase in channel cross-sectional area and discharge
- an increase in valley size
- a decrease in current velocity and therefore stream energy
- a decrease in the grain size of sediments on the stream bed
- a decrease in the number of stream segments and length of tributary streams.

It is important to realise that the presence of concave-upward longitudinal profiles is determined in part by the fact that rivers that flow into the sea cannot erode their beds below the level of the sea. The lowest level to which a river can erode its bed is known as the base level. In the first instance it is determined by the elevation of the river's mouth where the river enters the ocean. More localised base levels occur upstream of the mouth in areas where, for example, a tributary enters the main stream, since a tributary cannot erode to a level lower than the level of the river into which it flows. Similarly, significant impoundments along the course of a river act as local base levels. It needs to be noted that base levels may change, as an impoundment will not last forever, and neither is the level of the sea constant: during the last glacial maximum the sea level on the east coast of South Africa was

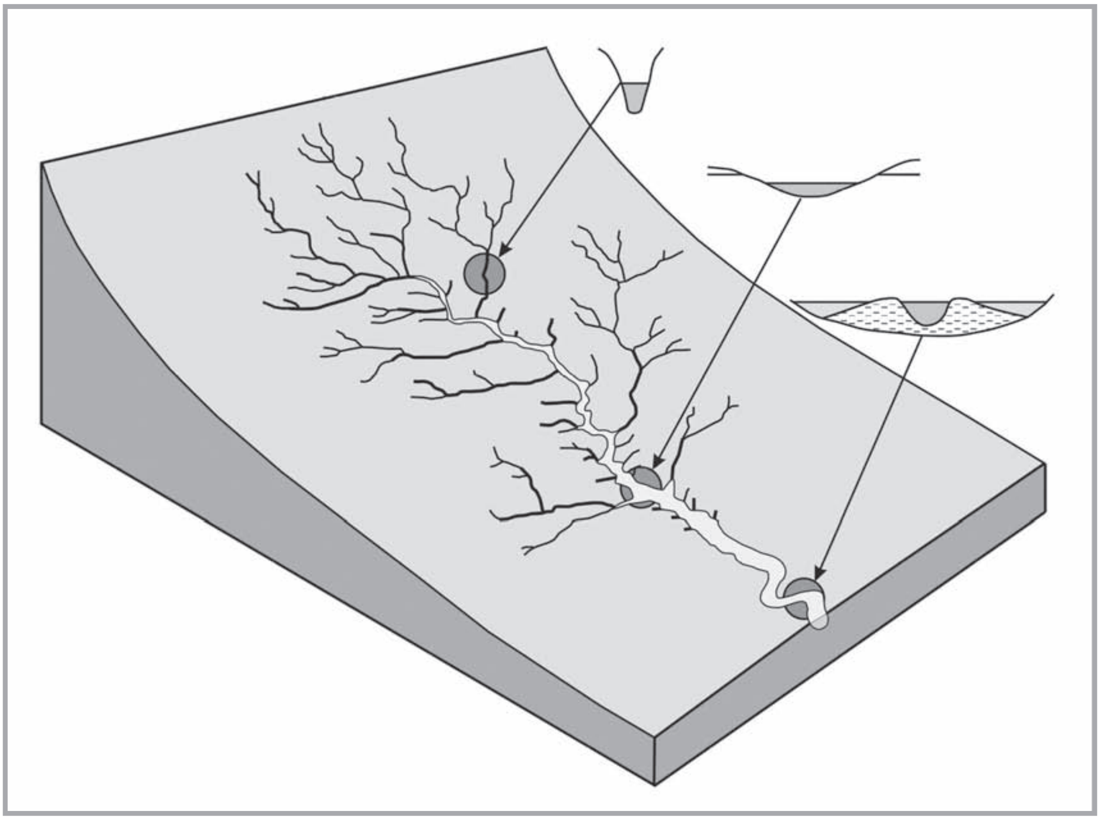

Figure 12: The typical longitudinal form of a drainage basin in which grade has been achieved, showing patterns of tributary inflow, and cross-sectional shape (after Hamblin, 1992)

something like 130m below its current level, at which time coastal rivers eroded their beds to depths tens of metres below their current elevation.

7.3 A graded river

The achievement of a concave upward longitudinal profile occurs because rivers function as unified entities, where a change in one part of a system affects other parts. Rivers function as integrated systems that are influenced in complex ways by a relatively small number of variables, the most important of which are discharge, velocity, channel shape, gradient, sediment load and base level. The important point here is that a stream tends to adjust gradient and channel geometry (shape and size) to accommodate the volume of water available (discharge), and to transport the available sediment load. A change in any one of these variables will cause the river to initiate compensating adjustments to restore equilibrium. A river is in equilibrium if its channel form and gradient are approximately balanced to transport the supplied water and sediment available so that neither deposition nor erosion occurs. If this condition is attained, it is referred to as a graded river. This does not mean that the river does not transport sediment, or that the headwaters of the river are not eroding, as most rivers work continuously towards this ideal condition. A graded river is constantly evolving as the land surface is gradually lowered by erosion.

A graded river may not have an entirely uniform concave upwards longitudinal profile because of variation in rock type along the river's length, and rivers typically have local gradient steepenings such that their longitudinal profiles are strongly stepped. The presence of tributaries and lakes, which act as local base levels, may also affect the uniformity of the gradient of a graded river.

Here we need to introduce two concepts that relate to the ability of a river to transport sediment:

- Competence is the largest size of grain that a river can move along its bed. Competence varies spatially downstream along the course of a river and it varies temporally at a given point depending on river discharge. The largest grains are transported and deposited during periods of high flow.
- Capacity refers to the maximum amount of sediment that a river can transport. Capacity depends upon gradient, discharge and the calibre (particle size) of the load.

Rivers will always tend to balance capacity and competence with the amount and calibre of the load (Morisawa, 1968). If the capacity and competence are in excess of those required to transport the load, the river will erode its course, thereby modifying slope and/or morphology (width, depth and bed roughness) and reducing capacity and competence. The smaller the river, the steeper the slope that is required to move water and the coarse sediment load that is typical in the upper regions of drainage basins. The relative roughness of the bed in the case of a small river is high and a steep gradient is required to sustain flow and sediment. In the case of a larger river, because of the increased volume of water, relative roughness is lower and a shallower slope is required to sustain the flow of water and the movement of finer sediment.

These concepts of adjustability in a river system can be appreciated by considering a change in flow characteristics of a hypothetical river in which equilibrium has previously been established. In Figure 13a, the variables of the river system (discharge, velocity, gradient, base level and load) are in balance so that neither erosion nor sedimentation occurs along the stream profile. There is just enough water to transport the available sediment load down the existing slope. If the river is interrupted by the construction of an impoundment along its course (Figure 13b), the sediment capacity of water entering the impoundment is reduced substantially, and sediment is deposited (Figure 13c). This leads to a reduction in gradient upstream of the impoundment, and over time the river will adjust its form in response to the creation of this new local base level (Figure 13d). The deposition of sediment in the impoundment means that the transport capacity of water leaving it will be higher than the available sediment load, leading to erosion and a consequent reduction in gradient downstream (a phenomenon termed 'hungry water', Kondolf, 1998, Figure 13c). The depth of erosion is limited by bedrock, and the length of the reach over which erosion takes place will extend downstream until transport capacity and sediment supply/load is again in balance. This combination of reducing the gradient where the transport capacity is lower than the load upstream of the impoundment, and of reducing the gradient where transport capacity is higher than the load downstream of the impoundment, leads to the establishment of a new equilibrium profile again over the entire length of the river (Figure 13e).

It is important to understand the natural evolution of the landscape, as well as appreciate the fact that if we continually modify rivers and their catchments to suit our needs, we must expect responses well beyond the domain of our activities alone. Construction of an impoundment, or variations in the amount and character of discharge from catchments as we affect

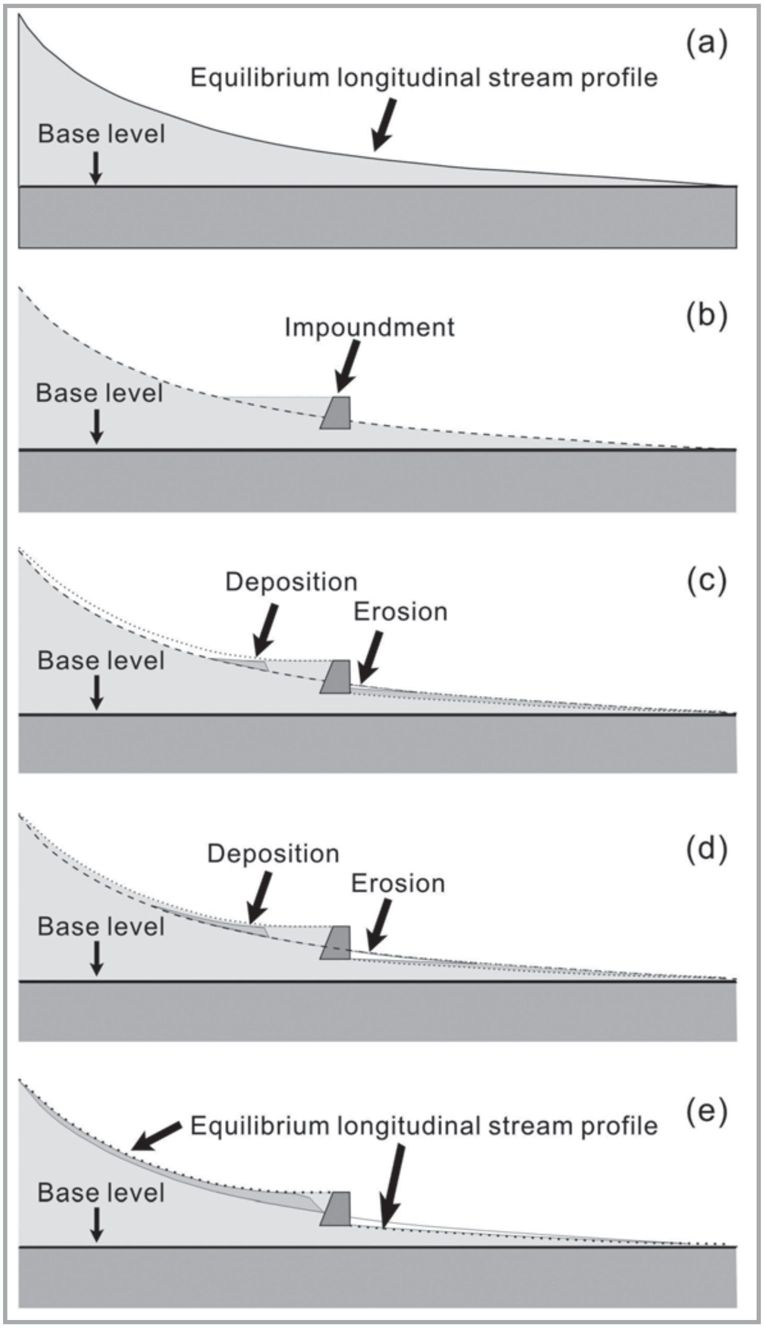

Figure 13: Illustration of the disruption of the gradient of a graded river (a) by construction of an impoundment in which the base level is artificially raised (b). This leads to sediment deposition at the impoundment (c). It also leads to interruption of sediment supply to the stream downstream of the impoundment, **which leads to erosion (c). The combination of deposition above and erosion below the impoundment (d) leads to the development of new graded longitudinal profiles upstream and downstream of the impoundment (e).**

them by afforestation or urban development, agricultural irrigation or human-induced climate change, should all be expected to result in river adjustment. In the case of wetland or river rehabilitation the clear aim is to reinstate characteristics that are sympathetic to and not in conflict with the natural dynamic. This is one of the challenging yet exciting prospects of wetland and river rehabilitation.

7.4 Surface water – groundwater interactions in rivers

Some rivers are perennial, others are seasonal, and yet others are ephemeral. Some rivers are perennial along a portion of their length, say in the upstream reaches, but then become seasonal lower down, or *vice versa*. These characteristics arise largely from the interaction between a river and the groundwater regime (see Parsons, 2003; Colvin *et al*., 2007).

Rivers all carry surface runoff, and during the rainy season runoff may make up a large proportion of the discharge. Sustained flow during the dry season results from groundwater seepage into the bed of the river. This will occur if the water table lies at a higher elevation than the river bed. Such rivers are referred to as 'gaining' rivers, as they are supplied with ground water (Figure 14a). Rivers that cease to flow in the dry season do so because the water table lies at a lower elevation than the river bed, and any water entering the river slowly infiltrates the bed. Such rivers are referred to as 'losing' rivers because they contribute flow to groundwater (Figure 14b). Losing rivers may become temporary gaining rivers as a result of rise of the water table in the rainy season, and may remain so for a period following the onset of the dry season, but as the water table falls below the bed of the river, they become losing rivers again and flow may cease.

Loss of flow to groundwater can have an important influence on the morphology of rivers. Normally rivers increase in cross-sectional area downstream, reflecting the increasing discharge. Typically, the grain size of the sediment becomes finer. However, where significant infiltration of water occurs through the river bed, the cross sectional area of the river may actually decrease downstream, and in extreme cases the river may lose definition altogether. This broad floodplain beyond the river terminus is known as a 'floodout', and generally occurs in more arid regions. For example, the Nyl River and its left bank tributaries all disappear as they approach the Nylsvlei Floodplain, and the Mkuze River gradually loses definition downstream in the Mkuze Floodplain.

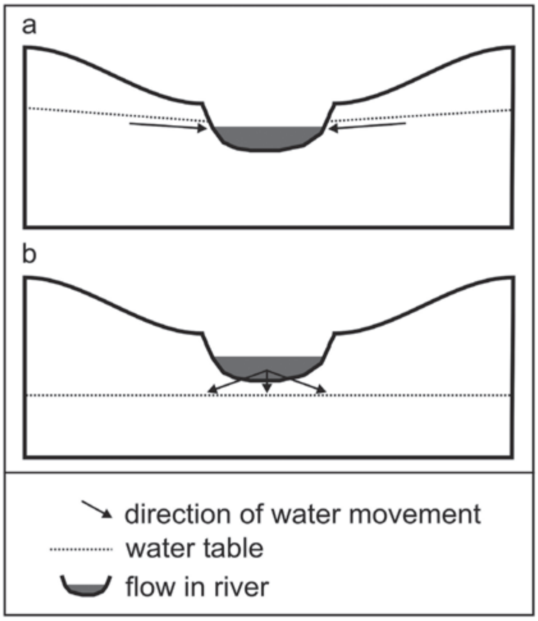

Figure 14: Schematic illustration of a gaining (a) and losing (b) river.

7.5 Stream orders

Stream ordering is a widely used method to classify streams, being based on the premise that stream order is in some way related to the size of the contributing area, to channel dimensions and to stream discharge. It offers a simple, rapid first approach to stream classification and describing relative stream size within a drainage basin (Gordon *et al*., 2004). In most stream ordering methods, smaller tributaries are given a lower order than larger streams and tributaries. Catchments can also be classified by order number such that a catchment containing a second-order stream would be classified as a second-order catchment.

There are various methods of stream ordering, but for purposes of applications relevant to southern African wetlands, a stream that occurs at the head of a catchment and has no tributaries is described as a first order stream. When two first order streams meet, then the resultant stream is described as a second order stream (Figure 15). Similarly, two second order streams join to form a third order stream, and so on. It is important to remember, however, that if a stream is joined by another stream of a lower order then the stream retains its original stream order status. For example, if a second order stream is joined by a first order stream, then it remains as a second order stream.

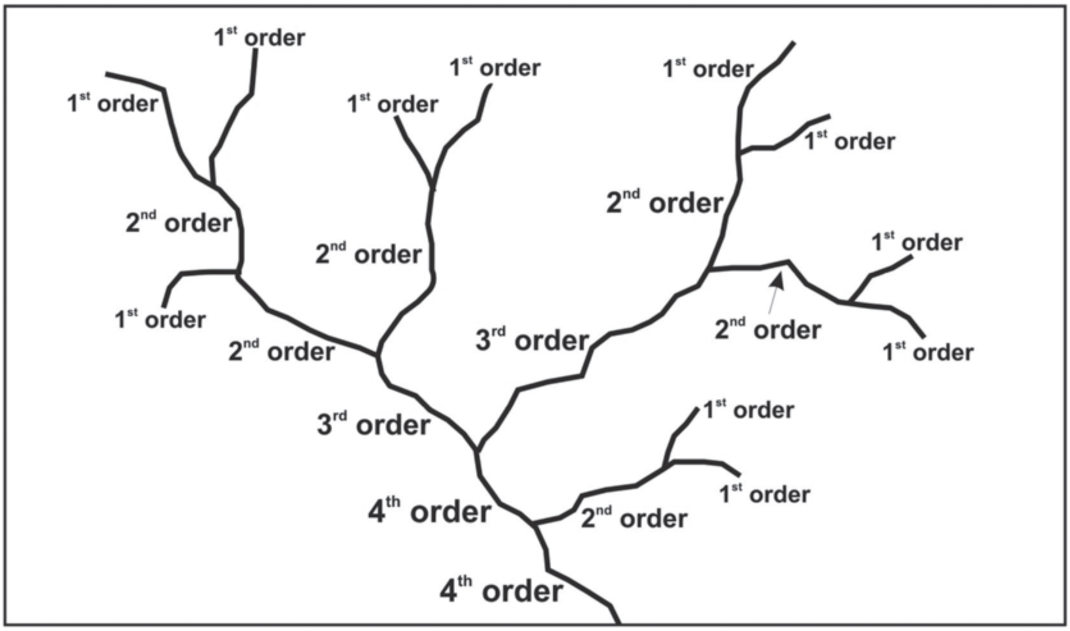

Figure 15: Representation of the stream ordering of a hypothetical stream network.

8 WETLAND HYDROLOGY AND HYDRAULICS

8.1 The water balance

Given the background to rivers presented in previous chapters, it is appropriate now to consider the origin of wetlands. Wetlands occur in areas where there is a water surplus at or close to the surface of the earth. The periodic saturation of soils by water is the defining feature of wetlands. Not only does the presence of excess water in soil bring about unique physiochemical conditions in a wetland, water also transports nutrients and sediment into a wetland and, in some cases, nutrients and sediments out of a wetland. In addition, these processes also involve the transfer of energy. It is this complex interaction of inflows and outflows of energy, sediment and nutrients which, over time, shapes the physical template of the wetland.

Determining the basic water budget of a wetland is important in developing an understanding of the functioning of the system, but it is also important for the rehabilitation of wetlands. Restoring a natural flow regime may be a key requirement for rehabilitation. The purpose of this section is to consider each component of the water balance in relation to its significance in rehabilitation.

A mass-balance approach is generally used to understand wetland hydrology and typically takes the form of an equation which states that the change in the volume of water storage in a wetland is equal to the balance of the inflows and outflows. While many forms of this equation are utilised in the literature, the form given by Mitsch and Gosselink (2000) is given here:

$$\Delta V/\Delta t = Pn + Si + Gi - ET - So - Go$$

where:

- V = volume of water in storage in wetland
- t = time
- ΔV/Δt = change in volume of water storage in wetland over time
- Pn = gross precipitation directly onto the wetland
- Si = surface inflows via streams or overland flow
- Gi = groundwater inflows
- ET = evapotranspiration
- So = surface outflows
- Go = groundwater outflows

The possible sources of water to a wetland are precipitation, surface inflows and groundwater inflows, and losses are as evapotranspiration, surface water outflows and groundwater outflows. In any given wetland, both inflows and outflows are from a combination of more than one of the potential sources and sinks, and clearly the size of the storage component varies in proportion to the relative contributions of inflows and outflows over time (seasonally and from year to year). Thus during the wet season or during the flood phase, the size of the storage component may be large, or during the dry season or when river water levels are low the storage component may be small.

This simple equation helps us to think about where wetlands occur. They occur where the sum of the input components is greater than the sum of the output components for some time during the year. Those factors that enhance inflows relative to outflows will increase the likelihood of wetland formation. The important point is that there is more than one way of increasing the size of the storage compartment: increase the rate of water inflow via rainfall, surface inputs or groundwater inputs, or decrease the rate of outflow to groundwater loss, surface outflow or evapotranspiration. Thus, in settings where inputs are small, wetlands can still occur where output is restricted in some way. Similarly, where inputs are large, wetlands will not occur if outputs can efficiently remove water from a site.

It is useful to think about the rates at which water can be added to a site, and the rates at which water can be removed from a site. Processes that add water rapidly to a site will increase the likelihood of wetland formation, as will factors that inhibit rapid water movement away from a site. Rainfall and surface inflow typically deliver water rapidly to a site, while surface outflow acts rapidly to remove water from a site. In the case of wetlands, it is those factors that inhibit surface water loss from a site that are most critical to examine in order to understand wetland formation. Such factors are most likely to be related to the geology and/or geomorphology of a site, such as a reduction in longitudinal gradient along a river due to the presence of a hard bedrock barrier, a fault that displaces a resistant layer of rock and reduces the rate of incision by a river, or sedimentation from a tributary that fills a valley and causes an upstream reduction in gradient. Where these factors impose a barrier to downward erosion, their effect is similar to the presence of the dam wall illustrated in Figure 13.

Since South Africa is a country with a relatively low mean annual rainfall, we should not expect the occurrence of many wetlands that rely primarily on rainfall. Such wetlands are likely to occur in areas of exceptionally high rainfall and low rates of potential evaporation. Such conditions only exist locally in southern Africa such as in the Lesotho Highlands and along the eastern and southern coastal regions. Since groundwater flow is typically very slow, wetlands that rely primarily upon groundwater or hillslope seepage inputs are likely to be small and situated close to sea level where the groundwater table is close to the land surface, such as along the coastal plain of KwaZulu-Natal and locally along the southern Cape coast, or in headwater settings. Most wetlands in our region - especially large wetlands - should therefore be linked to rivers.

This brings into focus the distinction between wetlands that occur as part of open drainage systems (floodplains, marsh and swamp systems) and those that are part of closed systems (endorheic or closed drainage pans of semi-arid regions, and groundwater-fed coastal pans that form part of the dune-swale topography of northern KwaZulu-Natal). We should expect wetlands to occur in settings where depressions are not connected to rivers that deliver water from continental areas to the sea, irrespective of the amount of rainfall present. The presence of endorheic pans throughout the semi-arid Kalahari and into the Orange Free State is testimony to the effect of restricted surface outflow as a determinant of wetland distribution. A further caveat needs to be added in the case of the seasonally inundated pans in semi-arid regions of southern Africa: the presence of relatively impermeable strata (rock layers) below surface that limit water loss as subsurface outflow. These endorheic pans are typically shallow features, and appreciable loss of surface water to groundwater is therefore likely to be negligible. However, the opposite is true for pans on the coastal plain of KwaZulu-Natal and in the eastern and western Cape, where the exchange of appreciable volumes of water between surface- and groundwater prevents integration of these systems with the open drainage network. Thus endorheic wetlands occur over areas with widely varying mean annual rainfalls. The distinguishing feature is the inability of surface water to erode channels that integrate pans with the drainage network.

8.2 Frequency and duration of inundation: wetland hydroperiod and its indicators

Mitsch and Gosselink (2000) refer to the hydroperiod of a wetland as the hydrological signature describing the seasonal pattern of water level fluctuations. This is the integration of all inflows and outflows and characterises the nature and constancy of fluctuations. For wetlands that are seasonally flooded, the flood duration (amount of time a wetland is in standing water) and the flood frequency (number of times that a wetland is flooded in a given period) are usually important characteristics (Table 3). These flood characteristics will vary seasonally and from year to year. From a rehabilitation perspective, it is important to characterise the hydroperiod for undisturbed conditions relative to current (disturbed) conditions. In many cases, reinstating the natural hydroperiod through environmental flows (prescribed floods) may be an important (in some cases critical) rehabilitation measure.

The hydroperiod is generally one of the most important factors affecting the functioning, management and rehabilitation of wetlands, and can be easily influenced by human activities in the catchment and wetland. It is therefore important that the hydroperiod be described in order to make informed management and rehabilitation decisions. As long term hydrological data are usually lacking, the best surrogate measure possible, soil morphology, should be used in combination with vegetation. A four class system (Kotze *et al*., 1994) is given in Table 4 for identifying wetness zones based on soil morphological features (notably colour of the soil matrix and the presence and abundance of mottles) and vegetation.

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Table 3: Definitions of wetland hydroperiods (after Mitsch & Gosselink, 2000)

Hydroperiod	Description
Permanently flooded	Flooded throughout the year in all years
Intermittently exposed	Flooded throughout the year except in years of extreme drought
Semi-permanently flooded	Flooded in the growing season in most years
Seasonally flooded	Flooded for extended periods in the growing season, but usually no surface water by the end of the growing season
Saturated	Substrate is saturated for extended periods, but standing water is seldom present
Temporarily flooded	Flooded for brief periods in the growing season, but water table is otherwise well below the surface
Intermittently flooded	Surface is usually exposed with surface water present for variable periods without detectable seasonal pattern

Table 4: Soil wetness zones (after Kotze *et al*., 1994)

	Soil Wetness Zones			
Soil Depth	Non-wetland	Temporary	Seasonal	Permanent / Semi-permanent
0-10 cm	Matrix usually brown/red (chroma >1)[1] No/very few mottles Low OM[2] Non sulphidic[3]	Matrix brown to greyish brown (chroma 0-3, usually 1 or 2)[1] Few/no mottles Low / Intermediate OM[2] Non sulphidic[3]	Matrix brownish grey to grey (chroma 0-2)[1] Many mottles Intermediate OM[2] Sometimes sulphidic[3]	Matrix grey (chroma 0-1)[1] Few/no mottles High OM[2] Often sulphidic[3]
30-40 cm	Matrix usually brown (chroma >2) No/few mottles	Matrix greyish brown (chroma 0-2, usually 1) Few/many mottles	Matrix brownish grey to grey (chroma 0-1) Many mottles	Matrix grey (chroma 0-1) No/few mottles
Vegetation	Dominated by plant species which occur extensively in non-wetland areas; hydrophytic species may be present in very low abundance	Predominantly grass species; mixture of species which occur extensively in non-wetland areas, and hydrophytic plant species which are restricted largely to wetland areas	Hydrophytic sedge and grass species which are restricted to wetland areas, usually <1m tall.	Dominated by: (1) emergent plants, including reeds (*Phragmites australis*), sedges and bulrushes (*Typha capensis*), usually >1 m tall (marsh); or (2) floating or submerged aquatic plants.

Key to Table 4:

1 Chroma refers to the relative purity of the spectral colour, which decreases with increasing greyness. To determine chroma, a Munsell colour chart is required. If this is not available, then in order to characterise the colour of the soil matrix, use the following colour descriptions, given in order of increasing greyness: brown/red, greyish brown, brownish grey, grey.

2 High OM: soil organic carbon is greater than 5% and often exceeds 10%.
Low OM: soil organic carbon is less than 2%
Intermediate OM: soil organic carbon is between 2% and 5%

3 Sulphidic soil material has sulphides present which give it a characteristic ‘rotten egg’ smell, and non sulphidic material lacks sulphides.

8.3 Relationships between ground and surface water in respect of wetlands

Mitsch and Gosselink (2000) describe a number of situations which illustrate both the nature and diversity of the relationships wetlands have with groundwater and surface water. Figure 16a shows that in some situations a wetland may occur because a topographic depression intersects the water table. Thus groundwater can be a major source of water for the wetland. Some wetlands are located at the base of steep slopes, where the groundwater surface intersects the surface of the land (Figure 16b). Riparian wetlands may have inflows and outflows of groundwater (Figure 16c), with seasonal flooding also contributing to the wetland water balance. In some situations wetlands recharge groundwater (Figure 16d) because the wetland is higher than the regional or local water table, and the rate of inflow of surface water exceeds the rate of recharge to the groundwater.

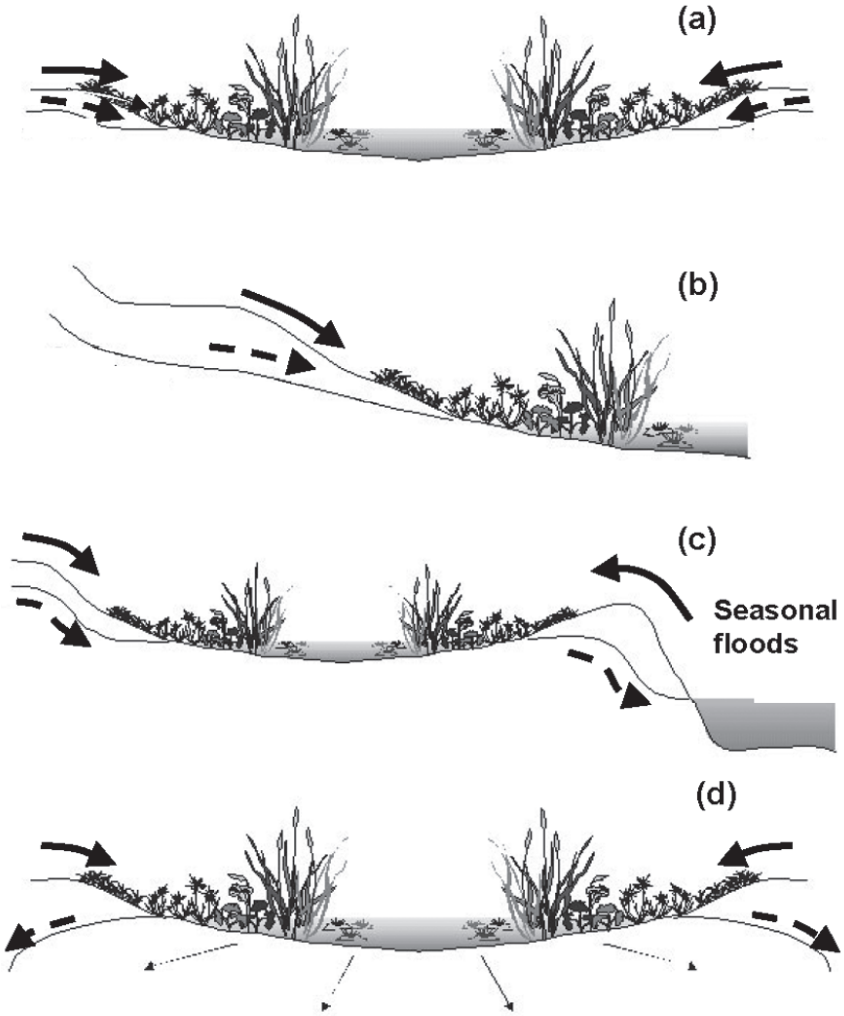

Figure 16: Various possible combinations of wetland – surface and groundwater interactions (after Mitsch and Gosselink, 2000) showing (a) groundwater depression wetland, (b) groundwater spring or seep wetland, (c) riparian floodplain wetland fed by groundwater and seasonal floods, and (d) groundwater recharge wetland. Bold solid arrows indicate surface water flow, while bold dashed arrows indicate groundwater flow. Input of rainfall is assumed in each case.

Relationships between surface and groundwater may be determined by augering a series of holes from the edge of the wetland into the adjacent area. The relative elevation of the land surface should be measured for each auger hole, as should its distance from the water's edge. The depth to the water table should be measured for each auger hole, and the relationship between the groundwater surface and the wetland can then be plotted in relation to the distance from the water's edge. By doing this systematically around the wetland it is possible to construct an understanding of relationships between the wetland and the adjacent groundwater. Because the flow of surface water is very efficient, it is often the case that wetlands in headwater settings are characterised by groundwater discharge to the wetlands. This may change to a groundwater recharge situation lower down the valley, depending upon wetland shape and catchment characteristics.

9 GEOLOGICAL CONTROL ON WETLAND HYDROLOGY AND GEOMORPHOLOGY

Geological controls on wetland distribution are significant, both in their effect on hydrology in the form of aquatards that prevent the flow of water through more permeable surrounding rock, and their effect on differential erosion of rock and valley cross-sectional characteristics.

9.1 Aquifers and aquatards

Fundamental to groundwater hydrology is the permeability of rock and its weathering products. Rocks vary in their hydraulic characteristics depending upon many factors that operate during rock formation and thereafter. The structure of voids in rock depends upon crystal size, mineralogy and crystal orientation, which are imparted during formation or are a product of secondary processes that create or fill existing voids. For example, igneous rock that cools rapidly has small crystals that typically make it impervious to water flow, while coarse-grained igneous and sedimentary rock is generally more permeable. Similarly, volcanic rocks with voids that were created by the presence of gas in the cooling magma are likely to be very permeable, while sedimentary rock will vary in permeability in relation to particle size. Secondary openings develop in rock by processes that affect rocks after they were formed, such as dissolution of minerals creating voids between crystals that are resistant to dissolution or the filling of voids due to precipitation of minerals in solution, such as amygdales in basalt. Dolomite is a rock type that is extremely prone to solution such that solution leads to massive underground caverns through which flow may be better understood as that of a stream, than that of groundwater governed by Darcy's Law.

From the perspective of wetland formation, aquatards that are impermeable to the flow of water may force subsurface water in an aquifer onto the surface such that wetlands form. Typical examples would be hillslope seepage wetlands (Figure 17). Wetlands in dolomitic settings are also typically a result of the presence of impermeable rock strata, such as dolerite dykes, which separate underground caverns, forcing water onto surface at dolomitic eyes as illustrated in Figure 18. Faulting and displacement of impermeable rocks, and folding of such rocks, can also give rise to wetlands by forcing water in an aquifer onto surface. These relationships may be complex, with regional movement of water taking place through hydraulic interactions and local and regional geological processes.

An example is the flow of water from the Waterberg into tributary valleys of Nylsvlei over distances of tens of kilometres where the Zebedela Fault crosses valleys that are filled with fine-grained sediments that act as an aquatard. Where the integrity of these sediments is disrupted through faulting, they become permeable such that water that is under pressure due to the head of water in the Waterberg some distance away rises to surface.

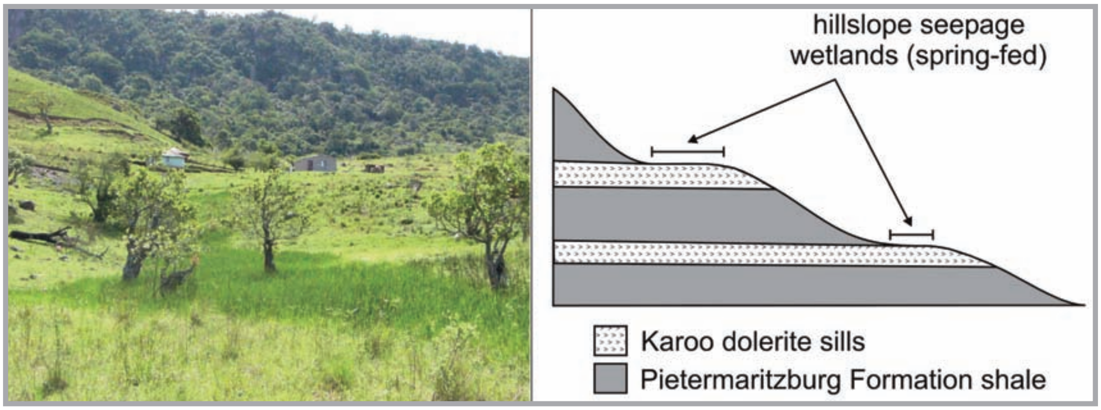

Figure 17: Presence of aquatards (dolerite sills in this case) that force groundwater onto surface and lead to the formation of hillslope seepage wetlands (diagram). The photograph is an example of a hillslope seepage wetland near Greytown in KwaZulu-Natal, with dark-green stand of sedges in the foreground and scattered umDoni (*Syzygium cordatum*) trees. This wetland is one of many in the region fed by springs that surface at the contact between Pietermaritzburg Formation shale and underlying Karoo dolerite sills. (Photograph: Suzanne Grenfell).

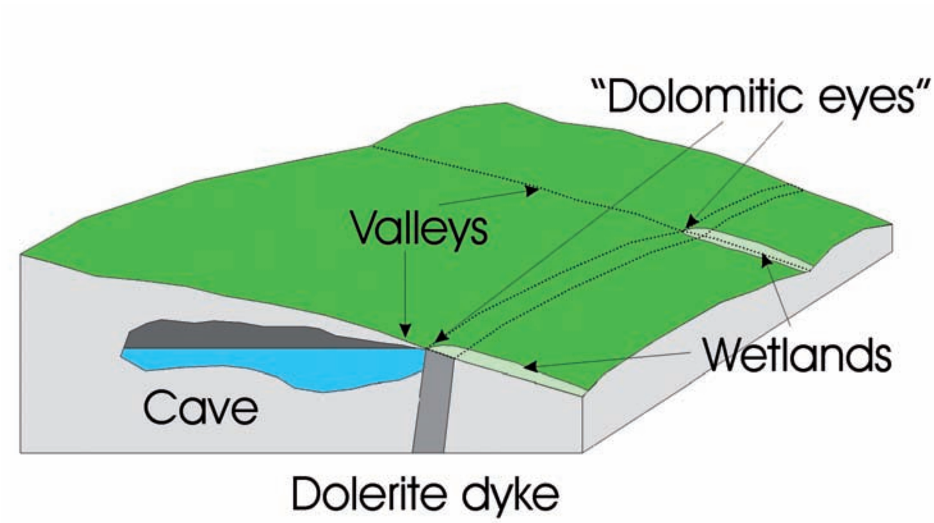

Figure 18: Dissolution of dolomite, forming caves that are compartmentalised by dolerite dykes, which are impervious to water flow and force water onto surface at dolomitic eyes.

9.2 Differential erosion of rock

Rocks vary in hardness and, by implication, resistance to erosion. This has a profound effect on wetland origin and evolution in a landscape that is undergoing erosion, since erosion of resistant strata proceeds very slowly, impeding the rate of erosion of less resistant surrounding rock, which is frequently the case in much of South Africa where soft Karoo sediments have been intruded by resistant dolerite dykes and sills (Figure 19). The phenomenon has been well described by Tooth *et al.* (2002; 2004) for the Klip River wetlands (also known as Memel Vlei) in the eastern Free State. Here, soft Karoo sediments are more easily eroded than is possible for a dolerite dyke that runs across the valley at the toe of the wetland. Given the river energy following Neogene uplift of the region, valleys will be degrading, but the rate of lowering of the land surface is limited by the rate of downcutting at the dolerite dyke, which forms a local base level. Because incision is retarded by the dyke, available energy is used to widen the valley, which results in a geomorphic setting conducive to the formation of wetlands. Wetlands in this setting are typically floodplains, and because of ongoing reworking of sediments in these systems, which are net exporters of sediment to rivers downstream, sediment accumulations here are fairly thin (typically < 4 m). Wetlands that form in this way typically have meandering channels and oxbow lakes that become increasingly prolific close to the dolerite dyke, and downstream of the contact between Karoo sediments and the dolerite dyke the valley is steep-sided and longitudinal slope generally increases.

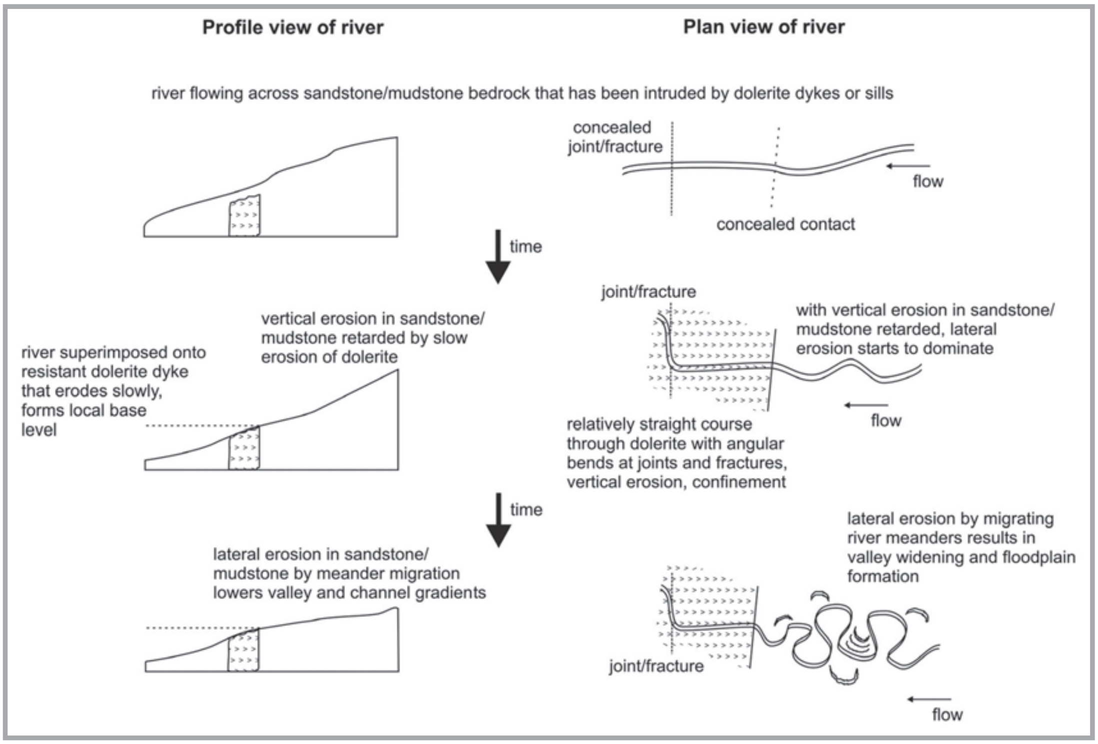

Figure 19: A conceptual model of wetland origin in Karoo sediment valleys upstream of resistant dolerite intrusions (after Tooth *et al.*, 2004).

Differential weathering of rock in headwater basin settings is a subject of ongoing research as a variation on this form of geological control. Different rocks have different weathering rates, and in some cases weathering rates will vary for a given rock type depending upon variation in chemistry and texture. For example, thick dolerite sills are coarse-grained and weather more readily than their thin, fine-grained counterparts (Bell and Jermy, 2000). Where a wetland system is underlain by a thick coarse-grained dolerite sill that abuts a fine-grained dolerite dyke, such as is the case at Dartmoor Vlei in the KwaZulu-Natal Midlands, it is suggested that limited weathering of the dyke would impede vertical drainage development, while extensive deep weathering and consequent subsidence of the sill would provide a setting conducive to wetland origin.

10 WETLAND GEOMORPHOLOGY: SEDIMENTATION AND EROSION IN WETLANDS AS DRIVING FORCES

Gross wetland dynamics at the level of individual wetland systems are the product of erosional (degradational) and depositional (aggradational) processes that take place within the system under consideration. Rejuvenation of relief by crustal movements such as faulting and warping, variation in sea level, and climate change may also affect wetland dynamics by changing these erosional and depositional processes. Thus the dynamics of wetlands at the system level are difficult to predict without understanding all of these processes and their interactions. However, erosion and deposition of sediments act in fundamental ways, and sometimes over surprisingly short time periods, to make wetlands dynamic features in the landscape. Unless we understand these processes of change, we tend to interpret any change as negative, and the temptation to intervene is great.

10.1 Deposition in wetlands

Reference has been made in Section 7.1 to three types of sedimentation that may take place in wetlands: clastic, chemical and organic. These typically take place in different regions of a wetland and lead to aggradation such that areas of relatively high elevation are formed where sedimentation is most active. In contrast, areas starved of sediment will form basins within the wetland. Differential rates of sedimentation within a wetland that may occur naturally will lead to wetland instability in that water will continually seek to flow from areas of active sedimentation (high elevation) to areas starved of sediment (low elevation). Therefore we should expect differential rates of sedimentation within a single wetland to create instability, and wetlands should be dynamic over time scales of decades to centuries, depending upon rates of sediment influx and patterns of deposition. Water distribution should shift over time from regions of high deposition and elevation to regions of low deposition and elevation through a process known as channel avulsion that is common in large floodplain wetlands around the world. In southern Africa, these processes have been well documented in the Mfolozi and Mkuze wetlands in Maputuland, KwaZulu-Natal (Ellery *et al*., 2003), the Klip River wetlands in the eastern Free State (Tooth *et al*., 2002), the Hlatikulu wetland in the foothills of the Drakensbeg west of Mooi River (Grenfell, 2006), and the Okavango Delta in Botswana (McCarthy *et al*., 1992). If the paradigm of widespread erosion in South Africa is correct, much of South Africa's lost soil should be trapped in wetlands, enhancing the rate at which water should shift from one region of a wetland to another. Either our understanding of wetland dynamics is incorrect, or we haven't studied the sedimentology of a sufficient number of wetlands.

Our view is that in general researchers have focused too strongly upon one type of sedimentation only - clastic sedimentation. They have not placed sufficient emphasis on organic and chemical sedimentation in wetlands, particularly the geomorphic setting in which these two types of sedimentation occur, and have also overlooked their hydrological, ecological and geomorphological consequences. All of these types of sedimentation may take place in a single wetland. Furthermore, they are likely to be interrelated through feedback processes that are probably linked to gradient such that their interactions serve to reduce gradient. This may be a reason that wetlands are surprisingly persistent and show resilience to large-scale incision over time scales of centuries to millennia. These three types of sedimentation will be briefly described in turn.

10.1.1 Clastic sedimentation

Deposition of waterborne clastic sediments takes place in wetlands in areas where there is a reduction in the ability of a stream to carry its sediment load. It may take place preferentially at the head of a wetland where the inflowing stream loses confinement or reduces its gradient, or it may take place along its length where tributary streams enter the wetland and supply additional sediment. In the former case, deposition will lead to a steepening of gradient downstream of the region of deposition, increasing the likelihood of channel switching or of erosion from the lower end of the wetland, depending upon valley width. In the latter case it will lead to a decrease in gradient of the trunk stream upstream of the site of sediment influx from the tributary stream, favouring wetland formation. In most wetlands, there may be a net accumulation of clastic sediment, provided space is available to accommodate it.

10.1.2 Organic sedimentation

Peat is un-decomposed organic material (mainly plants) that accumulates in flooded settings due to the presence of anaerobic conditions. The accumulation of peat in systems occurs where there is little or no suspended clastic sediment input, and where there is standing or slowly moving water (very low energy settings). Thus peat accumulation is a benign form of sedimentation that takes place in backswamp settings and leads to aggradation of the land surface and infilling of basins deprived of clastic sediment. Where clastic sedimentation is taking place at the head of a wetland, organic sedimentation will tend to reduce the difference in elevation between the aggrading source channel and the backswamp. Where a tributary stream introduces large quantities of clastic sediment into the lower reaches of a wetland, it will reduce the gradient of the trunk stream in an upstream direction, possibly leading to the formation of low-energy backwaters where peat formation then takes place. In this case peat formation should reduce the degree of undulation caused by such tributary deposition.

10.1.3 Chemical sedimentation

As alluded to above, an important process within wetlands that has been overlooked in wetland science is chemical sedimentation. This is a particularly important type of sedimentation in southern African wetlands because of the generally arid climate (rainfall < potential evaporation). Chemicals in solution are introduced into wetlands via the dissolved load in streams as part of the overall sediment load. This sediment is deposited within wetlands because of the water lost to the atmosphere via evaporation and transpiration. Transpiration is the dominant means of water loss from settings in which prolonged inundation, and limited surface and groundwater loss, are the norm. Through transpiration, surface water and its solute load are drawn down into the root zone of macrophytes. However, wetland plants are selective in what they take up through their roots, and many of the dissolved solutes are excluded from uptake. These solutes then saturate and precipitate out of solution, accumulating in the soil in the solid phase. Their accumulation in the soil causes a volume increase in the soil, leading mainly to vertical expansion and therefore to a lowering of gradient in the upstream direction.

The importance of chemical sedimentation can be gained simply by appreciating that the total quantity of chemical sediments accumulating in the Okavango Delta each year is in the region of 450 000 tonnes. Given that the total amount of clastic sediment that accumulates in this system each year is approximately 200 000 tonnes, it is clear that the importance of chemical sedimentation in this system is appreciable (McCarthy and Ellery, 1998). It is remarkable to think that the benign process of transpiration leads to aggradation of the land surface in wetland ecosystems. The precipitation of solutes in the soil in this way is likely to be widespread in wetlands, although this has not been particularly widely appreciated. Our view is that it is far more important than has been appreciated up to the present.

In systems where chemical sedimentation has been documented, it has been observed to take place in the lower regions of large wetland systems. Thus it is likely to reduce gradient upstream (in the wetland), promoting conditions that favour wetland formation.

10.2 The durability of sedimentary features in wetlands

Based on ongoing research, it is clear that the three types of sedimentation described in this document do not necessarily take place in all wetlands. Furthermore, the durability of features created through clastic, chemical and organic sedimentation vary considerably. Features created by clastic and chemical sedimentation are reasonably durable, whereas those features created by organic sedimentation are not. Peat can be created and/or destroyed over relatively short time periods, and this happens in systems where organic sedimentation has been observed in southern Africa. Regional droughts that lead to substantial lowering of water tables may leave the upper or entire peat deposit exposed so that it is susceptible to burning. Therefore many peat deposits have layers of ash interspersed in the profile. Also the instability caused by high rates of clastic sedimentation in localised regions of large wetlands such as the Okavango and Mkuze Systems may lead to diversion of water from one area to another through a process known as channel avulsion. This may lead to extensive drying of peat deposits in backswamps adjacent to the former channel, and these may burn.

Peat fires are probably another feature of wetlands in our region that make them substantially different from their counterparts in northern temperate settings. However destructive they may seem in the short term, research has shown that they are important in the

Okavango Delta as a means of promoting long-term ecosystem heterogeneity, particularly with respect to nutrient availability and therefore their ability to support herds of ungulate mammals (Ellery *et al*., 1989). In a nutrient-starved system like the Okavango, peat fires release nutrients into the soil, leading to the establishment of vegetation with high forage quality. These areas therefore attract large herds of ungulate mammals and are thus ecologically important. Peat fires constitute part of the natural dynamic of this system.

From a geomorphological perspective, the destruction of peat in such wetland systems leads to the restoration of the former relief and renewal of accommodation space such that these areas may be flooded again at some time in the future and begin again to accumulate organic matter. Therefore peat fires are also geomorphologically and hydrologically important.

10.3 Erosion

When viewed in their geomorphological setting, wetlands are generally regarded as sediment sinks (environments of deposition) rather than sediment sources. Erosion potentially threatens not just the health of a wetland, but it threatens the very existence of a wetland. Erosion may occur as a result of some human activity, such as the excavation of a furrow or confinement of flow through pipe culverts beneath a road. Erosion may also result naturally if the surface of a wetland is steepened longitudinally by prolonged sedimentation and ultimately exceeds a critical threshold of slope stability, or if the supply of sediment to a wetland from its catchment is reduced such as through hardening of surfaces or even erosion control activities, and the wetland is subject to relatively sediment-free flows with a high capacity to transport sediment. In their natural state, wetlands are self-regulating to some extent, so that, although they may change and evolve due to changes in the catchment or as a result of natural processes taking place within the wetland, they are surprisingly effective at maintaining system-level equilibrium over ecological timescales (10s to 100s of years) in the face of variation in external driving forces. Most erosion in wetlands is by gully erosion that is clearly visible on the surface of the land.

10.3.1 Surface erosion

Over-utilisation of a wetland may disturb the natural balances within the wetland. The main consequence of over-utilisation is a decrease in the vegetation cover, often in association with a transition from a permanently saturated to a seasonally or ephemerally saturated condition. Such change results in exposure of the soil to precipitation and wind, and to an increased likelihood of desiccation and cracking. Both of these scenarios increase the probability of soil erosion by processes such as rain splash and deflation. Similarly, changes in land use in the contributing catchment may disturb natural balances in wetlands. As water moves through the catchment, its potential energy is converted to kinetic energy. Many human practices in catchments result in a decrease in infiltration, and thus increase overland flow. Depending upon the activity, it may also increase (overgrazing) or decrease (urban development) sediment supply. An increase or decrease in sediment supply to a wetland from the catchment will similarly affect the natural balance between sediment supply and demand within the wetland, with potentially significant consequences.

Whether or not erosion will occur is governed by the balance between the forces of removal and the forces of resistance. The forces of removal are related to the eroding power (erosivity) of the water in motion, including (most notably) the impact of a falling raindrop, which will tend to disaggregate soil. The energy of a rainstorm is also important, which depends upon the drop size and rainfall intensity. Although this parameter will vary with each event, as a broad guideline thunderstorms will have a higher energy than post-frontal drizzle, while thunderstorms after a long dry spell tend to have most energy. Raindrops falling onto a thin film of water will increase the turbulence, thereby facilitating further entrainment of disaggregated material. Once the film is approximately 5 - 10mm deep, the cushioning effect of the surface water starts to counteract the effect of the splash.

In contrast, the forces of resistance are related to the susceptibility of the soil to be transported (erodibility), as controlled by the texture, aggregate stability and organic matter context of the soil. Other factors that increase the forces of resistance include vegetation cover, presence of fine roots, and the presence of armouring such as a layer of small pebbes on the soil surface.

Surface flow will soon start to concentrate into defined areas as a result of microrelief and erosion will therefore not be uniform over the surface, but will start to form microchannels (rills). As flow diminishes at the end of a runoff event, deposition will occur within these rills. They are transient to semi-permanent in nature, appearing and refilling regularly, and are characterised by being wider than deep and of a magnitude that makes it possible to remove them by conventional ploughing. Once they become too deep to remove easily, or when the depth of the feature exceeds the width, they are classified as gullies.

Rills are seldom associated with wetlands as the hydraulic regime of a wetland is such that erosion is more likely to manifest itself in the formation of gullies (when wetlands erode, they often erode spectacularly). This is principally related to considerations of topographic gradient in conjunction with discharge. An important exception to this is the 'psuedo-rill' created as a result of trampling by excessive numbers of livestock moving through a wetland. By contrast to the natural process of rill formation and potential infill, trampling tends to result in semi-permanent rills that may well develop into gullies and eventually channels.

A further important consideration is that many degraded wetlands will have been drained in the past by human excavation of artificial channels. Under these conditions the artificial channels effectively function as gullies and, as with natural gullies, the base of the gully (or artificial channel in this case) will represent the local base level to which the wetland will tend to drain. If the discharge capacity of the gully or artificial channel is sufficiently large to accommodate more water than the rate of recharge of the wetland, that area will eventually dry out. The Manning equation (Section 6.2) thus becomes pertinent, both from the perspective of estimating discharge, and that of determining the likelihood of scour. Erosional enlargement of the gully or artificial channel will be governed by the gradient of the channel bottom, the hydraulic radius, and the nature of the bank material. From the perspective of rehabilitation it is therefore important to infer the range of erosional processes that are operating and to counteract each of these. Certain wetland types, notably valley-fill (valley-bottom) wetlands, are particularly susceptible to gully erosion. In contrast to large floodplains within which sediment is continually reworked by processes of lateral channel migration, sediment accumulation within valley-bottom wetlands ultimately results in longitudinal steepening that exceeds a threshold of slope stability, of which gullying is a common consequence.

An exceptional case in terms of wetland erosion is posed by so-called 'extreme events'. These are usually high discharge episodes and, although they occur naturally in response to high rainfall conditions, their incidence has become considerably more frequent in response to changes in catchment conditions that promote rapid run-off and limit infiltration. Extreme events may well have the energy to scour a channel through the wetland and lower the downstream local base level. The consequence of such an event would normally signal the demise of the wetland within a natural geomorphic environment. Where the wetland is of ecological importance, it may well be wise to intervene and to attempt to rehabilitate. All the more so if the change was brought about by land use changes in the catchment upstream of the wetland, rather than by purely natural processes. Again, the principle of counteracting the effects of the erosional processes responsible for the problem at each stage applies.

Once gully erosion is initiated, gully form and activity tend to follow a set path of development (Figure 20). Gullies first deepen, then widen through bank undercutting and slumping, and eventually stabilise naturally and begin to aggrade. The inset to Figure 20 depicts changes in destructive gully activity (deepening and undercutting) with time. It supports Figure 20 in showing that destructive gully activity 'levels off' over time and stability is regained.

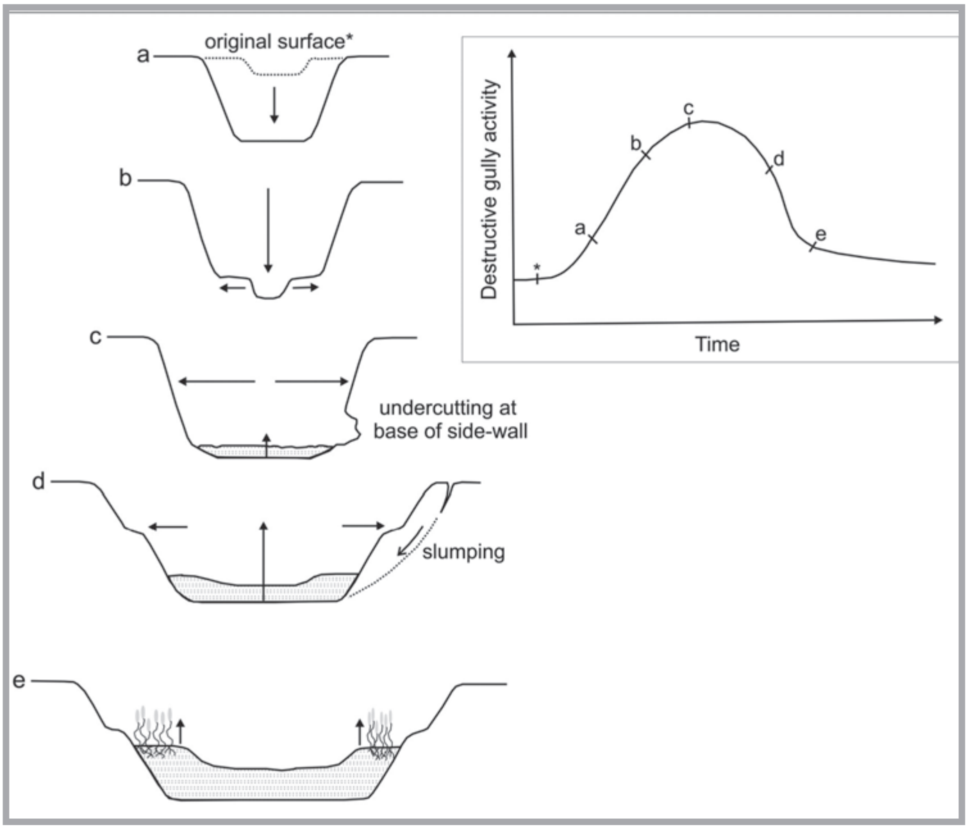

Figure 20: Evolution of a gully from initial incision (a, b) and widening (c, d) to aggradation (d) and eventual relative stability (e). Inset: curve showing changes in destructive gully activity with time. Adapted from Schumm (1994).

For a wetland that has been affected by gully erosion, one should consider the development stage (Figure 20) and the level of activity (Figure 20, inset) of gullies, when planning engineering interventions. This will provide an idea of the potential for stabilisation by engineering interventions and the likely cost of interventions required. At time 'a' when a gully is just initiating and at times 'd' and 'e' when a gully is almost naturally stabilised, destructive gully activity will be most easily and inexpensively controlled by engineering interventions. However, the efforts at times 'd' and 'e' will have little effect, as the gully is stabilising naturally. At times 'b' and 'c', control will be difficult and expensive, as one would have to work against the natural progression of destructive gully activity. Thus from a geomorphological perspective, it would be most sensible, and most lucrative (in wetland health and ecosystem services terms), to intervene at an early stage in gully development, and one should carefully weigh the benefits (again, in terms of wetland health and ecosystem services) of intervening at later stages in gully development, against the cost of interventions required.

10.3.2 'Hidden' erosion within wetlands

A potentially serious form of erosion within wetlands is related to the movement of water below the surface. Although Darcy's Law represents a first approximation to soil and groundwater movement (Section 6.3), it is important to remember that very little of that water movement will be uniform. Rather, flow will tend to concentrate along restricted paths (percolines) down the hydraulic gradient (Figure 21). A major impact of degradation within wetland systems is likely to be a progressive shift from a relatively uniform subsurface water percolation system of through-flow to one of intermittently concentrated flow. At the same time that the wetland is progressively dried out, desiccation-cracking becomes more frequent. The effect of this process is to enhance the concentration of water movement into the subsurface zone underlying a wetland and so facilitate drainage into pipes, gullies, or the artificial channel used to drain the wetland.

In essence, pipes are zones of concentrated water movement beneath the ground surface and form along zones of increased permeability. The difficulty is that once soil pipes have formed they will become self-sustaining, even if the pipes are only a few millimetres in diameter. Once established, the likelihood is high that the pipes will increase in size due to the natural erosion processes through the soil conduit. Such enlargement will frequently continue until the diameter of the pipe is such that the internal friction within the soil roof is exceeded by gravity, resulting in roof collapse and causing an instantaneous gully system. The implications of this for rehabilitation are significant as, once formed, these preferred drainage lines will tend to dominate future flow paths within the wetland unless they are physically disrupted.

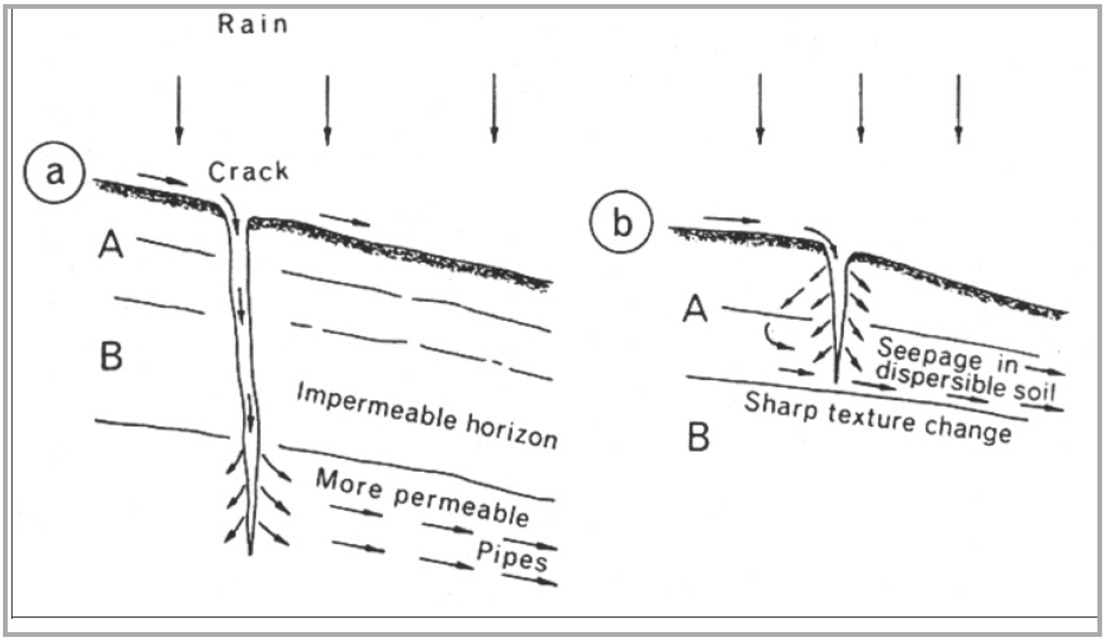

Figure 21: Conditions favouring the formation of pipes: (a) cracking and a permeable horizon below an impermeable horizon; (b) a horizon of dispersible clay.

10.4 Sedimentation, gradient and erosion in wetlands

Clastic, organic and chemical sedimentation in wetlands lead to aggradation, or an increase in the elevation of the land surface over time. These three types of sedimentation seem to interact to maintain overall gradient in ways that we are only starting to appreciate. Clastic sediments are typically deposited in the upper (proximal) reaches of wetland systems, or, in the case of floodplain systems, in areas adjacent to the main source river, leading to localised aggradation. Organic sedimentation occurs as a benign form of sedimentation in low energy situations of limited clastic sediment input and abundant water supply, once again leading to aggradation. This type of aggradation typically dominates in the middle reaches of large wetland systems. Chemical sedimentation tends to predominate in the lower (distal) reaches of wetland systems where clastic sedimentation is low, where residence times of water are long, and where transpiration draws solutes into the soil and they precipitate from solution. These three forms of sedimentation are interrelated in a feedback system such that overall gradient is likely to be maintained within a wetland system for prolonged periods. Thus excessive clastic sedimentation in the proximal part of a wetland will steepen gradient in a downstream direction, leading to increased flooding of distal reaches of a wetland, possibly giving rise to increased peat formation and chemical sedimentation in these reaches, which raises the land surface and thus maintains gradient overall. In the event of the gradient being lower at the proximal part of a wetland than at the distal part, water will have a longer residence time in the upper reaches of the system, leading to increased chemical and organic sedimentation in these reaches, such that overall gradient is maintained in the long term.

Although these three forms of sedimentation interact within a single system, clastic and chemical sedimentation drive the creation of topographic relief and produce durable features, while organic sedimentation is a passive response to other forms of sedimentation and their effects on gradient and water flow. Thus organic sedimentation forms in low-energy basins created by interactions between the existing land surface and clastic and chemical sedimentation.

10.4.1 The concept of an equilibrium slope in wetlands

Many wetlands do not aggrade in synchrony through these forms of sedimentation. In typical cases, clastic sedimentation will be the predominant form of sedimentation in wetlands, and since this typically happens preferentially in the upper reaches of wetland systems, the wetland will gradually steepen in a downstream direction to a gradient that is in equilibrium with discharge and sediment supply. In Figure 22 we consider the effect of deposition on gradient associated with the loss of confinement of a river. As a river loses confinement, a situation that applies to many wetlands that arise as a consequence of streams leaving a mountainous area and entering a flat plain, such as in the Eastern and Western Cape provinces as well as many wetlands of KwaZulu-Natal, gradient steepens as it deposits its load. This is because as flow spreads laterally over a larger area, the effects of friction increase, and the energy available to carry sediment decreases.

Research is showing that the gradient of a wetland is inversely dependent upon stream size, such that larger streams are broadly associated with shallower slopes. The gradient on these wetlands seems to be at a threshold such that an increase in discharge will result in erosion as the gradient established under lesser discharges is too steep for the prevailing increased discharge. Thus it seems that in some wetlands at least, the equilibrium gradient is close to a threshold that is very sensitive to external perturbations such as climatic fluctuations or human activities that disturb water or sediment supply. Human activities that affect water and sediment inputs from the catchment, or surface flow of water in the wetland itself may thus cause the wetland to become unstable.

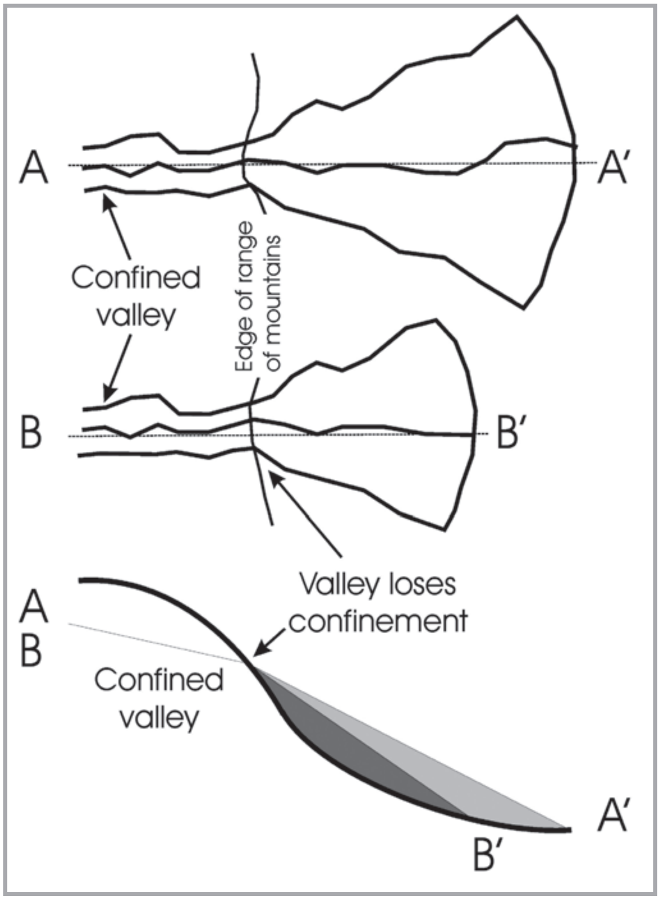

Figure 22: The change in gradient associated with the loss of confinement of a large river (A-A') and a small river (B-B')

Since the discharge associated with individual drainage lines and valleys is very rarely known, the relationship between valley gradient and discharge is often described with reference to wetland or catchment size. In many parts of the world, catchment size is highly correlated with discharge in that larger catchments tend to have higher discharges. The high variation in rainfall and evapotranspiration across the subcontinent means that this is not always the case in southern Africa (refer to Figure 4). Instead, research has shown that wetland size is the best predictor of wetland longitudinal slope. The relationship between wetland size, in a sense a proxy of discharge, and wetland gradient is shown in the inset of Figure 23. In general, smaller wetlands are steeper, while larger wetlands are more gently sloped. This variation also marks a continuum in wetland type, with small, steep wetlands being valley-bottom wetlands which grade into 'flat', large, floodplain wetlands (Figure 23). Based on this preliminary analysis, it seems that wetlands larger than 1 500ha tend to be floodplain wetlands.

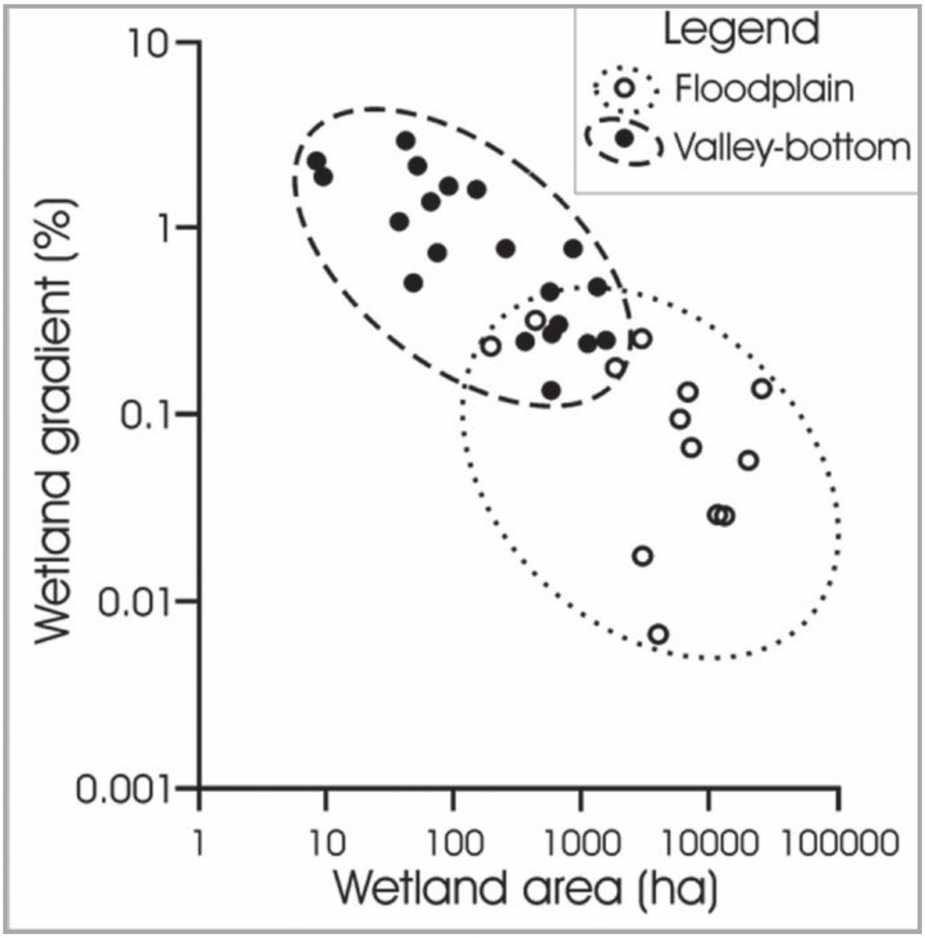

Figure 23: The relationship between longitudinal slope and size for valley-bottom and floodplain wetlands.

The relationship between slope and wetland size is critical in determining a wetland's vulnerability to erosion. Non-floodplain wetlands were examined with respect to whether or not they were incised. In general, wetlands with a steep slope for their size were incised, whereas those with a shallow slope for their size were not incised (Figure 24). Therefore an understanding of whether or not wetlands are inherently vulnerable to incision needs to consider longitudinal slope in relation to wetland size, as captured in Figure 25, which has been reproduced in *WET-Health* (McFarlane *et al*., 2009).

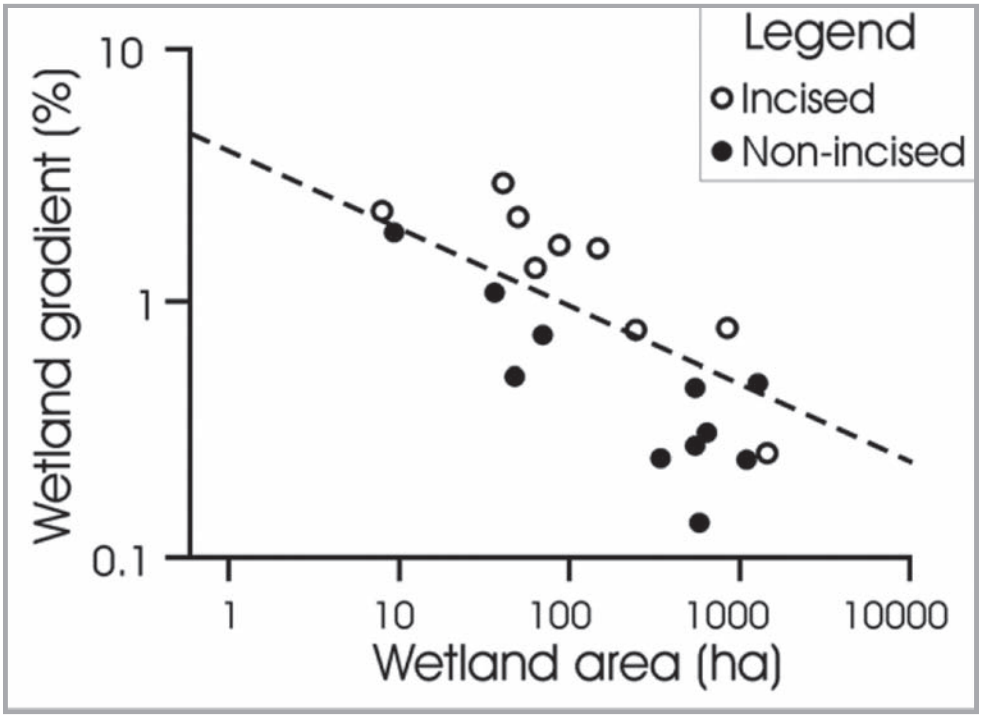

Figure 24: The relationship between slope and wetland area for valley bottom wetlands showing those that are incised **and non-incised. For a given size, those wetlands with a high slope are generally incised and those with a low slope are incised. The dashed line represents the threshold slope for current climatic conditions, above which wetlands are likely to incise.**

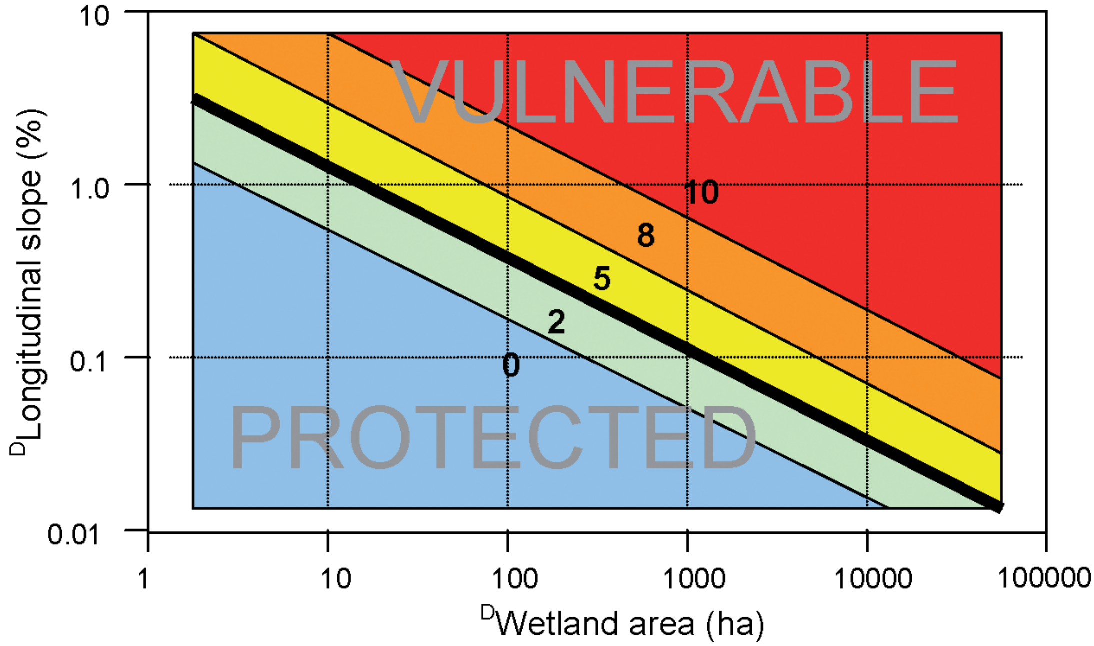

Figure 25: Wetland vulnerability to incision of valley-bottom wetlands based on the relationship between longitudinal slope and area (After Macfarlane *et al*., 2009).

It is interesting to consider what factors affect longitudinal slope. In Figure 19 we have illustrated how, in a floodplain system, a stream will erode a valley to a slope and width that is determined by factors such as the size of the stream and relative hardness of the resistant feature at the toe of the wetland and the more easily eroded rock upstream of this. In Figure 22 we have illustrated the effect of loss of confinement, where slope is determined largely by the size of the inflowing stream. Sedimentation at the head of a stream will steepen slope downstream, while sedimentation at the toe of a wetland, possibly due to sediment input from a tributary stream with an eroding microcatchment, will reduce slope upstream along the main (trunk) stream. Consideration of longitudinal slope for a given wetland offers insights into factors that might contribute in important ways to wetland formation.

10.4.2 Equilibrium slope and human activities or climate change

This model of wetland vulnerability allows one to interrogate the causes of wetland degradation in some depth and may explain why so many of South Africa's wetlands are eroding. Suppose we are correct in saying that wetland area is a proxy for discharge entering the wetland. An increase in discharge without a concomitant increase in sediment supply would mean that water flowing through the wetland was 'hungry for sediment', which would lead to erosion. An increase in sediment-free water as a result of hardening of surfaces in the catchment might, for example, increase discharge from t0 to t1, which would result in a stable wetland becoming unstable and prone to erosion (Figure 26).

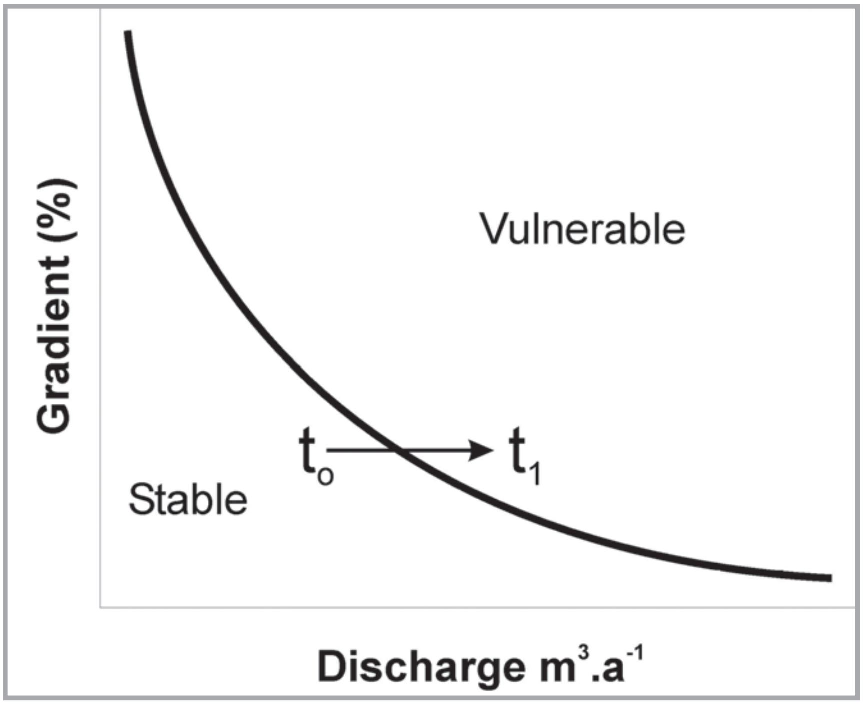

Figure 26: Illustration of how an increase in discharge from the catchment in its natural state (t_0) to its urbanised state (t_1) through hardening of surfaces, can lead to a wetland becoming vulnerable to erosion.

This model of wetlands and their vulnerability to variation in discharge relative to sediment supply also helps us to examine wetlands within the context of climate change (see Section 5). Wetlands may have evolved over geological time scales under drier conditions than we are currently experiencing, which is likely given the fact that we are in an unusually warm and wet period at the present time (see Figure 6). Under a drier climate, with lower discharges coming into wetland systems, discharge may have been sufficiently low for wetlands to persist. But the increase in discharge in a wetter climate may cause the wetlands to cross the threshold that separates stable and unstable wetlands, such that they are eroding. Given vegetation change following climate change over long time periods, our view is that wetland vulnerability is worsened even further. Vegetation in the catchment is likely to stabilise soils in the catchment, lowering the risk of erosion there under a warmer and wetter climate (Meadows, 1988). This would reduce sediment supply entering the wetland, which, given higher discharges, would increase the likelihood of erosion. It may well be that much erosion taking place in wetlands in South Africa is as much a consequence of climate change as of human activities in catchments and wetlands, and the surprising outcome of this analysis is that more water in a catchment may not necessarily be good news for wetlands.

Because wetland longitudinal gradient probably operates close to its threshold of stability, it is the factor that is sensitive to disturbance. Small disturbances to the relationship between water flow and sedimentation or erosion in wetlands are likely to have major impacts through initiating erosion, which may lead to wetland loss.

Note: we have focused here on regional gradient, but it needs to be said that the flow of water is particularly sensitive to local gradients, and that erosion may be initiated in response to local gradients created by depositional features within wetlands such as alluvial ridges and levees that are associated with fluvial processes.

10.5 Catchment impacts on wetland erosion and deposition

When considering wetland processes, it is essential not to view the specific process in isolation, but rather to place it within the catchment context. This is necessary as wetlands are generally a part of a larger fluvial system that functions as an integrated unit. The water, clastic sediment, and solute load from upstream of a wetland will thus enter the wetland and impact upon the manner in which it functions. Increasing clastic sediment input will steepen gradient in a downstream direction, leading to instability. Factors downstream of the wetland that lead to a lowering of the local base level may initiate headward erosion back into an existing wetland and potentially drain it.

In a broadly similar manner, it is essential to bear in mind the effect of land use change on water availability, especially water that moves over the land surface with relatively little impedance and is not confined in a channel. Water, flowing in response to gravity, will seek out the lowest point within the local topography and will therefore accumulate at the base of slopes and in valleys. Increases in surface runoff are therefore likely to have a proportional effect on channel discharge, the implication of which may well be a change in its competence and capacity. The consequence may then well be that a wetland system that was in equilibrium, with slight aggradation through which the vegetation was able to continually regenerate, is pushed to become an eroding system where channel incision occurs. Over time such a scenario is likely to result in a lowering of the local base level and a draining of the wetland, ultimately leading to its demise.

With respect to the geomorphology of wetlands, the human activity that has had a significant direct impact on wetlands is the construction of impoundments. These trap sediment to varying degrees, depending upon the nature of the clastic sediment load. All bedload sediment is trapped in an impoundment. In the case of suspended sediment which settles from suspension more slowly, the degree to which the impoundment traps sediment is related to size of the impoundment relative to the size of the stream, which affects the residence time of water in the dam. The interruption of sediment transport along streams by the construction of impoundments has a large impact upon wetlands since these will then enter a phase of erosion that will last as long as the impoundment traps sediment. The impact of the Pongolapoort Dam on the Pongola Floodplain has been particularly significant in this regard in that it has deprived the Pongola Floodplain of sediments, leading to the initiation of erosion of the floodplain by the Pongola River, thereby reducing the likelihood of inundation of the floodplain for a given discharge.

A further related activity is the effect upon stream capacity of interbasin transfers. Generally water with low sediment load is introduced into a drainage basin where the existing stream has adjusted its dimensions and gradient to existing flows and sediment inputs. If this additional water increases the transport capacity of the river, erosion may be initiated on a grand scale. Similar indirect impacts occur when catchments are developed to urban and industrial complexes. More sediment-starved water is introduced into the stream that will therefore have the capacity to erode (McCarthy *et al.*, 2007). Thus, more water in a stream is not necessarily a good thing for wetlands.

11 HYDROLOGICAL AND GEOMORPHOLOGICAL CONTROL OF WETLAND DISTRIBUTION

11.1 An introduction to wetland classification

Having provided a brief overview of geomorphology and hydrology with a special emphasis on river systems, it should be clear that the occurrence of wetlands is related to both hydrological and geomorphological factors. Wetlands generally occur in geomorphic settings where river transport capacity is less than or equal to load. Current velocities and discharges in wetlands are thus usually sufficiently low to limit or prevent erosion, and wetlands occur primarily in settings that overall are non-erosional or are depositional. We are of the view that the inability of water to erode is as important a factor sustaining wetlands as is the presence of water at or close to the surface of the earth. It highlights the fact that erosion is a significant threat to wetland systems, and in a natural context it may be the most important process leading to wetland degradation and loss. Given that anthropogenic interventions may be varied and detrimental, it is not the only threat, but in the absence of erosion, wetlands will shrink or expand in response to natural or human-induced variation in water availability. Humans too may alter patterns of biodiversity or vegetation structure in a wetland, but once a wetland starts to erode it may be fundamentally and substantially altered and/or lost.

It is possible to crudely classify wetlands according to hydrogeomorphic characteristics that relate to those factors that give rise to wetland formation. As we have seen previously, there is a close relationship between surface water, saturation of soil horizons and groundwater. Wetlands can recharge groundwater (i.e. supply water to groundwater) or they may be supplied with groundwater. Surface runoff or periodic inundation by river flooding may also be important. Which of these processes dominates is largely controlled by the topography of the area (landforms), although the ability of the soil or rock to transmit water is also important. The landform setting of a wetland has a strong influence over:

- local patterns of water movement (surface and sub-surface, and the interactions of these)
- the degree to which wetlands are open to lateral exchanges of water, sediment, nutrients and pollutants (Bedford and Preston, 1988).

Landform setting is an important factor in determining the key components of the water balance and in understanding geomorphological processes that maintain wetland functions.

11.2 A hydrogeomorphic classification of wetlands

Wetland classification systems have preoccupied wetland scientists for a considerable length of time. The classification system that is developed will primarily reflect the purpose of the classifier. So, some classification systems attempt to capture variation in vegetation, some attempt to capture variation in wetland structure and/or function, while others attempt to reflect the predominant hydrological characteristics. Thus many classification systems have been developed nationally in South Africa and internationally, and the terminology associated with these classification systems has given rise to conflicting use of terms and a degree of confusion. The best known wetland classification systems are the Cowardin System (Cowardin *et al.*, 1979; USA) and the system of Noble & Hemens

(1978; South Africa). More recently Dini *et al*. (1998) and Dini and Cowan (2000) have presented a classification system for South Africa based largely upon the Cowardin System. However, the focus in this report is on a small number of classes in the Dini *et al*. (1998) system. For the purposes of wetland rehabilitation and for appraising functional values of wetlands, it is clear that a more appropriate system is the hydrogeomorphic classification system that has been championed internationally by Mark Brinson of the USA (Brinson, 1993). There are features of his classification system that we like, but, as has been pointed out previously, wetlands in southern Africa differ in many ways from their northern hemisphere counterparts. It is difficult to transfer a system from a part of the world that has been recently glaciated and where mean annual rainfall is considerably greater than ours.

The most recently proposed classification system for South African wetlands (Ewart-Smith, 2006) is based on principles of the HGM approach, but incorporates aspects of the Cowardin system adapted by Dini and Cowan (2000) as well as aspects of a Mediterranean classification for wetland inventory (Farinha *et al*., 2005). The purpose of the Ewart-Smith (2006) system is to assist in the classification of wetland units delineated within the Advanced Wetland Layer (AWL) of the National Land Cover (NLC) initiative for broad-scale management and conservation planning. In this and other reports in the Wetland Rehabilitation series, we have modified Brinson's HGM system that has been developed for the USA, because the type of information provided by this system allows finer-scale, more comprehensive understanding of the fundamental hydrological and geomorphological drivers of wetland structure and function, allowing one to better address the causes of wetland degradation rather than just the symptoms. The following classification system gives a variety of different landform settings in which South African wetlands are typically found.

The inputs, throughputs and outputs of water will obviously be affected by the specific circumstances at each site. However, some generalizations can be made based on landform type and geomorphic setting (Table 5).

Table 5: Wetland landform settings and their influence over a wetland's hydrological components (adapted from Kotze, 1999 and Brinson, 1993)

LANDFORM SETTING	DEFINITION	HYDROLOGICAL COMPONENTS		
		Inputs	Throughputs	Outputs
Hillslope seepage not feeding a watercourse	Concave or convex slopes characterized by the colluvial (transported by gravity) movement of materials. Typically not connected to the drainage network.	Predominantly groundwater and interflow or diffuse surface flow	Interflow & diffuse surface flow	Evapotranspiration and groundwater flow
Hillslope seepage feeding a watercourse	Concave or convex slopes characterized by the colluvial (transported by gravity) movement of materials. Outflow is typically by channel into the drainage network.	Predominantly groundwater and interflow or diffuse surface flow	Interflow & diffuse surface	Variable but usually by channel flow and evapotranspiration
Valley bottom without a channel	Valley bottom areas of low relief with no clearly defined stream and situated on alluvial fill.	Channel entering the wetland and adjacent hillslopes	Diffuse surface and subsurface flow	Channel outflow and evapotranspiration
Valley bottom with a channel	Valley bottom areas with a well defined stream channel but lacking characteristic floodplain features. Water inputs are mainly from adjacent slopes while the channel itself is typically not a major source of water for the wetland.	Channel flow and adjacent hillslopes	Diffuse flow on elevated valley bottom and channel flow	Channel flow and evapotranspiration
Floodplain	A riparian area of low relief characterized by the alluvial transport and deposition of material by a well defined stream channel, which gives rise to characteristic floodplain features such as levees and oxbow lakes.	Primarily as channel overspill and/or tributary supply	Channel flow that during flood events becomes extensive diffuse surface flow	Channel flow and evapotranspiration
Depression (includes pans)	A basin shaped area with a closed elevation contour that usually is not connected via an outlet to the drainage network.	Variable	Insignificant	Evapotranspiration
Fringe wetlands	Areas on the edge of open water provided by lakes, dams or estuaries	Lake or estuary (tidal)	Diffuse surface flow	Lake or estuary (tidal)

11.2.1 Hillslope seepage wetlands not feeding a watercourse

Brinson (1993) identifies two processes that give rise to hillslope seepage wetlands, which are also sometimes called groundwater slope wetlands. The first arises because the water table intersects the land surface, either at the groundwater rest level or due to impermeable strata directing groundwater flow to the surface. The second is due to the upward movement of groundwater due to hydraulic forces, and it usually manifests in the lower portion of a break in slope. Such processes result in a small but consistent supply of water, which explains why these wetlands are characteristically small in spatial extent. A remarkable feature is that these wetlands may occur on very steep slopes of close to or greater than 30% (Kotze, 1999). Due to low discharges and diffuse flows, even on steep slopes, water in hillslope seepage wetlands is incapable of moving sediment, and wetlands thus form.

11.2.2 Hillslope seepage wetlands feeding a watercourse

In the source areas of streams, water from the local catchment enters the valley as diffuse flow from the wetland perimeter. Surface water flows in a slow and diffuse manner across the wetland in view of the high wetted perimeter in relation to wetland size. Such wetlands have a low cross-sectional area of inundation (low hydraulic radius in Manning's equation) and high Manning's roughness co-efficient due to dense vegetation cover, which contribute to the low velocities of water flow. As inflow of water increases downstream, so do water depth and velocity (and hence discharge) and a channel may form. Such channels typically lead into the drainage network.

11.2.3 Valley bottom wetlands without a channel

Valleys in upper catchments typically aggrade with sediment derived from the adjacent slopes. This sediment may be introduced from valley sides, which will tend to reduce gradient upslope of the point of sediment input. Alternatively, sediment may be introduced from the head of the valley, which will have the effect of steepening the gradient on the wetland surface downstream of the region of active sedimentation. Wetlands adjust gradient through the interaction of sedimentary processes, but if discharge and gradient are sufficiently low, and sediment supply is such that this low gradient is maintained, the wetland will be unchannelled.

Along higher order streams, gradient declines downstream and valleys may lose confinement. The capacity of the stream to transport sediment declines as a consequence, and flow spreads diffusely across the valley floor, even under low flow conditions, creating an unchannelled wetland. Alternatively, as a stream enters a region of very low relief, water may be lost downstream through evapotranspiration and loss to groundwater such that channel size and definition decline downstream (floodouts referred to in Section 7.4). The occurrence of unchannelled valley fill wetlands may be associated with such a loss of discharge downstream. Wetlands in lower catchment positions may thus be unchannelled for various reasons.

11.2.4 Valley bottom wetlands with a channel

In certain wetlands a channel may form due to high discharges and low rates of sediment input, with the channel leading into the fluvial network. In such cases the result is a channelled wetland that is not shaped fundamentally by fluvial processes typical of floodplains. Lateral channel migration is limited, and features indicative of lateral migration (meander cutoffs, oxbow lakes) are absent. Channels within valley-bottom wetlands are likely a response to valley climato-geomorphic characteristics such as high discharges and low rates of sediment input, whereas channels typical of large floodplains play a more active role in shaping the valley through which they flow.

11.2.5 Floodplain wetlands

On gentle slopes, most river valleys are covered with large quantities of alluvial sediment that make up a flat surface through which a river flows in a well defined channel. This surface adjacent to the river is called the floodplain as it is flooded during high flows when floodwaters overtop the riverbanks. Predominantly, channel flow occurs during most of the year and diffuse flow occurs on the floodplain during flood events. The frequency with which flooding takes place will vary greatly depending on local circumstances. Some floodplains flood several times a year, while others only flood once a year or every few years.

An important aspect of these settings is that deposition of bedload sediment may take place continuously in the channel, while suspended sediment is deposited on the floodplain only during large flood events. Deposition of this sediment is focused in close proximity to the channel. Channel morphology will vary depending upon the nature of the sediment load, with braided streams tending to characterise areas dominated by bedload sediment, whereas meandering channels tend to dominate areas with mixed sediment load.

Wetlands in this category contain many geomorphic features that make these systems heterogeneous in terms of substratum characteristics. On floodplains of meandering rivers, oxbow lakes abound and levees provide locally elevated ground. Extensive areas of prolonged, shallow flooding may occur in backswamps. In braided systems, islands and channels make up a complex environmental mosaic.

11.2.6 Depression wetlands (including pans)

As depressions (pans) tend to be isolated from the main drainage network, they are generally supplied predominantly by minor streams, groundwater and interflow. Depressions, by definition, have a closed elevation contour that promotes the accumulation of surface water. Thus, while some depressions may have an outlet, the outflow of surface water is generally very limited in these settings. The impermeable base of many depressions means that sub-surface loss of water is also limited.

Pans occur in a range of climatic settings and their origin is attributed to the interaction of geological, climatic and biological processes. They may occur as a result of drainage disruption due to warping or tilting of the earth’s crust in settings where topography is unusually flat. Drainage impedance due to the presence of impermeable substrata is also a factor contributing to pan formation. Such substrata may be present *in situ* in the geological strata underlying pans, or they may be deposited during humid phases when depressions would form lakes that would be associated with the deposition of fine sediments.

Along the coastal plain of northern KwaZulu-Natal a number of pans occur where depressions associated with beach ridges and coastal dune cordons intersect an elevated groundwater table. Closed drainage features may provide local catchments with surface water runoff or groundwater that discharges into the low-lying inter-dune depressions (pans). As such, pan inundation in these moist areas is linked to variation in groundwater elevation that takes place seasonally and over longer time periods. Lack of integration into the drainage network in this case is related to the exceptionally high porosity of these sandy soils, which tends to restrict surface runoff, erosion and development of channel networks.

11.2.7 Fringe wetlands

Fringe wetlands occur naturally on the edges of lakes. In South Africa, natural lakes are very uncommon. Lake Fundudzi in the northern part of South Africa is the only true inland lake in South Africa and owes its origin to a landslide across a river. In the inland areas of South Africa, fringe settings are largely confined to the edges of man-made impoundments. Coastal lakes support fringe wetlands that are seasonally flooded in response to seasonal variation in water level, as well as in permanently flooded areas that are sufficiently shallow to allow light penetration to the lake bed.

12 CASE STUDIES OF WETLAND ORIGIN AND EVOLUTION

Here we simply describe a number of case studies that have been undertaken through the Wetland Rehabilitation Research Programme investigating wetland origin and dynamics, which should illustrate the kind of data that one can assemble in order to understand wetlands.

12.1 Climate and base level: the Mfolozi Floodplain

The Mfolozi River floodplain is located on South Africa's subtropical eastern seaboard, approximately 250 km north of Durban (Figure 27). It is an extensive floodplain wetland system some 19 000 hectares in extent, of which 61% has been converted into highly productive sugar cane estate with the remainder being protected within the Greater St Lucia Wetland Park on the seaward end of the floodplain. The system is approximately 26 km in length and is bounded by the Lebombo Mountains to the west and the Indian Ocean to the east. The wetland system is fed by two main channels: the Mfolozi River, which enters the head of the floodplain via a confined valley through the Lebombos in the west, which tends to hug the northern floodplain boundary; and the Msunduze River, which enters the floodplain from the southwest and flows along the southern margin, and is diverted northwards close to the dune cordon before joining the Mfolozi River a short distance from the sea. The combined stream flows eastwards into the sea. Multiple lakes and pans of various sizes are located on the northern and southerm floodplain boundaries.

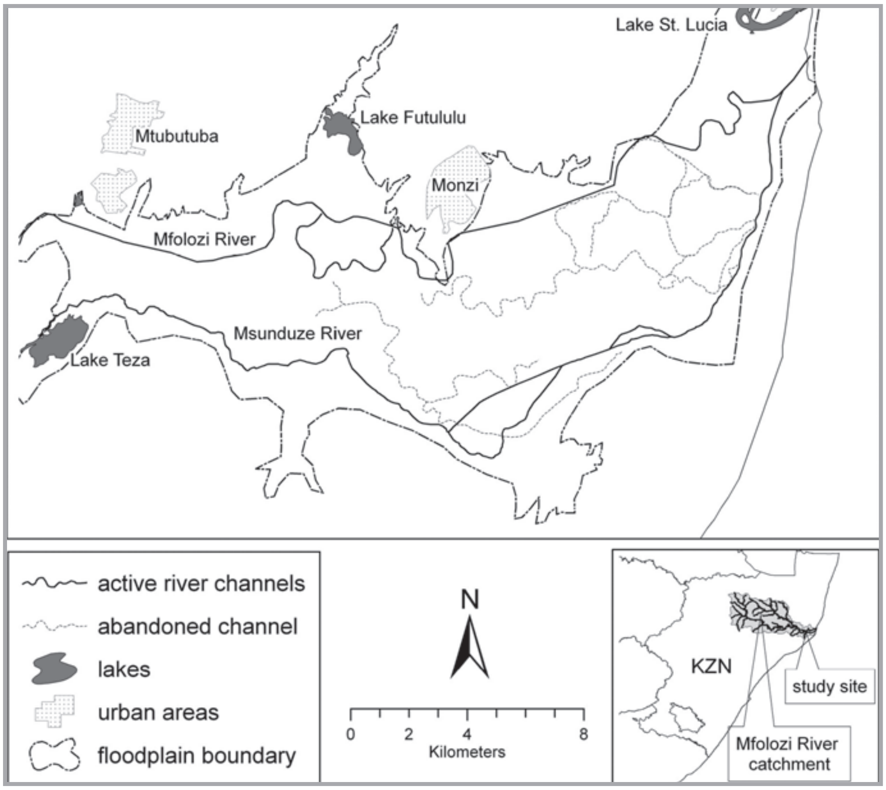

Figure 27: The Mfolozi floodplain on South Africa's subtropical eastern seaboard.

The origin of this wetland system owes much to the geological history of the area, as well as to the existing local setting of the floodplain. Approximately 179 Ma, the region was exposed to an episode of rifting that resulted in the eruption of the Lebombo Group rhyolites and basalts. This early event, occurring on the super continent of Gondwana, was the first episode to lead to the formation of a sedimentary basin in northern Natal in which the Mfolozi floodplain is now situated. The crust was further extended during rifting events that eventually separated the continents of Africa, South America and Australia, leading to localised subsidence. The Zululand Group was subsequently deposited in the newly formed basin, initially comprising alluvial deposits, and slowly grading into marine sediments as the ocean filled the expanding basin. Although the area underwent additional marine transgressions that initiate erosion and transgressions that initiate deposition, a major uplift event occurred 20 million years BP followed by a second uplift event 5 million years BP, which together amounted to well over 1000m of uplift. Thus marine sediments were exposed. During the last Ice Age that was initiated about 20 000 BP, sea level again dropped, reaching a maximum of 120m below MSL. Approximately 18 000 BP, a new erosional phase began, resulting in the carving of deep coastal valleys. However, sea level rise following the last Ice Age caused sea level to reach its current elevation of approximately 6 500 BP, which has led to the drowning and infilling of previously incised coastal valleys. It is the most recent rise in sea level that is largely responsible for the formation of the Mfolozi floodplain wetlands. Thus a change in base level ultimately altered the character of the Mfolozi floodplain from an area of incision to one of deposition. However, while the location of sea level exercises a strong control on the continued

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existence of the lower Mfolozi floodplain wetlands, the upper region is also affected by the shape of the floodplain.

Above the floodplain, the Mfolozi River follows a course in an incised confined valley (Fig 28A). Upon passing through the Lebombo Mountains, the valley widens considerably from 915 m to over 6 km in just 1.15 km. This rapid change from confinement to a broad floodplain setting also results in a reduction of carrying capacity of the Mfolozi River, creating a node of large-scale deposition at the floodplain head in the form of an alluvial fan (Fig 28B). Deposition in this region causes local steepening of the valley's longitudinal profile, with a gradient of 0.1% (Figure 28, longitudinal profile). Furthermore, the alluvial fan appears to have created lakes along the floodplain boundary where tributaries have been cut off by the fan's progradation. Contrastingly, the mid- floodplain is almost flat, with a decrease in elevation of just 1m over almost 6km (0.02%, Figure 28, longitudinal profile). The lower floodplain (Fig 28C), which appears to be largely controlled by base level, has a steeper gradient of 0.05% (Figure 28, longitudinal profile). The reason for the rather drastic slope break in the mid-floodplain is currently unknown, although it may be related to faulting in the underlying rocks of the Zululand Group, which is currently concealed by more recent deposits.

Overall, a preliminary analysis of the Mfolozi floodplain wetlands suggests that an influx of sediment is vitally important in maintaining the integrity of the wetland system. Without ongoing sedimentation, natural subsidence of the floodplain (with compaction and dewatering of the floodplain sediments) would result in marine incursion. All activities that disrupt sedimentation on the floodplain should thus be controlled, particularly in light of current predictions of global warming and sea level rise.

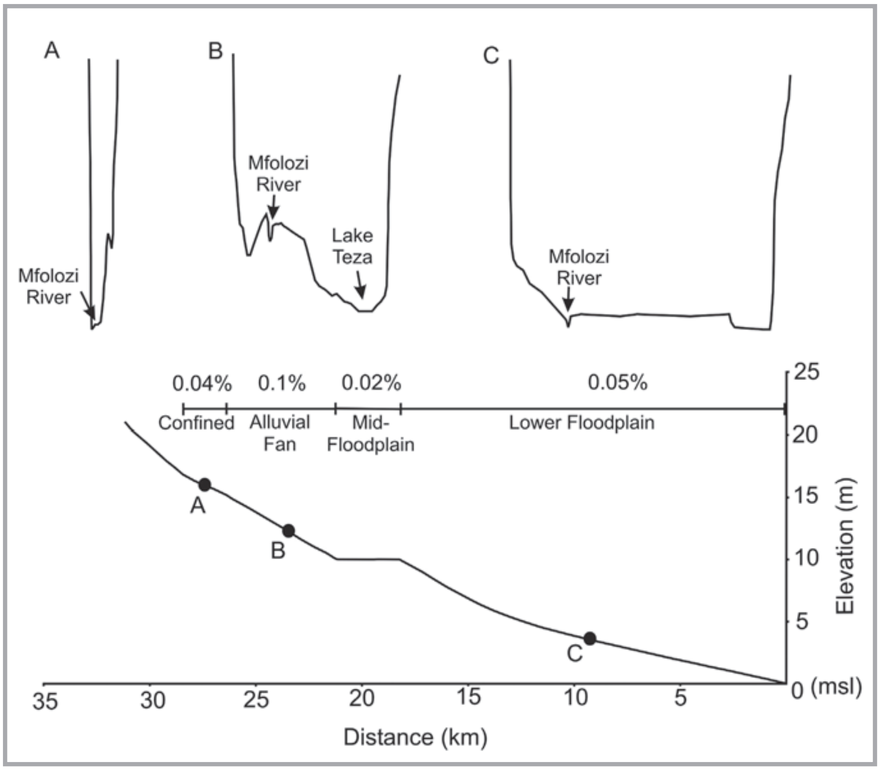


Figure 28: Cross sections and longitudinal profile of the Mfolozi River valley and floodplain

12.2 Geomorphological controls: the Nylsvlei Wetland

The Nylsvlei wetland occupies the valley of the Nyl/Mogalakwena River and stretches over a distance of approximately 70km (Figure 29). The longitudinal profile of the Nyl/Mogalakwena River (Figure 30) shows that the wetland occupies the valley where the longitudinal slope is 0.05%, and downstream of the wetland the slope steepens by an order of magnitude to 0.6%. The wetland terminates at this break in slope. Boreholes in the wetland have been put in place to provide water supply, and indicate the depth to bedrock. Bedrock is only exposed in the bed of the river below the Nebo Granite.

The Nyl/Mogalakwena River and wetland spans a range of geological formations and several faults, and there is no link between the break in slope and any geological features. The positions of the confluences of the larger tributaries to the Nyl/Mogalakwena River are also shown in Figure 30. The two tributaries between the Ysterberg Fault and the change in slope, the Rooisloot River and the Dorps River, drain large and elevated catchments to the east of the wetland. They flow on extensive alluvial deposits in the vicinity of their confluences with the Nyl/Mogalakwena River. This reduces gradient upstream along the Nyl/Mogalakwena River, and has led to sedimentation along the Nylsvlei upstream of this point that is responsible for origin of the Nyl floodplain and wetland.

The longitudinal profile illustrated in Figure 30 has been compiled from a series of 1:50 000 maps, 1:10 000 orthophotographs and the 1:250 000 geological map of the area. Depth to bedrock was obtained from external sources. It is clear that the break in slope at the toe of the wetland is linked to the termination of the wetland, neither of which is linked to the presence of a geological structure or change in lithology. A field investigation revealed the break in slope and termination of the wetland to be associated with coarse deposits (boulders grading downstream into coarse sand) of the two tributary streams, the Dorps River and the Rooisloot River, which extend to the floodplain. These sediments contrast with those of the floodplain itself, which comprises clay sediments. These coarse deposits in the vicinity of the Dorps and Rooisloot Rivers represent large alluvial fans from tributary streams that are drowning the Nylsvlei Valley from the south-east, lowering gradient upstream and leading to wetland formation.

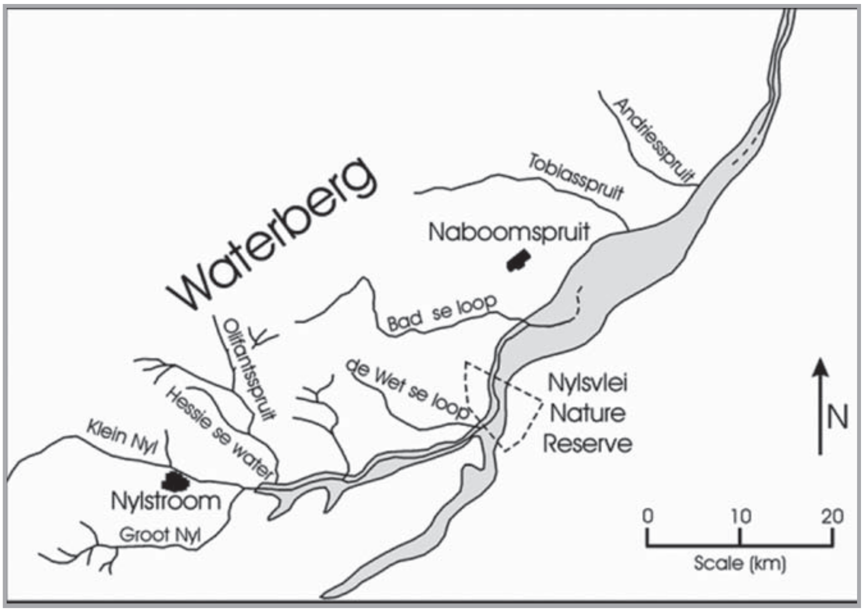


Figure 29: Nylsvlei and surrounding catchment

12.3 Geological control: Stillerust Vlei and Hlatikulu Vlei

Stillerust Vlei and Hlatikulu Vlei are large wetland systems located approximately 150km northwest of Durban in the foothills of the KwaZulu-Natal Drakensberg Mountains (Figure 31).

12.3.1 Stillerust Vlei

Stillerust Vlei is a 189ha wetland system comprising a floodplain of the Mooi River and a floodplain-abutting valley bottom wetland, associated with two small tributaries to the Mooi. The Mooi River meanders extensively within the floodplain of Stillerust Vlei, forming numerous oxbow lakes through meander cutoff (Figure 32a), but flows on a straighter course with abrupt, angular changes in orientation immediately upstream and downstream of the floodplain, where the river is superimposed upon dolerite, or dolerite crops out in the valley side-walls (Figure 32b). In cross-section, the Mooi River valley is confined within steep-sided valleys through dolerite reaches (profiles A and C, upstream and downstream of the wetland respectively, Figure 33), but is broad and gently-sloped through reaches underlain by Tarkastad Formation sediments (profile B, in the middle reaches of the wetland, Figure 33). It is within this broad, gently-sloped valley (profile B, Figure 33) that Stillerust Vlei has formed.

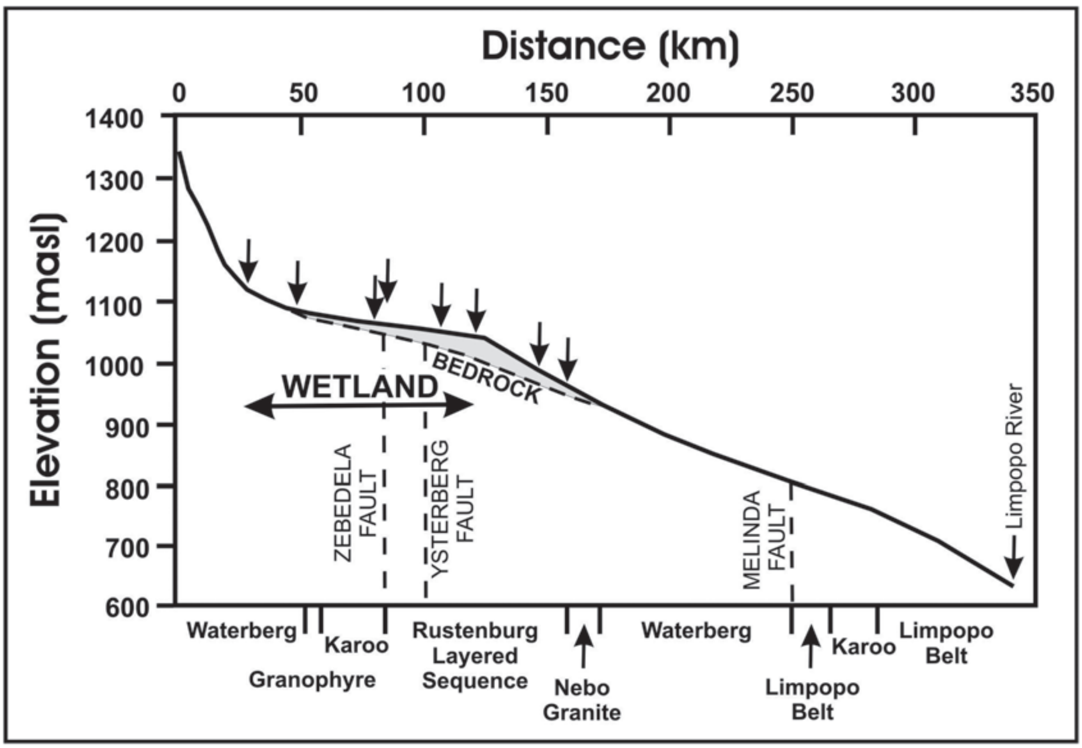
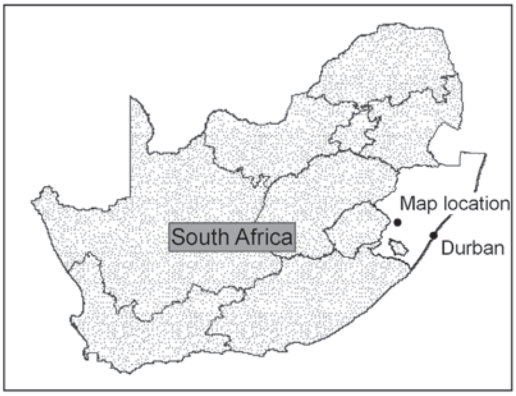


Figure 30: The longitudinal gradient of the Nylsvlei wetland superimposed on geological features (bedrock and structural) and the points of entry of tributary streams into the wetland (downward-pointing arrows). The break in slope at the lower end of the wetland is associated with incision of a stream draining the wetland (Mogalakwena).

The longitudinal profile of the Mooi River through Stillerust Vlei (Figure 34) shows that the longitudinal slope of the valley occupied by the wetland is low (about 0.2%), while downstream of the wetland within the confined dolerite valley there is a step-change in slope (from 0.2 % to about 4.5%). This change in slope quite spectacularly marks a transition from slow vertical erosion along joints and fractures in the highly resistant dolerite sill at the toe of the wetland, to relatively more rapid lateral erosion associated with bedrock planing of the less resistant Tarkastad Formation sediments underlying the wetland itself. The dolerite sill marking the toe of Stillerust Vlei is harder and more resistant to erosion than the Karoo Supergroup sediments into which it intruded. Thus, following superimposition of the Mooi River upon the sill, the sill has eroded more slowly than the surrounding Karoo sediments, forming a stable local base level for the river upstream. Most of South Africa's rivers are in a long term state of active incision (down-cutting) following intense continental-scale uplift between 20 and 5 million years BP (McCarthy and Hancox, 2000). Where down-cutting is impeded following the superimposition of existing river courses on dolerite intrusions, rivers use available energy to laterally plane the less resistant rocks upstream of the erosion-resistant dolerite dykes. As a result, wide gently-sloping valleys are carved by rivers upstream of the dolerite local base levels and floodplain wetlands result. This process is described in detail by Tooth *et al*. (2002, 2004).



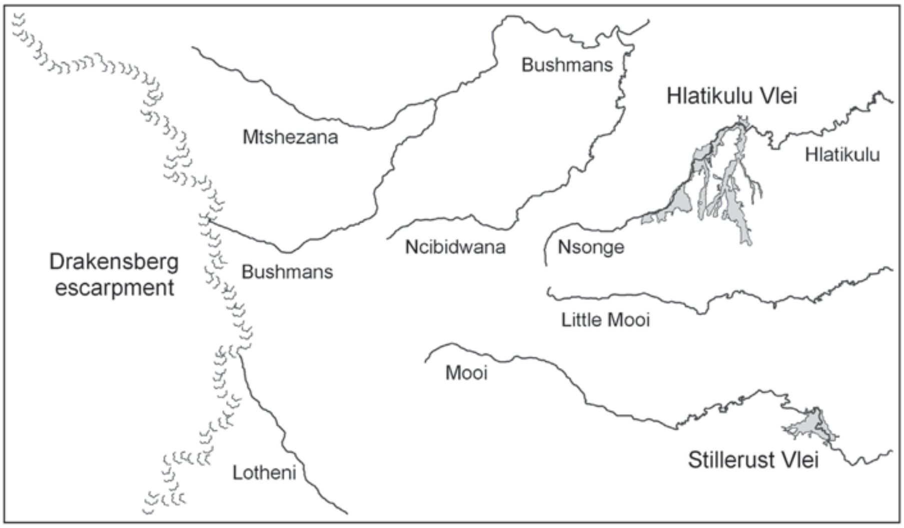


Figure 31: Location of Stillerust Vlei and Hlatikulu Vlei in relation to the KwaZulu-Natal Drakensberg escarpment, and major rivers of the region.

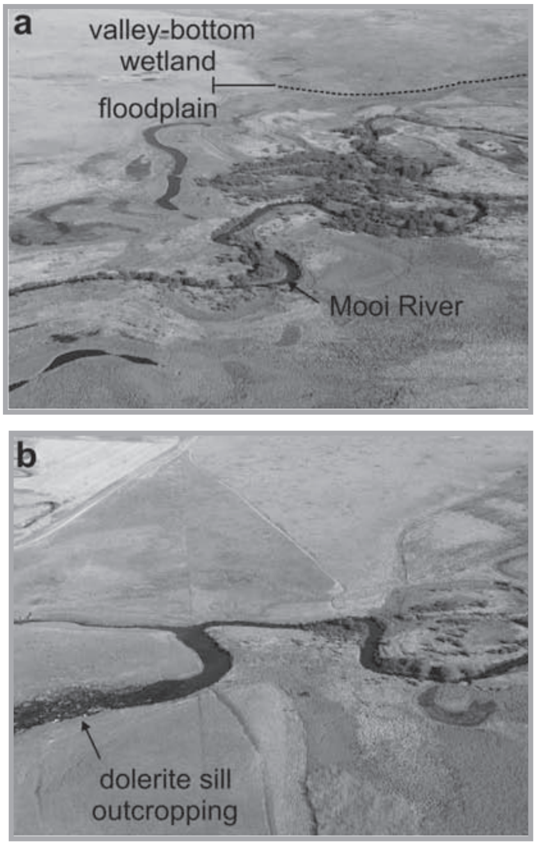


Figure 32: Photographs of Stillerust Vlei floodplain and abutting valley bottom wetland (a), and the large dolerite sill marking the distal part of the system (b). Note the angular orientation of the Mooi River where it is superimposed upon the dolerite sill, and meandering planform and **oxbow lakes of the river within the floodplain.**

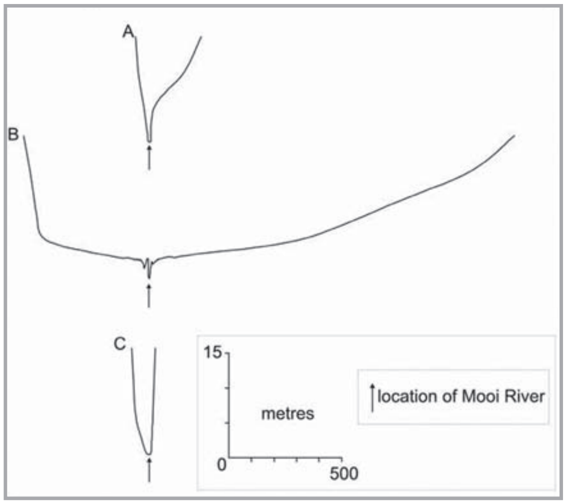


Figure 33: Cross-sections of the Mooi River through Stillerust Vlei, showing underlying lithology (adapted from Grenfell, 2007). Compiled from orthophotographs with a 5m contour interval, and differentially corrected GPS data.

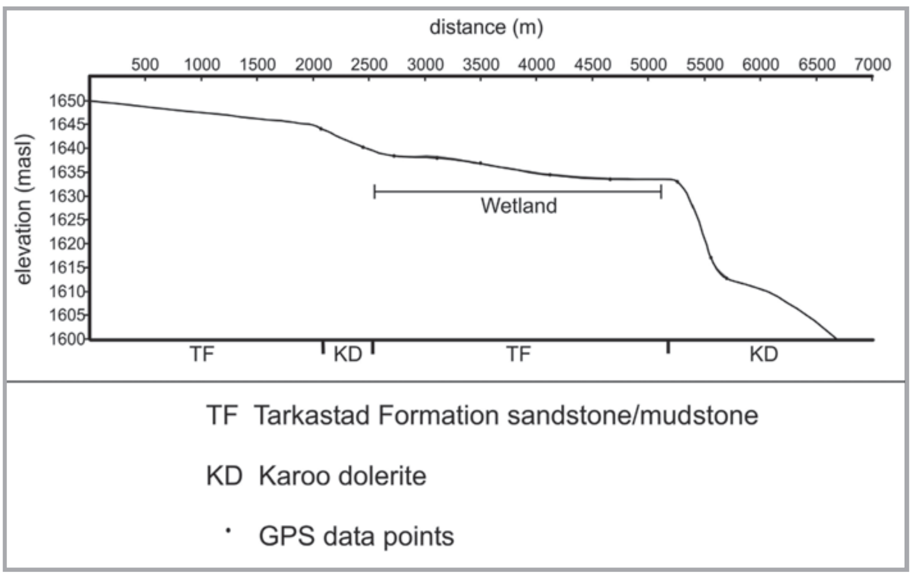


Figure 34: Longitudinal profile of the Mooi River valley in the region of Stillerust Vlei (adapted from Grenfell, 2007).

12.3.2 The Nsonge River floodplain at Hlatikulu Vlei

Description of the system

Hlatikulu Vlei is a 731 ha system of floodplain and valley bottom wetlands comprising two 'arms' that drain northwards towards their coalescence immediately upstream of a small dolerite dyke, marking the distal end or 'toe' of the system (Figure 36 on following page). This dyke has influenced the geomorphic evolution of the Nsonge River and floodplain in ways described for the Mooi River and floodplain in the Stillerust Vlei case study. The Nsonge River meanders through the western arm of Hlatikulu Vlei within a mostly broad floodplain, but flows on a relatively straight course through the lower floodplain due to a recent avulsion (wholesale abandonment of one river course in favour of another). Sinuosity of the pre-avulsion Nsonge River approaches ~ 3 in places and it is this meandering planform to which the river likely owes its name (*Nsonge* is an isiZulu word for 'bent' or 'twisted'). A large portion of the Nsonge River floodplain has been deep-flooded following the emplacement of a dam across the valley, and there is evidence in the form of a large lacustrine delta and several sedimentary islands (Figure 35 below) that this dam has trapped a large amount of sediment. This dam, together with the road (28S; Figure 38) crossing the lower floodplain, has profoundly influenced floodplain geomorphology, as will be described next.

Figure 35: An aerial view of the dam on the Nsonge River. Note the large lacustrine delta at the entry point of the river to the dam and several reed-covered sedimentary islands.

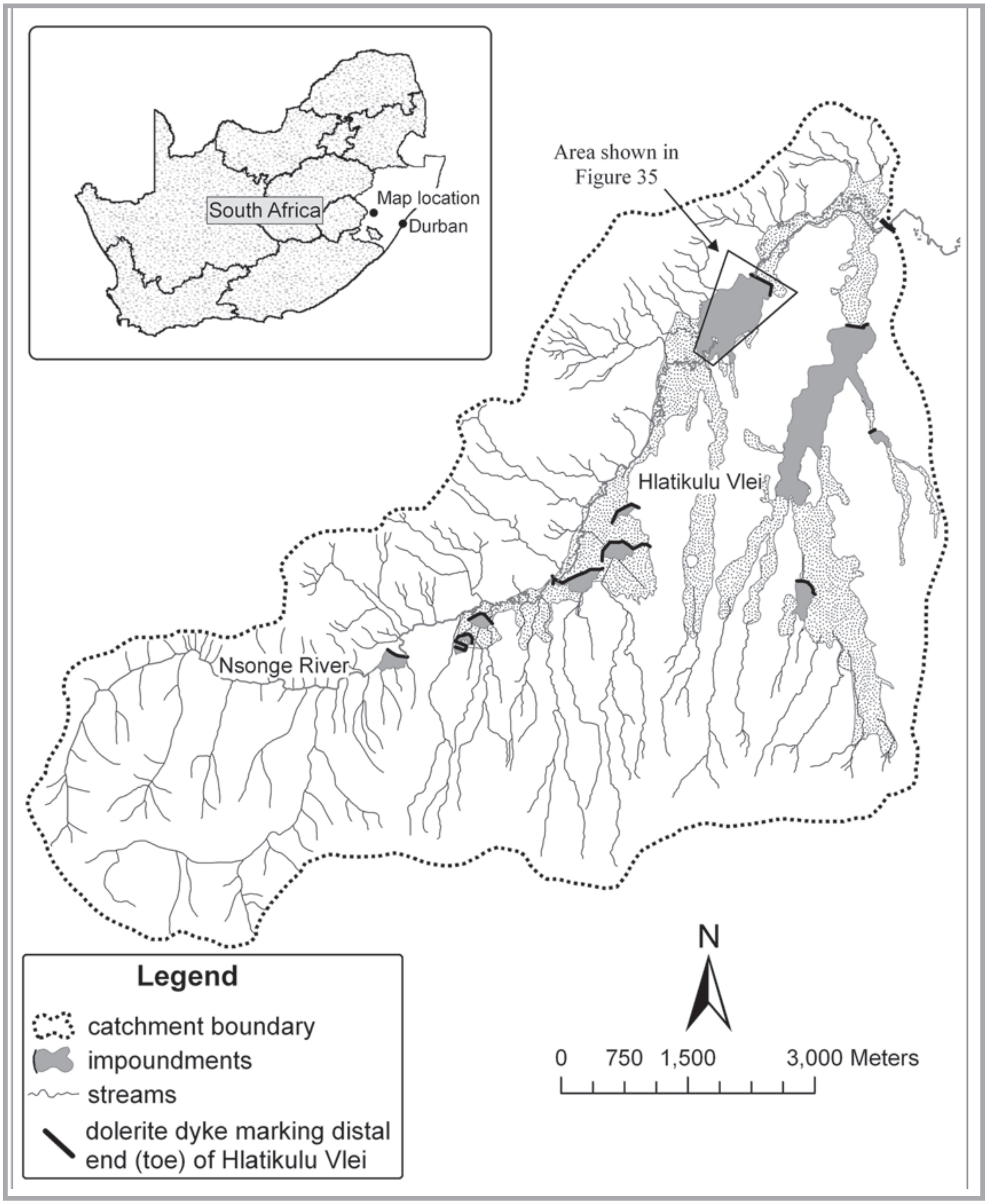


Figure 36: A map of Hlatikulu Vlei, showing the location of road crossings and impoundments within the system.

Processes of change within the Nsonge River floodplain

Inspection of historical aerial photography reveals that several changes to the geomorphology of the Nsonge River floodplain have occurred in recent time (Figure 38 on following page). By 1944, several willow trees (*Salix* spp.; Figure 37) had colonised the banks of the Nsonge River (in the region of 'a', Figure 38). Later settlement of the steep southeast-facing slopes adjacent to the floodplain near 'a' (Figure 38) and concomitant overgrazing by cattle, possibly increased sediment loads supplied to the Nsonge River by tributaries draining these slopes. In c.1960, the road (28S) crossing the lower Nsonge River floodplain was formalised by (1), raising and straightening the dirt track laid across the alluvial ridge of the river, and (2), excavating a furrow parallel to the road ('b' in Figure 38) to reduce flooding. This furrow was linked to a pipe culvert beneath a farm road that allowed access to the 28S from a dwelling located on the low ridge of land separating the eastern and western arms of Hlatikulu Vlei. Two culverts were emplaced beneath the 28S, one at the crossing of the Nsonge River, and one connecting the furrow with the Nsonge River as it exits the floodplain and enters the confined valley below the floodplain (below the dyke). While the former culvert effectively 'anchored' the Nsonge River at the road crossing, locally restricting lateral migration, the latter provided an efficient and direct exit path for floodwaters impounded by the road, and restricted local passage of water to the northernmost part of the floodplain. A dumpy level survey at the crossing of the 28S indicated that the thalweg of the furrow at this point is 0.43 m lower than that of the former meandering Nsonge River course.

Figure 37: Willow trees (*Salix* spp.) at the point where the Nsonge River breached its channel.

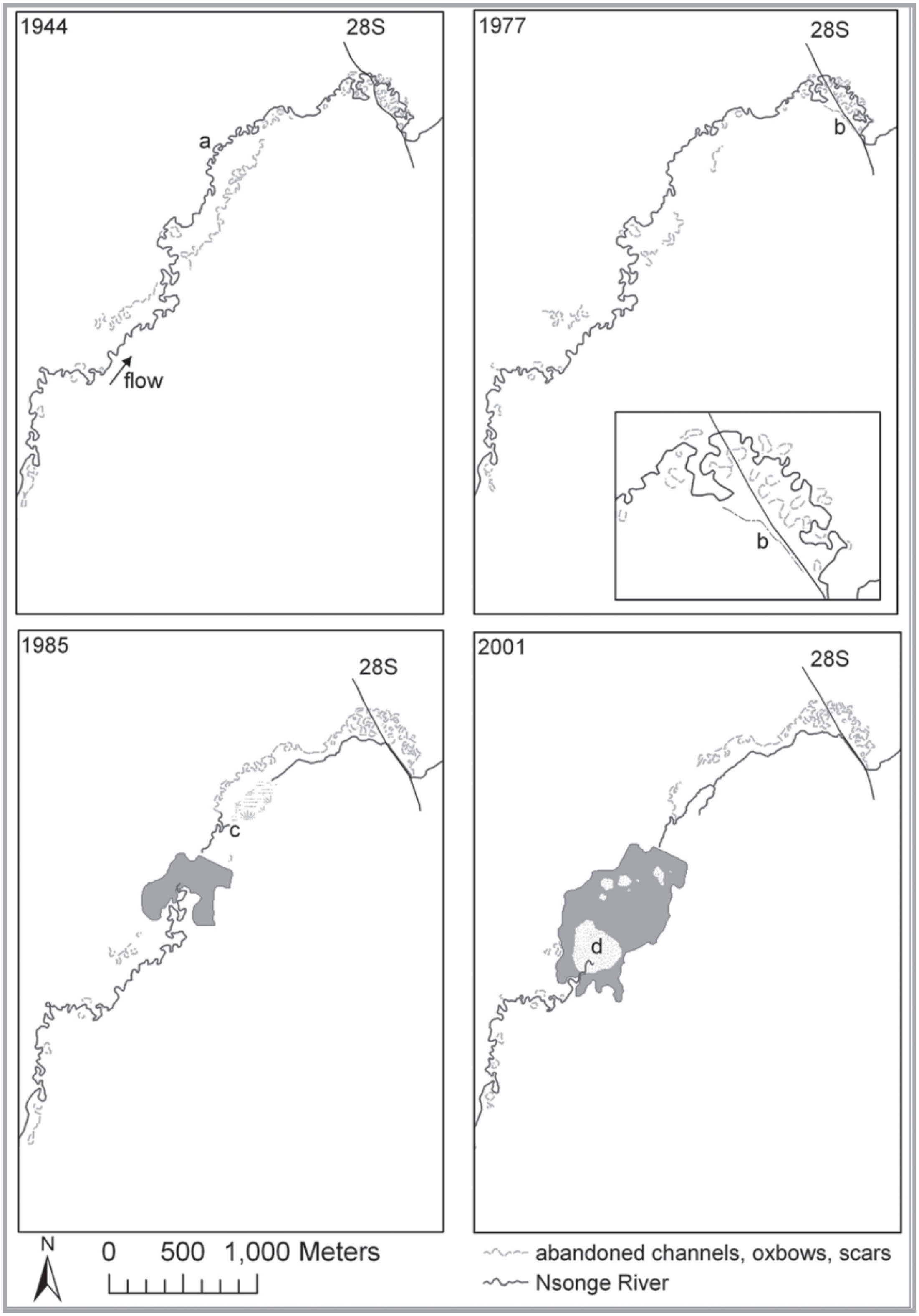


Figure 38: Geomorphic change within the Nsonge River floodplain, 1944 – present.

In 1983, a dam was built across the Nsonge River floodplain. In the 1985 photography it is evident that the Nsonge River had breached the right levee (at 'c' in Figure 37) and had begun to abandon its course along the northwestern margin of the floodplain in favour of one to its south. In addition, the furrow parallel to the 28S had eroded headward, through the culvert beneath the farm access road, a considerable distance upstream (0.9 km from the head of the furrow parallel to the 28S) along the south-eastern margin of the floodplain. At this stage, however, the breach of the Nsonge River and the channel eroding headward from the furrow were separated by an area of intact backswamp.

The dam across the floodplain was raised in 1993, deep-flooding a large area of floodplain and trapping large quantities of sediment (evident in the lacustrine delta, 'd' in Figure 38, and islands of sediment deposited close to the dam before it was raised; Figure 36). Low flows exit the dam via a pipe drop-outlet linked to the Nsonge River course on the western side of the dam. However, the flood spillway of the dam is located on the eastern side of the dam, routing flood flows directly through the backswamp in this area. As a consequence, a secondary channel has eroded headward into the backswamp from the new course of the Nsonge River. By 2001, the breach and headward-eroding channel (from the furrow at the 28S) had joined, and the Nsonge River had established a new course through the floodplain. The former river channel is now barely evident near the stand of willows, as it has been filled in by sediment from a tributary draining the steep adjacent southeast-facing slope.

Understanding the dynamics

Abandoned meander belts within the lower Nsonge River floodplain evident in 1944 aerial photography indicate that avulsions of the Nsonge River had occurred prior to the most recent avulsion, and in the absence of roads, dams and other major human infrastructure or influence. Meandering rivers over time become primed for avulsions due to (1) an increase in gradient away from the river channel (across-valley) through the building of natural levees and an alluvial ridge, and/or (2) a decrease over time in the hydraulic and sediment transport capacity of a channel that promotes increasingly frequent and repetitive overbank flows such as are due to increases in sinuosity. When and where avulsions occur within a floodplain may depend upon temporally and spatially intermittent phenomena, such as the excavation of the furrow parallel to the 28S.

The likely mechanism by which channel realignments occur in the Nsonge River floodplain is 'incisional avulsion' (Slingerland and Smith, 2004): incision associated with the re-entry of floodwaters from the backswamp to the river channel via low points in the levee or bank, and consequent headward erosion of the newly incised channel through the backswamp to a point where it intersects the original channel upstream. However, it appears that the most recent avulsion occurred following development of two initial channels, one an overbank breach of the Nsonge River channel ('progradational avulsion', Slingerland and Smith, 2004; usually associated with sediment lobes that fan out away from the breached channel, called crevasse splays, that are not present at Hlatikulu Vlei due to the limited and fine-grained sediment load of the Nsonge River), the other an actively headward-eroding channel that originated at the furrow adjacent to the 28S.

Thus the perception that the recent avulsion in the lower Nsonge River floodplain was entirely a consequence of recorded human land use and management practices should be avoided. What is clear, however, is that the avulsion was greatly accelerated by (1) excavation of a furrow providing an hydraulically efficient path of flow by which floodwaters could drain from the backswamp adjacent to the elevated alluvial ridge, (2) emplacement of a dam on the Nsonge River trapping sediment and thus increasing the capacity of flows below the dam ('hungry water'; Kondolf, 1997), and (3) the cluster of Salix spp. and elevated sediment supply from adjacent slopes in combination impeding flow and causing within-channel aggradation, thus locally reducing the hydraulic and sediment transport capacity of the channel. These practices controlled when, where and partly how the avulsion occurred. However, human infrastructure and influence did not determine why the avulsion occurred, because the effects of human infrastructure and influence on the fundamental controls of the avulsion (discussed earlier), although produced at an accelerated rate, were the same as those produced in these settings without human infrastructure and influence.

Death of a floodplain, birth of channelled valley bottom wetland

Prior to the avulsion, the culvert beneath the 28S 'anchored' the Nsonge River at a fixed point, locally restricting lateral migration. Since the avulsion, the new course of the Nsonge River has begun to erode laterally and establish a meandering planform. However, with the river now anchored at the culvert of the furrow that forms part of its present course, the potential for the Nsonge River to naturally reinstate the lateral migration/cutoff/avulsion geomorphic dynamic characteristic of these floodplains is low as the road crossing limits the potential for future change. Besides, the establishment of meandering along the new channel will likely take several millennia, as has been the case for avulsed channels of the Klip River (Tooth *et al.*, 2007). In addition, with the dam on the Nsonge River depriving the floodplain downstream of sediment, the lower floodplain has become an environment of sediment export, whereas before it was one of sediment accumulation. Thus, for as long as the 28S and dam remain, so too will their effects on the lower Nsonge River floodplain.

While the rehabilitation of fluvial systems, including wetlands, is largely concerned with rectifying effects of past disturbances, for interventions to be sustainable it is important to understand how a system is likely to change in future (Brierley and Fryirs, 2005). Understanding the origin and evolution of a wetland allows one to diagnose causes of change, and thus to better predict future effects of interventions. An attempt will be made within the next few years to rehabilitate the lower Nsonge River floodplain by emplacing several small weirs across the newly avulsed channel, effectively converting part of the floodplain to discontinuous-channelled valley bottom wetland. The intention of the planned intervention in the lower Nsonge River floodplain is to recover desired, rather than former ecosystem structure, function, biotic composition and/or ecosystem services. It is acknowledged that this approach is a poor surrogate to allowing the floodplain to recover by natural processes (or to assisting its recovery by removing the dam and moving the road), but it is considered a cost-effective way of recovering some ecosystem services lost following the avulsion (such as flood attenuation and sediment trapping), since Working for Wetlands are unlikely to have the resources to remove the dam and move the road. Without removing the dam and moving the road, the former natural geomorphic dynamic of the Nsonge River floodplain will not be reinstated, but it is hoped that the wetland will at least provide habitat for biota and ecosystem services to society to a greater extent than it does currently.

Perceptions of geomorphic change are often based upon a superficial understanding of a system, or local knowledge of a system that spans a single human lifetime. This case study shows how developing an understanding of wetland origin and evolution, an understanding that extends beyond what is surficially observable or recordable in human memory, provides an invaluable context within which to interpret geomorphic change. An understanding of the natural geomorphic dynamic of a wetland also allows the determination of natural ecosystem recovery and rehabilitation potential following human disturbance. In this case, the lower Nsonge River floodplain will not recover by natural processes unless the dam on the Nsonge River is removed and the road crossing the lower floodplain moved. Thus it is understood that reinstating the former natural dynamic of the floodplain is possible, but the interventions required are perhaps not justified given the scarcity of resources allocated across a range of similar wetlands in the region.

12.4 Conclusion

The case studies illustrate the nature of natural and human-induced controls on wetland behaviour. The area of research is at an early stage of its development and South Africa offers remarkable opportunities to appreciate wetland origin in a setting that differs fundamentally from northern temperate settings, which, unlike South Africa, are situated at relatively low elevation, have experienced recent glaciation that ended approximately 8000 years BP, and have climates that are more conducive to wetland formation.

13 KEY HYDROLOGICAL AND GEOMORPHOLOGICAL INFORMATION FOR WETLAND REHABILITATION

13.1 Introduction

In order to rehabilitate a wetland effectively, it is necessary to treat the causes of degradation rather than just the symptoms. Here we provide some information on the kinds of insights you can readily obtain in order to help you understand the causes of degradation. These methods are of interest if you are simply trying to understand a wetland, or if you are using the tool WET-Health that forms part of this series. We will focus primarily on geological, geomorphological and hydrological information that may be useful. Before embarking on any rehabilitation work on a wetland, it is important to establish, in general terms at least, why the wetland formed where it did and how it functions. Processes taking place in a wetland that appear to be degrading it may in fact simply be part of normal wetland evolution, and in such cases intervention should work in sympathy with natural processes. In some cases it may even be undesirable to attempt rehabilitation. Understanding how a wetland formed, how the wetland changes naturally over time and how humans have influenced or altered the natural character and functioning of the wetland is an exciting learning process, but may initially seem daunting. In Figure 39, we present a framework designed to guide you through this learning process. It engages questions such as ‘What is the system like?', and 'How does the system work?', and attempts to gain some understanding of natural change and the apparent future trajectory of change. It also attempts to assess the extent to which human intervention has altered the natural dynamic. Sections 13.2 to 13.4 offer practical guidance in applying the framework, and we return to describing the framework in more detail after these sections. The thinking behind Figure 39 is strongly based on the 'River Styles Framework' of Brierley and Fryirs (2005), used extensively in planning river management and rehabilitation programmes in Australia.

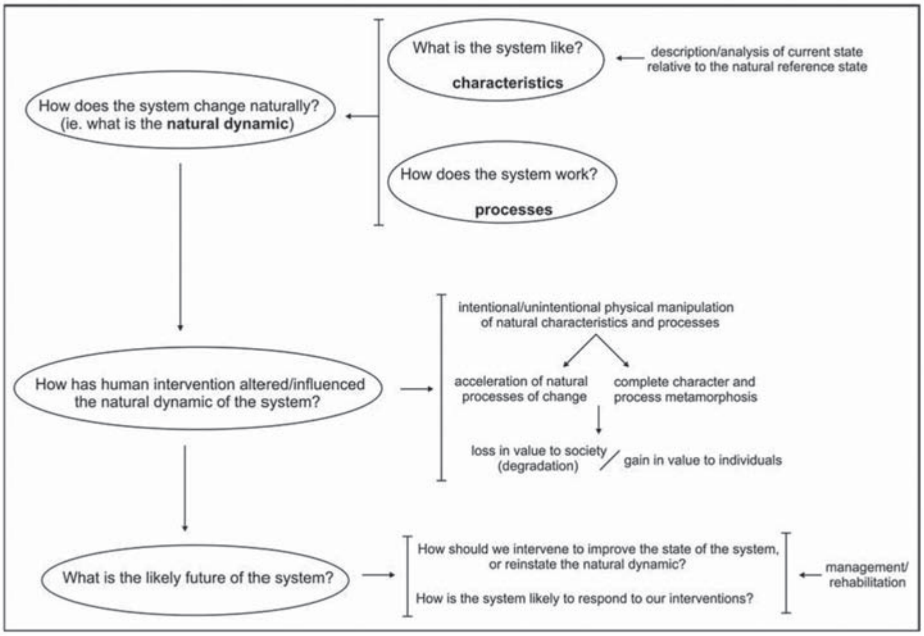


Figure 39: A framework for assessing wetland origin and evolution and applying the understanding to wetland management and rehabilitation (based on Brierley and Fryirs, 2005).

13.2 Geological and geomorphological setting

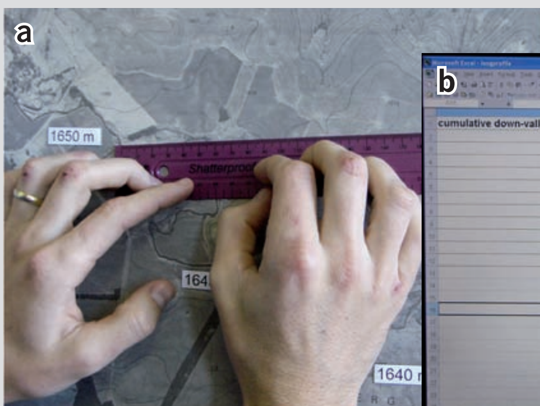
13.2.1 Material and tool requirements

- Geology maps (1:250 000 scale, or finer resolution if available): contact the Council for Geoscience, Pretoria, or your local University Geology Department.
- Orthophotographs (1:10 000 scale, contour interval varies): contact Surveys and Mapping, Mowbray, Cape Town.
- Topographical maps (1: 50 000 scale, 20 m contour interval): as for orthophotographs.
- Aerial photography (scale varies, try to obtain a sequence of photographs from the 1930s/40s, when the first flights were undertaken, to present): contacts as for orthophotographs.
- GIS (or tracing paper, graph paper, ruler)
- Spreadsheet software (MSExcel or equivalent)

13.2.2 Data requirements

The geomorphic setting of a wetland is best understood by determining wetland longitudinal gradient and cross-sectional characteristics from the most detailed topographic maps or orthophotographs available. Orthophoto maps are readily available from relevant Government Departments, and are the best map to use for this purpose. For the wetland in which you are working, plot a longitudinal profile (Figure 41 on following page) of the valley as far downstream as its confluence with the next large stream you encounter, even if this is several or even tens of kilometres downstream for large wetlands. Follow this by plotting the longitudinal profile of the main stream into which your tributary flows, or if you are working on a wetland that is on the main stream, plot the longitudinal profiles of significant tributaries that join the main stream. Plot these on the same set of axes as the longitudinal profile.

Plotting a longitudinal profile is a simple exercise. Begin by noting the points at which contours cross the thalweg of the valley you are working in (contour crossings, Figure 41). Next you should draw (or digitise, if you have access to GIS software) the valley axis line – a line approximately marking the valley thalweg. The valley axis line will track the river in confined parts of the valley, but will cut straight down-valley where the river meanders over gently sloping, unconfined valley floor (Figure 41). Now you should measure cumulative down-valley distance from your chosen starting point to your chosen end point (Figure 40a), and record, in a spreadsheet, measurements of cumulative down-valley distance where each contour crosses the valley and the corresponding elevation of this contour (Figure 40b). Finally, use the spreadsheet software to plot a scatter graph of your data, with cumulative down-valley distance from the chosen starting point on the x-axis against elevation on the y-axis (Figure 40c). This graph will



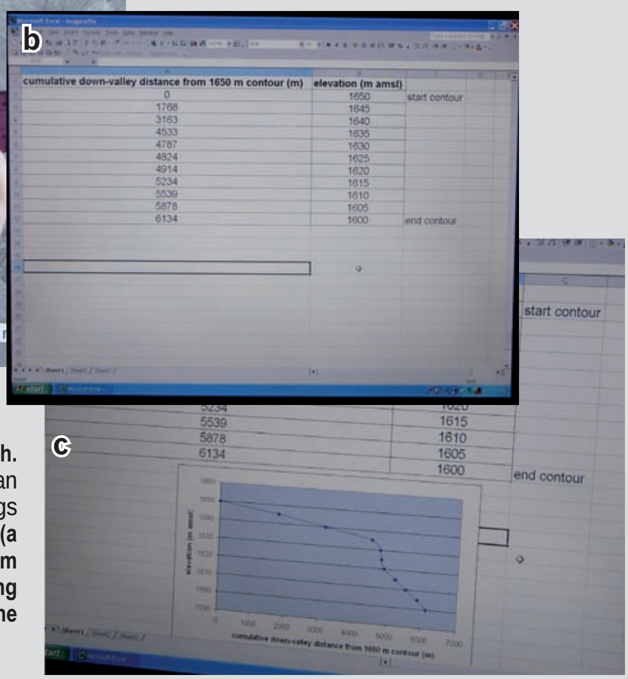


Figure 40: Plotting a valley longitudinal profile using contour crossings of the Mooi River on a 1: 10 000 orthophotograph. The sequence of images shows an orthophotograph on which contour crossings **and the valley axis line have been marked (a - Fig 41), measuring cumulative distance from the chosen starting point (b), and capturing the data in a spreadsheet (c), and plotting the graph (d).**

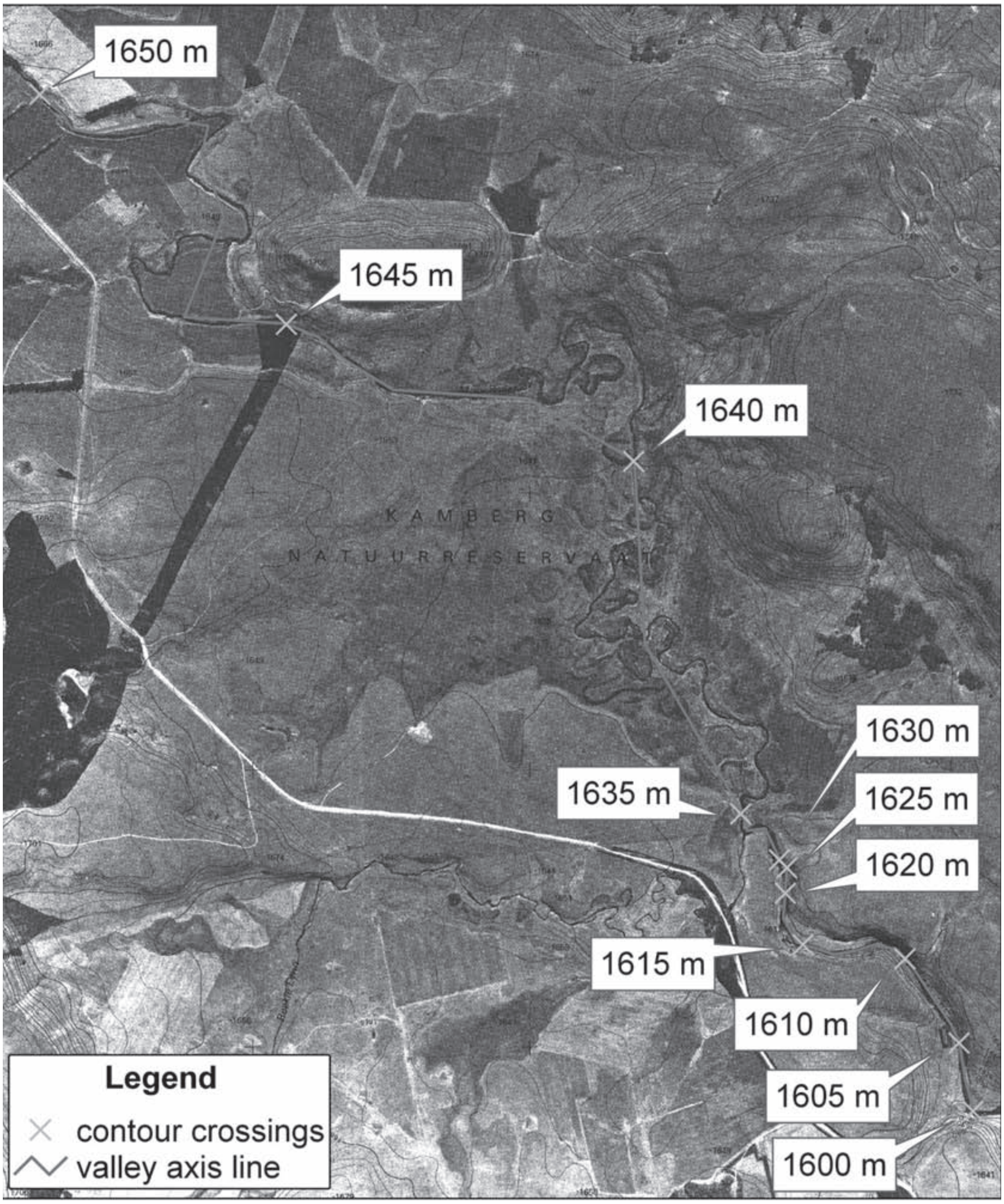


Figure 41: Plotting a valley longitudinal profile using contour crossings of the Mooi River on a 1: 10 000 orthophotograph. The sequence of images shows an orthophotograph on which contour crossings and the valley axis line have been marked (Fig. 41), measuring cumulative distance from the chosen starting point (Fig. 40a), and capturing the data in a spreadsheet (Fig. 40b), and plotting the graph (Fig. 40c).

form the basic longitudinal profile on which you will situate features of interest such as underlying lithology or tributary confluences.

It is useful to get a sense of the variation in valley cross-sectional characteristics along the valley being investigated. Is the valley confined upstream and downstream of the wetland, and how does valley cross-section vary with longitudinal slope? There may be a sudden increase in longitudinal slope as the stream leaves the wetland, suggesting geological control of the wetland, or there may not be a dramatic reduction in valley width as longitudinal slope increases, suggesting a geomorphological control such as a lateral alluvial fan from a tributary stream entering the valley. Use your abilities as a detective to appreciate why your wetland exists. You will discover a deep sense of gratitude as you begin to appreciate why wonderful, wonderful wetlands exist, and how you can begin to address the underlying causes of their degradation, rather than just treating the symptoms.

Next you should attempt to establish how the wetland is related to its sediment fill. If the stream or wetland is incised, try and find areas of rock outcrop along this valley that have been exposed by erosion, and plot the location and elevation of the bedrock on the longitudinal profile. Carefully note the nature of material exposed in the gully walls, looking for evidence as to its origin (e.g. alluvial or colluvial valley fill). Generally, colluvial sediment (sediment that moves down a valley side slope under the influence of gravity) is poorly sorted, the particles varying in size, and it lacks stratification, with particles not arranged in defined layers. In contrast, alluvial sediment (sediment that is carried and deposited by flowing water) is better sorted. Particles of a similar size are carried a similar distance by the flow of water. Thus large particles carried in flow will be deposited in higher-energy environments such as alluvial fans. Small particles carried in flow will be deposited in lower energy environments such as floodplain backswamps, and exhibit stratification Successive flows onto a floodplain will result in the deposition of layer-upon-layer of clastic sediment. These layers would be observable in a gully side-wall or in a soil core. If the wetland is small, auger some holes or take a number of cores in the middle of the valley in which the wetland is situated to establish the depth to bedrock. In the case of large wetlands, boreholes may exist that will provide depths to bedrock. Alternatively, the construction of bridges across rivers on floodplains will require geotechnical information that involves drilling to bedrock. Plot the depth to bedrock on the longitudinal profile in their correct locations. Now locate the positions of any geological features that may form a barrier of some kind. It is useful to transpose the main geological formations onto the longitudinal topographic profile using information readily available from 1:250 000 scale geological maps.

If the wetland is receiving sediment, say from a river, it is important that you try to understand, at least qualitatively, the sediment budget. Is the wetland accumulating sediment, or is sediment likely to be passing through the wetland? In this regard, locate the erosional feature that you are attempting to rehabilitate on your profile, and try and understand why the erosion occurs where it does. Alternatively, stand on the stream bank and get a sense of whether a levee is present, and of whether the channel banks are elevated relative to the surrounding wetland terrain, in which case the sediment that created these features will come from the inflowing stream. Is it downstream of a minor tributary where the local catchment has been developed into a complex of townhouses or retirement homes? In such a case the focus of rehabilitation attention may best be on this portion of the catchment. Perhaps the erosional feature starts or ends at a significant change in slope that is associated with a major geological feature such as a fault or the presence of a dolerite dyke that is resistant to erosion, or some other geological feature. This is a key point in the wetland that may well be focused upon during rehabilitation, and if erosion has progressed through such a key point, rehabilitation measures may need to proceed as far downstream as this. Perhaps the change in slope is linked with the presence of tributaries that have introduced large quantities of sediment into the main valley, reducing slope in an upstream direction and steepening slope in a downstream direction. In such a case it may be appropriate to focus on the erosion in the wetland and not so much on erosional features in the tributary streams. In cases where the key point relies on an input of sediment from the surrounding catchment, erosion control in the catchment may explain the gully in the wetland you are working in.

The point here is that it is necessary to find an explanation for the erosion and consider its origin in as broad a context as possible. Obtain the necessary information to do this, starting with a longitudinal profile. Note changes in longitudinal slope and try and explain these using geological and drainage maps. Then try and determine the origin of problems in your wetland based on the understanding you have gained. You may need to make further observations such as getting a sense of the nature and extent of fluvial deposition and depth of accumulated sediment, but this is not always necessary.

13.3 Hydrological characteristics

13.3.1 Key questions

Many impacts on wetlands occur through the relationship between discharge, stream capacity and load. Remember that a central idea in this document is that wetlands typically occur in settings where stream transport capacity is less than its sediment load. In considering the problem with which you are faced in wetland rehabilitation, it is helpful to consider the hydrological characteristics of the wetland. Modification of wetland hydrology may be the primary cause of degradation, with effects on geomorphology as the wetland and its stream or streams, adjust to the newly imposed hydrological conditions. Therefore if the hydrology of the wetland can be broadly understood, then the rehabilitation intervention may be more appropriately tailored to address the problem. To come to grips with these issues it is useful to ask a few questions as follows:

- What are the sources of the water entering the wetland and their relative contribution (precipitation, groundwater, channel flow, diffuse surface inflow)? Has the input of water to the wetland been altered?
- How does water pass through the wetland (channel flow or diffuse flow)? Has the way that water passes through the wetland been altered?
- How does water leave the wetland and how significant are each of these outflows (channel flow, groundwater, evapotranspiration)? Has the way that the water leaves the wetland been altered?
- How does the volume of the outflow compare to the volume of inflow? Here you can superficially compare the size of the inflowing and outflowing streams respectively.

If inflow has been substantially increased or the timing of its discharge into the wetland shortened such that inflows are more intense, natural balances in the wetland may have been altered, such as more or reduced sediment volume entering the wetland, more rapid through flow, or reduced retention time.

A broad understanding of a wetland's water budget is required in order to answer the questions posed above. The water budget can be described through modelling and comprehensive long-term monitoring, but you will usually lack the resources and time to do this. Thus very often you will be required to undertake a rapid assessment. This section highlights some of the key features relevant to a wetland's water budget (see Table 6) and provides a tool to assist you with such an evaluation. Describing the key features in the table helps you place the wetland in a hydrological context.

13.3.2 Precipitation and potential evaporation

Mean annual precipitation and potential evaporation estimates are readily available at a national level (e.g. Weather Bureau data, 1988; Schulze *et al*., 1989; Schulze, 1997; or contact your local Agricultural Extension Office). Rainfall data provide a sense of the quantities and timing of rainfall and therefore runoff. Potential evaporation provides an indication of the atmospheric demand for water, and differences between these two variables, together with their timing, indicate periods of water excess and deficit. Understanding how flow in the wetland compares to seasonal patterns of rainfall and potential evapotranspiration helps identify important water sources for the wetland, which may affect the nature of rehabilitation interventions.

The amount of water evaporating from the wetland surface in response to atmospheric demand will be influenced by several features of the wetland such as the structure of the vegetation and vegetation growth and dormancy. In herbaceous wetlands, the amount of water lost to the atmosphere through evaporation and transpiration will tend to be less than that lost from open water, but riparian forests are likely to transpire larger quantities than would be lost from open water. This is also likely to be seasonally variable, such that at the height of the growing season transpiration should be greater than during seasons of dormancy, when dead leaf tissue is not photosynthetically active. Also, during the dormant season the dead leaf tissue will cover the water surface, further reducing water loss from the wetland.

For virtually all of South Africa, annual potential evaporation exceeds precipitation. However, the magnitude of this difference varies considerably from approximately 500 mm per annum in some of the eastern parts of the country to >2800 mm in the west. While factors such as landform and

Table 6: Readily described features of a wetland and its catchment influencing the hydrological components of the wetland

Hydrological features of interest	Source of information
Precipitation and potential evapotranspiration	Weather Bureau data (Schulze *et al*., 1989; Schulze, 1997)
Proportion of catchment occupied by wetland	1:50 000 or 1:10 000 maps
Infiltration capacity in wetland's catchment	Field inspections
Relationship between wetland and groundwater	Field inspections and augering

catchment characteristics obviously have an important influence on water supply to a wetland, generally where the deficit exceeds 1 200 mm a wetland is unlikely to support permanently wet areas unless it has a consistent water supply (e.g. from a river draining a catchment with a higher rainfall).

Human activities may have an important influence over evapotranspiration that directly affects the output component of the wetland's water budget. In wetlands, water is readily available to any plant present. The introduction of exotic shrubs and trees with high water demands (e.g. *Eucalyptus grandis*) is therefore likely to increase evapotranspirative loss from the wetland compared to natural herbaceous vegetation cover. Activities which increase evapotranspirative loss in the surrounding catchment reduce stream inflows and subsurface water input to the wetland in the interval between rainfall, but have little effect on runoff during heavy rainfall.

13.3.3 Proportion of the catchment occupied by the wetland

With all other factors being equal, the greater the proportion of the catchment occupied by the wetland, the greater will be the wetted perimeter of the wetland relative to the area of the catchment. This in turn increases the wetlands capacity for intercepting subsurface water flow. Thus the greater the proportion of the catchment occupied, the greater will be the groundwater contribution relative to surface water.

In South Africa, where rainfall is low and evaporation greatly exceeds precipitation, wetlands generally require input of water from a catchment. Thus where a wetland occupies >15% of its catchment, although this may seem to be a small proportion, it is considered to be relatively high. In areas where precipitation equals or exceeds potential evapotranspiration (e.g. in some northern hemisphere temperate regions) it is not unusual for wetlands to occupy much of their catchments.

The size of the wetland can be reduced (e.g. through drainage) or increased (e.g through structures which detain and spread water flow). The size of the catchment is essentially fixed but can be effectively increased through inter-basin transfer, which would increase the surface water contribution to the wetland.

13.3.4 Infiltration capacity in the wetland's surrounding catchment

Where the infiltration and hydraulic conductivity are low in the slopes surrounding the wetland, inputs to the wetland are likely to be dominated by surface flows (see discussion on Darcy's Law in Section 6.3). Conversely, where the infiltration and hydraulic conductivity are high, subsurface flow may predominate, particularly if a wetland occupies a high proportion of its catchment.

Infiltration in the surrounding catchment is one of the factors readily influenced (reduced) by management action. It will affect the partitioning of rainfall between surface and subsurface flow, and therefore the timing and quantity of water flow delivered to the wetland. Decreased infiltration in the catchment may increase peak flows in the wetland and reduce base flows, which may have significant impacts for the flow transport capacity. Reduced catchment infiltration typically results from hardened urban surfaces (e.g. buildings, roads and parking lots), overgrazing leading to soil compaction and reduced vegetation cover, and poor crop management practices (e.g. exposed soils, soil compaction).

13.3.5 Relationship between the wetland and groundwater

Remember from earlier discussion in Section 6.4 that water will move down a slope, and that in the case of groundwater flow, the velocity of flow will be proportional to hydraulic conductivity and slope. If the groundwater surface slopes away from the wetland, the predominant movement of water will be out of, rather than into, the wetland. Conversely, if the groundwater slopes towards the wetland, water will tend to flow into the wetland from the adjacent groundwater. In certain wetlands there may be regions of groundwater discharge and regions of groundwater recharge. The significance for wetland rehabilitation is that in unchannelled or channelled flats, the presence of groundwater recharge areas demonstrates the importance of surface water flow down the valley such that rehabilitation interventions may need to focus more on this than on lateral flow of water from adjacent hillslopes into the valley. Also, surface flow in the wetland is likely to decline downstream. Conversely, where valley fill wetlands have groundwater discharge, flow will increase downstream, and attention may then need to focus on gully side walls as well as the headcut itself.

13.4 Alterations to landforms within the wetland

The flow of water in a wetland may be greatly influenced by morphological characteristics such as the presence or absence of channels. Modification of morphology through a variety of activities may therefore have a major impact on throughflow and the overall water budget (Table 7). Here we discuss interventions that may impact upon wetlands that have not been mentioned previously in Section 11.1 or 11.2.

The introduction of artificial interception channels on the sides of a wetland will reduce water supply from lateral sources. Such channels are led back into the valley at some point. If this is done such that large volumes of intercepted water are introduced at a single point, erosion may result, depending upon local circumstances. The introduction of artificial channels into a non-channelled flat will cause water levels in the adjacent wetland to drain to the level of the artificial bed, but the extent of such drainage will be dependent upon the porosity of the adjacent soils as described in the discussion of Darcy's Law (Section 6.3). The velocity of water flow in the artificial channel will be higher than in the adjacent wetland and may lead to vertical and headward erosion. A change in the retention of water may have a feedback effect through its influence on vegetation structure. A reduction in the retention time of water in the wetland (e.g. through artificial drainage) will reduce long term soil wetness. This in turn, may result in reduced wetland vegetation growth. The reduced resistance offered by the diminished wetland vegetation growth would further reduce the retention capacity of the wetland, and moreover worsen erosion in the wetland.

Shortening of stream channels increases the velocity of throughflow, thus potentially increasing water loss from the site. However, the most significant impact is the steepening of the gradient on the water surface, which may similarly increase velocity sufficiently to initiate erosion. Through a process of headward erosion, this may threaten wetland integrity beyond the region of human activity. Alteration of the capacity of channels within a wetland may have similar effects.

Introduction of obstacles to flow within a wetland will reduce wetland functioning upstream if wetland is converted to open

Table 7: **Common human-induced modifications to wetland morphology and their effects on the water budget**

Human modifications to wetland morphology	**General effects on the water budget**
Introduction of interception channels[1] on the edge of the wetland	Interception of lateral (surface and subsurface) water input to the wetland
Introduction of channels[1] entering or within a non-channelled, diffuse flow area.	Increased velocity of throughflow leading to reduced retention capacity; lowers water table and initiates downward and headward erosion
Shortening of stream channels	As above and also steepens gradient on water surface, increasing downward and headward erosion
Changing capacity of existing channels (e.g. by deepening and/or widening)	As above
Introduction of obstacles to flow (e.g. a dam wall)	Increased retention capacity above the wall (but if wetland is replaced with open water, wetland functions are lost over that area). Likely erosion downstream of wall
Removal of obstacles (e.g. natural levees, hummocks)	Reduced retention capacity, possible downward and headward erosion depending upon local gradients

[1] This includes artificial drainage channels that are purposefully dug as well as erosion gullies that develop as a result of poor land-use practices (eg. overgrazing).

water. It may also increase the likelihood of erosion downstream, particularly if flow is concentrated through culverts or over a spillway. This water will likely be free of sediment and may thus erode material to compensate.

Finally, the removal of obstacles such as levees may have dramatic effects through flow concentration along an oversteepened slope. This may initiate erosion that may ultimately divert water radically within the wetland along a course that may not have been expected naturally. Such an event has been described in the Mkuze Wetland in northern KwaZulu-Natal (Ellery *et al*., 2003). In this case a hippo trail was deepened by a farmer to draw off a small volume of water into a floodplain pan in order to provide water for livestock. This minor excavation eroded to a depth of approximately 6 m and width of 25 m, to capture greater than 95% of the flow along the Mkuze River. Thus the impact was probably enormous, leading to a substantial change in hydrology.

13.5 Drawing together your understanding of the wetland

We have suggested ways of investigating the wetland that you are trying to rehabilitate, and intend improving the framework as part of ongoing research. The important thing to do is to try and understand why the wetland exists and why it is degrading. It is difficult to separate out anthropogenic factors from those that are natural, but our view is that more degradation than we might at first expect may be due to natural causes. Thus at the outset of the wetland rehabilitation planning process, several questions should be asked of the system concerned (Figure 39). One should ask what the system is 'like', and structure an answer based on investigation of the physical characteristics or form of the system and surrounding catchment (using methods described in sections 13.2 – 13.4). It would also be useful to determine the state of the system in terms of how similar its characteristics are to those one would expect of the system in a natural state (using *WET-Health*, McFarlane *et al*., 2009). One should ask how the system 'works', and structure an answer based on investigation of the physical processes operative within the system and surrounding catchment (using methods described in sections 13.2 – 13.4). It would then be appropriate to attempt to relate form and process, to develop an understanding of how particular processes have shaped the system and, as a corollary, how particular characteristics affect processes operative within the system (try to link the characteristics of the system with the processes you observe, and vice-versa). Since all systems change naturally with time, one should ask how the system changes over time, and structure an answer based on investigation of process-form relationships that underpin the natural dynamic of the system, *viz.*how, and how often, the system changes naturally with time. For example, if one of the observed processes changes, how might the related characteristics change?

Once the characteristics, processes and natural dynamic of the system are known and understood, only then should one attempt to determine how human intervention has altered or influenced natural process-form relationships and natural processes of change. Often the temptation to forgo initial investigations of characteristics and processes is overpowering, and effects of human intervention are investigated out of context, leading to erroneous perceptions of change (Schumm, 1994). Humans alter or influence natural systems by physically manipulating natural characteristics and processes, whether intentionally or not. Human manipulations of natural systems often accelerate natural processes of change (such as erosion by gullying, river avulsion, or eutrophication), and may in extreme cases lead to complete character and process metamorphosis, forcing a system to an alternative developmental pathway than the one it followed naturally, a pathway on which former natural characteristics and processes (and the former natural dynamic) cannot be reinstated. A possible consequence of the change to a system following human manipulation is that the system loses some of its value to society, while often becoming more valuable to a select few individuals (Kotze *et al.*, 1999). A wetland that is filled-in for a housing development, for example, will no longer provide the ecosystem services to society that it did naturally, but has provided a source of flat land from which the developer and immediate dependents will benefit. However, they often flood during periods of unusually high rainfall.

An understanding of the characteristics, processes and natural dynamic of a system, together with an interpretation of effects of human intervention on natural process-form relationships and natural processes of change, provides the requisite background for conceptualising likely 'futures' for the system, given various scenarios of future human intervention. These conceptual 'futures' may be drafted to appraise proposed rehabilitation interventions, and to determine how a system is likely to respond to these interventions. Only at this stage of understanding should one begin to make management and rehabilitation decisions. Thus the argument raised in the preceding discussion is that wetland management and rehabilitation can only proceed effectively once managers have gained a particular level of understanding of system characteristics, processes, and natural drivers of change. Without this understanding (often specific to an individual system), managers will tend to conceptualise interventions, and base intervention design, on their perceptions of what the system is like and how it works. Even expert scientists are susceptible to erroneous assumptions on the workings of nature (Schumm, 1994). Thus it is critical that all who are involved in wetland management and rehabilitation thoroughly investigate the characteristics, processes, and natural drivers of change of the systems under their care, and are faithful to the data thus generated when developing the understanding upon which management and rehabilitation decisions will be based.

14 CONCLUSION

14.1 The origin of wetlands

McCarthy and Hancox (2000) have attempted to describe the geomorphological controls on selected wetlands in the southern African region. They list the following factors as important in determining the distribution of wetlands in the region:

- changes in sea level
- fluvial sedimentation in deltas, alluvial fans and on floodplains
- present climate and climate change
- chemical sedimentation from ground water
- neotectonic activity
- vegetational succession and plant-water interactions
- aeolian processes, including deflation and dune formation
- geohydrological factors, and
- anthropogenic factors.

These general factors can be grouped into those that:

- alter the integration of drainage (e.g. aeolian processes of deflation and dune formation)
- affect the fluvial processes driving competence and capacity by affecting gradient, discharge, and sediment supply and character (e.g. clastic sedimentation, chemical sedimentation, peat formation and organic matter accumulation, base level elevation, neotectonic activity, climate and climate change, and anthropogenic activity)
- affect groundwater tables (e.g. geohydrological factors).

Based on the preceding analysis it should be clear that wetlands in southern Africa differ fundamentally from their northern hemisphere counterparts, primarily in that most of ours are more dependent upon fluvial systems. Two massive uplift events of the subcontinent further mean that the region is erosional, which is bad news for wetlands.

It is hoped that the analysis of fluvial processes helps to create some understanding of factors that determine wetland distribution in our region. Any given wetland will exist due to a combination of a number of hydrological and geomorphological circumstances, but much remains to be done to clarify the combinations in a general way. Nevertheless it is important to focus not just upon water inputs, but to consider constraints on the rate of outflow of water into the drainage network. There is thus a considerable amount of work to be done to develop general theoretical understanding of why wetlands occur where they do.

14.2 Wetland character and evolution

The character and dynamics of a wetland depend largely upon the character and dynamics of the inflowing stream and its sediment load. However, the preferential accumulation of clastic sediment locally in wetland basins must lead to the creation of topographic gradients away from areas of active sedimentation adjacent to the inflowing stream into depressions that do not receive sediment. This leads to the development of steep gradients that will favour water flow. Given sufficient difference in elevation, water distribution will change over relatively short time spans of decades to centuries. Thus one should expect channels in wetlands dominated by clastic sedimentation to be inherently unstable.

Chemical sedimentation is a process that has been overlooked in our wetlands, yet there is no doubt that it is more prevalent than has so far been considered. It is geomorphologically and ecologically important in that it affects soil exchange properties and porosity and leads to the creation of topographic relief. It mainly takes place in the lower reaches of wetlands and therefore counteracts the downstream gradient increase caused by clastic sedimentation in the upper reaches of wetlands, which helps to enhance wetland stability.

Peat formation is a response to an abundant supply of sediment-free water. It typically accumulates in the accommodation space created by the spatial separation of regions of clastic and chemical sedimentation. Unlike processes associated with clastic or chemical sedimentation, peat formation passively accumulates to the mean elevation of minimum flooding. On its own it cannot therefore lead to the creation of relief. However, it can focus flow and sediment locally to within channel areas, thereby acting as an important determinant of wetland structure and function.

14.3 Human intervention that is positive

The formation of wetlands is associated with climatic, geological, geomorphological and biological processes. Superimposed on these, the role of humans needs to be considered in that we are capable of modifying many of the driving variables deliberately or accidentally. Our actions may be negative or positive. Hopefully, deliberate intervention by wetland rehabilitation enthusiasts will bring about positive effects, but this requires a sound understanding of the system being dealt with and appropriate integration with careful design and construction principles.

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GLOSSARY

Aeolian	Relating to, caused by, or carried by the wind.
Aggradation	Filling and raising the level of the land surface by deposition of sediment.
Anaerobic	In the absence of oxygen.
Anastomosing	A stream where separate channels divide and rejoin around permanent islands.
Anthropogenic	Of, relating to, or resulting from the influence of human beings on nature.
Anticyclone	High atmospheric pressure caused by descending air, which becomes warm and dry. Winds radiate from a calm centre in an anticlockwise direction in the southern hemisphere.
Aquatic	Consisting of, relating to, or being in water.
Aquiclude	Sediment body, rock layer, or soil horizon that is incapable of transmitting significant quantities of water under normal hydraulic gradients.
Auger	An instrument used for boring or perforating soils or rocks, in order to determine the quality of soil, or the nature of the rocks or strata upon which they lie, and for obtaining water.
Backswamp	Extensive, marshy or swampy, depressed areas of floodplains between natural levees and valley sides or terraces.
Base level	The lowest level to which a stream can erode its bed.
Bedload	Sediment that is transported by being rolled or bounced along the bed of the stream.
Bedrock	The solid rock that underlies unconsolidated material, such as soil, sand, clay, or gravel.
Biodiversity	The variety of living things - from genes to species to ecosystems.
Biophysical	The biological and physical components of the environment.
Bog	Peat-accumulating wetland that has no significant inflows or outflows.
Brackish	Slightly saline, with a dissolved salt content less than that of seawater.
Braided stream	A stream with multiple channels that interweave as a result of repeated division and rejoining of flow around interchannel bars, resembling (in plan view) the strands of a complex braid.
Catchment	All the land area from mountaintop to seashore which is drained by a single river and its tributaries. Each catchment in South Africa has been subdivided into secondary catchments, which in turn have been divided into tertiary. Finally, all tertiary catchments have been divided into interconnected quaternary catchments. A total of 1946 quaternary catchments have been identified for South Africa. These subdivided catchments provide the main basis on which catchments are subdivided for integrated catchment planning and management (consult DWAF [1994]).
Channel	The part of a river-bed containing its main current, naturally shaped by the force of water flowing within it.
Chroma	The quantitative measure of the relative purity of the spectral colour of a soil, which decreases with increasing greyness. A Munsell colour chart is required to measure chroma.
Clastic sediment	The particles of minerogenic material (clay, silt, sand, cobbles and boulders) that are moved by running water.
Colonisation	The gradual spread of plant species into an area.

Darcian flow	The near uniform flow of water through unconsolidated soil and rock material .
Deposition	The laying down of material which has been transported by running water (or wind).
Desiccation	The loss of moisture from material.
Detrimental solute	Solutes present in water that do not stimulate, or may even inhibit, the growth of organisms if their concentration increases.
Disaggregate	To break down aggregated material.
Discharge wetland	Wetlands where groundwater discharges into the wetland.
Distal reaches of wetland	Lower (in the sense of being downstream) reaches of the wetland.
Drainage basin	General term for a region or area bounded by a drainage divide and occupied by a drainage system.
Drainage network	The arrangement of the main river channel and its tributaries within a drainage basin.
Dune (Aeolian)	A mound, ridge, bank or hill of unconsolidated, windblown, granular material (generally sand), either bare or covered with vegetation.
Ecosystem	An ecological system in which there is constant interaction between the biotic and abiotic components and in which nutrients are cycled.
Endorheic	Basin or region from which there is little or no outflow of water (either on the surface as rivers, or underground by flow or diffusion through rock or permeable material).
Ephemeral wetland	Wetland or portion thereof with markedly short-lived inundation.
Erosion	Physical and chemical processes that remove and transport soil and weathered rock.
Escarpment	A steep slope interrupting the general continuity of the landscape.
Evaporation	The physical process of molecular transfer by which a liquid is changed into a gas.
Evapotranspiration	The loss of moisture from the terrain by direct evaporation plus transpiration from vegetation.
Exorheic	A basin or region characterized by outflow of water, usually involving drainage to the ocean.
Fault	A surface of fracture or rupture of strata, involving permanent dislocation and displacement within the earth's crust, as a result of the accumulation of strain.
Flood duration	Length of time a wetland is in standing water.
Flood extent	The surface area of a wetland that is flooded.
Flood frequency	The average number of times that a wetland is flooded in a given period.
Floodplain	Valley bottom areas with a well defined stream channel, gently sloped and characterized by floodplain features such as oxbow depressions and natural levees and the alluvial (by water) transport and deposition of sediment, usually leading to a net accumulation of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.
Fluvial	Related to running water (e.g. a river).
Geology	The study of the composition, structure and processes of the rock layers of the earth.
Geomorphology	The study of the origin and development of landforms of the earth.
Graded stream	Where the channel slope is adjusted to transport the water and sediment available so that neither deposition nor erosion occurs.

Groundwater	Subsurface water in the zone of saturation above an impermeable layer.
Groundwater flow	The naturally or artificially produced movement of water in the zone of saturation.
Gully	A well defined, channel carved by water on a hillside.
Headwaters	The uppermost region of a catchment.
Herbaceous	A non-woody plant.
Horizon	Each main layer or zone within a soil profile.
Hortonian flow	Excess flow during a rainstorm that cannot infiltrate into the soil and thus flows over the land surface (infiltration excess water).
Hydraulic conductivity	A measure of the rate at which water can move through a permeable medium, such as soil or rock.
Hydraulic radius	The cross-sectional area (mean stream width multiplied by mean depth) divided by the combined length of the bed and banks that are wet (wetted perimeter).
Hydrology	The study of the properties, distribution, and circulation of water on the earth.
Hydroperiod	The hydrological signature describing the seasonal pattern of water level fluctuations in a wetland.
Hydrophyte	Any macrophytic plant that grows in water or on a substrate that is at least periodically deficient in oxygen as a result of excessive water content.
Infiltration	The slow passage of water through a filtering medium.
Interflow	Near-horizontal flow of water through the subsurface soil profile.
Inter-Tropical Convergence Zone	The zone of convergence of easterly moving air masses in the region of the thermal equator.
Landform	Any distinctive geomorphological feature on the earth's surface.
Macrophyte	Any non-microscopic plant growing in water or wet soil.
Macropore	Spaces between soil aggregates.
Mass-balance approach	The accounting of all inputs and outputs to a defined system (see water budget).
Microcatchment	Local catchment.
Microhabitat	Localized areas occupied by certain organisms because of small scale variation in environmental conditions.
Mottle	Soils with irregular colour patterns, with the least pure colour present being described as the matrix, and the areas of purer colour as mottles.
Neotectonic	Currently active earth movements.
Nutrient solute	A solute that leads to an increase in biological productivity if its concentration is increased.
Ombrotrophic	Wetlands deriving water and minerals solely from the atmosphere (e.g. in rain or snow).
Orthophotograph	A photograph derived from a conventional perspective photograph by simple or differential rectification so that image displacements caused by camera tilt and relief of terrain are removed.
Overland flow	Flow of water across the land surface, commonly as a broad, thin sheet.
Pan	Roughly circular depression that has no connection to the drainage system via surface flow.

Peat	Partially carbonized vegetable matter in wetlands with prolonged flooding and little or no clastic sediment deposition (bogs and fens).
Perched wetland	A wetland where the wetland water table is higher than the local and regional water table.
Percoline	Zone within the soil where flow is preferential.
Permeability	The state of allowing the passage of water.
Precipitation	The deposition of moisture on the earth's surface from the atmosphere, including dew, hail, rain, sleet and snow.
Proximal reaches of wetland	Upper (in the sense of being upstream) reaches of the wetland.
Recharge wetland	Where the slope of the water table is oriented away from or depressed below the wetland such that the groundwater is supplied by infiltration from surface water in the wetland.
Regolith	The layer of loose rock and mineral material that covers many land surfaces. As it becomes mixed with water and organic matter, it is gradually transformed into soil.
Rehabilitation	Restoring processes and characteristics that are sympathetic to and not conflicting with the natural dynamic of an ecological or physical system.
Rejuvenation	The revival of erosive activity by a river because of a change in base level due to local uplift or a lowering of sea level.
Rill	Small-scale channels formed by the uneven removal of surface soil. They may coalesce into larger gullies.
Riparian	Of, on, or relating to the banks of a natural course of water.
Runoff	The surface discharge of water from rainfall down a slope or the flow in a river channel.
Stream capacity	The maximum amount of sediment that a stream can transport in a given flow.
Stream competence	The largest grain size that a stream can move along its bed.
Substrata	Underlying layers.
Suspended sediment	Sediment that is transported by being held aloft the water column, typically comprising silt- and clay- sized particles.
Terrestrial	Of, relating to, or inhabiting the land (as opposed to the sea or air).
Transpiration	Process in which water is absorbed by the root systems of a plant, moves up through the plant, passes through pores (stomata) in leaves, and then evaporates into the atmosphere as water vapour.
Tributary	A stream that joins a larger one.
Vegetation succession	A gradual (non-seasonal) sequence of changes in vegetation following a disturbance, until equilibrium is attained and a climax community established.
Warping	A gentle deformation (e.g. uplift, tilting) of the Earth's crust over a considerable area.
Water budget	An assessment of all the inputs and outputs to a hydrologic system over a fixed period.
Water table	The upper surface of the zone of saturation in permeable rocks, sediment or soil.
Weathering	The breakdown of rock through mechanical or chemical processes.
Wetland	Land where an excess of water is the dominant factor determining the nature of the soil development and the types of plants living there.

Working for Wetlands

Working for Wetlands (WfWetlands) uses wetland rehabilitation as a vehicle for both poverty alleviation and the wise use of wetlands, following an approach that centres on cooperative governance and partnerships. The Programme is managed by the South African National Biodiversity Institute (SANBI) on behalf of the departments of Environmental Affairs and Tourism (DEAT), Agriculture (DoA), and Water Affairs and Forestry (DWAF). With funding provided by DEAT and DWAF, WfWetlands forms part of the Expanded Public Works Programme (EPWP), which seeks to draw unemployed people into the productive sector of South Africa's economy, gaining skills while they work and increase their capacity to earn income. Rehabilitation projects maximise employment creation, create and support small businesses, and transfer relevant and marketable skills to workers.

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The Water Research Commission

The Water Research Commission (WRC) aims to develop and support a representative and sustainable water-related knowledge base in South Africa, with the necessary competencies and capacity vested in the corps of experts and practitioners within academia, science councils, other research organisations and government organisations (central, provincial and local) that serve the water sector. The WRC provides applied knowledge and water-related innovations by translating needs into research ideas and, in turn, transferring research results and disseminating knowledge and new technology-based products and processes to end-users. By supporting water-related innovation and its commercialisation where applicable, the WRC seeks to provide further benefit for the country.

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