Wetland Health and Importance Research Programme

5

A Method for Assessing Cumulative Impacts on Wetland Functions at the Catchment or Landscape Scale

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WETLAND HEALTH AND IMPORTANCE RESEARCH PROGRAMME

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A METHOD FOR ASSESSING CUMULATIVE IMPACTS ON WETLAND FUNCTIONS AT THE CATCHMENT OR LANDSCAPE SCALE

Report to the
Water Research Commission

by

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Front Cover: The head of the Goukou wetland near Riversdale, Western Cape, South Africa
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PREFACE

This report is one of the outputs of the Wetland Health and Importance (WHI) research programme which was funded by the Water Research Commission. The WHI represents Phase II of the National Wetlands Research Programme and was formerly known as "Wetland Health and *Integrity*". Phase I, under the leadership of Professor Ellery, resulted in the "WET-Management" series of publications. Phase II, the WHI programme, was broadly aimed at assessing wetland environmental condition and socio-economic importance.

The full list of reports from this research programme is given below. All the reports, except one, are published as WRC reports with H. Malan as series editor. The findings of the study on the effect of wetland environmental condition, rehabilitation and creation on disease vectors were published as a review article in the journal Water SA (see under "miscellaneous").

An Excel database was created to house the biological sampling data from the Western Cape and is recorded on a CD provided at the back of Day and Malan (2010). The data were collected from mainly pans and seep wetlands over the period of 2007 to the end of 2008. Descriptions of each of the wetland sites are provided, as well as water quality data, plant and invertebrate species lists where collected.

An overview of the series

Tools and metrics for assessment of wetland environmental condition and socio-economic importance: handbook to the WHI research programme by E. Day and H. Malan. 2010. (This includes "*A critique of currently-available SA wetland assessment tools and recommendations for their future development"* by H. Malan as an appendix to the document).

Assessing wetland environmental condition using biota

Aquatic invertebrates as indicators of human impacts in South African wetlands by M. Bird. 2010.

The assessment of temporary wetlands during dry conditions by J. Day, E. Day, V. Ross-Gillespie and A. Ketley. 2010.

Development of a tool for assessment of the environmental condition of wetlands using macrophytes by F. Corry. 2010.

Broad-scale assessment of impacts and ecosystem services

A method for assessing cumulative impacts on wetland functions at the catchment or landscape scale by W. Ellery, S. Grenfell, M. Grenfell, C. Jaganath, H. Malan and D. Kotze. 2010.

Socio-economic and sustainability studies

Wetland valuation. Vol I: Wetland ecosystem services and their valuation: a review of current understanding and practice by Turpie, K. Lannas, N. Scovronick and A. Louw. 2010.

Wetland valuation. Vol II: Wetland valuation case studies by J. Turpie (Editor). 2010.

Wetland valuation. Vol III: A tool for the assessment of the livelihood value of wetlands by J. Turpie. 2010.

Wetland valuation. Vol IV: A protocol for the quantification and valuation of wetland ecosystem services by J. Turpie and M. Kleynhans. 2010.

WET-SustainableUse: A system for assessing the sustainability of wetland use by D. Kotze. 2010.

Assessment of the environmental condition, ecosystem service provision and sustainability of use of two wetlands in the Kamiesberg uplands by D. Kotze, H. Malan, W. Ellery, I. Samuels and L. Saul. 2010.

Miscellaneous

Wetlands and invertebrate disease hosts: are we asking for trouble? By H. Malan, C. Appleton, J. Day and J. Dini (Published in Water SA 35: (5) 2009 pp 753-768).

EXECUTIVE SUMMARY

This tool enables assessment of the effects on wetland functionality of the cumulative impacts of human activities at a landscape scale. It uses two metrics – the **land cover change impact metric** and the **loss of function metric** to produce a functional effectiveness score that is translated to functional hectare equivalents (Figure E.1). The difference between the functional hectare equivalents of an unimpacted catchment is compared with the current state to assess the cumulative impacts of human activities on wetland functionality.

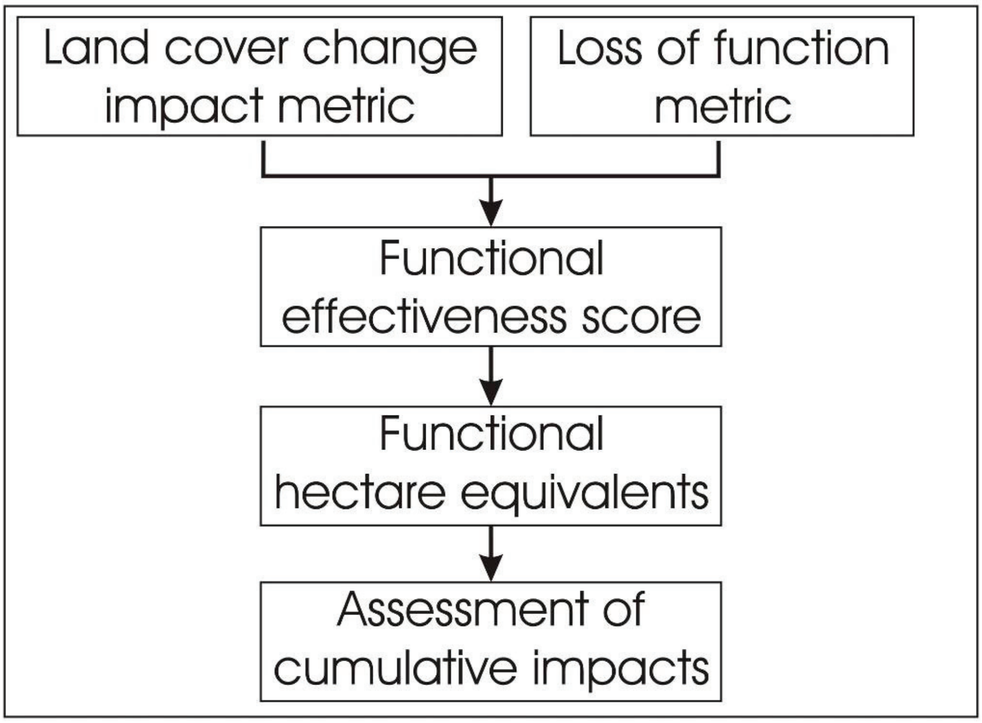

Figure E1: Summary of the relationships between different components of this study

A range of land cover classes based on the National Land Cover database for South Africa have been identified with respect to their impacts on water inputs to, and retention of water within, wetlands. If present in the catchment, these land cover classes can either 1) increase or 2) decrease water inputs to a wetland, OR if present in a wetland itself, they can 3) increase direct water losses from the wetland, 4) reduce surface roughness, 5) impede the flow of water in a wetland or 6) enhance the flow of water in a wetland. The effect of each category of land cover change from the natural condition on each of these parameters has been assigned an intensity of impact score.

The method considers the impact of land cover change on wetland health using a **land cover change impact metric**. This metric is based on the recognition that wetland structure and function are fundamentally affected by the hydrological regime. The land cover change impact metric requires that the extent of each land cover category is determined as a proportion of the catchment and wetland area, and that this is multiplied by the intensity of impact score, to produce a magnitude of impact score.

The manner of entry into and pattern of water flow through a wetland affects the extent to which a wetland is able to deliver particular ecosystem services. Therefore, for purposes of this assessment, floodplain wetlands have been distinguished from valley-bottom wetlands. For wetlands other than these two hydrogeomorphic (HGM) types, the method applicable to valley-bottom wetlands should be used.

A second metric, the **loss of function metric**, describes the relationship between the magnitude of impact score and wetland functionality for a total of 6 ecosystem services: A) flood attenuation, B) streamflow regulation, C) sediment trapping, D) nitrogen removal, E) phosphate removal or F) toxicant removal. These relationships have been developed based on limited field testing, and there is a need to verify their applicability.

The land cover change impact metric and the loss of function metric are combined in a structured way to produce a functional effectiveness score for each ecosystem service. When scaled for the area of each wetland, the functional hectare equivalents for each wetland function can be calculated, which, when compared to the functional hectare equivalents of an unimpacted catchment, is translated to an assessment of cumulative impacts.

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ABBREVIATIONS

CAPE – Cape Action Plan for People and the Environment

CSIR – Council for Scientific and Industrial Research

DEAT – Department of Environmental Affairs and Tourism

DEM – digital elevation model

DWAF – Department of Water Affairs and Forestry

GIS – geographical information system

HGM – hydrogeomorphic

IBT – inter-basin transfer

LC – land cover (category)

NLC – National landcover

WWTW – wastewater treatment works

1. INTRODUCTION

1.1 Background

Wetlands occupy a position in the landscape between terrestrial and aquatic (Mitsch and Gosselink, 2007; Keddy, 2000; Rogers, 1997) such that they are negatively impacted by human activities occurring within the wetland boundary as well as within the wetland's catchment. The degradation of wetlands as a consequence of impacts caused by human activities has been captured in a measure that we refer to as "wetland health". Although the term "environmental condition" is probably more correct than "health", the recently developed "WET-Health" (Macfarlane *et al.,* 2008) has been used as the basis for the development of this tool, and the term "health" has therefore been adopted for this study. WET-Health uses an impacts-based approach that enables assessment of the negative impacts of human activities on wetland health in a semi-quantitative manner.

Wetlands are being degraded and lost nationally as a consequence of activities in wetland catchments, which alter the quantity and quality of water reaching wetlands, as well as the timing and magnitude of peak flows (Kotze and Breen, 1994). Activities within wetlands such as excavation of drains, cultivation, erosion and road construction across wetlands, are also leading to widespread wetland degradation. The tool "WET-Health" (Macfarlane *et al.,* 2008) allows for the assessment of the condition of individual wetlands by examining the likely impacts of human activities in catchments and wetlands on wetland structure and function. This tool is very useful for assessment of individual wetlands, but it is not easily translated to examination of multiple wetlands within a whole catchment or at the landscape scale.

Degradation of wetlands through impacts in catchments or in wetlands themselves is resulting in the reduction and loss of their functional effectiveness and ability to deliver ecosystem services or benefits to humans and the environment (Kotze *et al.,* 2008). The recently developed tool "WET-EcoServices" (Kotze *et al.,* 2008) assesses the provision of ecosystem services by individual wetlands, but the method (tool) does not allow comparison between different wetlands because it simply assesses ecosystem service provision by a given wetland, relative to the best possible delivery of ecosystem services by wetlands in general. Thus a large floodplain might be assessed as having the same functional effectiveness in terms of flood attenuation as a small one, when, in reality, the large floodplain might attenuate much larger floods than the small one. The lack of an area-weighted assessment of wetland functional effectiveness makes it impossible to compare and contrast the provision of ecosystem services between different wetlands. Furthermore, the method is useful for assessment of the provision of ecosystem services of individual wetlands, but it is not useful for considering the impacts of human activities on many wetlands within a catchment or at the landscape scale.

A further problem that exists with the current methods is that there is no explicit link between the health of a wetland and its ability to provide ecosystem services. As an example, the excavation of drains in a wetland reduces its health as water drains rapidly from the system due to increased hydraulic efficiency caused by reduced surface roughness. By lowering the residence time of water in the wetland, its ability to improve water quality is reduced, such that people downstream do not derive the benefit of these ecosystem services. In order to assess wetland health and the provision of ecosystem services, both in the above case and in general, it is necessary to apply WET-Health and WET-EcoServices separately. This is tedious in broad-scale strategic assessments that are designed to promote effective wetland management at the scale of a catchment or landscape. It would be very useful to capture the provision of ecosystem services as a function of wetland health such that for broad-scale (catchment or landscape scale) studies and for the assessment of cumulative impacts[1] of different activities in wetlands and catchments, it would be possible to assess the provision of ecosystem services by simply doing an assessment of wetland health. In this regard it would be very useful to link wetland health and the provision of ecosystem services to national land cover change data sets, which are generally readily available. In the present study, land cover is used as an indicator of impacts to hydrological functioning. Although it is recognised that there may be inaccuracies in using coarse-resolution land cover categories to assess impacts to wetlands, such data is generally readily available, and at the broad scale at which this tool is being applied, and for the purpose of strategic assessments, it is likely to be sufficiently accurate.

In order to capture the impacts of human activities on wetland functions and the provision of ecosystem services at the catchment or landscape scale, a new methodology needs to be developed. Such a methodology needs to allow assessment of:

- relationships between land cover change as mapped nationally and wetland health;
- provision of ecosystem services in relation to wetland health;
- provision of ecosystem services on an area-weighted basis such that comparisons between wetlands are possible; and

[1] Cumulative impacts refer to the combined incremental effects of human activity on the environment, which in themselves may seem insignificant, but which collectively can result in serious degradation of environmental resources

- cumulative impacts of human activities on the provision of ecosystem services at a landscape scale.

1.2 An overview of wetland health assessment

The health or integrity of individual wetlands in South Africa can be assessed using the recently developed tool WET-Health (Macfarlane *et al.,* 2008). In this tool the assessment of ecosystem health is carried out by using an impact-based approach on a scale of 0 to 10 such that a score of 0 suggests that the wetland is identical to the natural reference condition, while a score of 10 suggests that it is completely transformed. Based on the methodology of Macfarlane *et al.* (2008) it is possible to translate the health score to a score of "hectare equivalents of wetland health" such that both the health score and wetland size are integrated into an area-weighted health score. This is achieved by multiplying the health score in an appropriately scaled way by the size of the wetland, to produce an area-weighted health score that makes it possible to compare different wetlands. The benefit of this relates to the effectiveness of allocating limited resources to the management or rehabilitation of one or a small number of wetlands, when many wetlands need rehabilitation or improved management. It is therefore possible to assess which wetland or wetlands would be most cost-effectively rehabilitated. The use of hectare equivalents of wetland health also makes it possible to compare investment in different management or rehabilitation options within a single wetland, and can form a useful component of setting measurable objectives and evaluating the outcomes of particular interventions.

1.3 An overview of wetland ecosystem service assessment

It is possible to assess the extent to which individual wetlands in South Africa deliver a wide range of ecosystem services using the recently developed tool WET-EcoServices (Kotze *et al.,* 2008). Using this tool, the assessment of ecosystem services is based on a scale of 0 to 4 such that a score of 4 represents the provision of an ecosystem service at the highest possible level for any wetland, while a score of 0 suggests that the wetland is not at all effective in delivering that particular ecosystem service. However, as mentioned previously, the score for the provision of ecosystem services bears no relationship whatsoever to the size of the wetland. The delivery of ecosystem services is simply related to a number of properties of the wetland such as longitudinal slope, roughness, the way in which water enters, flows through and leaves a wetland. Because these properties do not depend on wetland size it is possible for two wetlands of completely different sizes to present the same score for the provision of a particular ecosystem service. Thus a small headwater stream may present a score of 2.5 for flood attenuation while a large floodplain may present the same score, but the magnitude of floods attenuated by these two wetlands will be markedly different. The method of assessing wetland ecosystem services is useful if one is considering what improved management is likely to achieve in a single wetland, but it is not at all useful for meaningful comparisons between wetlands. It is therefore also not useful in considering the cumulative impacts of different activities at a catchment (quaternary or tertiary) or a landscape scale.

1.4 The aim of this study

Given these issues, the overall aim of this study is to develop a method that allows for assessment of the provision of ecosystem services at a catchment or landscape scale based on impacts of human activity on wetland hydrological health. This approach is used, since the hydrological regime is the most important determinant of wetland structure and function (Mitsch and Gosselink, 2007). The specific objectives of this study are to:

- develop a measure that describes the impact of land cover change as mapped nationally in National Land Cover datasets on wetland hydrological health in the form of a **land cover change impact metric**;
- relate wetland hydrological health to the provision of a given ecosystem service in the form of a **loss of function metric**;
- integrate the land cover change impact metric and the loss of function metric to produce a **functional effectiveness score**;
- develop an approach for meaningfully translating the functional effectiveness score on an area-weighted basis as **functional hectare equivalents** for a range of ecosystem services; and
- scale-up the consequences of human activities on the provision of ecosystem services, from an individual wetland to a catchment or landscape scale such that many wetlands can be considered jointly and **cumulative impacts** can be assessed.

The relationship between these objectives is depicted in Figure 1.1.

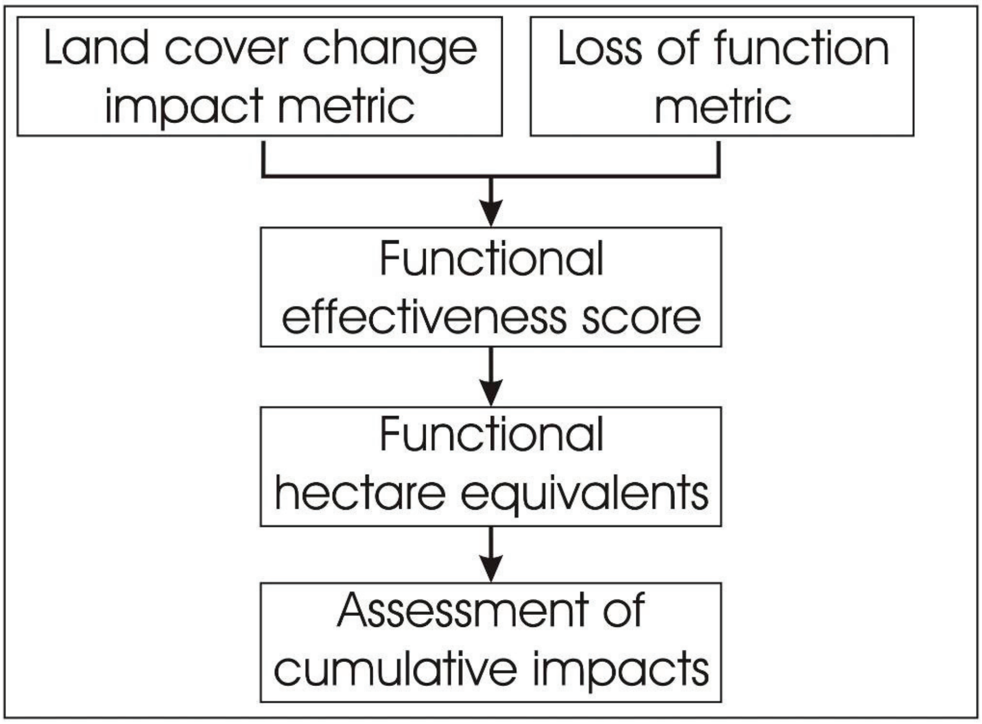


Figure 1.1: Summary of the relationships between different components of this study

2. DEVELOPMENT OF A LAND COVER CHANGE IMPACT METRIC TO DESCRIBE IMPACTS OF LAND COVER CHANGE ON WETLAND HYDROLOGICAL HEALTH

2.1 Introduction

This section presents a metric that describes an intensity of impact score in relation to land cover change (a "**land cover change impact metric**"). The intensity of impact score for land cover change is then multiplied by the extent of the given land cover in the catchment or the wetland to produce a magnitude of impact score, which is used subsequently in conjunction with the "**loss of function metric**" to determine the functional effectiveness of a wetland given the observed land cover change measured in the catchment or landscape. The approach of multiplying the **intensity** of impact by the **extent** of impact in order to obtain a **magnitude** of impact score is the same as that used in WET-Health (Macfarlane *et al.,* 2008).

2.2 Grouping National Land Cover classes based on impacts to runoff

Land-use changes in catchments affect the timing and amount of runoff flow into a wetland, and land-use change within a wetland affects the pattern of water flow through the wetland and its residence time. These factors impact the hydrological health of wetlands in a fairly predictable way as described in WET-Health (Macfarlane *et al.,* 2008).

The National Land Cover Project was initiated by the Chief Directorate of Surveys and Mapping, South Africa, to map land cover or land use across South Africa. For the purposes of this study, the 31 National Land Cover (NLC) classes as currently defined have been grouped into 12 categories based upon an estimation of their impact on runoff (Table 2.1).

Table 2.1: National Land Cover (NLC) codes, classes and categories as defined in this study

NLC Code	Land cover class	Land cover category
1 2 3 4 5 6 7 10 11	Forest and woodland Forest Thicket, scrub forest, bushland and high fynbos Shrubland and low fynbos Herbland Unimproved grassland Improved grassland Wetlands Bare rock	Natural
8	Forest plantations	Forest plantations
9	Water bodies	Water bodies
12	Dongas and sheet erosion	Dongas and sheet erosion
13 14 15 16 17	Degraded forest and woodland Degraded thicket, scrub forest, bushland and high fynbos Degraded shrubland and low fynbos Degraded herbland Degraded unimproved grassland	Degraded vegetation (vegetation cover reduced)
18 21	Cultivated permanent commercial irrigated Cultivated temporary commercial irrigated	Cultivated, irrigated
19 20 22 23	Cultivated permanent commercial dryland Cultivated permanent commercial sugarcane Cultivated temporary commercial dryland Cultivated temporary subsistence dryland.	Cultivated, dryland
24	Urban residential – high density	Urban residential – high density
25 26 27 28	Urban residential (smallholdings – forest and woodland) Urban residential (smallholdings – thicket, scrub forest, bushland and high fynbos) Urban residential (smallholdings – shrubland and low fynbos) Urban residential (smallholdings – grassland).	Urban residential – low density
29	Urban commercial	Urban commercial
30	Urban industrial/transport	Urban industrial/transport
31	Mines and quarries	Mines and quarries

Land cover change that is being considered in this study can be either in the catchment or the wetland, with different intensities of impact in each case. Furthermore, only the major effect of land cover change on runoff into and flow through a wetland is considered.

2.2.1 Natural (classes 1-7, 10, 11)

This category includes the following NLC classes: Forest and woodland; Forest; Thicket, scrub forest, bushland and high fynbos; Shrubland and low fynbos; Herbland; Unimproved grassland; Improved grassland; Wetlands; and Bare rock. These land cover classes either represent natural conditions, or conditions that do not differ significantly from natural, and therefore are considered to have no hydrological impact (assessed as a deviation from the natural condition).

2.2.2 Forest Plantations (class 8)

This NLC class may critically modify the hydrology of the catchment or the wetland itself, depending on where plantations are established, by reducing water inputs, mainly through canopy interception, or through evapotranspiration. *Note: these impacts should only be applied where former land cover was comprised of grassland, herbland, shrubland or fynbos, and not in cases where natural forest was replaced by plantations.*

2.2.3 Water Bodies (class 9)

Artificial impoundments may largely modify the hydrology of a wetland's catchment by reducing water inputs, and may critically modify the hydrology of the wetland itself by increasing wetness and deep flooding areas of wetland vegetation. *Note: these impacts should only be applied in the case of artificial water bodies.*

2.2.4 Dongas and Sheet Erosion (class 12)

This NLC class may largely modify the hydrology of a wetland's catchment by increasing water inputs, and may variably modify the hydrology of the wetland itself, depending upon the particular characteristics of the erosional features within the wetland (e.g. depth, density, alignment).

2.2.5 Degraded Vegetation (classes 13-17)

This category includes the following NLC classes: Degraded forest and woodland; Degraded thicket, scrub forest, bushland and high fynbos; Degraded shrubland and low fynbos; Degraded herbland; and Degraded unimproved grassland, and refers specifically to a decrease in vegetation cover. Areas of degraded vegetation may modify the hydrology of a wetland's catchment by increasing water inputs due to lower interception of rainfall, and the hydrology of the wetland itself through a reduction in surface roughness. *Note: alien vegetation is considered as a form of forest plantation establishment since its impact on water yield from catchments is similar to the situation where trees are deliberately planted.*

2.2.6 Irrigated Cultivation (classes 18, 21)

This category includes the following NLC classes: Cultivated permanent commercial irrigated; and Cultivated temporary commercial irrigated. Irrigated cultivation may largely modify the hydrology of a wetland's catchment by reducing water inputs (or increasing water inputs if irrigation involves an inter-basin transfer of water), and the hydrology of the wetland itself through a reduction in surface roughness if this activity occurs within the wetland. *Note: the impact of irrigated cultivation on wetland surface roughness, however, should only be applied in cases where measures have been taken to prevent saturation of cultivated lands, such as the excavation of drains and development of cambered beds, or where the land surface is likely to be stripped of vegetation for considerable periods of time.*

2.2.7 Dryland Cultivation (classes 19, 20, 22, 23)

This category includes the following NLC classes: Cultivated permanent commercial dryland; Cultivated permanent commercial sugarcane; Cultivated temporary commercial dryland; and Cultivated temporary subsistence dryland. Dryland cultivation has less of an effect on the hydrology of a wetland's catchment than irrigated cultivation, moderately reducing water inputs to the wetland. If dryland cultivation occurs in the wetland itself it may largely modify the hydrology of the wetland through a reduction in surface roughness. In the case of subsistence agriculture that uses irrigation, the same impact as dryland agriculture should be used because the frequency and quantity of water used is likely to be less than for commercial agriculture with irrigation. *Note: the impact of dryland cultivation on wetland surface roughness should only be applied in cases where measures have been taken to prevent saturation of cultivated lands, such as the* *excavation of drains and development of cambered beds, or where the land surface is likely to be stripped of vegetation for considerable periods of time.*

2.2.8 Urban Residential – High Density (class 24)

High density urban residential development may largely modify the hydrology of a wetland's catchment by increasing water inputs and peak flows, and may critically modify the hydrology of the wetland itself – where hardened surfaces are emplaced within the wetland – by reducing surface roughness.

2.2.9 Urban Residential – Low Density (classes 25-28)

This category includes the following NLC classes: Urban residential (smallholdings – forest and woodland); Urban residential (smallholdings – thicket, scrub forest, bushland and high fynbos); Urban residential (smallholdings – shrubland and low fynbos); and Urban residential (smallholdings – grassland). Low density urban residential development has less of an effect on the hydrology of a wetland's catchment than high density development, moderately increasing water inputs, but may critically modify the hydrology of the wetland itself – where hardened surfaces are emplaced within the wetland – by reducing surface roughness.

2.2.10 Urban Commercial (class 29)

Urban commercial development may critically modify the hydrology of a wetland's catchment by increasing water inputs, and the hydrology of the wetland itself – where hardened surfaces are emplaced within the wetland – by reducing surface roughness.

2.2.11 Urban Industrial/Transport (class 30)

Urban industrial/transport development may critically modify the hydrology of a wetland's catchment by increasing water inputs, and the hydrology of the wetland itself – where hardened surfaces are emplaced within the wetland – by reducing surface roughness. In addition, in cases where a road crosses a wetland, the road may impede flow through the wetland, greatly modifying wetland hydrology.

2.2.12 Mines and Quarries (class 31)

Mines, quarries and associated infrastructure may greatly modify the hydrology of a wetland's catchment by increasing water inputs, and where such activities occur within the wetland itself, they may critically modify wetland hydrology by reducing surface roughness.

2.3 Intensity of hydrological impacts of altered land cover

The nature of the human activities that impact on wetland health will influence the provision of ecosystem services in different ways. For example, the drainage of a wetland by artificial drains may increase hydraulic efficiency and lead to drying out of a wetland, which will reduce the ability of a wetland to remove pollutants from inflowing water. On the other hand, this activity may increase the flood attenuation function as flood attenuation relies on the available pore space in the soil, which will be greater if the wetland dries out. Another example is the effect of hardening of surfaces in the catchment of the wetland, which will increase the input of water to the wetland, and (in the short-term at least) will promote the presence of wetter hydrological zones in the wetland thereby increasing the ability of the wetland to remove pollutants from inflowing water. However, this activity will reduce the flood attenuation function due to reduced pore space in the soil as a consequence of the increased wetness. Given this variation in response to human activities, the present study has focussed on the most common impacts on wetland hydrological health as follows:

Catchment Impacts

1. **Increased catchment water inputs**: an increase in the volume of discharge and frequency of water inputs from the catchment into a wetland, due to for example, hardening of catchment surfaces, reduction in catchment vegetation cover, stormwater inputs, and inter-basin water transfer.
2. **Reduced catchment water inputs:** a decrease in the volume of discharge to a wetland due to catchment afforestation, alien infestation, abstraction for irrigation, and storage of water in dams.

Within-Wetland Impacts

3. **Increased wetland direct water losses:** a reduction in wetness due to alien plant infestation or commercial afforestation within a wetland.

4. **Reduced wetland surface roughness:** a decrease in wetland vegetation cover and/or weakening in vegetation structure due to clearing of vegetation for agriculture, trampling by livestock, or excessive burning.
5. **Wetland flow impediment:** a change in water distribution and increased water retention within the wetland due to impoundment by dams and un-vented or poorly vented road crossings.
6. **Wetland flow enhancement:** a change in water distribution and decreased water retention within the wetland due to confinement of surface flow and groundwater drawdown by agricultural drains and gullies.

Wetland health is scored in relation to the magnitude of human impacts, on a scale of 0 to 10 (Table 2.2). An impact score of 0 translates to a health score of 0 such that the wetland is not impacted at all and would be considered to be representative of a wetland in its natural reference condition.

Table 2.2: Impact scores and categories in relation to a description of wetland ecological condition (from Macfarlane *et al.,* 2008)

IMPACT CATEGORY	DESCRIPTION	IMPACT SCORE RANGE
None	No discernible modification or the modification is such that it has no impact on wetland integrity.	0-0.9
Small	Although identifiable, the impact of this modification on wetland integrity is small.	1-1.9
Moderate	The impact of this modification on wetland integrity is clearly identifiable, but limited.	2-3.9
Large	The modification has a clearly detrimental impact on wetland integrity. Approximately 50% of wetland integrity has been lost.	4-5.9
Serious	The modification has a clearly adverse effect on this component of habitat integrity. Well in excess of 50% of the wetland integrity has been lost.	6-7.9
Critical	The modification is present in such a way that the ecosystem processes of this component of wetland health are totally / almost totally destroyed.	8-10

However, an impact score of 10 translates to a health score of 10 such that the wetland is greatly impacted and would be considered to be critically transformed to a land cover unit no longer recognisable as a wetland. A health score of 3 indicates a wetland that has been moderately impacted. Given this, and the fact that **intensity X extent = magnitude** of impact (see Section 2.1), the intensity of impact scores arising from different land cover changes are also scored on a scale of 0 to 10. Based on the broad predictions in WET-Health (Macfarlane *et al.,* 2008), impact intensity scores have been assigned to each land cover category as shown in Table 2.3.

Attention needs to be paid to whether the land cover change (and the associated impact) is located in the catchment or within the wetland itself as shown in Table 2.3. The six types of impacts considered here for which intensity of impact scores have been provided correspond to those considered in Section 3 of this report (see Section 3.3).

Table . :

Land cover category	Intensity of impact score					
	Catchment land cover		Within-wetland land cover			
	1. Increased water inputs	2. Reduced water inputs	3. Increased direct water losses	4. Reduced surface roughness	5. Flow impediment	6. Flow enhancement
Natural	0	0	0	0	0	0
Forest plantations		9 (forest) 7 (heavy alien plant infestation) 5 (modest alien plant infestation) 3 (light alien plant infestation)	9 (forest) 7 (heavy alien plant infestation) 5 (modest alien plant infestation) 3 (light alien plant infestation)			
Water bodies		5	6*** (for area of wetland below the dam in the wetland)		9 (for area of wetland above the dam in the wetland)	
Dongas and sheet erosion	5					9
Degraded vegetation	3			3		
Irrigated cultivation	3 (if IBT*)	5		5		
Dryland cultivation,		3		5		
Urban residential – high density	5 (9 if WWTW present**)			7		
Urban residential – low density	3 (9 if WWTW present**)			5		
Urban commercial	7 (9 if WWTW present**)			9		
Urban industrial/transport	9		4*** (for area of wetland above road across a wetland)	9	5 (for area of wetland above road across a wetland)	
Mines and quarries	5			9		

* Refers to irrigation that involves importation of water into the catchment by inter-basin transfer (IBT).

** Refers to the presence of wastewater treatment works (WWTW) where these occur in the catchment

*** The area of wetland used in the calculation of the magnitude of impact is scaled to account for variation in the depth of the dam. This is described in the text that follows Table 4.6.

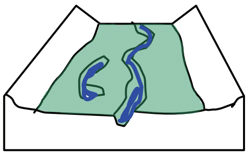
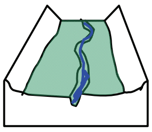
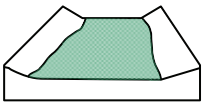
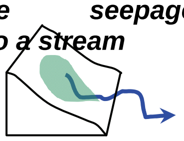
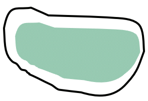
3. DEVELOPMENT OF A LOSS OF FUNCTION METRIC TO ASSESS PROVISION OF ECOSYSTEM SERVICES IN RELATION TO IMPACTS ON WETLAND HYDROLOGY

3.1 Wetland hydrogeomorphic units

Given that human activities affect the pattern of water flow into and through a wetland in addition to causing sediment erosion or deposition, an understanding of human impacts on wetlands is best achieved by considering the hydrogeomorphic setting of the wetland. The tool "WET-Health" thus starts its assessment with the division of a wetland into hydrogeomorphic (HGM) units as these are distinguished on the basis of the geomorphological setting and pattern of water flow into and through the wetland. There are 6 HGM units used in WET-Health, with descriptions of each of these provided in Table 3.1 (after Kotze *et al.,* 2008).

Floodplains receive water inputs from inflowing rivers and water flows through floodplains within a river channel, except during flood events when there is inundation of the floodplain due to lateral movement of flood water as the river banks are over-topped. Floodplains are typically sites of sediment storage such that depositional features (e.g. alluvial fill, levees and alluvial ridges) are present. Valley-bottom wetlands can be channelled or unchannelled. Channelled valley-bottom wetlands generally receive water from a stream channel, and water leaves the wetland via a stream. Unchannelled valley-bottom wetlands receive inputs via diffuse flow or streams, and flow through these wetlands is mainly diffuse. Water typically leaves unchannelled valley-bottom wetlands via a stream. Hillslope seepage wetlands receive water via groundwater inputs, and water flows through these wetlands as diffuse flow. Water may leave the wetland via groundwater recharge ("isolated hillslope seepage" wetland) or via a stream ("hillslope seepage linked to a stream"). Depressions typically receive water inputs as diffuse overland flow and typically do not integrate with the drainage network. Depressions located on the coastal plain may simply represent the intersection of the water table with the surface of the earth.

Table 3.1: Wetland hydrogeomorphic (HGM) types typically supporting inland wetlands in South Africa (modified from Marneweck and Batchelor, 2002; Kotze, 1999 and Brinson, 1993)

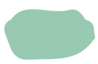
Hydrogeomorphic types	**Description**	**Source of water maintaining the wetland[1]**	
		Surface	**Sub-surface**
Floodplain 	Valley-bottom areas with a well defined stream channel, gently sloped and characterized by floodplain features such as oxbow depressions and natural levees and the alluvial (by 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.	***	*
Valley-bottom, channelled 	Valley-bottom areas with a well defined stream channel but lacking characteristic floodplain features. May be gently sloped and characterized by the net accumulation of alluvial deposits or may have steeper slopes and be characterized by the net loss of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*/ ***
Valley-bottom, unchannelled 	Valley-bottom areas with no clearly defined stream channel usually gently sloped and characterized by alluvial sediment deposition, generally leading to a net accumulation of sediment. Water inputs mainly from channel entering the wetland and also from adjacent slopes.	***	*/ ***
Hillslope seepage linked to a stream 	Slopes on hillsides, which are characterized by the colluvial (transported by gravity) movement of materials. Water inputs are mainly from sub-surface flow and outflow is usually via a well defined stream channel connecting the area directly to a stream channel.	*	***
Isolated Hillslope seepage 	Slopes on hillsides, which are characterized by the colluvial (transported by gravity) movement of materials. Water inputs mainly from sub-surface flow and outflow either very limited or through diffuse sub-surface and/or surface flow but with no direct surface water connection to a stream channel	*	***
Depression (includes Pans) 	A basin shaped area with a closed elevation contour that allows for the accumulation of surface water (i.e. it is inward draining). It may also receive sub-surface water. An outlet is usually absent, and therefore this type is usually isolated from the stream channel network.	*/ ***	*/ ***

[1] Precipitation is an important water source and evapotranspiration an important output in all of the above settings

Water source: * Contribution usually small

*** Contribution usually large

*/ *** Contribution may be small or important depending on the local circumstances

Wetland 

This classification is aligned closely with the “inland wetland” classes of the classification of Ewart-Smith *et al.* (2006), which was developed subsequent to WET-EcoServices. The main difference between the classification in this table and that of Ewart-Smith *et al.* (2006) is that the latter includes “depressions linked to streams”, which is a rarely occurring wetland type, and “channels” (i.e., streams and rivers), which are beyond the scope of WET-Health since they would form part of an assessment of riverine environmental condition (health).

3.2 Wetland ecosystem services

The provision of ecosystem services by wetlands is largely dependent upon the pattern of water flow through the wetland, such that the HGM unit also forms the basic unit for the assessment of ecosystem service provision in WET-EcoServices (Kotze *et al.,* 2008). The tool “WET-EcoServices” assesses a wide range of direct and indirect ecosystem services (Table 3.2), with the direct ecosystem services being of benefit mainly to local landowners or communities dependant on the system for subsistence use, while the indirect ecosystem services are of benefit to society as a whole.

For the purposes of this assessment the focus will be on examining a range of indirect hydrogeochemical ecosystem services because this tool is designed to promote effective management of wetlands for the benefit of society at large rather than of individuals benefitting at the cost of society. We are not therefore assessing provision of such resources as reeds, fish and other materials directly provided by wetlands, nor are we considering the more intangible benefits such as conservation or cultural importance. The six ecosystem services assessed by this tool are:

A. Flood attenuation;
B. Streamflow regulation;
C. Sediment trapping;
D. Nitrogen removal;
E. Phosphate removal; and
F. Toxicant removal.

Table 3.2: Ecosystem services included in WET-EcoServices (from Kotze *et al.,* 2008)

Ecosystem services supplied by wetlands	Indirect benefits	Regulating & supporting benefits		Flood attenuation	The spreading out and slowing down of floodwaters in the wetland, thereby reducing the severity of floods downstream
				Streamflow regulation	Sustaining streamflow during low flow periods
			Water quality enhancement benefits	Sediment trapping	The trapping and retention in the wetland of sediment carried by runoff waters
				Phosphate assimilation	Removal by the wetland of phosphates carried by runoff waters
				Nitrate assimilation	Removal by the wetland of nitrates carried by runoff waters
				Toxicant assimilation	Removal by the wetland of toxicants (e.g. metals, biocides and salts) carried by runoff waters
				Erosion control	Controlling of erosion at the wetland site, principally through the protection provided by vegetation.
				Carbon storage	The trapping of carbon by the wetland, principally as soil organic matter
				Biodiversity maintenance	Through the provision of habitat and maintenance of natural process by the wetland, a contribution is made to maintaining biodiversity
	Direct benefits	Provisioning benefits		Provision of water for human use	The provision of water extracted directly from the wetland for domestic, agriculture or other purposes
				Provision of harvestable resources	The provision of natural resources from the wetland, including livestock grazing, craft plants, fish, etc.
				Provision of cultivated foods	The provision of areas in the wetland favourable for the cultivation of foods
		Cultural benefits		Cultural heritage	Places of special cultural significance in the wetland, e.g., for baptisms or gathering of culturally significant plants
				Tourism and recreation	Sites of value for tourism and recreation in the wetland, often associated with scenic beauty and abundant birdlife
				Education and research	Sites of value in the wetland for education or research

A. Flood attenuation generally results as a consequence of the shallow longitudinal slope and horizontal cross-sectional morphology of wetlands that presents a large wetted perimeter for the discharge, such that the velocity of water flow is low. The presence of depressions and pore space in soils when the wetland is relatively dry, result in wetlands being able to retain a large volume of water. Friction caused by dense vegetation cover on the wetland surface also slows the passage of water through the wetland. Floodplains typically have elevated channels due to the presence of alluvial ridges and/or levees such that water during a flood is readily discharged onto the floodplain (or backswamp) from the stream without easily re-entering it.

B. Streamflow regulation: This term is used to describe the role of wetlands in maintaining base flows that improve water security in drainage systems. The maintenance of base flows depends partly on reduced velocity of water flow during flood events or peak flows, which is released back to the stream later. It also depends upon the ability of organic sediments to swell as a result of increased water pressure in the system during the wet season, which then sags to a reduced volume during the dry season, gradually releasing water back to the stream.

C. Sediment trapping: The ability of wetlands to trap sediments is largely related to reduced velocity of water flowing from steeper catchments into gently sloping wetland basins, which results in deposition. This is particularly the case for floodplains where sediment is trapped during both low flows (in point bars present on meandering streams) when sediment flux is low, and during high flows (on the levees, alluvial ridge and floodplain surface) when sediment flux is high. The presence of wetland vegetation also enhances the sediment-trapping capability of these systems.

D. E. and F. Removal of nitrogen, phosphorus and toxicants: The ability of wetlands to trap phosphate, nitrate and toxicants is related to a wide variety of biogeochemical processes in wetlands. Many of these processes are microbially driven, related to adsorption of cations onto negatively charged clay particles and organic sediment, to precipitation reactions that result from water loss by evaporation or transpiration and to the uptake of solutes by plants. It is difficult to predict outcomes of biogeochemical processes for most of these materials since they are chemically variable and the receiving environments are biogeochemically complex (Mitsch and Gosselink, 2007). However, broad generalisations are possible and are used in this study.

3.3 Relationships between provision of ecosystem services and human impacts

If one plotted the functional effectiveness of wetlands in terms of the provision of ecosystem services (on a scale of 0 to 4 as measured in WET-EcoServices) in relation to the impacts of human activities on wetlands (i.e. wetland health – on a scale of 0 to 10 as measured in WET-Health), one would expect a negative relationship. This is simply because human impacts generally have unintended negative effects on ecosystem functioning, with negative consequences for the provision of ecosystem services.

If the relationship between functional effectiveness and health is negative and linear it would be described by the general equation;
y = mx + c (A; Figure 3.1)

with ‘m’ being the slope (negative) and ‘c’ the y-intercept (when x=0 the y-value is from 0 to 4). It should be noted that the y-intercept is a measure of the effectiveness of a wetland to deliver a particular ecosystem service in an unimpacted state. Nonlinear relationships are possible (and likely), and they could be described by logarithmic, exponential or polynomial functions that express systematic (nonlinear) variation in functional effectiveness with variation in impact scores. Whatever the form of the equation, there will be a y-intercept with a score from 0 to 4.

An example of an impact type that exhibits a linear relationship with a particular ecosystem service (A; Figure 3.1) might be abstraction of water for irrigation in a catchment. This may well affect water availability in a wetland, causing a linear negative impact on the maintenance of base flows. In some cases wetland functions may be reduced drastically with even small impacts (B; Figure 3.1), such as erosion, where small increases in discharge caused by activities such as hardening of surfaces or poor land management in a catchment can cause drastic erosion in wetlands with negative impacts on functionality (McCarthy *et al.,* 2007). In some cases small impacts may have little effect on wetland functionality, but the negative impact on functionality increases more and more as the impact score increases (C; Figure 3.1). Such a relationship may be demonstrated with increased exposure of a wetland to pollutants, which may not have noticeable impacts on functional effectiveness at first, but are likely to become increasingly damaging to wetland functioning as pollution levels increase, and for example, there is dying-back of a dominant plant species. A fourth scenario can be envisaged, in which small impacts may increase the provision of ecosystem services, followed by a drastic decline in the provision of ecosystem services with large impacts (D; Figure 3.1). An example of such a relationship might be the effect of gullies on flood attenuation, where small gullies increase the available pore space for water storage during a flood event, which improves flood attenuation functionality, but large gullies intercept runoff and deliver it immediately and efficiently to downstream areas, thereby reducing flood attenuation functionality.

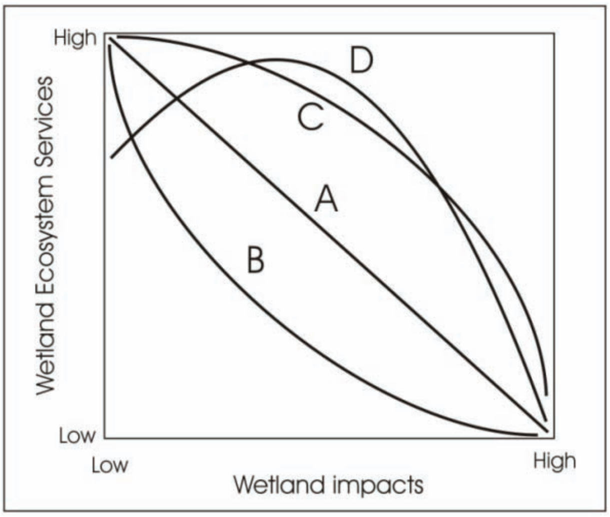


Figure 3.1: Possible relationships that might be expected between functional effectiveness scores (i.e. the provision of wetland ecosystem services, as assessed using WET-EcoServices) and wetland impact scores (as assessed using WET-Health).

The difficulty with developing individual relationships between the provision of ecosystem services and wetland health is that there are a large number of combinations of factors possible in terms of HGM type, wetland ecosystem service and types of impact. For instance, the functions provided by wetlands vary between different HGM types (floodplains, valley-bottom, seeps etc.). Given that there are 6 HGM types (Table 3.1), the proposed methodology would have to develop relationships for all of these. Similarly, the effectiveness of ecosystem service provision varies between different ecosystem services for a given HGM type. There are many ecosystem services, of which 6 will be assessed using this tool (Section 3.2), thus he combination of HGM type and ecosystem services being assessed requires the development of 36 relationships. Furthermore, wetland functional effectiveness for a given ecosystem service varies depending on the nature of the impact/s to the wetland. There are many impacts considered by WET-Health, of which we have chosen to deal with 6 (two within-catchment and 4 within-wetland – see Section 2.3), thus the number of relationships that is required for this tool is 216. This is a task that is extraordinarily ambitious, and that is unlikely to be useful since its application will be inordinately complex.

An approach has therefore been adopted that simplifies the combination of factors that should be considered in relating the provision of ecosystem services to health. We have chosen to focus on only 2 HGM types (floodplains and valley-bottom wetlands) since these are spatially extensive and common in South Africa. Where a wetland is not a floodplain or a valley-bottom wetland, the method for valley-bottom wetlands should be used. Our approach has therefore been to develop relationships for 2 HGM types (floodplains and valley-bottom wetlands), 6 ecosystem services (as listed in Section 3.2) and 6 impact types (Section 2.3). This matrix is shown as Table 3.3. Therefore, the number of relationships has been reduced from 216 to 72. Even this is more complex than is desirable.

Table 3.3: Matrix showing the combinations of wetland ecosystem services and catchment and wetland impacts considered in this study for each of floodplain and valley-bottom HGM types

	Catchment impacts		**Within-wetland impacts**			
	1. Increased water inputs	2. Decreased water inputs	3. Increased wetland water losses	4. Reduced wetland surface roughness	5. Wetland flow impediment	6. Wetland flow enhancement
A. Flood attenuation						
B. Streamflow regulation						
C. Sediment trapping						
D. Nitrogen removal						
E. Phosphate removal						
F. Toxicant removal						

The following sections therefore first attempt to:

- establish the extent of delivery of ecosystem services of unimpacted ("natural") wetlands using empirical data; and
- develop relationships between wetland health due to a given type of impact and the consequent effectiveness in the provision of a particular ecosystem service.

3.4 Ecosystem service provision by unimpacted wetlands: empirical studies

Data have been used from a set of floodplains and unchannelled valley-bottom wetlands with varying degrees of impact, in order to establish the relationships between impacts and the provision of each of the ecosystem services being assessed. The case study illustrating relationships for valley-bottom wetlands is presented as Appendix 1 but the data for floodplains has not been included in this report. By plotting the variation in the provision of ecosystem services in relation to wetland health it was possible to broadly understand the major factors determining this relationship. More importantly, this exercise provided an indication of the level of provision of all ecosystem services for each of these wetland types in an unimpacted state, which is indicated by the y-intercept (impact score = 0) when illustrated graphically as in Figure 3.1. These results are provided in Table 3.4 and discussed for each ecosystem service below.

Table 3.4: The ecosystem service scores* for unimpacted floodplain and valley-bottom wetlands for each of the six ecosystem services analysed as part of this study

Ecosystem service	Valley-bottom	Floodplain
A. Flood attenuation	2.2	3.1
B. Streamflow regulation	2.3	2.6
C. Sediment trapping	1.1	3.1
D. Phosphate trapping	3.2	2.4
E. Nitrate removal	3.7	2.1
F. Toxicant removal	3.1	2.5

* On a scale of 0-4 as used in WET-EcoServices (Kotze *et al.,* 2008).

A. Flood attenuation

Based on the ecosystem service scores shown in Table 3.4, it is evident that valley-bottom wetlands are moderately effective at attenuating floods as they spread inflowing waters over a large area, slowing it down due to friction. Floodplains are very effective with respect to flood attenuation as they spread floodwaters of substantial magnitude over a large surface area, greatly reducing flow velocities. Some of the water spread over the wetland surface is stored in depressions or in the soil, to be evaporated or used by plants and lost to the atmosphere by transpiration.

B. Streamflow regulation

The streamflow regulation function of both valley-bottom wetlands and floodplains is typically moderately high since they are generally well connected to streams. Valley-bottom wetlands typically supply effluent streams on a fairly sustained basis due to their fairly high slopes, which promotes outflow from the wetland to the effluent stream, and the general occurrence in many valley-bottom wetlands of seasonally and/or permanently flooded wetland in reasonably close proximity to the effluent stream. Where there is a reasonable accumulation of organic matter, this function is likely to be very effective due to the sponge-like properties of organic sediment. Floodplains also sustain base flows, as the floodplain surface or backswamp in zones of seasonal or permanent inundation will link to the effluent stream at the lower end of the floodplain via a channel.

C. Sediment trapping

Valley-bottom wetlands are not very effective at trapping sediment since the input of sediment to these systems is generally not particularly high because flow into them is often diffuse. Inflowing water is therefore not sediment-rich. Where there is input of water by a stream, the sediment is disposed of at the head of the wetland. In contrast, floodplains are very effective at trapping sediment, particularly where there is a meandering river present. Meandering rivers effectively dispose of sediments in point bar deposits, which largely redistribute sediment along the channel course but which do accumulate some sediment that is typically fairly coarse. Irrespective of the fluvial style of the floodplain river, floodplains effectively trap sediment during flood events as the velocity of water flow on the floodplain surface is much lower than in the floodplain river, promoting the accumulation of fine material on the floodplain surface.

D. Phosphate trapping

Phosphorus may be adsorbed to sediment such that the phosphate trapping function of wetlands is similar to their sediment trapping function, or it may be present in dissolved form and be taken up by plants or involved in sorption reactions with soil or organic matter depending upon geochemical circumstances. Nevertheless, the large proportion of diffuse flow associated with valley-bottom wetlands makes this HGM type especially effective at trapping phosphate, especially in its dissolved form, since biological processes in wetlands allow phosphate trapping. Trapped phosphate is incorporated into organic matter and sediments, or where it is present in plant tissue, it is incorporated into ash or it is discharged into the atmosphere during burning in veld fires. Floodplains are moderately effective at trapping phosphorus that is adsorbed to sediment, or, where water rich in dissolved phosphorus reaches the floodplain surface, it will be effectively trapped through biological processes. However, during low flows (when flow is confined within the floodplain river), very little phosphate is trapped in floodplains. For this reason floodplains are considered to be less effective than valley-bottom wetlands in carrying out this function.

E. Nitrate removal

Nitrate removal is effectively achieved in valley-bottom wetlands through biological processes, including uptake by plants as well as microbial transformations. These microbial processes mainly take place in anaerobic conditions such that the extent and duration of flooding is critical when considering nitrate removal. Floodplains are moderately effective at removing nitrate through similar processes, but during low flows there is very little nitrate removal.

F. Toxicant removal

Valley-bottom wetlands are effective at toxicant removal due to the diffuse flow of water and the large quantity of water that is lost to the atmosphere as transpiration. This loss of water to the atmosphere is not accompanied by loss of solutes, so that these accumulate in plant tissue or wetland soils, typically in an insoluble form that is ecologically harmless. The same occurs in floodplains, but it is spatially restricted to the channel margin during low flows, although during flood events it is far more extensive.

3.5 Relationships between ecosystem service provision and wetland health: interpretive studies

3.5.1 Simplifying the y-intercept values for use in interpretive studies

Having established the y-intercepts (effectiveness of ecosystem service provision) for valley-bottom and floodplain wetlands in the unimpacted state (Table 3.4), the next step is to examine the effect of impaired wetland health on the provision of those ecosystem services. First, however, it was considered desirable to simplify both the scores used to denote wetland health and those that denote provision of ecosystem services. Therefore, the midpoints of each of the health classes (on a scale of 0 to 10) developed by Macfarlane *et al.* (2008) and shown in Table 2.2, were used in this study and a set of 5 scores (on a scale of 0 to 4) were used to denote the effectiveness of ecosystem service delivery (Table 3.6).

Table 3.5: Impact scores assigned to health categories in the determination of the relationships between the provision of ecosystem services and wetland health

HEALTH CATEGORY	Natural	Largely natural	Moderately modified	Largely modified	Greatly modified	Critically modified
IMPACT SCORE RANGE	0-0.9	1-1.9	2-3.9	4-5.9	6-7.9	8-10
IMPACT SCORE	0.5	1.5	3	5	7	9

Table 3.6: Scores assigned to the extent of the provision of an ecosystem service

PROVISION OF ECOSYSTEM SERVICE	Low	Moderately low	Intermediate	Moderately high	High
RANGE	0-0.49	0.5-1.19	1.2-1.99	2.0-2.99	3-4
SCORE	0.3	0.8	1.7	2.5	3.5

Given this background, the y-intercept scores (where x = 0; see Table 3.4) for the relationship between ecosystem services provision and wetland health for unimpacted wetlands were modified (Table 3.7) to use the midpoints of each ecosystem service class as described in Table 3.6.

Table 3.7: The final y-intercepts for floodplain and valley-bottom wetlands for each of the ecosystem services analysed in this study

Function	**Valley-bottom**	**Floodplain**
A. Flood attenuation	2.5	3.5
B. Streamflow regulation	2.5	2.5
C. Sediment trapping	1.7	3.5
D. Phosphate trapping	3.5	2.5
E. Nitrate removal	3.5	2.5
F. Toxicant removal	3.5	2.5

3.5.2 Relationships between ecosystem service provision and wetland health

In addition to determining the y-intercepts (i.e. the level of service provision in the natural, unimpacted condition) for valley-bottom and floodplain wetlands, simple linear relationships were determined for each of the impacts that affect the ability of a wetland to deliver the ecosystem services analysed in this study. This assessment is based on current understanding of the effect of impacts on wetland hydrological health and the subsequent provision of ecosystem services. The individual relationships are described in the following section and presented according to the matrix in Table 3.3. For each of the six impacts (as listed below), the likely effect on each of the six ecosystem services is described. These relationships are presented separately for the two HGM types namely; valley-bottom and floodplain wetlands.

Catchment Impacts

1. Increased catchment water inputs.
2. Reduced catchment water inputs.

Within-Wetland Impacts

3. Increased direct wetland water losses.
4. Reduced wetland surface roughness.
5. Flow impediment in the wetland.
6. Flow enhancement in the wetland.

3.5.2.1 Increased catchment water inputs

An increase in the frequency and volume of water inputs (total water input) and peak flows from a wetland's catchment may occur due to hardening of catchment surfaces, reduction in catchment vegetation cover, stormwater inputs from urban and industrial catchments, and inter-basin water transfers. Increased water inputs affect the delivery of most ecosystem services as indicated in Figure 3.2.

A. Flood attenuation

Valley-bottom and floodplain wetlands: Increased water inputs negatively affect flood attenuation since storage capacity in localised depressions and relative friction are reduced.

B. Streamflow regulation

Valley-bottom wetlands: With increased water inputs the wetland will flood more frequently due to increased peak flows and average discharges, which for small increases in water inputs will connect the wetland more strongly with the stream leading from the wetland (the effluent stream). Although this will increase the streamflow regulation function slightly, it will not be sufficient to increase it by a functionality class.

However, as peak flows and average discharges increase the wetland behaves more like a stream and streamflow functionality decreases.

Floodplain wetlands: For small increases in water inputs and peak flows, the wetland will flood more frequently due to increased peak flows and average discharges, which for small increases in water inputs will connect the floodplain more strongly with the floodplain channel as well as to the effluent stream, which will increase the streamflow regulation function. However, as flow increases the stream flow regulation function will be reduced because the wetland will behave more and more like a stream.

C. Sediment trapping

Valley-bottom wetlands: Increased water inputs to valley-bottom wetlands will reduce the opportunity to trap sediments as the additional inputs of water are typically sediment starved. For small increases in water inputs this is not sufficient to reduce sediment trapping efficiency by a class. However, with large increases in discharge of largely sediment-free water, the wetland will erode and its sediment trapping function will be reduced as the system yields, rather than traps, sediment.

Floodplain wetlands: Sediment trapping efficiency of floodplains will change little for small increases in inflows as the floodplain surface will flood more frequently but sediment inputs should not increase. However, during moderate to large floods, floodplains will still trap sediment effectively. During large floods, which may happen more frequently, the overall sediment trapping function will decline, particularly as erosion in the wetland will occur and the floodplain will start to yield sediment.

D. Phosphate trapping

Valley-bottom and floodplain wetlands: Phosphate trapping is related to sediment trapping as phosphate is often adsorbed to sediments. However, biological uptake in phosphorus-limited systems also leads to removal of dissolved phosphorus. Although sediment inputs are unlikely to increase with increased water inputs, in some situations there is likely to be increased dissolved phosphorus input arising from interbasin transfers linked to waste water treatment works. Erosion of the wetland will occur following substantially increased flows, and the phosphate trapping function will then decrease.

E. Nitrate removal

Valley-bottom and floodplain wetlands: The increased presence of anaerobic soils and organic matter accumulation arising from increased areal extent (and duration) of inundation, will increase the nitrate removal function in the case of floodplains, and will maintain this function at a high level in the case of valley-bottom wetlands. However, as water inputs increase the wetland will erode and the nitrate removal function will decline since the retention time of the water will be reduced.

F. Toxicant removal

Valley-bottom and floodplain wetlands: For solutes that are not limiting, some may be adsorbed to sediment or organic matter, while others may be precipitated from solution through water loss by evaporation or transpiration. Increased wetness will increase the presence of permanently wet soils, which will increase plant productivity and transpirational water loss such that the toxicant removal function of floodplains will increase, while this function will remain at a high level in valley-bottom wetlands. However, as water input increases above a certain threshold, erosion will occur, reducing the effectiveness of this function for both floodplain and valley-bottom wetlands since the retention time of water will be reduced.

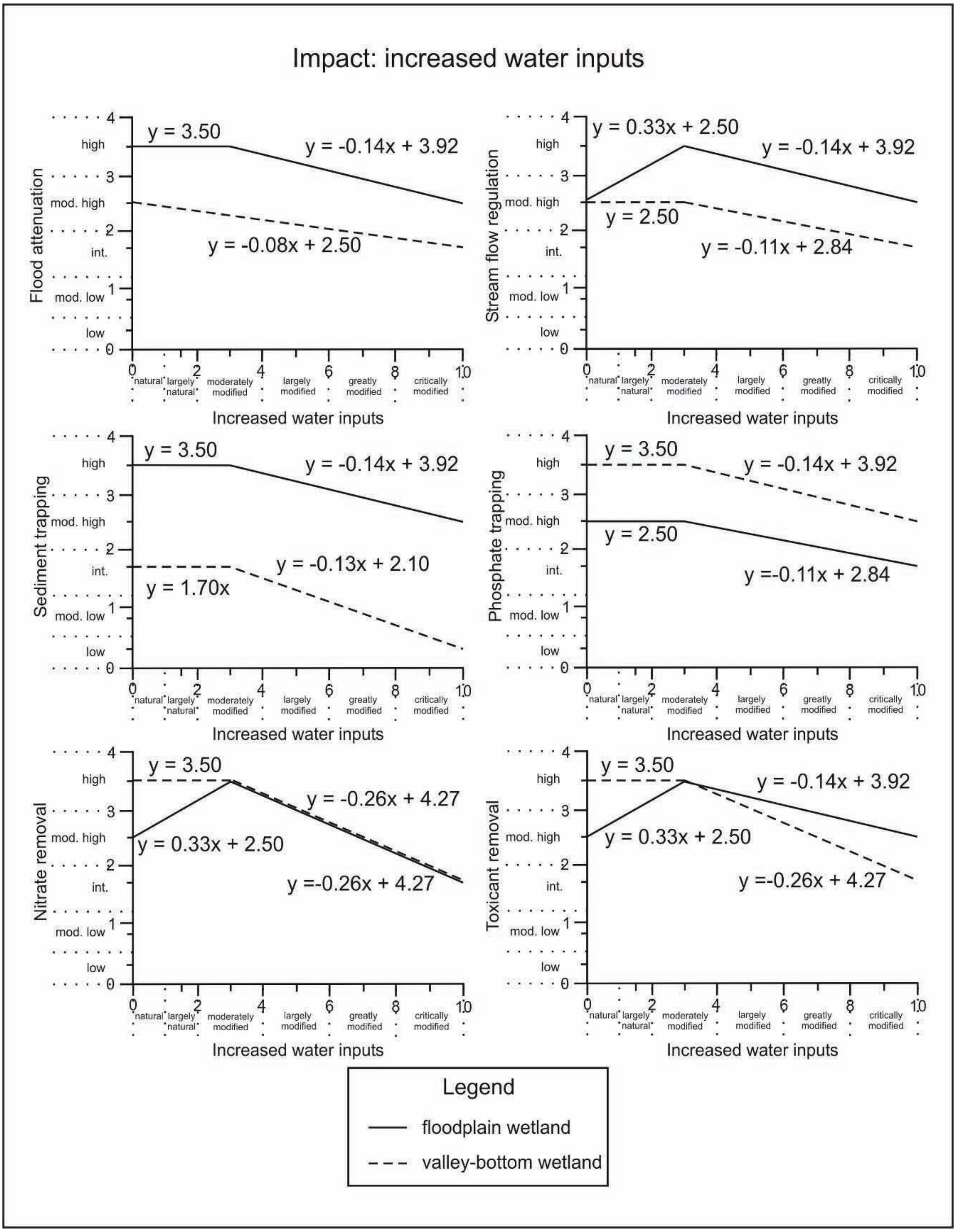


Figure 3.2: Relationships between the provision of ecosystem services and wetland health given increased water inputs from the catchment for floodplains and valley-bottom wetlands.

3.5.2.2 Reduced catchment water inputs

A decrease in catchment discharge to a wetland may arise from impacts in the catchment such as afforestation, alien infestation, abstraction for irrigation and the presence of dams. These activities affect the delivery of ecosystem services as illustrated in Figure 3.3.

A. Flood Attenuation

Valley-bottom wetlands: A reduction in catchment water inputs to a wetland results in drying of the wetland and an increase in available pore space and depression storage to hold incoming flood water. Therefore, there is a net gain in flood attenuation performance due to these factors initially, followed by a decline in performance once health is increasingly modified. At higher levels of impact the vegetation will change in character, with a concomitant reduction in roughness, therefore reducing flood attenuation functionality.

Floodplain wetlands: A reduction in catchment water inputs to a floodplain wetland results in drying of the wetland and an increase in available pore space and depression storage to hold incoming flood water. However, because floodplains are in the highest category for flood attenuation these factors do not lead to a measurable increase in flood attenuation characteristics for small reductions in water inputs. As water inputs decline substantially, water supply to the wetland reduces to a level where the wetland floods less frequently, and vegetation changes in character leading to reduced roughness, therefore reducing flood attenuation functionality. The impact on flood attenuation functionality is greater for valley-bottom wetlands than for floodplains because the former have less depression storage than the latter.

B. Streamflow Regulation

Valley-bottom wetlands: Reduced water inputs to a wetland decrease the likelihood of organic matter accumulation, and increase the likelihood of decomposition of existing organic sediments, reducing streamflow regulation functionality. Furthermore, reduced water inputs will decrease connectivity between the flooded surface of the wetland and the influent and effluent streams, which all reduce streamflow regulation performance. The relationship is likely to be a simple negative one such that valley-bottom wetlands will drop by two functional effectiveness classes over the range of possible health classes.

Floodplain wetlands: Reduced water inputs will decrease connectivity between the flooded surface of the wetland and the influent and effluent streams, which reduces streamflow regulation performance by a single class over the range of possible health classes.

C. Sediment Trapping

Valley-bottom and floodplain wetlands: Reduced water inputs will be associated with reduced sediment inputs, and this function will be curtailed to a greater and greater extent as water inputs are increasingly reduced.

D. Phosphate Removal

Valley-bottom and floodplain wetlands: The phosphate removal function is partly related to the sediment trapping function since phosphorus may be adsorbed to sediment particles. Further to this, plant productivity will be reduced due to reduced water inputs such that the uptake of dissolved phosphorus by plants will be reduced. Therefore, the phosphate removal function of valley-bottom and floodplain wetlands will be reduced as water inputs decline.

E. Nitrate Removal

Valley-bottom and floodplain wetlands: A reduction in catchment water inputs negatively affects the denitrification process, which requires prolonged saturation and anaerobic soil conditions. Thus the provision of this ecosystem service declines with increasing desiccation. The relationship is likely to be a simple negative one with valley-bottom and floodplain wetlands dropping two classes with respect to the nitrate removal function over the range of health classes.

F. Toxicant Removal

Valley-bottom and floodplain wetlands: A reduction in catchment water inputs to a wetland affects sediment trapping performance and alters the hydrological regime of the wetland, reducing the extent and duration of anaerobic conditions as well as plant productivity and evapotranspirational water loss. These factors reduce the toxicant removal function increasingly as the wetland dries out.

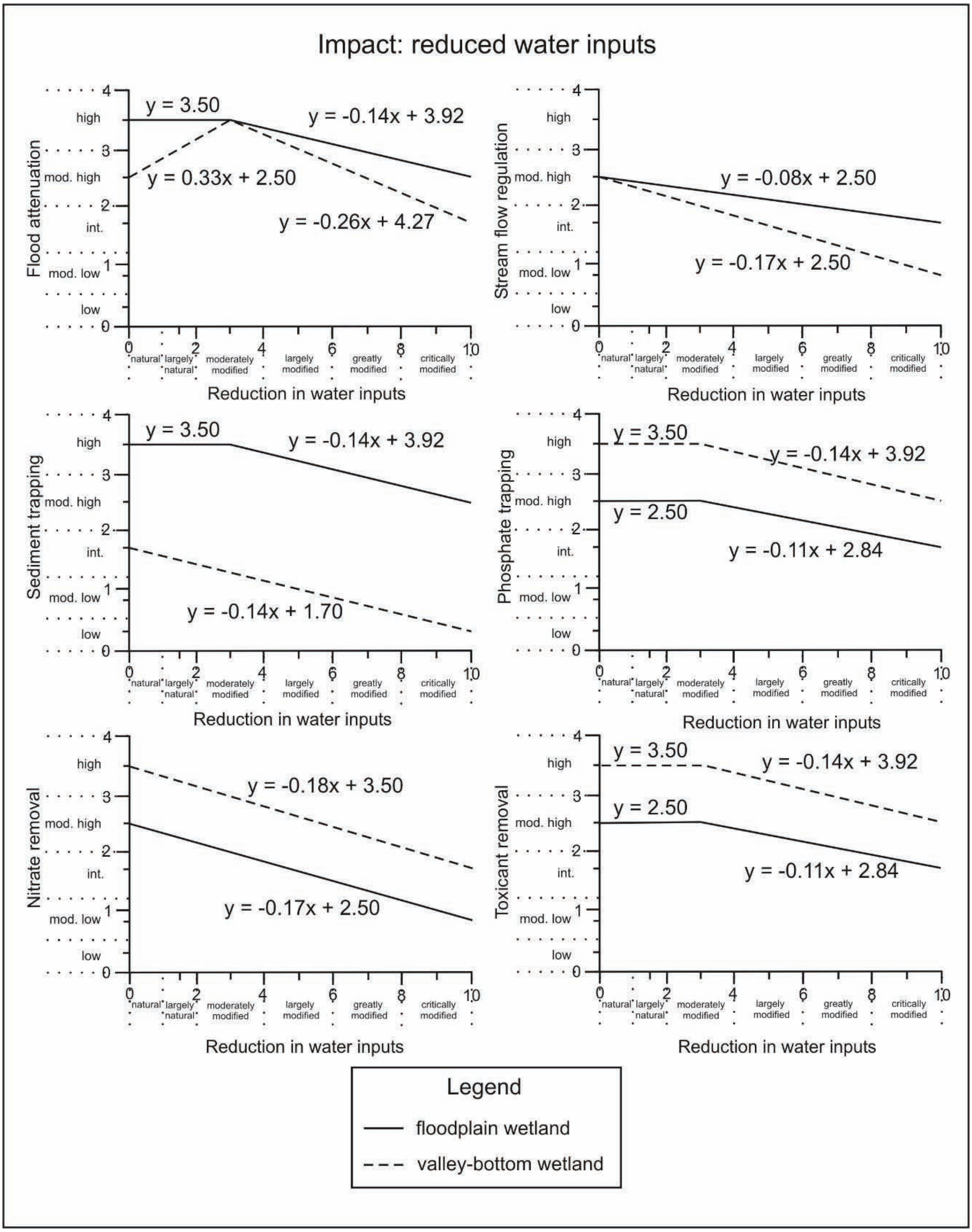


Figure 3.3: Relationships between the provision of ecosystem services and wetland health given decreased water inputs from the catchment for floodplains and valley-bottom wetlands.

From a consideration of the effect of catchment impacts on wetland functioning, direct impacts to the wetlands themselves will now be considered.

3.5.2.3 Increased direct losses of water from the wetland

A reduction in wetness due to direct water losses generally occurs due to infestation within a wetland of alien trees and shrubs or other plants with a very high leaf area index and high water demand. The likely consequences for the provision of ecosystem services are presented in Figure 3.4. Where the invasion of alien species results in erosion by gullying due to the exclusion of indigenous vegetation with a dense fine root mass, the impact should rather be considered as “flow enhancement” (see Section 3.5.2.6). This is because the hydrological impact due to gully formation is considered to be more severe than the increased evapotranspiration brought about by alien species.

A. Flood attenuation

Valley-bottom wetlands: As direct water losses increase and the wetland becomes dry, the available pore space and storage depression to attenuate floods increases, and concomitantly the wetland’s overall ability to attenuate floods increases. However, as direct water losses increase markedly, wetland vegetation will die back and roughness will decline. Some subsidence may take place due to dewatering, which may increase surface water storage but reduce available pore space for subsurface water storage. Therefore, with high levels of water loss, flood attenuation functionality will decline.

Floodplain wetlands: In floodplains, since this ecosystem service is already at the highest possible level, there is little possible enhancement of the flood attenuation function. However, as direct water losses increase markedly, wetland vegetation will die back and roughness will decline. Some subsidence may take place due to dewatering, which may increase surface water storage but reduce available pore space for subsurface water storage. Therefore, with high levels of water loss, flood attenuation functionality will decline. The impact in floodplains will not be as great as in valley-bottom wetlands due to the presence of greater depression storage in floodplains.

B. Stream flow regulation

Valley-bottom and floodplain wetlands: The stream flow regulation requires the wetland to ‘store’ water and release it slowly to the effluent stream, which is increasingly reduced as the wetland progressively dries. Effectiveness decreases by two classes for valley-bottom wetlands and by a single class for floodplains. This is because floodplain storage is recharged by large flood events that typically occur fairly frequently, which means that stream flow regulation is not very badly impacted in this type of HGM unit.

C. Sediment trapping

Valley-bottom and floodplain wetlands: As direct water losses increase the effectiveness with which a wetland traps sediment will also increase until wetland vegetation starts to die back, at which point effectiveness with respect to this ecosystem service will decrease. Effectiveness in valley-bottom wetlands when direct water losses are small remains constant due to the general lack of sediment input to these systems, but at high water losses sediment trapping decreases by 2 classes. In floodplains, there is limited potential enhancement of the sediment trapping function as this ecosystem service is already at the highest possible level, and at high levels of water loss functionality with respect to this ecosystem service decreases by only a single class because the morphology of floodplains allows them to trap some sediment during large flood events irrespective of vegetation cover.

D. Phosphate trapping

Valley-bottom and floodplain wetlands: As direct water losses increase, the effectiveness with which a wetland traps phosphorus increases because of increased water retention in the soil until wetland vegetation starts to die back, at which point effectiveness with respect to this ecosystem service will decrease. Thus, for small water losses, effectiveness will remain constant (valley-bottom wetlands) or increase (floodplains), but for large water losses phosphate trapping will decrease.

E. Nitrate removal

Valley-bottom and floodplain wetlands: Drying of wetlands leads to reduced nitrate removal due to a reduction in the extent and duration of anaerobic conditions. As such, direct water losses will result in wetlands becoming less effective at removing nitrates. The loss for both floodplains and valley-bottom wetlands is likely to be by one ecosystem service class.

F. Toxicant removal

Valley-bottom and floodplain wetlands: Because the wetland becomes drier due primarily to increased transpirational water loss, the wetland becomes more effective at removing toxicants. However, for large direct water losses wetland vegetation will die

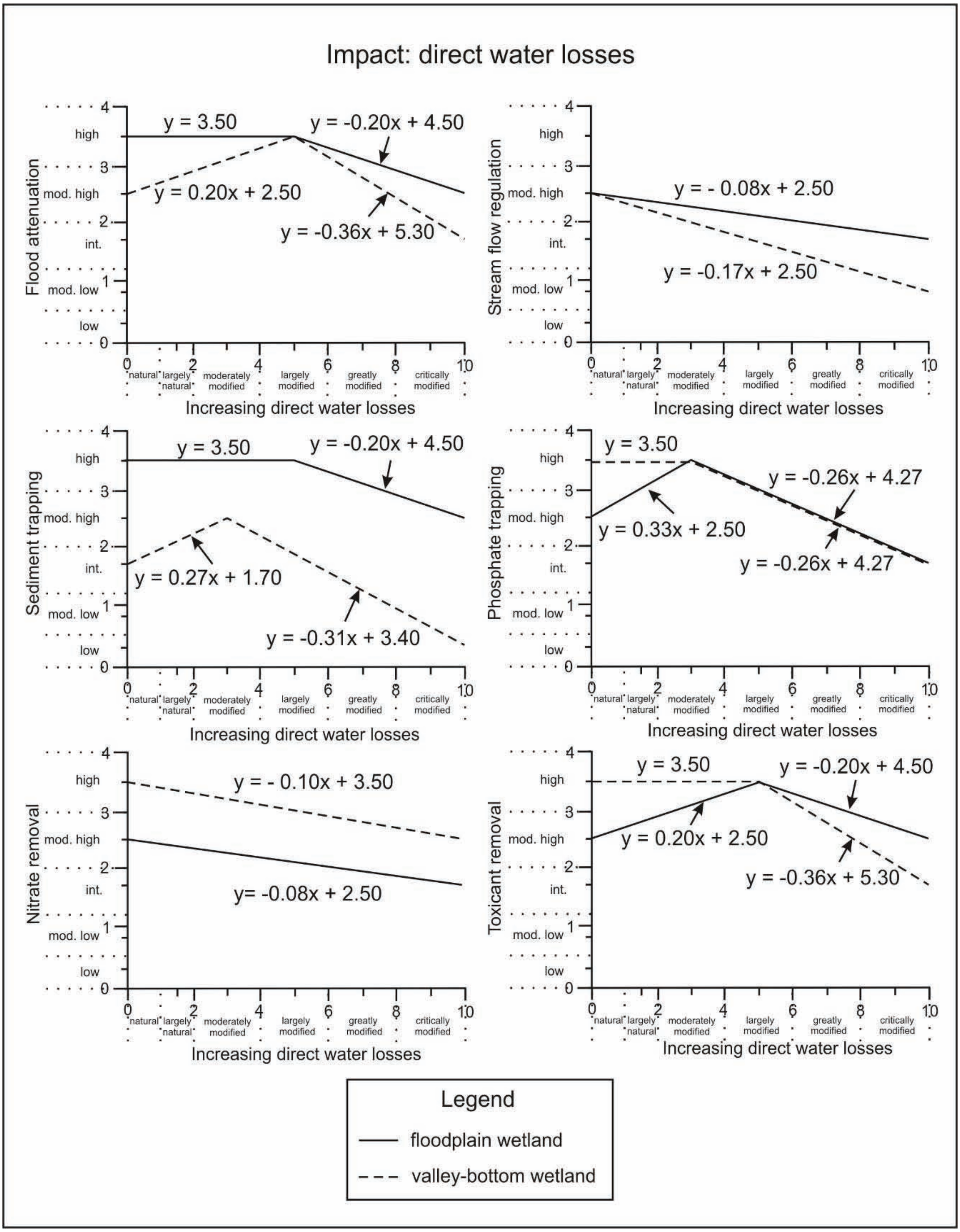


Figure 3.4: Relationships between the provision of ecosystem services and wetland health given increased direct water losses from the wetland for floodplains and valley-bottom wetlands.

back such that the wetland becomes less effective as a sink for toxicants due to reduced transpirational water loss. Valley-bottom wetlands decrease by 2 classes whereas floodplains decrease by a single class because of the morphology of floodplains and the presence of depression storage, which will allow localized solute processing and retention.

3.5.2.4 Reduced surface roughness

A decrease in wetland vegetation cover and/or weakening in vegetation structure may occur due to clearing of vegetation for agriculture, trampling by livestock, and excessive burning, which affect the delivery of ecosystem services. Likely effects of this impact are presented in Figure 3.5.

A. Flood attenuation

Valley-bottom and floodplain wetlands: As the surface roughness of a wetland decreases, the ability of the wetland to offer resistance to flood waters decreases, resulting in a decrease in flood attenuation effectiveness. The flood attenuation effectiveness is likely to drop by 2 classes for valley-bottom wetlands and 1 class for floodplains over the entire range of impact intensities.

B. Stream flow regulation

Valley-bottom wetlands: Changes to surface roughness will have a small negative impact on stream flow regulation for small decreases in surface roughness. However, as surface roughness declines in valley-bottom wetlands, the stream flow regulation function declines substantially because the wetland behaves more like a stream and water is efficiently delivered downstream rather than stored in the wetland and discharged during the dry season.

Floodplain wetlands: For floodplains the stream flow regulation function changes less than one class for small decreases in surface roughness, and by a single class for large reductions in surface roughness because relative friction across the floodplain surface is still fairly high, slowing water flow that gradually flows back into the floodplain stream.

C. Sediment trapping

Valley-bottom and floodplain wetlands: Due to decreases in flood attenuation effectiveness resulting from less frequent flooding of the wetland, sediment trapping effectiveness will also decrease. The sediment trapping effectiveness drops by two classes for valley-bottom wetlands and one class for floodplains.

D. Phosphate trapping

Valley-bottom and floodplain wetlands: Decreases in flood attenuation and sediment trapping will make the wetland less effective as a node of clastic sediment deposition and the capacity for phosphate trapping therefore declines. In addition, vegetation is required to assimilate phosphates, and with lower vegetation cover phosphate trapping function declines. Thus, decreases in surface roughness, particularly if associated with a loss of vegetation cover, will reduce phosphate trapping effectiveness for both valley-bottom and floodplain wetlands.

E. Nitrate removal

Valley-bottom and floodplain wetlands: A reduction in vegetation cover will reduce the ability of a wetland to assimilate nitrates, mainly because of decreased water retention within the wetland.

F. Toxicant removal

Valley-bottom and floodplain wetlands: Decreases in flood attenuation and sediment trapping will make the wetland less effective as a node of deposition, and toxicant removal function therefore declines. In addition, vegetation aids toxicant removal through precipitation reactions within the root zone caused by transpirational water loss and solute exclusion by plants. Thus, decreases in surface roughness, as well as a loss of vegetation, will reduce the effectiveness of toxicant removal.

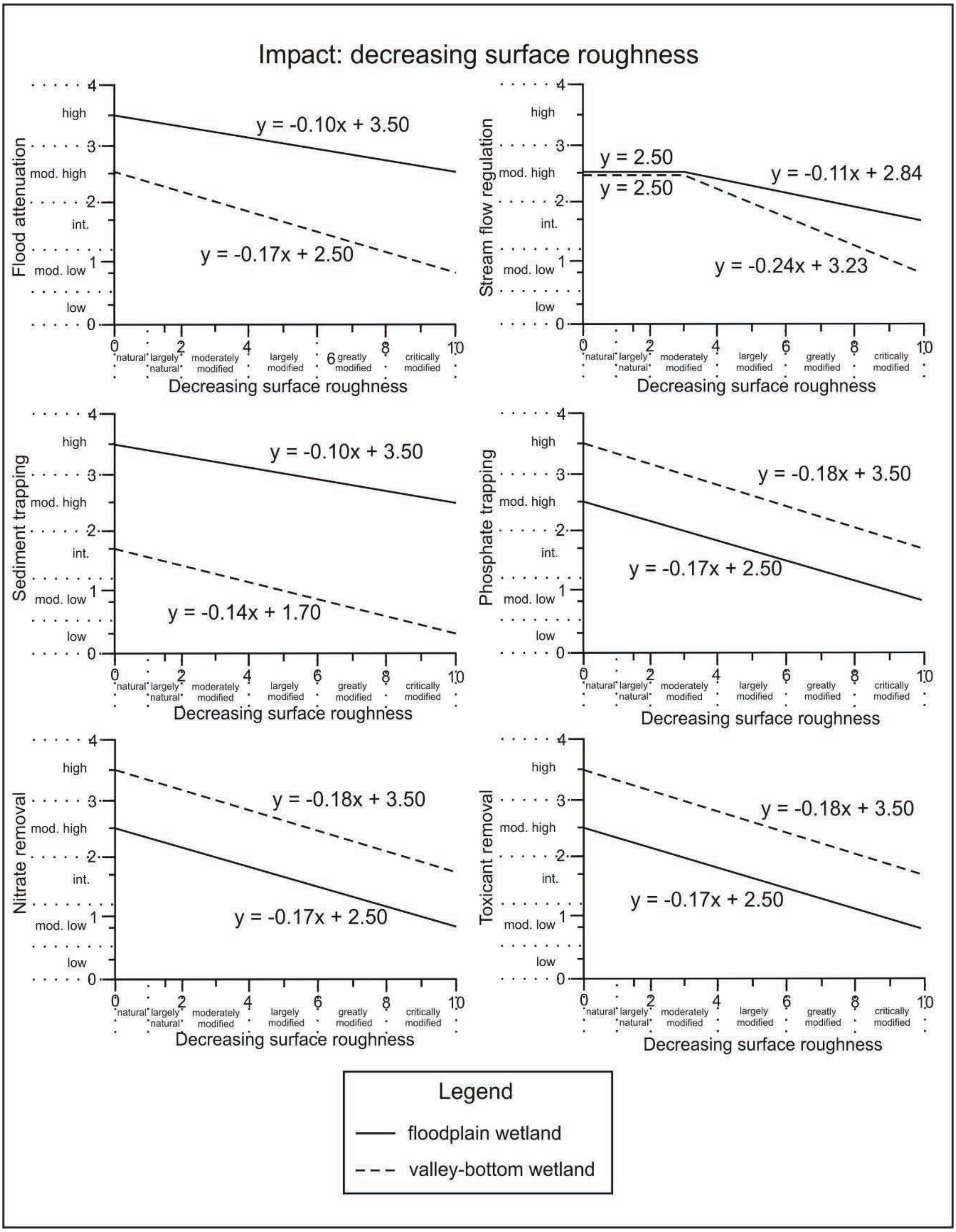


Figure 3.5: Relationships between the provision of ecosystem services and wetland health given reduced surface roughness in floodplains and valley-bottom wetlands.

3.5.2.5. Flow impediment within the wetland

This section focuses on the zone of the wetland upstream of the impediment where there is increased duration of flooding. For drying that occurs below a structure that impedes flow, the section dealing with increased direct use of water from the wetland should be consulted. Increased water retention may occur due to impoundment by dams and un-vented or poorly vented road crossings, which affects the delivery of ecosystem services in the area upstream. Results are presented in Figure 3.6.

A. Flood Attenuation

Valley-bottom wetlands: The impact of impeding features on flood attenuation performance varies seasonally and with impoundment size. During the early wet season, when dam water levels are likely to be below capacity, dams may increase depression storage within valley bottom wetlands, in which depressions are not naturally prolific. However, dams reduce depression storage during the late season within valley bottom wetlands, as once full; water entering a dam simply displaces water within it (there is no net storage). Evaporation from the dam surface is insignificant during periods of flooding, and will therefore not result in improved flood attenuation performance. Thus, the overall impact of impoundments on flood attenuation performance is neutral for valley-bottom wetlands for small impoundments, and since large dams increase depression storage, it is positive for large impoundments.
Floodplain wetlands: For floodplains, although dams increase storage depression, there is not a great deal of possible enhancement of the flood attenuation function as this ecosystem service is already the highest possible.

B. Streamflow Regulation

Valley-bottom and floodplain wetlands: Although some earthen dams may be permeable (‘leaky’), this is seldom part of the design, and dams generally withhold flow to lower landscape units in the dry and early wet season, but may, depending on the size of the impoundment, have no effect on flow in the late wet season (explained under ‘flood attenuation’ above). Where there is no opportunity for regulating flows from impoundments, impeding features reduce streamflow regulation performance for both floodplains and valley-bottom wetlands.

C. Sediment Trapping

Valley-bottom and floodplain wetlands: Impeding features, particularly dams, reduce the velocity of flow and are thus highly effective sediment traps. However, erosion may be initiated below the impoundment. Valley bottom wetlands do not receive much sediment and their sediment trapping function therefore remains constant over the range of health classes. In contrast, floodplains are typically very effective at trapping sediment, but their functional effectiveness does not change as a result of flow impediment.

D. Phosphate Removal

Valley-bottom wetlands: The effectiveness of valley-bottom wetlands with respect to phosphate trapping remains constant for small impoundments, but would decrease for large impoundments with respect to dissolved phosphates, as biological removal from these aquatic ecosystems is much lower than for wetlands due to reduced primary productivity in open water compared to that of emergent wetland vegetation.

Floodplain wetlands: For floodplains there would be a small change in phosphorus trapping as they effectively trap sediment and therefore phosphorus, although this would depend to some extent upon how water was discharged back into the wetland below the impoundment. Thus in situations where water is discharged from the impoundment into the floodplain stream, phosphate removal would be reduced to a greater extent than if it is discharged into the backswamp.

E. Nitrate Removal

Valley-bottom and floodplain wetlands: Roads and shallow dams quickly colonised by emergent vegetation will slightly improve denitrification by ensuring prolonged saturation of the soil, while deep dams prevent the colonisation of emergent vegetation and thus negatively affect denitrification. Nitrate removal performance for floodplains and valley-bottom wetlands therefore remains constant initially (small, shallow dams), but it drops a class for large impoundments on floodplains and valley-bottom wetlands.

F. Toxicant Removal

Valley-bottom and floodplain wetlands: Toxicant removal performance partly tracks sediment trapping and in part, tracks nitrate removal performance. Impeding features are effective sediment (and toxicant) traps and thus effectively trap toxicants adsorbed to sediments. However, impeding features reduce biological productivity, and due to reduced transpiration, toxins would increase in concentration in surface water as the

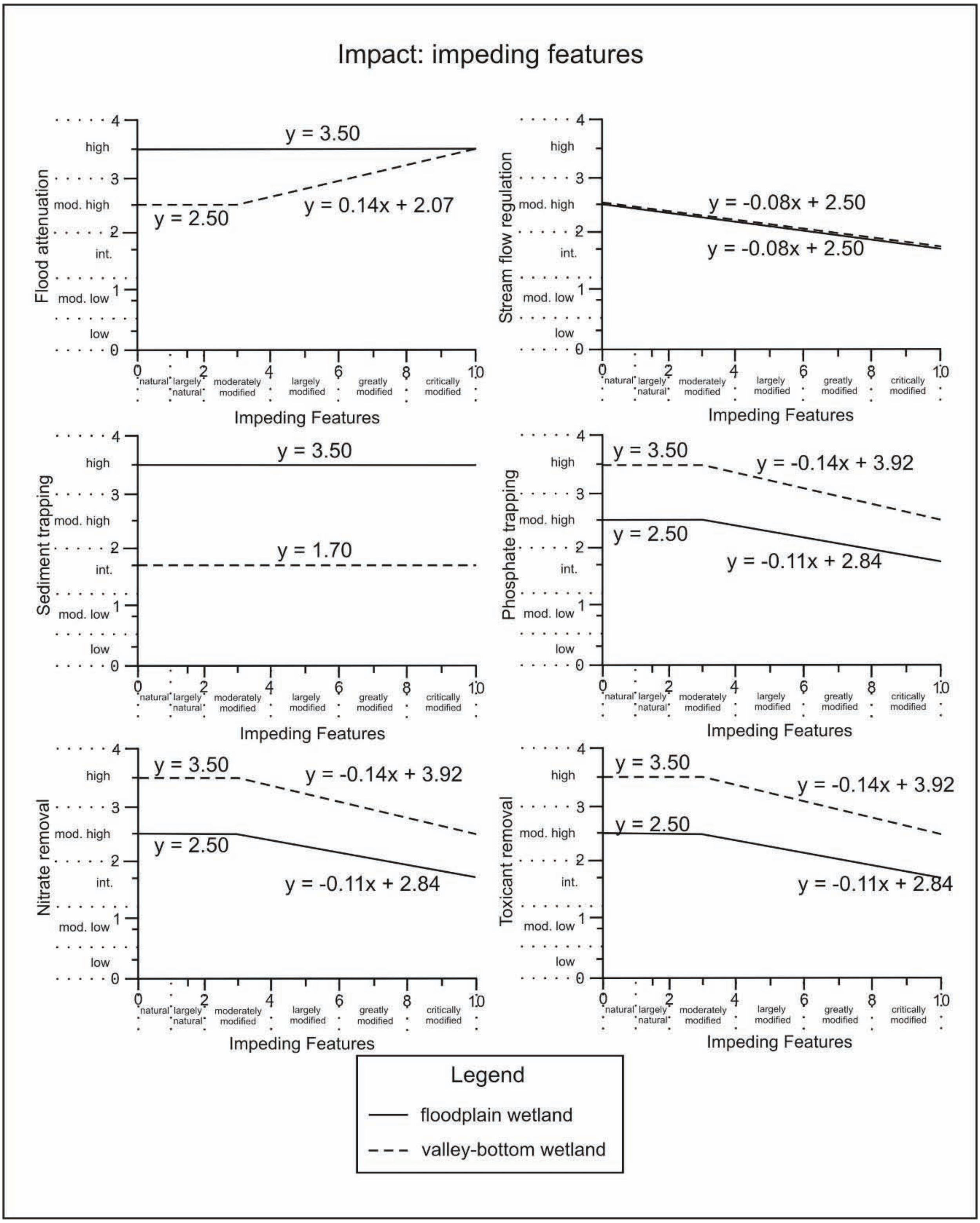


Figure 3.6: Relationships between the provision of ecosystem services and wetland health given the presence of flow impeding features in floodplains and valley-bottom wetlands.

ability of wetlands to immobilise them is lost. Overall, there is thus no change in toxicant removal performance due to this impact initially, followed by a decline in performance once health is ‘moderately modified’.

3.5.2.6. Flow enhancement within the wetland

A change in the distribution of water, and decreased water retention may occur within a wetland due to surface flow confinement and groundwater drawdown by agricultural drains and erosion gullies. Both drains and gullies have similar effects on water flow and subsequent impacts on wetland functionality are therefore considered together. These impacts affect the delivery of ecosystem services as shown in Figure 3.7.

A. Flood attenuation

Valley-bottom wetlands: Available pore space in valley-bottom wetlands increases with the presence of drains or gullies, which marginally increases flood attenuation function when drains are of limited depth and extent. However, as drains and gullies increase in extent, there is a decrease in flood attenuation function because the wetland functions increasingly like a stream. Therefore, for valley-bottom wetlands where drains and gullies are limited in size and extent, flood attenuation remains constant, but as drains increase in size and extent, flood attenuation function decreases appreciably (by 3 classes).

Floodplain wetlands: Available pore space in floodplain wetlands increases with the presence of drains or gullies, which enhances the flood attenuation function to a limited extent when drains are of limited depth and extent. However, as drains and gullies increase in extent, there is a decrease in flood attenuation function because the wetland functions increasingly like a stream. Therefore, for floodplain wetlands where drains or gullies are limited in size and extent, flood attenuation remains constant, but as drains increase in size and extent, flood attenuation function decreases. However, due to the physiography of floodplains, where channels are elevated relative to backswamp areas due to the presence of an alluvial ridge or levee such that backswamps act as flood storage basins, gullies do not have such a big impact on flood attenuation functions as they do in valley-bottom wetlands. Hence, floodplain functional effectiveness with respect to flood attenuation decreases by a single class over the range of possible impact scores.

B. Streamflow regulation

Valley-bottom wetlands: Gullies and drains are hydraulically efficient and result in reduced water storage, with negative impacts for streamflow regulation that becomes increasingly worse with drainage or erosion. As drains increase in size and/or extent, water storage decreases such that valley-bottom wetlands drop by three classes with respect to the delivery of this ecosystem service.

Floodplain wetlands: Increased hydraulic efficiency of drains also reduces water storage in this HGM type, such that the streamflow regulation function decreases. However, because floodplain channels are elevated relative to backswamp storage areas, the impact of drains is not as great on floodplains as it is on valley-bottom wetlands. Therefore, floodplains drop by only 1 class over the range of possible impact scores.

C. Sediment trapping

Valley-bottom and floodplain wetlands: The formation of gullies or drains yields sediment such that when erosion occurs in a wetland, sediment delivery to the stream below the wetland is increased. Therefore, the impact of erosion in wetlands on the sediment trapping function is a result of the balance between the amount trapped within the wetland and the amount produced through erosion of the gullies and drains. Over time, erosion of drains or gullies will be towards the head of the wetland where sediment deposition is concentrated such that the sediment trapping function is lost.

D. Phosphate trapping

Valley-bottom and floodplain wetlands: The phosphate trapping function of valley-bottom wetlands is reduced in the presence of drains or gullies since diffuse flow is reduced and phosphate deposition or biological uptake of phosphate is also reduced. The impact increases as the extent and density of drains or gullies increase, with equivalent effects on phosphate trapping in valley-bottom and floodplain wetlands.

E. Nitrate removal

Valley-bottom and floodplain wetlands: The reduced extent of both anaerobic soils and of diffuse flow, reduce the nitrate removal function as the density and/or size of drains and/or gullies increase. The effect of drains or gullies on the nitrate removal function for valley-bottom wetlands is similar to floodplains.

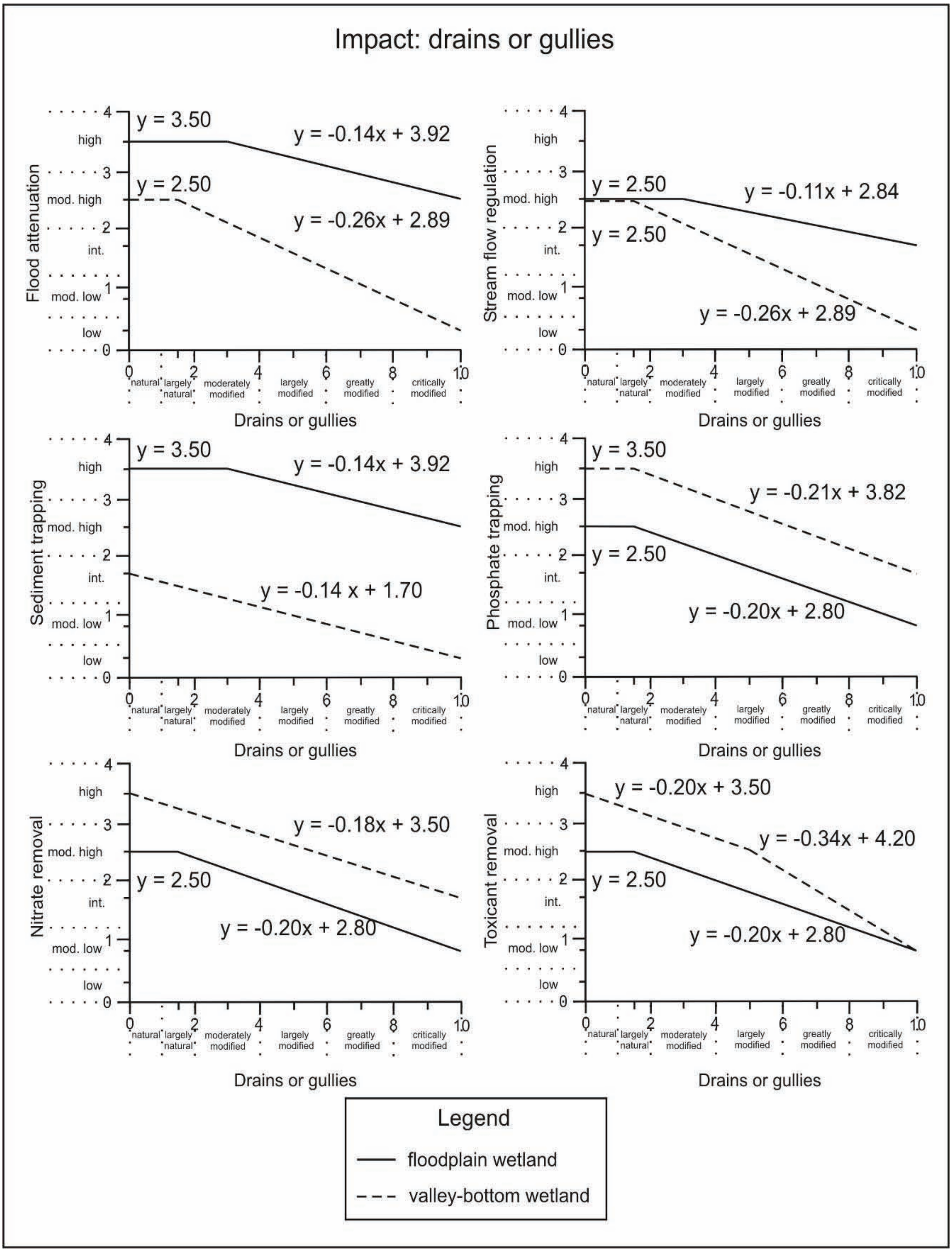


Figure 3.7: Relationships between the provision of ecosystem services and wetland health given the presence of drains or gullies in floodplains and valley-bottom wetlands.

F. Toxicant removal

Valley-bottom and floodplain wetlands: Reduced diffuse flow, the consequent decreased plant productivity and associated reduction in transpirational water loss, all result in lower levels of toxicant removal as drains or gullies increase in extent. The impact of drains or gullies increases as the extent of these features increases, such that valley-bottom wetlands drop by 3 classes while floodplains drop by 2 classes over the range of possible impact scores.

3.6 Summary of the "loss of function metric"

The set of relationships developed in this study (presented as Figures 3.2 to 3.7) allow the provision of ecosystem services to be inferred from the determination of wetland health alone. Thus, a practitioner should be able to infer the likely provision of several ecosystem services following the determination of wetland health. It should be recognised, however, that although the generalised trends are likely to be valid, the exact mathematical relationships (equations) are unlikely to be accurate. The conceptual impact intensity-functionality models are presented as equations in this document in order to enable calculation. The authors recognise, however, that these need to be validated using extensive experimental data from wetlands from all over South Africa.

4. CALCULATING THE MAGNITUDE OF IMPACT OF LAND COVER CHANGE ON WETLAND FUNCTIONALITY AS A FUNCTIONAL EFFECTIVENESS SCORE

4.1 Introduction

In the previous steps, determination of the intensity of impact scores linked to catchment and wetland land cover classes was introduced (Section 2; Table 2.3) and the impacts of human activities on wetland functionality were described for a range of ecosystem services (Section 3; Figures 3.2 to 3.7). In this step the *intensity* of impact scores is multiplied by the *extent* of impact scores to calculate a *magnitude* of impact score for each land cover class in the catchment and the wetland (Figure 4.1).

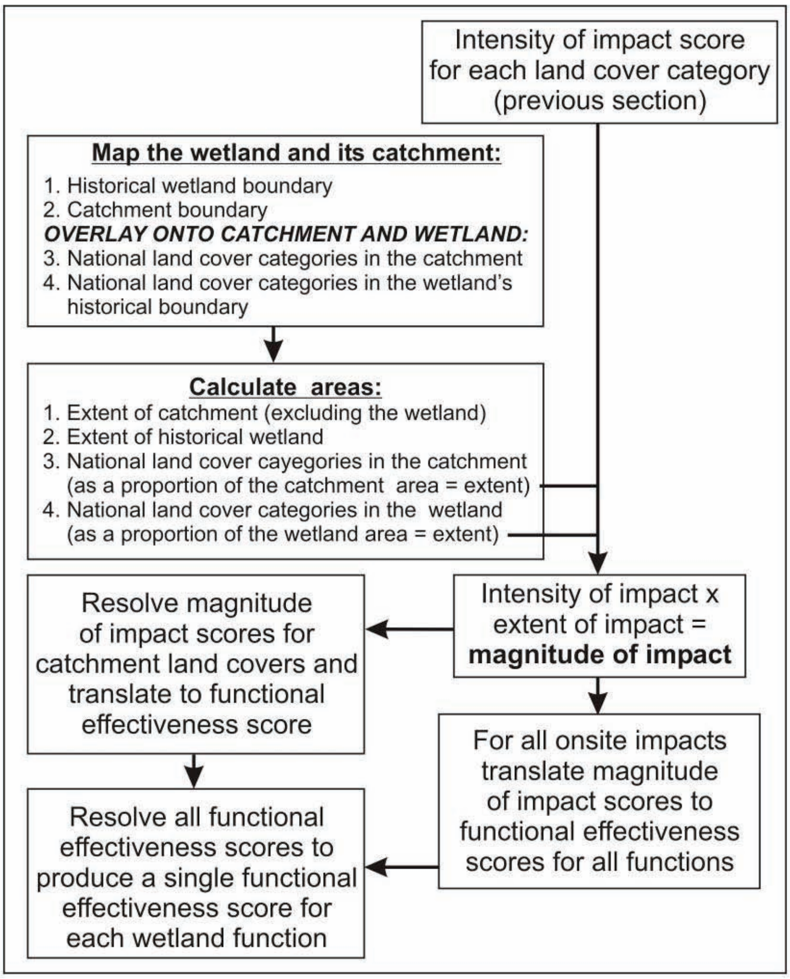


Figure 4.1: The series of steps covered in this section of the document.

The magnitude of impact scores of activities in the *catchment* are combined to produce a single catchment magnitude of impact score, which is translated into a measure of the functional effectiveness of the impacted wetland. The same is done for all activities in the *wetland*, giving a number of wetland functional effectiveness scores for onsite activities. These scores are then resolved to produce a single functional effectiveness score for onsite activities with reference to the impacted wetland. The catchment and wetland functional effectiveness scores are then combined to produce a single functional effectiveness score for each wetland function.

For purposes of illustration a hypothetical case study will be used as a running example in this section of the document (Box 1). A case is chosen of a wetland 22 ha in extent in a catchment of an additional 39 ha. Three land cover classes are present in both the catchment outside of the wetland and in the wetland itself, namely: commercial afforestation, irrigated agriculture and high density urban development.

Box 1: Description of the catchment, wetland and land cover categories used in the running example to show computations required in the assessment of wetland functionality

An imaginary catchment containing a wetland and three categories of land cover is used as a running example to illustrate computations required in calculating the magnitude of impacts of land cover change on wetland health, and translation to functional effectiveness scores. The catchment covers a total of 61 ha, of which 22 ha is occupied by the wetland (Fig. 4.2). Three land cover categories are present in the catchment, all of which occur both in the catchment outside of the wetland as well as within the wetland itself:

- Commercial afforestation (8 ha in total of which 5 ha is in the catchment outside of the wetland and a further 3 ha is in the wetland),
- Irrigated cultivation (6 ha in total of which 4 ha is in the catchment outside of the wetland and a further 2 ha is in the wetland), which uses water from within the catchment, and
- High density residential (8 ha in total of which 5 ha is in the catchment outside of the wetland and a further 3 ha is in the wetland)

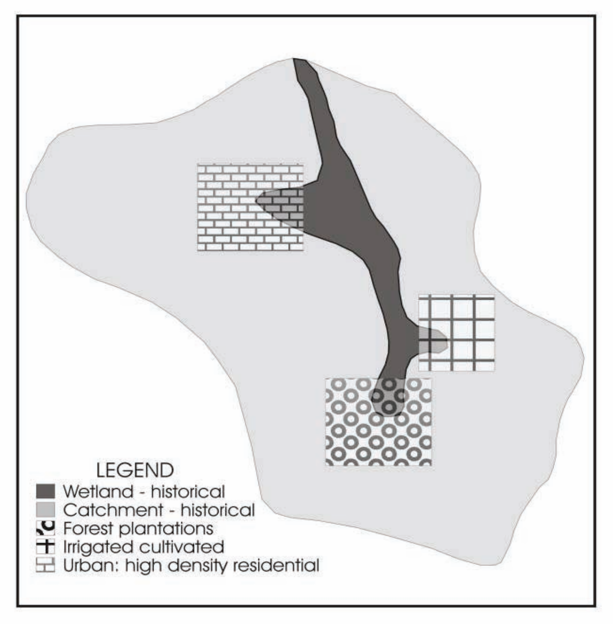


Figure 4.2: Hypothetical catchment and wetland used in the running example throughout this part of the document for illustrative purposes.

4.2 Calculating the magnitude of impact scores

An assessment of wetland ecosystem service provision at the landscape-level begins with detailed mapping of land cover in the catchment being considered. Firstly, the extent of the catchment being examined, the historical wetland boundaries[2] and the subcatchments of individual wetlands or HGM Units in the catchment should be delineated. Then, the NLC classes present in both the historical wetland and the catchment outside of the wetland must be individually mapped and if necessary be combined to be consistent with land cover categories as shown in Table 2.1. The extent (in hectares, and as a proportion of the catchment and wetland areas) of each land cover category is then determined. The extent and intensity scores of each land cover category (from Table 2.3) should then be multiplied to give a magnitude of impact score. A worked example of how to calculate magnitude of impact scores is shown in Box 2 for the running example.

Box 2: Use of the running example to show calculation of magnitude of impact from extent and intensity of impact scores of each land cover change

The likely intensity of impact scores for a particular land cover category are presented in Table 2.3. These scores are multiplied by the extent of each land cover category to produce a magnitude of impact score for both the wetland and the catchment area outside the wetland as illustrated in Table 4.1 for the imaginary catchment of 61 ha with a 22 ha wetland (see Box 1 for details).

Table 4.1: Magnitude of impact scores calculated using the proportion of the wetland or the catchment of each land cover category multiplied by the intensity of impact scores (from Table 2.3) for the hypothetical wetland illustrated in Figure 4.2.

Land cover category	**Catchment impacts**			**Wetland impacts**		
	Area (ha)	Increased water inputs	Decreased water inputs	**Area (ha)**	Increased water use	Reduced surface roughness
Natural vegetation	25			14		
Forest plantations	5		5/39x9 = **1.15** *	3	3/22x9 = **1.23**	
Irrigated cultivation	4		4/39x5 = **0.51**	2		2/22x5 = **0.45**
Urban residential – high density	5	5/39x5 = **0.64**		3		3/22x7 = **0.95**
TOTALS	**39**	0.64	1.66	**22**	1.23	1.40

*Magnitude of impact = proportional extent of impact * intensity of impact =5/39*9 = 1.15.

[2] The historical wetland boundary refers to the boundary of the wetland prior to land-use change by human activities. Therefore, it includes those areas that have soils that exhibit indicators of temporary, seasonal or permanent flooding, irrespective of land cover.

4.3 Resolving reduced and increased water inputs from catchment impacts

The next step is to resolve increased water inputs and decreased water inputs from the catchment, which is achieved by subtracting the total for 'decreased water inputs' from the total for 'increased water inputs'. This is simply because land use activities that increase water inputs offset those activities that reduce water inputs. In reality the timing of flows reaching the wetland will be altered, but this technique is an approximation and does not examine very subtle effects such as this. An illustration of the calculation of overall magnitude of catchment impacts is presented as the running example in Box 3.

Box 3: Use of the running example to show calculation of overall magnitude of catchment impacts

It is necessary to resolve the effects of activities in the catchment that increase water inputs to the wetland with those that decrease water inputs to the wetland. This is simply calculated as the difference between these values for the catchment (increased water inputs minus decreased water inputs). Therefore, for the running example the overall impacts of catchment activities is 0.64 - 1.66 = -1.02, which means that there is a net decrease in water inputs with a magnitude of impact of 1.02 on a scale of 0 (no magnitude of impact) to 10 (critically impacted).

4.4 Determining the relationship between the "magnitudes of impact" and the provision of ecosystem services: functional effectiveness

It is now possible to consider the effect of each individual impact on the provision of ecosystem services. This is simply undertaken by using the equations in Tables 4.2 to 4.7, which are presented below. These equations were compiled from Figures 3.2 to 3.7 in Section 3 of this document and represent the approximate numerical relationships between each of the six impacts (Section 2.3) and the six ecosystem services (Section 3.2) for the two wetland types (valley-bottom and floodplain).

Catchment impacts

- for increased water inputs, consult Table 4.2; and
- for reduced water inputs, consult Table 4.3.

Within-wetland impacts

- for direct water losses from the wetland, consult Table 4.4;
- for reduced surface roughness, consult Table 4.5;
- for impeding features in the wetland, consult Table 4.6; and
- for drains or gullies in the wetland, consult Table 4.7.

Table 4.2: Equations describing the relationships between impacts that result from increased water inputs from the catchment and the provision of a number of ecosystem services

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of impact scores for applying equation**	**Equation**	**Range of impact scores for applying equation**	**Equation**
Flood attenuation	0-3	y=3.50	0-10	y=-0.08x + 2.50
	3-10	y=-0.14x + 3.92		
Stream flow regulation	0-3	y=0.33x + 2.50	0-3	y=2.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.11x + 2.84
Sediment trapping	0-3	y=3.50	0-3	y=1.70
	3-10	y=-0.14x + 3.92	3-10	y=-0.13x + 2.10
Phosphate trapping	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Nitrate removal	0-3	y=0.33x+2.50	0-3	y=3.50
	3-10	y=-0.26x + 4.27	3-10	y=-0.26x + 4.27
Toxicant removal	0-3	y=0.33x+2.50	0-3	y=3.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.26x + 4.27

Table 4.3: Equations describing the relationships between impacts that result from decreased water inputs from the catchment and the provision of a number of ecosystem services

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of impact scores for applying equation**	**Equation**	**Range of impact scores for applying equation**	**Equation**
Flood attenuation	0-3	y=3.50	0-3	y=0.33x + 2.50
	3-10	y=-0.14x + 3.92	3-10	y=-0.26x + 4.27
Stream flow regulation	0-10	y=-0.08x + 2.50	0-10	y=-0.17x + 2.50
Sediment trapping	0-3	y=3.50	0-10	y=-0.14x + 1.70
	3-10	y=-0.14x + 3.92		
Phosphate trapping	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Nitrate removal	0-10	y=0.17x + 2.50	0-10	y=-0.18x + 3.50
Toxicant removal	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92

Table 4.4: Equations describing the relationships between impacts that result from increased direct water losses from the wetland and the provision of a number of ecosystem services

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of impact scores for applying equation**	**Equation**	**Range of impact scores for applying equation**	**Equation**
Flood attenuation	0-5	y=3.50	0-5	y=0.20x + 2.50
	5-10	y=-0.20x+4.50	5-10	y=-0.36x+5.30
Stream flow regulation	0-10	y=-0.08x + 2.50	0-10	y=-0.17x + 2.50
Sediment trapping	0-5	y=3.50	0-3	y=0.27x + 1.70
	5-10	y=-0.20x+4.50	3-10	y=-0.31x+3.40
Phosphate trapping	0-3	y=0.33x + 2.50	0-3	y=3.50
	3-10	y=-0.26x+4.27	3-10	y=-0.26x+4.27
Nitrate removal	0-10	y=-0.08x + 2.50	0-10	y=-0.10x + 3.50
Toxicant removal	0-5	y=0.20x + 2.50	0-5	y=3.50
	5-10	y=-0.20x + 4.50	5-10	y=-0.36x + 5.30

Table 4.5: Equations describing the relationships between impacts that result from reduced surface roughness in the wetland and the provision of a number of ecosystem services

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of impact scores for applying equation**	**Equation**	**Range of impact scores for applying equation**	**Equation**
Flood attenuation	0-10	y=-0.10x + 3.50	0-10	y=-0.17x + 2.50
Stream flow regulation	0-3	y=2.50	0-3	y=2.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.24x + 3.23
Sediment trapping	0-10	y=-0.10x + 3.50	0-10	y=-0.14x + 1.70
Phosphate trapping	0-10	y=-0.17x + 2.50	0-10	y=-0.18x + 3.50
Nitrate removal	0-10	y=-0.17x + 2.50	0-10	y=-0.18x + 3.50
Toxicant removal	0-10	y=-0.17x + 2.50	0-10	y=-0.18x + 3.50

Table 4.6: Equations describing the relationships between impacts that result from the presence of impeding features in the wetland and the provision of a number of ecosystem services

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of impact scores for applying equation**	**Equation**	**Range of impact scores for applying equation**	**Equation**
Flood attenuation	0-10	y=3.50	0-3	y=2.50
			3-10	y=0.14x + 2.07
Stream flow regulation	0-10	y=-0.08x + 2.50	0-10	y=-0.08x + 2.50
Sediment trapping	0-10	y=3.50	0-10	y=1.70
Phosphate trapping	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Nitrate removal	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92
Toxicant removal	0-3	y=2.50	0-3	y=3.50
	3-10	y=-0.11x + 2.84	3-10	y=-0.14x + 3.92

In the case of impoundments in wetlands that impede the flow of water, the magnitude of impact of water retention upstream of the impediment is based on the area of the impounded area multiplied by the intensity of impact. However, downstream of the impoundment, the wetland is starved of water due to evaporation from the water surface of and direct water use from the impoundment, such that the impoundment can be considered to be a direct user of water for the area downstream of the impoundment. Therefore, impeding features increase wetness upstream of the impeding structure, but for the wetland downstream of the impeding feature they have the same effect as increased water use. The **intensity** of this impact is moderate (intensity of impact score equal to 6 – see Table 2.3), but for the area downstream of the impoundment the **extent** of impact should be scaled based on the depth of the impoundment. For shallow dams (<2.5m high dam walls) and for road crossings, the area to be used should be the same as for the impoundment size (i.e. the surface area). Where impoundments are between 2.5 and 8m high, the area of wetland impacted should be 1.5 times the surface area of the impoundment, while for dam walls higher than 8m, the area of the impoundment should be multiplied by 2. The maximum area to be used should not be greater than the area of wetland below the impoundment. In other words, choose the ***lowest*** of the area of wetland below the impoundment and the extent of impact as calculated from the above.

Table 4.7: Equations describing the relationships between impacts that result from the presence of drains or gullies in the wetland and the provision of a number of ecosystem services

	Floodplain wetlands		**Valley-bottom wetlands**	
Ecosystem service	**Range of impact scores for applying equation**	**Equation**	**Range of impact scores for applying equation**	**Equation**
Flood attenuation	0-3	y=3.50	0-1.5	y=2.50
	3-10	y=-0.14x + 3.92	1.5-10	y=-0.26x + 2.89
Stream flow regulation	0-3	y=2.50	0-1.5	y=2.50
	3-10	y=-0.11x + 2.84	1.5-10	y=-0.26x + 2.89
Sediment trapping	0-3	y=3.50	0-10	y=-0.14x + 1.70
	3-10	y=-0.14x + 3.92		
Phosphate trapping	0-1.5	y=2.50	0-1.5	y=3.50
	1.5-10	y=-0.20x + 2.80	1.5-10	y=-0.21x + 3.82
Nitrate removal	0-1.5	y=2.50	0-10	y=-0.18x + 3.50
	1.5-10	y=-0.20x + 2.80		
Toxicant removal	0-1.5	y=2.50	0-5	y=-0.20x + 3.50
	1.5-10	y=-0.20x + 2.80	5-10	y=-0.34x + 4.20

The equations presented above are to be used to determine the functionality score (score for the level of provision of ecosystem services) for impacts in the catchment and in the wetland. The magnitude of impact score is the x-value shown in equations in Tables 4.2 to 4.7, such that use of the relevant equation makes it possible to calculate the functionality score by solving for y. Thus the magnitude of impact score is the x-value, and substitution of this value into the relevant equation (bearing in mind the type of impact, the value of the magnitude of impact score, the ecosystem service and the wetland type being considered) yields a functionality score (the y-value) for that ecosystem service. This is illustrated for a single function (flood attenuation) using the running example (Box 4).

Box 4: Use of a running example to show calculation of catchment impacts on wetland functionality

For our running example presented in Table 4.1, because there is a net decrease in water inputs to the wetland from the catchment (refer to Box 3), Figure 3.3 (or Table 4.3) should be consulted. Furthermore, because impacts are scored between 0 and 10, we use the absolute value (positive value) of the overall catchment impacts. This means in this case (for assessing flood attenuation), instead of using -1.02 to show that catchment activities have reduced water inputs, we simply use an overall magnitude of impact score for reduced water inputs of +1.02.

It is possible to estimate the provision of **all** the ecosystem services presented in Figure 3.3 and Table 4.3, but for purposes of illustration just one ecosystem service, flood attenuation, will be considered. As indicated in Figure 4.3 (extracted from Figure 3.3), for an impact score of 1.02, floodplain wetlands have a functionality score for flood attenuation of 3.50, while valley-bottom wetlands have a functionality score for flood attenuation of 2.85. This is equivalent to substituting the magnitude of impact score of x=1.02 into the relevant equations in Table 4.3: i.e. y=3.50 for floodplains and y=0.33x + 2.50 for valley-bottom wetlands).

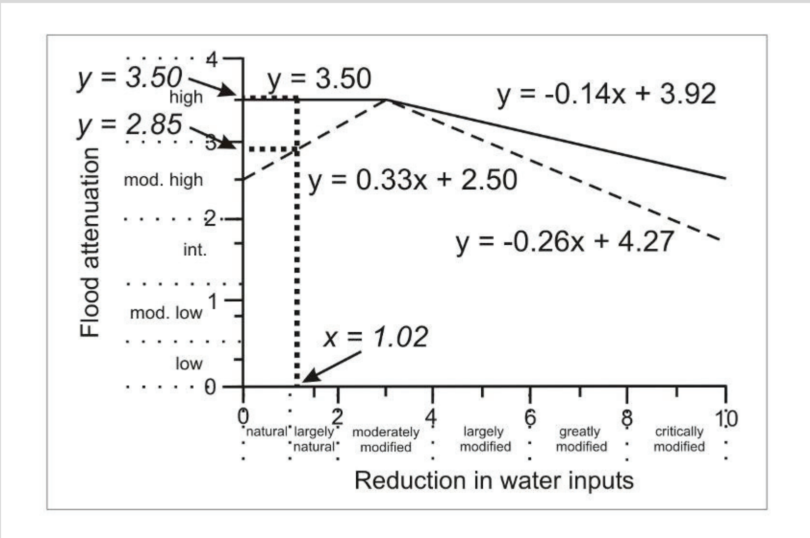


Figure 4.3: Calculation of ecosystem service functionality by graphical interpretation by reading the y-axis score (functionality) for the appropriate x-axis score (magnitude of impact = 1.02) for floodplain and valley-bottom wetlands. This figure is extracted from Figure 3.3.

These scores therefore indicate that the impacts of the three land use activities in the surrounding catchment are small, since in an unimpacted state, floodplains have a functionality score of 3.50 while valley-bottom wetlands have a functionality score of 2.50 for flood attenuation. The impacts of land use change within the wetland itself are calculated in the next section.

For impacts that result from activities within wetlands, the same method is applied to determine their effect on the provision of ecosystem services, as for estimating catchment impacts. The x-value indicating the magnitude of impact for each onsite impact (Table 4.1) is substituted in the relevant equation and the functional effectiveness score for each ecosystem service is calculated (see Box 5 for an illustration of how this score is derived).

Box 5: Use of a running example to show calculation of effect of onsite impacts on functionality

For our example, increased water use and reduced surface roughness are the onsite (within-wetland) impacts that reduce the provision of ecosystem services. For illustrative purposes, we will describe the effect of onsite impacts (increased water use with a magnitude of impact score of 1.23 and decreased surface roughness with a magnitude of impact score of 1.40) on flood attenuation.

As a consequence of the increased water use caused by water abstraction by trees, a floodplain would be predicted to exhibit a functionality score for flood attenuation of 3.50 while a valley-bottom wetland would have a functionality score for flood attenuation of 2.75 (Figure 4.4 and using equations in Table 4.4).

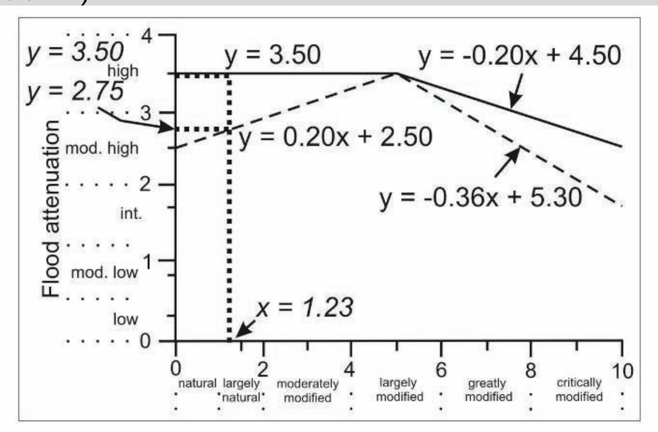


Figure 4.4: Calculation of ecosystem service functionality by reading the y-axis score (flood attenuation) for the appropriate x-axis score (magnitude of impact resulting from increased water use = 1.23) for floodplain and valley-bottom wetlands. This figure is extracted from Figure 3.4.

As a consequence of **reduced surface roughness** caused by residential development in the wetland, a floodplain scores a functionality score of 3.36 for flood attenuation, while a valley-bottom wetland would score a functionality score of 2.26 for this ecosystem service (Figure 4.5 and using equations in Table 4.5).

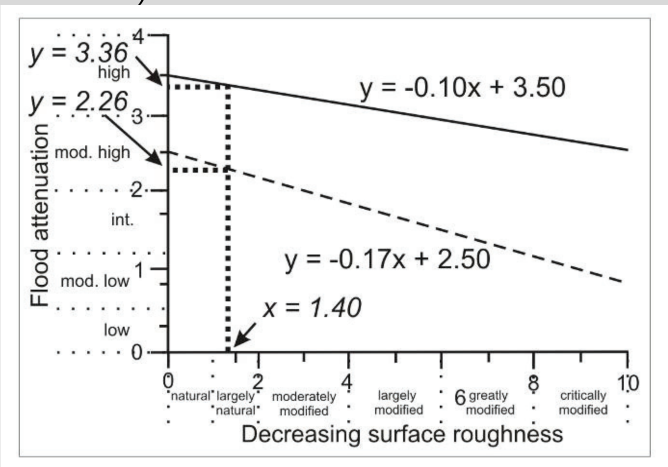


Figure 4.5: Calculation of ecosystem service functionality by reading the y-axis score (flood attenuation) for the appropriate x-axis score (magnitude of impact resulting from decreased surface roughness = 1.40) for floodplain and valley-bottom wetlands. This figure is extracted from Figure 3.5.

4.5 Resolving functionality scores for all onsite activities

The effects of different onsite (within-wetland) activities on the provision of ecosystem services now need to be resolved. Some activities (direct water losses, reduced surface roughness and the presence of drains or gullies) will *reduce* the duration and extent of inundation, while the presence of impeding features might prolong it (since the presence of impeding features increases water retention above the impeding feature and reduces water retention below it). In order to resolve these issues, the **lowest functionality score** for each ecosystem service is taken and adjusted for the additive effects of additional onsite activities. This is achieved by subtracting the values in Table 4.8 (shown below) for each of the other impacts identified, from the lowest functionality score. This is illustrated for the hypothetical wetland in Box 6.

Box 6: Use of a running example to show calculation of the ecosystem service score for all onsite impacts

In our example calculations in Box 4, the functionality scores for flood attenuation of impacts in the wetland – namely increased water use and reduced surface roughness – are quite similar to each other for floodplains (3.50 for increased water use and 3.36 for reduced surface roughness). The functionality scores for flood attenuation of impacts in the wetland (increased water use and reduced surface roughness) are also similar to each other for valley-bottom wetlands (2.75 for increased water use and 2.26 for reduced surface roughness). In each case these are in the same functionality category (high for floodplains and moderately high for valley-bottom wetlands).

However, the additive impact of onsite activities needs to be calculated using the scaling indicated in Table 4.8. The lowest score for all impacts is taken and scaled by subtracting the values indicated in Table 4.8 depending upon the functionality scores for the other impacts. In the case of floodplains the lowest score is 3.36 (for reduced surface roughness). It is not changed since the score for the other impact (increased direct water losses) is between 3 and 4 such that it does not affect the functionality score for flood attenuation. However, for the valley-bottom wetland, the lowest score is 2.26 (for reduced surface roughness). It is scaled by subtracting 0.1 since increased water use (direct water loss) has a functional effectiveness value between 2 and 3, giving a final functional effectiveness score of 2.16 for flood attenuation based on impacts in the wetland.

4.6 Combining functionality scores for catchment and onsite impacts

In a manner analogous to resolving within wetland impacts, the total impact of catchment and within wetland land use change on delivery of ecosystem services is calculated. To resolve the functionality score for the catchment and onsite activities, scores for catchment and onsite impacts are compared such that the lowest of these scores is chosen and scaled by **subtracting** the value in Table 4.8 selected on the basis of the other score (Box 7).

Box 7: Use of a running example to show calculation of the combined ecosystem service score for catchment and onsite impacts

In our example, where catchment activities result in a functionality score for flood attenuation of the floodplain of 3.50 and of the valley-bottom wetland of 2.85, and onsite activities result in a functionality score for flood attenuation of 3.36 and 2.16 respectively, the final functionality scores for floodplains and valley-bottom wetlands respectively are 3.36 and 2.06. These values are obtained as follows:

- Floodplain: 3.38 (onsite impacts) – 0 (reduced water inputs from the catchment has a functionality score between 3 and 4) = 3.38
- Valley-bottom wetland: 2.16 (onsite impact) – 0.1 (reduced water inputs from the catchment has a functionality score between 2 and 3) = 2.06.

Table 4.8: Values to be used to scale functionality scores in valley-bottom wetlands as determined for a range of catchment and onsite (within-wetland) impacts

Functionality score range	Flood attenuation		Stream flow regulation		Sediment trapping		Phosphate trapping		Nitrate removal		Toxicant removal	
Increased water inputs	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3- 4	0	0	0	0	0	0	0	0	0	0	0	0
2-2.99	0.1	0	0.1	0	0.1	0	0	0	0.1	0.1	0.1	0.1
1.2-1.99	0.2	0.1	0.2	0.1	0.2	0	0.1	0.1	0.2	0.2	0.2	0.2
0.5-1.19	0.3	0.2	0.3	0.2	0.3	0.1	0.2	0.2	0.3	0.3	0.3	0.3
<0.5	0.4	0.3	0.4	0.3	0.4	0.2	0.3	0.3	0.4	0.4	0.4	0.4
Decreased water inputs	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3-4	0	0	0	0	0	0	0	0	0	0	0	0
2-2.99	0.1	0.1	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2-1.99	0.2	0.2	0.1	0.1	0.2	0	0.1	0.1	0.1	0.2	0.1	0.2
0.5-1.19	0.3	0.3	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.4	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.3	0.4
Direct water losses	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3-4	0	0	0	0	0	0	0	0	0	0	0	0
2-2.99	0.1	0.1	0	0	0.1	0	0.1	0.1	0	0.1	0.1	0.1
1.2-1.99	0.2	0.2	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.2	0.2	0.2
0.5-1.19	0.3	0.3	0.2	0.2	0.3	0.2	0.3	0.3	0.2	0.3	0.3	0.3
<0.5	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.4	0.3	0.4	0.4	0.4
Decreased surface roughness	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3-4	0	0	0	0	0	0	0	0	0	0	0	0
2-2.99	0.1	0	0	0	0.1	0	0	0	0	0.1	0	0.1

1.2-1.99	0.2	0.1	0.1	0.1	0.2	0	0.1	0.1	0.1	0.2	0.1	0.2
0.5-1.19	0.3	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.3	0.4
Impeding features	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**
3-4	0	0	0	0	0	0	0	0	0	0	0	0
2-2.99	0.1	0.1	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2-1.99	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.2	0.1	0.2
0.5-1.19	0.3	0.3	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.4	0.3	0.4
Drains or gullies	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**V-B**	**FP**	**VB**
3-4	0	0	0	0	0	0	0	0	0	0	0	0
2-2.99	0.1	0	0	0	0.1	0	0	0	0	0.1	0	0.1
1.2-1.99	0.2	0.1	0.1	0.1	0.2	0	0.1	0.1	0.1	0.2	0.1	0.2
0.5-1.19	0.3	0.2	0.2	0.2	0.3	0.1	0.2	0.2	0.2	0.3	0.2	0.3
<0.5	0.4	0.3	0.3	0.3	0.4	0.2	0.3	0.3	0.3	0.4	0.3	0.4

5. CALCULATING FUNCTIONAL HECTARE EQUIVALENTS

The next step in determining landscape-level functionality is to calculate functional hectare equivalents for each ecosystem service. The functional hectare equivalents for each ecosystem service are simply calculated as:
Functional hectare equivalents = final functional effectiveness score / 4 * size of wetland (ha)

The functionality score is divided by 4 to scale it between 0 and 1, and this is multiplied by the size of the wetland (in ha). An illustration of this is provided using the running example (Box 8).

Box 8: Use of the running example to show calculation of functional hectare equivalents

Functional hectare equivalents are calculated as follows:

Functional hectare equivalents = final functionality score / 4 * size of wetland (ha)

In our example wetland of 22ha its functionality score for flood attenuation would be 18.48 ha if it was a floodplain (3.36/4*22) and 11.33 ha if it was a valley-bottom wetland (2.06/4*22). This compares with 19.25 ha and 13.75 ha if we were dealing with an unimpacted floodplain and valley-bottom wetland respectively, since unimpacted floodplains have a functionality score of 3.50 and valley-bottom wetlands a score of 2.50 for flood attenuation.

6. ASSESSMENT OF CUMULATIVE FUNCTIONALITY AND IMPACTS

The cumulative functionality of a number of wetlands in a catchment or landscape is determined by summing the functional hectare equivalents for each wetland examined. In calculating the cumulative functionality, each wetland is examined for its own subcatchment only – such that subcatchments of any wetlands upstream are excluded from the computations.

Cumulative impacts on wetland functionality are assessed as the difference between the total functionality (in functional hectare equivalents) of all wetlands in their current state compared to their unimpacted state. Therefore, although the four wetlands depicted in Figure 6.1 occur within the same catchment, the overall functionality of wetlands in this catchment would be computed separately for each subcatchment. As such, wetlands 1 and 3 would be considered in the light of land use in their entire catchments, but wetland 2 would be considered excluding wetland 1 and its catchment, and wetland 4 would be considered excluding the wetlands and catchments of wetlands 1, 2 and 3.

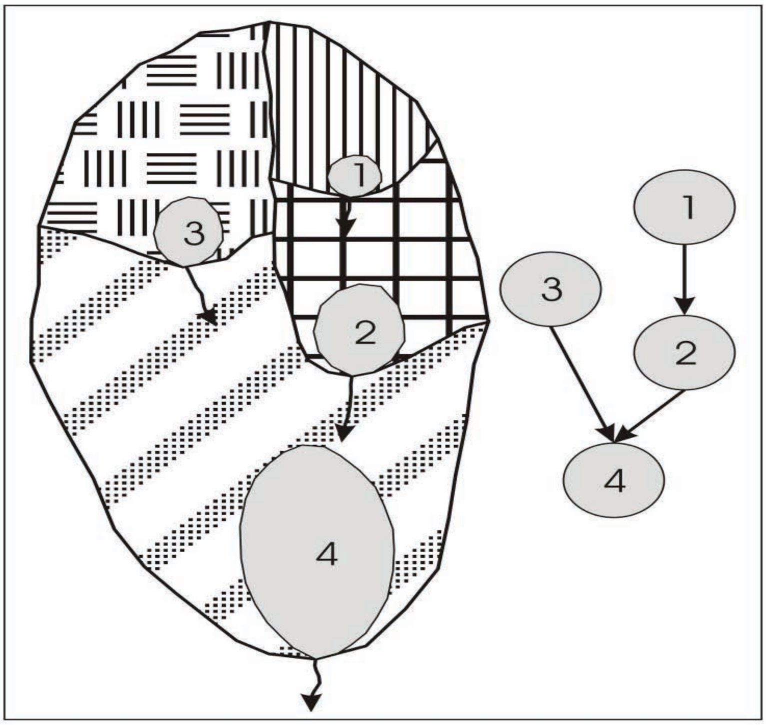


Figure 6.1: Configuration of nested wetlands in a hypothetical catchment, showing the configuration of subcatchments and wetlands that would be analysed in the assessment of wetland functionality and cumulative impacts. Arrows indicate the direction of water flow from the toe of individual wetlands and the inset shows the relationships between wetlands schematically.

7. WORKED EXAMPLES

The following worked examples illustrate the process of calculating hectare equivalents of wetland ecosystem service provision. For ease of explanation, the examples demonstrate calculations for a single ecosystem service; flood attenuation. In the first example, calculations for hectare equivalents of flood attenuation functionality in a catchment hosting two wetlands (a floodplain and a valley-bottom wetland) are determined. This example illustrates how a catchment is divided into individual wetland subcatchments, with each subcatchment assessed separately. The second and third examples demonstrate calculations for hectare equivalents of flood attenuation functionality in catchments hosting a single wetland, but under various land cover scenarios. These examples demonstrate an important application of the tool, namely, predicting relative hectare equivalents of ecosystem service functionality under different land-use or land management and rehabilitation scenarios.

7.1 Worked hypothetical example 1: flood attenuation functionality for two wetlands in a rural catchment

In this worked example the flood attenuation functionality of the two wetlands in adjacent subcatchments (Figure 7.1) is examined. One of the wetlands (Catchment A) is a 30 ha floodplain occupying a subcatchment of an additional 100 ha, of which 40 ha is commercial forestry plantation. The other wetland (Catchment B) is a 30 ha valley-bottom wetland in the adjacent subcatchment, with both wetlands leaving their subcatchments at a common point. The valley-bottom wetland occupies a catchment of an additional 90 ha, of which 30 ha is commercial forestry plantation.

The calculation of the magnitude of impact scores for these wetlands is shown in Table 7.1. The intensity of impact of commercial forestry (from Table 2.3) is 9 and this is multiplied by the extent of this activity as a proportion of the respective subcatchments, giving a magnitude of impact score for activities in the catchment of -3.60 for the floodplain and -3.00 for the valley-bottom wetland. This indicates that water inputs into these wetlands have been reduced appreciably, since the scale of impacts ranges from 0 (no impacts) to 10 (critically impacted).

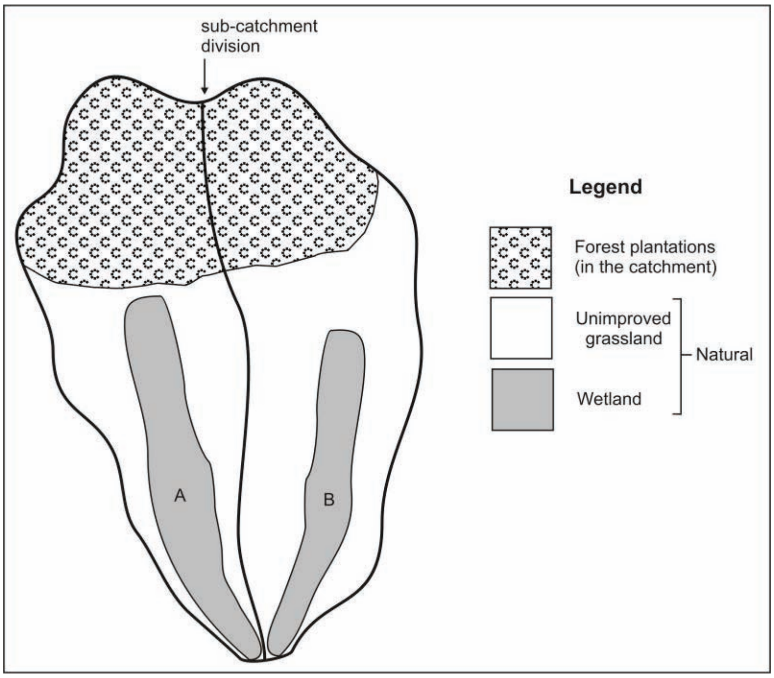


Figure 7.1: Schematic representation of a hypothetical rural catchment, showing Wetlands A (floodplain) and B (valley-bottom) in their respective subcatchments, and the land cover categories present.

Table 7.1: Calculation of the magnitude of impact on flood attenuation in a hypothetical catchment containing a floodplain wetland (Catchment A) and a valley-bottom wetland (Catchment B) from the intensity of impact scores for each land cover category (Table 2.2) and the area

	Catchment A				**Catchment B**			
Land cover category	**Catchment impacts**			**Wetland impacts**	**Catchment impacts**			**Wetland impacts**
	Area	**Intensity of impact (reduced water inputs**	**Magnitude of impact**	**Area**	**Area**	**Intensity of impact (reduced water inputs)**	**Magnitude of impact**	**Area**
Natural vegetation	60			30	60			20
Forest plantations	40	9	3.60		30	9	3.00	
TOTALS	100		3.60	30	90		3.00	20
Total magnitude of impacts (catchment)			**-3.60**				**-3.00**	

In the consideration of wetland functionality, the relevant equations need to be obtained – in this case Table 4.3 should be consulted, which describes the relationships between impacts that result from decreased water inputs from the catchment (the most important impact on hydrology likely to arise from forestry plantations) and the provision of a number of ecosystem services. Since Table 4.3 describes the impact of reduced water inputs, the positive value is used. Recall, that this value is on a scale of 0 to 10.

The calculation of wetland functionality (on a scale of 0 to 4) is undertaken by using the equations for flood attenuation functionality bearing in mind both the HGM type and the range in which the magnitude of impact score falls. Results for the hypothetical catchments are shown in Table 7.2 such that the magnitude of impact calculated in Table 7.1 is substituted as the x-value into the equation presented in Table 7.2, giving a functionality score of 3.42 in subcatchment A and 3.50 in subcatchment B. Given the wetland sizes of 30 and 20 hectares for wetlands in subcatchments A and B respectively, the floodplain in subcatchment A delivers 25.65 functional hectare equivalents for flood attenuation functionality and the valley-bottom wetland in catchment B provides 17.50 functional hectare equivalents.

Table 7.2: Calculation of functional hectare equivalents for flood attenuation from the magnitude of impact scores in two hypothetical catchments

	Catchment A			**Catchment B**		
Impact	**Magnitude of impact (from Table 7.1)**	**Equation for functionality score**	**Functionality score**	**Magnitude of impact (from Table 7.1)**	**Equation for function ality score**	**Functio-nality score**
Decreased water inputs	3.60	y=-0.14x + 3.92	3.42	3.00	y=0.33x + 2.50	3.50
Catchment impacts functionality score			3.42			3.50
Final functionality score			3.42			3.50
Size of wetland (ha)			30			20
Functional hectare equivalents			**25.65**			**17.50**
Functionality score for unimpacted wetlands			3.50			2.50
Functional hectare equivalents for unimpacted wetlands			**26.25**			**12.50**

The cumulative functionality for these two wetlands is 26.25 + 17.50 = 43.15 functional hectare equivalents for flood attenuation. In comparison to the situation before the establishment of commercial forestry plantations, the floodplain is now little different in terms of flood attenuation to the unimpacted situation – scores were 25.65 and 26.25 functional hectare equivalents respectively before and after the impacts. However, the same change in land use in the case of the valley-bottom wetland has *increased* flood attenuation functional effectiveness from 12.50 to 17.50 functional hectare equivalents.

The overall flood attenuation functionality for both wetlands before afforestation was 38.75 functional hectare equivalents, while it is now 43.15 functional hectare equivalents following afforestation of the catchments. As such afforestation increased flood attenuation functionality by approximately 4.4 functional hectare equivalents. It should be noted though that although afforestation in the catchment has increased the potential ability of wetland B to attenuate floods, this is only one of the functions that are carried out by wetlands. Other ecosystem services may well have been decreased by this change in land use.

7.2 Worked hypothetical example 2: flood attenuation functionality for a valley-bottom wetland in a peri-urban catchment under various land cover scenarios.

A single valley-bottom wetland of 10 ha and its catchment of an additional 100 ha is examined under 3 scenarios of land cover (Figure 7.2):

- **Scenario A:** natural;
- **Scenario B:** largely natural with limited dryland cultivation in both the catchment (10 ha) and the wetland (3 ha); and
- **Scenario C:** limited dryland cultivation in the catchment (10 ha) and the wetland (3 ha) and considerable urban, industrial and transport development (50 ha) in the catchment.

Under each scenario of catchment and wetland land cover, the magnitude of impacts are calculated by multiplying the intensity of impact score for each land cover type by the extent of that land cover type in the catchment and wetland (Table 7.3). The magnitude of impact scores are:

- Scenario A = 0 for catchment impacts and 0 for onsite (wetland) impacts since the catchment and the wetland are natural (Table 7.3);
- Scenario B = -0.3 for catchment impacts (indicates reduced water inputs), and 2.7 for onsite (wetland) impacts (reduced surface roughness), both resulting from dryland cultivation (Table 7.3); and

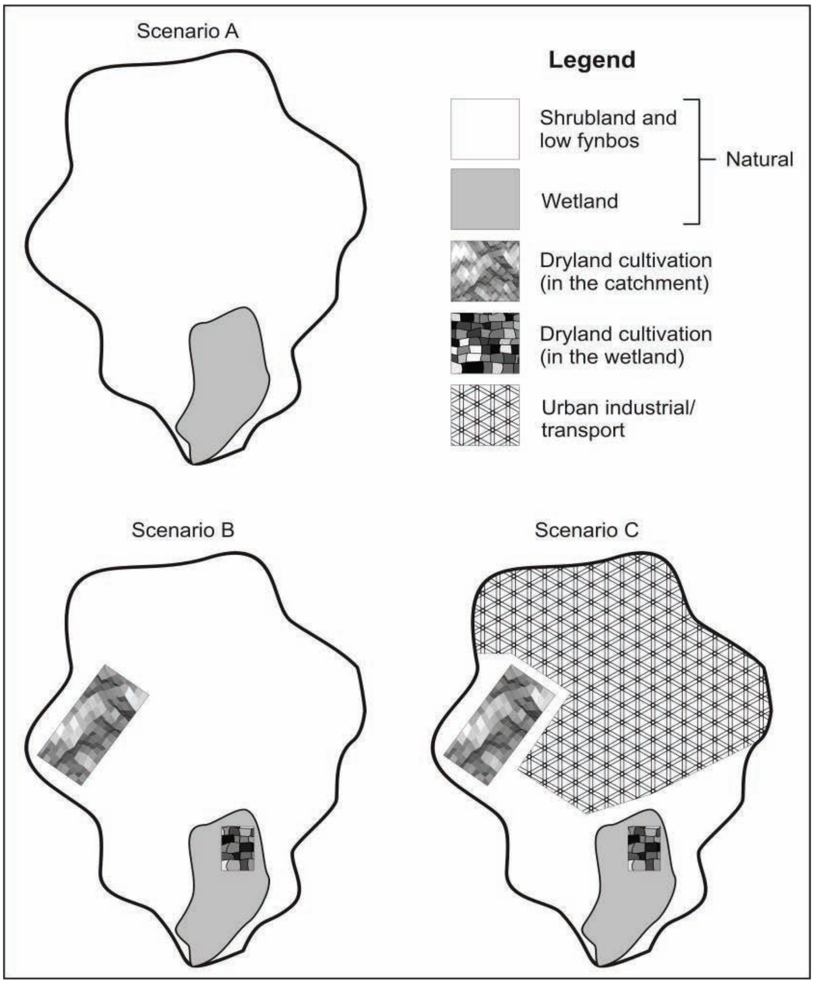


Figure 7.2: Schematic representation of a hypothetical peri-urban catchment under various land cover scenarios.

- Scenario C = 4.2 for catchment impacts (i.e. 4.5-0.3; indicates increased water inputs); the net result as a consequence of decreased water inputs from dryland cultivation and increased water inputs due to increased run-off from hardened surfaces (Table 7.3). Onsite (wetland) impacts are 2.7 (a consequence of reduced surface roughness).

The functionality scores for catchment impacts are calculated using equations in Tables 4.2 and 4.3 (increased and reduced water inputs respectively) and for onsite impacts using Table 4.5 (reduced surface roughness). The magnitude of impact score in each case is substituted in the relevant equation from Tables 4.2 and 4.3 for catchment impacts and Table 4.5 for onsite (wetland) impacts as shown in Table 7.4. Thus, for Scenario A, the functionality score is 2.50 for both catchment and wetland impacts, for Scenario B it is 2.60 and 2.07 for catchment and wetland impacts respectively. For

Scenario C, the functionality score is 2.16 and 2.04 for catchment and wetland impacts respectively. These scores are resolved for the wetland as a whole for each scenario by choosing the lowest functionality score and scaling it for the other functionality score using the appropriate value in Table 4.8. Therefore, functionality scores for flood attenuation for Scenarios A, B and C are 2.40, 1.97 and 1.58 respectively, which translates to functional hectare equivalents scores for flood attenuation of 6.00, 4.93 and 3.95 functional hectare equivalents for each scenario respectively. By comparing the unimpacted scenario (6.00 functional hectare equivalents) with the most severely impacted scenario (3.95 functional hectare equivalents), it is evident that the cumulative impact of these activities is 2.05 functional hectare equivalents with respect to flood attenuation.

Table 7.3: Calculation of the magnitude of impact on flood attenuation given three scenarios of land cover in a hypothetical catchment containing a valley-bottom wetland (Figure 7.2). The intensity of impact scores (Table 2.3) are shown as bold text in brackets in the relevant cells

	Scenario A: Natural		Scenario B: Cultivation				Scenario C: Cultivation and urban				
Land cover category	**Catchment**	**Wetland**	**Catchment impacts**		**Wetland impacts**		**Catchment impacts**			**Wetland impacts**	
	Area	**Area**	**Area**	**Reduced water inputs**	**Area**	**Reduced surface roughness**	**Area**	**Increased water inputs**	**Reduced water inputs**	**Area**	**Reduced surface roughness**
Natural vegetation	100	10	90		7		40			7	
Dryland cultivation			10	**(3)** 0.3	3	**(9)** 2.7	10		**(3)** 0.3	3	**(9)** 2.7
Urban industrial / transport							50	**(9)** 4.5			
TOTALS	**100**	**10**	**100**	**0.3**	**10**	**2.7**	**100**	**4.5**	**0.3**	**10**	**2.7**
Total catchment magnitude of impacts		**0**		**-0.3**		**2.7**		**4.2**			**2.7**

Table 7.4: Calculation of functional hectare equivalents for the flood attenuation function from the magnitude of impact scores for three hypothetical scenarios of land cover in a single catchment

		Scenario A: Natural			Scenario B Cultivation			Scenario C Cultivation and urban		
	Impact	**Magnitude of impact**	**Equation for functionality score**	**Functionality score**	**Magnitude of impact**	**Equation for functionality score**	**Functionality score**	**Magnitude of impact**	**Equation for functionality score**	**Functionality score**
Catchment impacts	Decreased water inputs				0.3	y=0.33x + 2.50	2.60			
	Increased water inputs							4.2	y=-0.08x + 2.50	2.16
Wetland impacts	Reduced surface roughness				2.7	y=-0.17x + 2.50	2.04	2.7	y=-0.17x + 2.50	2.04
Catchment impacts functionality score				2.50			2.60			2.16
Wetland impacts functionality score				2.50			2.07			2.04
Final functionality score*				2.40			1.97			1.58
Hectare equivalents**				6.00			4.93			3.95

*Calculated by selecting the lowest functionality score for wetland impacts and subtracting the scaling factor as indicated in Table 4.8 for the other impacts

**Calculated as the final functionality score / 4 x wetland area (ha)

7.3 Worked hypothetical example 3: flood attenuation functionality before and after rehabilitation of a valley-bottom wetland affected by gully erosion

The final hypothetical worked example considers the impact of rehabilitation on a wetland. A series of drains are present in the wetland. This worked example calculates the potential change in flood attenuation capacity of the wetland under the present scenario (Scenario A), and if the drains are blocked during the rehabilitation exercise (Scenario B). The catchment is 80 ha in extent and the wetland is an additional 10 ha in extent. For the purposes of this example, the only impacts in the catchment and wetland are the presence of drains that effectively drain 6 ha of wetland (Figure 7.3).

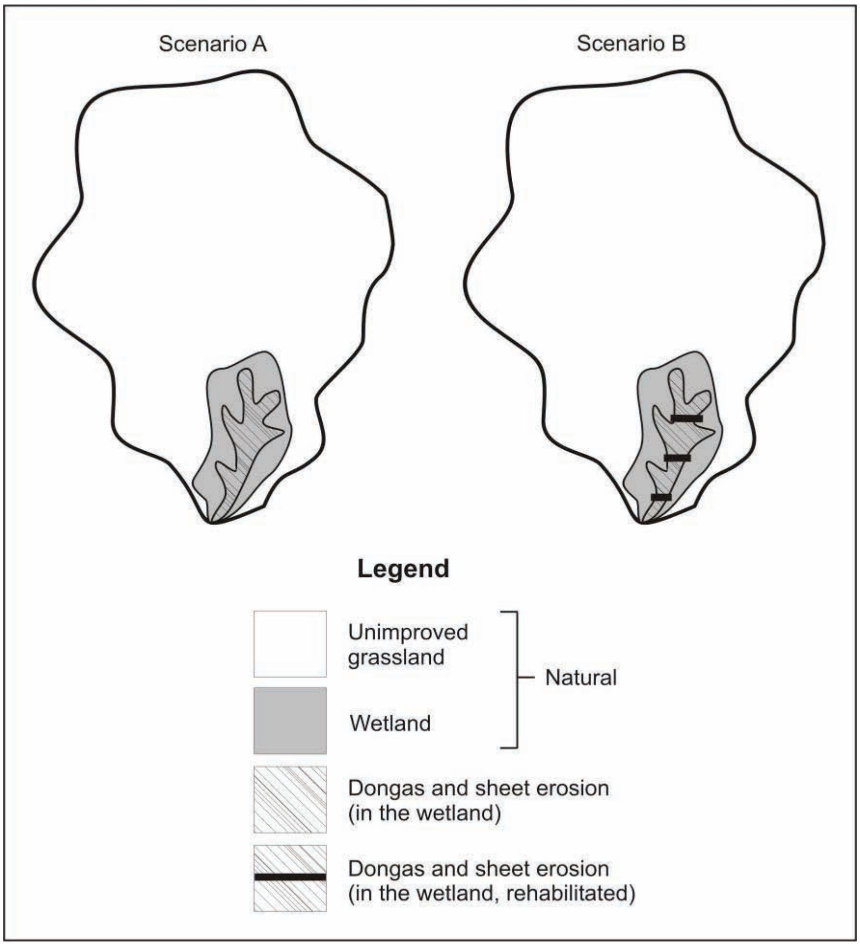


Figure 7.3: Schematic representation of a hypothetical catchment before and after rehabilitation of gullies in a valley-bottom wetland.

Based on these characteristics, the magnitude of impact of drains is calculated to be 5.4 (on a scale of 0 (natural) to 10 (critically modified)). However, rehabilitation is considered to have completely negated impacts of the gullies on flow enhancement. The magnitude of impact score for scenario A is 5.40, while that for scenario B is 0 (Table 7.5).

Table 7.5: Calculation of the magnitude of impact on flood attenuation given land cover categories and their extent in a hypothetical catchment containing a drained floodplain wetland (scenario A; Figure 7.3) where the drains had been artificially blocked (scenario B; Figure 7.3)

		Scenario A		**Scenario B**	
Land cover category	**Catchment**	**Wetland impacts**		**Wetland impacts**	
	Area	**Area**	**Flow enhancement**	**Area**	**Flow enhancement**
Natural vegetation	80	4		4	
Artificial drains		6	**(9)** 5.40	6	**(0)** 0
TOTALS	**80**	**10**	**Magnitude of impact = 5.40**	**10**	**Magnitude of impact = 0**

Based on the impact of drains on flow enhancement, without rehabilitation the wetland can be considered to provide 3.73 functional hectare equivalents for flood attenuation, while in a rehabilitated state it delivers 6.25 functional hectare equivalents for flood attenuation (Table 7.6). Therefore, rehabilitation can be considered to reinstate approximately 1.5 functional hectare equivalents of flood attenuation.

Table 7.6: Calculation of functional hectare equivalents from the magnitude of impact scores in two hypothetical catchments

	Scenario A			**Scenario B**		
Impact	**Magnitude of impact**	**Equation for functio-nality score**	**Functio-nality score**	**Magnitude of impact**	**Equation for functio-nality score**	**Functio-nality score**
Flow enhance-ment	5.40	y=-0.26x + 2.89	1.49	0	y=2.50	2.50
Final functionality score			1.49			2.50
Hectare equivalents*			3.73			6.25

* Hectare equivalents = functionality score / 4 * area of wetland = 1.49 / 4 * 10 = 3.73 functional hectare equivalents for Scenario A and 2.50 / 4 * 10 = 6.25 functional hectare equivalents for Scenario B

8. A CASE STUDY OF A CATCHMENT-SCALE ANALYSIS USING GIS: THE GOUKOU RIVER

This case study applies the methodology presented in this document to the upper Goukou catchment in the Western Cape. This catchment was chosen because there was detailed GIS data available following a study carried out for CAPE (Cape Action Plan for People and the Environment; Helme, 2008). The study illustrates the use of GIS in applying the methodology, and compares wetland ecosystem service provision with respect to toxicant removal for wetlands in their current state compared to wetland ecosystem provision prior to impacts by humans.

8.1 GIS as a tool for analysis

Assessing the cumulative impacts of human activities on wetland functions can be quite daunting because of the computational complexity involved. However, the use of an appropriate geographic information system (GIS) makes the process more manageable. As pointed out by Johnston (1994),

> *"cumulative impact assessment requires new tools capable of analyzing multiple wetlands and multiple perturbations spread over large distances and long time periods. Geographic Information Systems (GIS) provide these capabilities…"*

With a suitable wetland map and an appropriate GIS, many quantitative measures can be calculated, including; the loss of wetland area, decrease in the number of wetlands in the landscape, decrease in wetland density, altered connectivity, the loss of different wetland types, and the loss of wetland functions.

The creation of a GIS based upon the concepts described in this study would be useful to wetland scientists, conservationists and planners alike. The process of doing so is both long and detailed, but not difficult given appropriate expertise. The process of GIS automation begins with development of a model such as the model developed and described in this study. Data inputs and desired results must be identified, as well as the steps that will allow the user to go from starting data to finished data. This "algorithm of model logic" then allows for the construction of a model in Model Builder in ArcGIS with user-defined buttons and tools that allow for the steps to be taken to reach the desired end result. Alternatively, an application may be developed that can be used in another GIS application, such that information is shared between them. The product of such automation is usually in the form of a Graphical User Interface (GUI), an interactive interface that allows the user to access the programme via graphical components (Bishop and Horspool, 2004), as opposed to text and keyboard commands that were previously used to achieve a desired result (TechTarget, 2008). The elements of a GUI include windows, menu bars, pull-down menus, scroll bars, and buttons, each of which is encoded with a method to respond to user stimuli. The automated product may then be tested and reviewed and eventually presented as a product in the form of software.

8.2 The upper Goukou River case study

The methodology developed in this research was applied to the upper quaternary catchment of the Goukou River, which encompassed 49 valley-bottom wetlands, each in their own subcatchment. The stages of data pre-processing and integration of layers was conducted using ArcGIS 9.2, and the analyses that followed were conducted using Microsoft Excel. The case study considers a single ecosystem service, that of toxicant removal.

8.2.1 The Goukou catchment

On the south coast of the Western Cape Province of South Africa, in the vicinity of the towns of Riversdale and Stilbaai, lies the Goukou Forum of the Gouritz Water Management Area (WMA) (DWAF, 2005; Figure 8.1). The Goukou Forum encompasses a number of quaternary catchments, all of which are a product of the 67km long Goukou River, which originates on the southern slopes of the Langeberg Mountains (Carter and Brownlie, 1990; DEAT, 2008).

On its way toward the coastline, the Goukou River carves its way through more than 10km of Tertiary deposits, upstream of which a further 40km is comprised of mainly Palaeozoic Bokkeveld Shales (Carter and Brownlie, 1990) that weather relatively easily to produce rich-coloured, textured, well-drained soils. However, to the north and in the upper part of the catchment, rocks are predominantly metamorphosed and folded sandstone and quartzite of the Cape Supergroup with skeletal soils on bedrock. Climatic conditions include all year-round rainfall, with mean annual precipitation for the area of 865mm along the coast (DWAF, 2005), with average daily maximum temperatures reaching 26°C in January and 18°C in July (WeatherSA, 2008). The geology and climate of the area has allowed for the formation of a number of wetlands, particularly in the upper reaches of the catchment.

Vegetation in the Goukou Forum is dominated by vegetation of the East Coast Renosterveld bioregion, while the southern parts of the area are classified as South Coast Fynbos (Vlok and de Villiers, 2007). Approximately 63% of land-cover in the area is natural (DEAT, 2008). There are significant occurrences of Restionaceae, Bruniaceae and sedges (Rogers, 1997), and much of the natural land-cover also comprises water bodies and wetlands. Agriculture accounts for approximately 35% of the land-cover of the Goukou River catchment, which is made up of a combination of commercial dryland agriculture, commercial forestry, commercial irrigated agriculture and improved grassland (DEAT, 2008). Approximately 2% of the catchment is degraded shrubland, with just 1% in the form of urban land cover comprising residential and industrial developments in the towns of Stilbaai and Riversdale. Given the agricultural activity in the catchment and the likely return flow of water from agricultural land into the Goukou River, water quality enhancement is an ecosystem service that is very relevant to the Goukou Catchment.

Figure 8.1: Locality map of the Goukou Forum in which the case study area is situated (DWAF, 2005).

8.2.2 Application of catchment scale analysis

The first step in applying a catchment scale analysis involves the mapping of all wetlands present and delineating their catchments, including the land-use categories within each wetland and its catchment (Figure 8.2). This may be achieved through the use of aerial photos, orthophotos, digital elevation models (DEMs), remote sensing imagery and/or topographic maps of the area of interest. Often, depending on the area being investigated, wetlands, land-cover and vegetation maps may have already been generated. Such data were available in this study where GIS data in the form of wetland shapefiles, their classification into HGM type, vegetation maps, and land-cover grids had been compiled by members of the CAPE fine-scale planning project for the Riversdale Domain. Catchment boundaries of individual wetlands had not been delineated and each subcatchment was thus mapped using a DEM of the area along with a rivers layer, which is widely available for South African rivers. An external application, ArcHydro, was used in ArcMap Version 9.2 to perform the delineation of catchments.

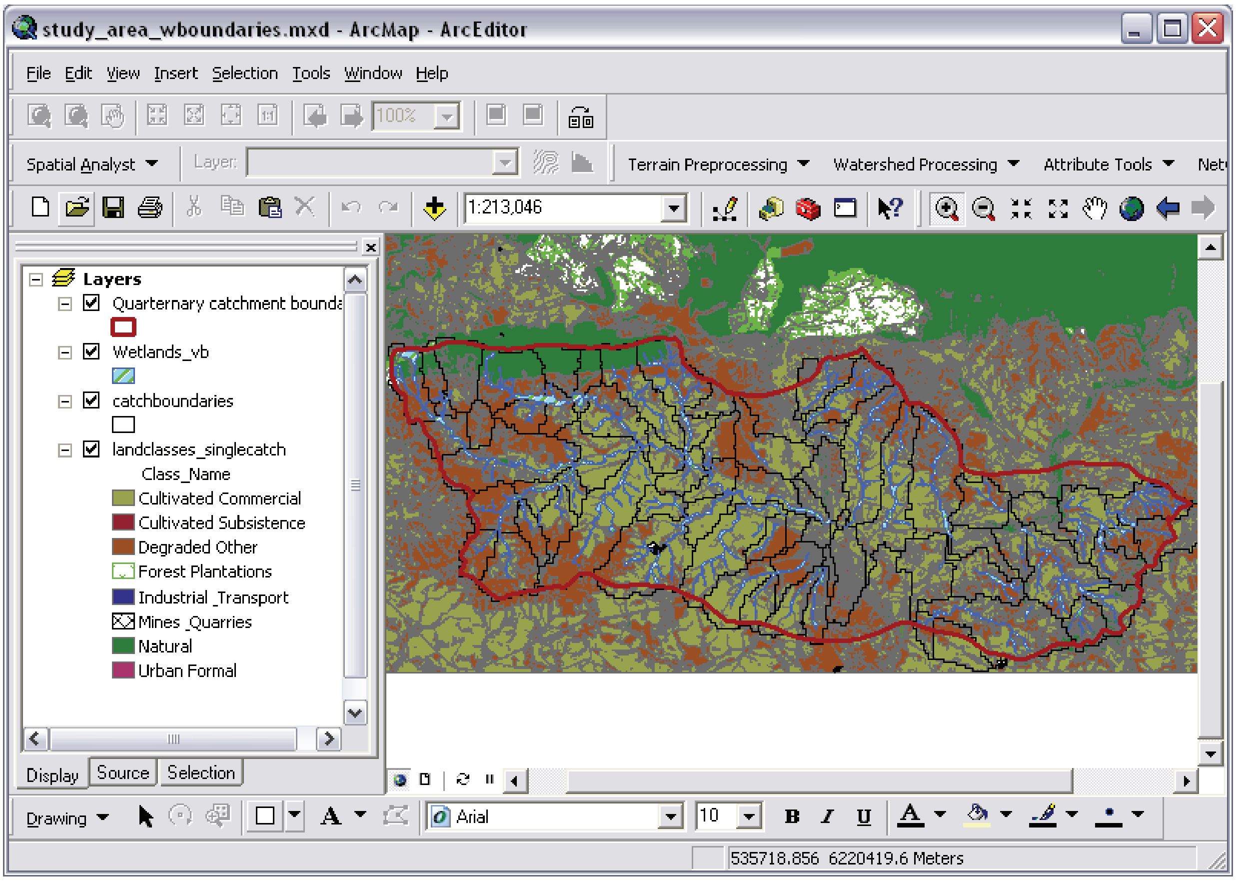
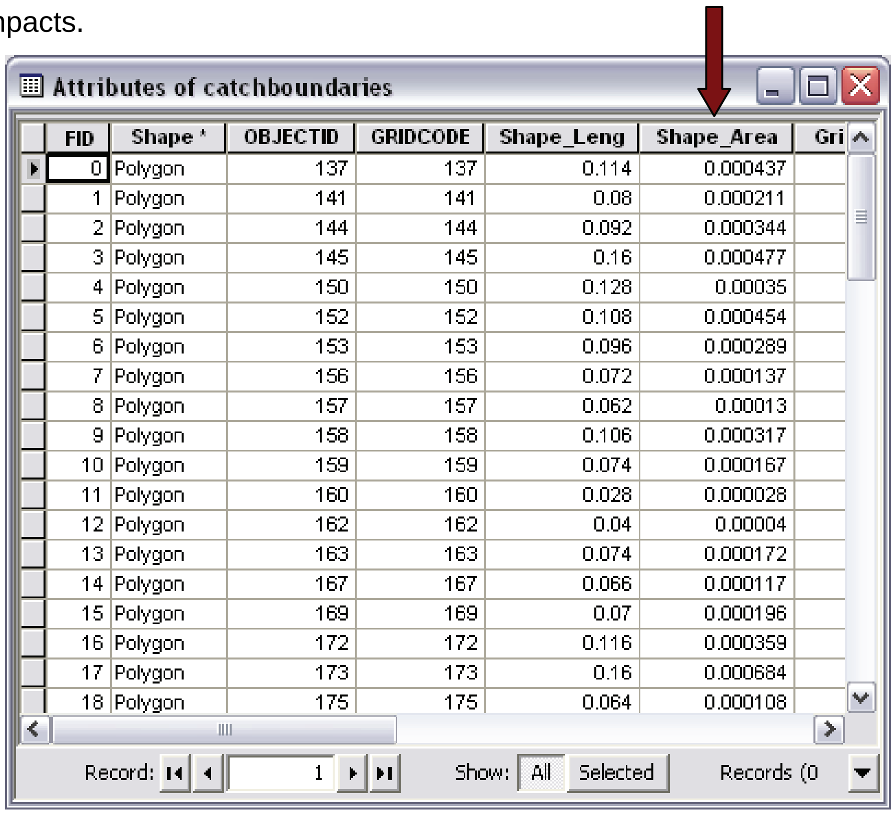


Figure 8.2: Mapped wetlands and their catchments together with land cover of the upper Goukou River catchment.

In ArcMap, the various layers were geo-referenced such that the area of interest was co-incident with that of the quaternary catchment of the upper Goukou River (Figure 8.2). It should be noted that the grey areas in Figure 8.2 are not formal land-cover classes, but indicate that at the projected scale, the resolution of the land-cover grid is too high for the picture to display land-cover.

Once mapping and overlaying the different land cover datasets had been completed, the areal extents of historical wetland, subcatchments, and land-cover categories in the catchments and wetlands were calculated using GIS, as indicated in the attribute tables of each of the layers being considered (Figure 8.3). Areal extent was measured using the measuring tool in ArcMap.

The relevant areal extents for each wetland and its corresponding subcatchment were exported from the ArcMap attribute table into a Microsoft Excel spreadsheet, which allowed for easy computation (Table 8.1[3]). The extent of each land-cover category for both the wetlands and their subcatchments (Table 8.2) were then multiplied by the relevant intensity of impact score (from Table 2.3), producing a magnitude of impact score for each land-cover category for each impact type, both for catchment and within-wetland impacts.


Attributes of catchboundaries

FID	Shape *	OBJECTID	GRIDCODE	Shape_Leng	Shape_Area	Gri
0	Polygon	137	137	0.114	0.000437	
1	Polygon	141	141	0.08	0.000211	
2	Polygon	144	144	0.092	0.000344	
3	Polygon	145	145	0.16	0.000477	
4	Polygon	150	150	0.128	0.00035	
5	Polygon	152	152	0.108	0.000454	
6	Polygon	153	153	0.096	0.000289	
7	Polygon	156	156	0.072	0.000137	
8	Polygon	157	157	0.062	0.00013	
9	Polygon	158	158	0.106	0.000317	
10	Polygon	159	159	0.074	0.000167	
11	Polygon	160	160	0.028	0.000028	
12	Polygon	162	162	0.04	0.00004	
13	Polygon	163	163	0.074	0.000172	
14	Polygon	167	167	0.066	0.000117	
15	Polygon	169	169	0.07	0.000196	
16	Polygon	172	172	0.116	0.000359	
17	Polygon	173	173	0.16	0.000684	
18	Polygon	175	175	0.064	0.000108	

Record: 1 Show: All Selected Records (0

Figure 8.3: An example of an attribute table in ArcMap with arrow indicating area in km^2.

[3] Tables for this section are large and have therefore been attached at the end.

The impact of catchment land-use activities was resolved for each wetland by computing an overall magnitude of catchment impact score, achieved by subtracting the total for ‘decreased water inputs’ from the total for ‘increased water inputs’ (Table 8.3). Activities in the Goukou Catchment led to both decreased and increased water inputs. Therefore, when dealing with decreased water inputs, for impact scores with an absolute value from 0.0 to 3.0, a value of 3.50 was assigned for toxicant removal functionality, while for impact scores with an absolute greater than 3.0, the equation $y = -0.14x + 3.92$ was applied (from Table 4.3). For increased water inputs, Table 4.2 was consulted, whereby a value of 3.50 was assigned for toxicant removal functionality for impact scores with an absolute value from 0.0 to 3.0, while the equation $y=-0.26x + 4.27$ was applied for impact scores with an absolute greater than 3.0. The application of these values and equations produced a score for functional effectiveness with respect to toxicant removal for each of the 49 wetlands examined (Table 8.4).

The impacts of land-use activities within wetlands were translated to impact scores with respect to increased water use, reduced surface roughness and flow impediment (Table 8.3). For onsite activities for increased wetland water use, for impact scores from 0.0 to 5.0, a value of 3.50 was assigned for toxicant removal functionality, while for impact scores greater than 5.0, the equation $y=-0.36x + 5.30$ was used (from Table 4.4). For activities leading to flow impediment, a value of 3.50 was assigned to impact scores from 0.0 to 3.0 for toxicant removal functionality, while for values greater than 3.0 for these activities, the equation $y=-0.14x + 3.92$ was applied (from Table 4.6) to produce scores for functional effectiveness with respect to toxicant removal (Table 8.5). For the impact of decreased surface roughness within the wetland, the magnitude of impact scores for each wetland were translated to functionality scores for toxicant removal using the equation $y=-0.18x + 3.50$ (from Table 4.5). Functionality scores for all onsite activities were then resolved by taking the lowest functionality score and adjusting for the additive effects of additional onsite activities (using Table 4.8) as described in the methodology (section 4.5).

Overall functionality with respect to toxicant removal was then determined based on Table 4.8 and functional hectare equivalents for each wetland were then calculated by dividing the final functional effectiveness score for toxicant removal by 4, and then multiplying the result by the area of each wetland (Table 8.6). The overall functional hectare equivalent score for toxicant removal, or the cumulative functionality for the catchment as a whole, was found to equal **638.8** hectare equivalents of toxicant removal functionality. In their unimpacted state, it was determined that the same wetlands would provide **716.9** hectare equivalents of toxicant removal functionality (since unimpacted valley-bottom wetlands have a functionality score of 3.50 for toxicant removal). **The cumulative impact of human activity on wetland functionality was therefore found to be reduced by 78.1 hectare equivalents of toxicant removal functionality for this quaternary catchment of the Goukou River.**

Given the differing degrees of impact that are evident in the wetlands of the upper Goukou River catchment, it now becomes possible to distinguish wetlands that have been greatly compromised in terms of ecosystem functionality with respect to toxicant removal. Figure 8.4 shows the extent to which toxicant removal functionality has been reduced as a percentage of the historical functionality such that most wetlands have been moderately modified (10 to 15% reduction in toxicant removal functionality). A small number of wetlands have been greatly compromised with respect to this ecosystem service (>20% reduction in toxicant removal functionality) and a moderate number have had fairly limited impacts with respect to this ecosystem service (<10% reduction in toxicant removal functionality). In focussing wetland management or rehabilitation efforts strategically it may be useful to focus on large wetlands that have been moderately impacted or smaller wetlands that have been more heavily impacted with respect to toxicant removal functionality, given a strategic vision to improve water quality in the Goukou Catchment. The focus on moderately impacted wetlands is justified because of the likely high cost of rehabilitation of heavily impacted wetlands to a sufficient degree for water quality enhancement.

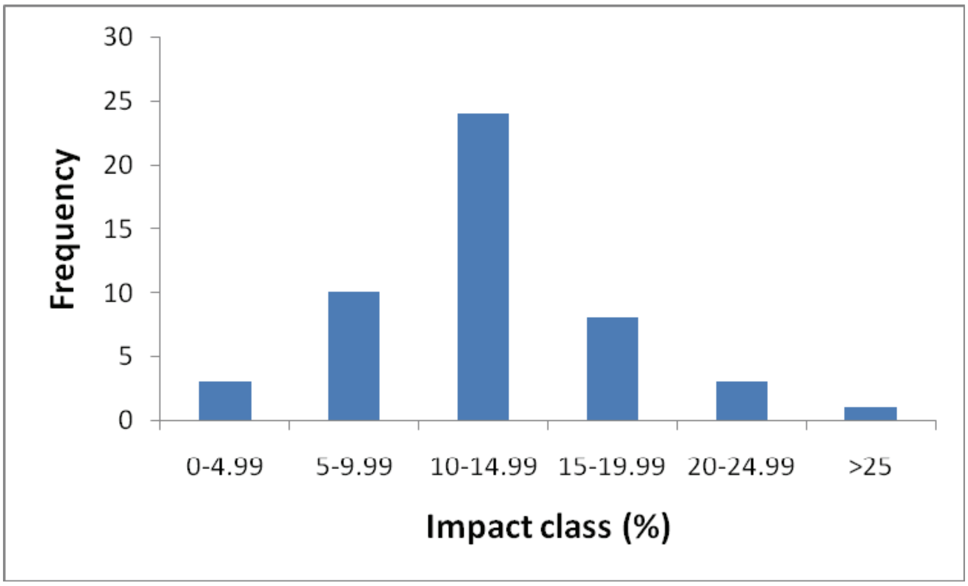


Figure 8.4: Impact classes that represent the extent to which current toxicant removal functionality has been reduced from the historical condition for wetlands in the upper Goukou River catchment.

Given that modest interventions in moderately impacted large wetlands may offer effective opportunities for reinstating functional hectare equivalents with respect to toxicant removal, it is useful to examine the relationship between the degree of impact to the toxicant removal functionality and wetland size (Figure 8.5). In this case there is some relationship evident between these two variables, with large wetlands typically being less impacted than small wetlands with respect to this ecosystem service. Therefore, if one was interested in reinstating ecosystem functionality with respect to toxicant removal, large wetlands that have been moderately impacted may offer good opportunities for rehabilitation (Figure 8.5). As a second option, it may be useful to consider smaller wetlands for rehabilitation that have been greatly impacted, since small wetlands often require smaller interventions than large wetlands. Therefore, the sort of broad-scale analysis considered in this study may be very useful with respect to developing strategic insights into prioritising wetlands for rehabilitation or more effective management.

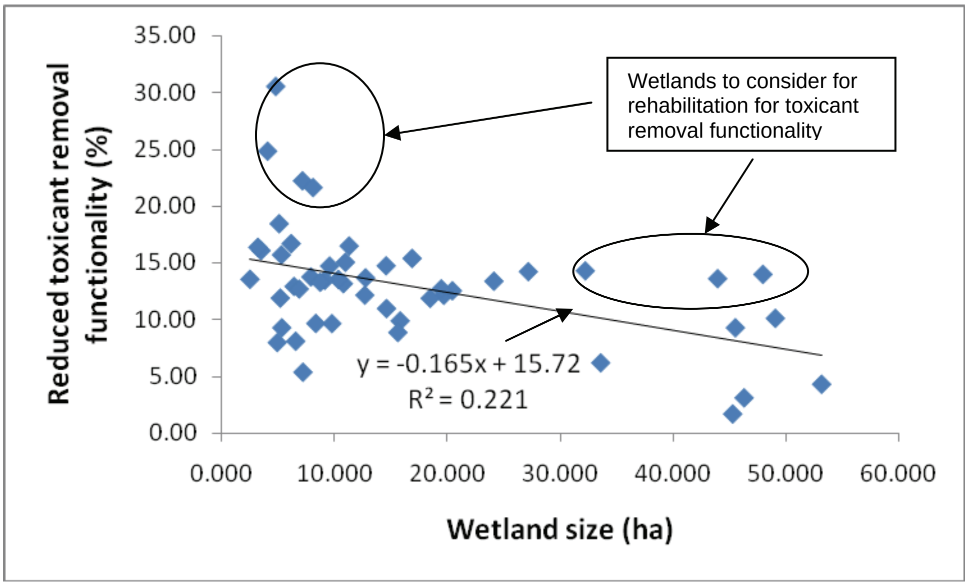


Figure 8.5: Relationship between the extent to which ecosystem functionality with respect to toxicant removal has been compromised and wetland size.

An even more useful approach that is being investigated (Jaganath, C., 2009, pers. comm., University of KwaZulu-Natal, Durban) is to identify areas in the catchment where water quality is being reduced through human activities, and to focus on damaged wetlands in close proximity to such areas.

8.3 Conclusion

The sort of broad-scale (catchment or landscape scale) analyses considered in this study may be very useful for strategic insights into prioritising wetlands for rehabilitation or more effective management. This approach can be used for any of the ecosystem services described in this report, and should be undertaken in accordance with one or a few strategic catchment objectives in mind. Once the analysis is complete, wetlands of differing degrees of modification from the natural reference condition could be colour-coded and the broad-scale strategic assessment could be more narrowly focussed for purposes of wetland management and intervention (such as rehabilitation), in order to maximise the benefits of funds spent on wetland management.

Table 8.1: Areal extent of wetlands and their subcatchments in the upper Goukou River Quaternary catchment

Wetland number	Wetland area (m²)	Wetland area (ha)	Catchment number	Catchment area (km^2)	Catchment area (m²)	Catchment area (ha)	Extent of catchment (excluding wetland)
0	463698	46.37	0	0.00044	4360000	436	389.63
1	453519	45.35	9	0.00032	3170000	317	271.65
2	532525	53.25	5	0.00045	4530000	453	399.75
3	197115	19.71	6	0.00029	2880000	288	268.29
4	272129	27.21	3	0.00048	4770000	477	449.79
5	336358	33.64	4	0.00035	3500000	350	316.36
6	491419	49.14	17	0.00068	6840000	684	634.86
8	97745	9.77	13	0.00017	1720000	172	162.23
9	440196	44.02	23	0.00065	6530000	653	608.98
10	95728	9.57	4	0.00035	3500000	350	340.43
11	50918	5.09	16	0.00036	3590000	359	353.91
12	64051	6.41	18	0.00011	1080000	108	101.59
13	61534	6.15	30	0.00079	7860000	786	779.85
14	51945	5.19	25	0.00043	4250000	425	419.81
16	65528	6.55	24	0.00017	1720000	172	165.45
17	40565	4.06	27	0.00086	8550000	855	850.94
18	34735	3.47	22	0.00015	1520000	152	148.53
21	24955	2.50	29	0.00017	1710000	171	168.50
22(1)	53271	5.33	39	0.00014	1440000	144	138.67
22(2)	83497	8.35	34	0.00021	2110000	211	202.65
24	52896	5.29	31	0.00010	1010000	101	95.71
25	31993	3.20	19	0.00073	7310000	731	727.80
26	71544	7.15	27	0.00086	8550000	855	847.85
27	455949	45.59	38	0.00031	3090000	309	263.41
28	107912	10.79	42	0.00030	3040000	304	293.21
29	109701	10.97	35	0.00020	2010000	201	190.03
33	127581	12.76	40	0.00016	1630000	163	150.24
35	80985	8.10	27	0.00086	8550000	855	846.90
36	322717	32.27	41	0.00064	6370000	637	604.73
38	126945	12.69	59	0.00039	3870000	387	374.31
39	204679	20.47	57	0.00024	2370000	237	216.53
40	72002	7.20	38	0.00031	3090000	309	301.80
42	158281	15.83	48	0.00035	3500000	350	334.17
44	68683	6.87	45	0.00015	1460000	146	139.13
46(1)	480352	48.04	53	0.00058	5780000	578	529.96

Wetland number	Wetland area (m²)	Wetland area (ha)	Catchment number	Catchment area (km^2)	Catchment area (m²)	Catchment area (ha)	Extent of catchment (excluding wetland)
46(2)	184952	18.50	69	0.00021	2080000	208	189.50
46(3)	156251	15.63	70	0.00024	2350000	235	219.37
47	49194	4.92	60	0.00036	3620000	362	357.08
48	79061	7.91	58	0.00019	1910000	191	183.09
50	113033	11.30	47	0.00078	7770000	777	765.70
51	47883	4.79	52	0.00020	1950000	195	190.21
52	146212	14.62	47	0.00078	7770000	777	762.38
53(1)	103442	10.34	61	0.00023	2300000	230	219.66
53(2)	91427	9.14	67	0.00033	3330000	333	323.86
53(3)	87288	8.73	68	0.00017	1730000	173	164.27
56	145857	14.59	65	0.00025	2490000	249	234.41
57	194792	19.48	66	0.00018	1750000	175	155.52
58	241532	24.15	64	0.00034	3350000	335	310.85
62	168891	16.89	71	0.00081	8100000	810	793.11

Table **8.2**: Areal extent of land cover categories (LC) of wetlands and their sub-catchments in the upper Goukou River Quaternary catchment

Wetland number	Landcover in wetland	Area of wetland LC (ha)	Catchment FID	Landcover in catchment	Area of catchment LC (ha)
0	Natural	37.09	0	Natural	92.49
	Degraded Vegetation	9.28		Degraded Vegetation	176.49
				Cultivated, irrigated	120.65
1	Forest Plantations	17.67	9	Forest Plantations	37.44
	Cultivated, irrigated	1.38		Natural	81.89
	Degraded Vegetation	2.63		Degraded Vegetation	152.32
	Natural	23.67			
2	Cultivated, irrigated	7.33	5	Natural	223.61
	Natural	43.33		Cultivated, irrigated	10.91
	Degraded Vegetation	2.59		Degraded Vegetation	165.23
3	Natural	8.57	6	Natural	23.42
	Cultivated, irrigated	6.50		Cultivated, irrigated	184.12
	Degraded Vegetation	4.64		Degraded Vegetation	60.74
4	Cultivated, irrigated	3.64	3	Natural	114.81
	Degraded Vegetation	18.95		Cultivated, irrigated	272.47
	Natural	4.62		Degraded Vegetation	62.51
5	Natural	20.19	4	Natural	17.04
	Degraded Vegetation	13.45		Degraded Vegetation	167.70
				Cultivated, irrigated	131.62
6	Natural	18.67	17	Natural	16.83
	Degraded Vegetation	28.01		Degraded Vegetation	235.97
	Cultivated, irrigated	2.46		Cultivated, irrigated	382.06
8	Natural	3.82	13	Degraded Vegetation	125.93
	Degraded Vegetation	5.73		Natural	0.50
	Cultivated, irrigated	0.22		Cultivated, irrigated	35.61
				Forest Plantations	0.19
9	Cultivated, irrigated	8.17	23	Urban industrial/transport	4.82
	Natural	10.75		Urban residential- low density	0.98
	Degraded Vegetation	25.09		Natural	15.21
				Degraded Vegetation	136.00

Wetland number	Landcover in wetland	Area of wetland LC (ha)	Catchment FID	Landcover in catchment	Area of catchment LC (ha)
				Cultivated, irrigated	451.97
10	Cultivated, irrigated	3.83	4	Natural	24.61
	Natural	3.02		Cultivated, irrigated	128.57
	Degraded Vegetation	2.73		Degraded Vegetation	162.87
				Forest Plantations	0.32
11	Degraded Vegetation	3.41	16	Degraded Vegetation	132.17
	Natural	0.08		Cultivated, irrigated	221.09
	Cultivated, irrigated	1.60		Natural	0.65
12	Natural	1.36	18	Forest Plantations	1.59
	Degraded Vegetation	4.57		Natural	3.19
	Cultivated, irrigated	0.47		Cultivated, irrigated	60.63
				Degraded Vegetation	35.96
				Urban industrial/transport	0.23
13	Cultivated, irrigated	0.74	30	Degraded Vegetation	422.77
	Degraded Vegetation	5.42		Natural	21.47
				Cultivated, irrigated	335.61
14	Degraded Vegetation	1.95	25	Degraded Vegetation	209.30
	Cultivated, irrigated	1.23		Cultivated, irrigated	202.39
	Natural	2.02		Natural	2.34
				Forest Plantations	3.17
				Urban industrial/transport	2.61
16	Degraded Vegetation	2.37	24	Forest Plantations	1.65
	Cultivated, irrigated	0.64		Natural	2.96
	Natural	3.55		Degraded Vegetation	108.84
				Cultivated, irrigated	51.41
				Urban industrial/transport	0.59
17	Cultivated, irrigated	3.53	27	Degraded Vegetation	302.87
	Urban industrial/transport	0.05		Cultivated, irrigated	547.16
	Degraded Vegetation	0.48		Urban industrial/transport	0.91
18	Natural	0.40	22	Degraded Vegetation	24.79
	Degraded Vegetation	2.27		Cultivated, irrigated	120.38
	Cultivated, irrigated	0.80		Urban industrial/transport	1.79

Wetland number	Landcover in wetland	Area of wetland LC (ha)	Catchment FID	Landcover in catchment	Area of catchment LC (ha)
				Natural	0.81
				Urban residential- low density	0.75
21	Natural	0.64	29	Natural	2.57
	Cultivated, irrigated	0.40		Degraded Vegetation	31.63
	Cultivated, dryland	0.10		Cultivated, irrigated	132.00
	Degraded Vegetation	1.35		Urban residential- low density	1.13
				Urban industrial/transport	1.17
22(1)	Natural	2.13	39	Natural	1.49
	Degraded Vegetation	3.20		Degraded Vegetation	96.20
				Cultivated, irrigated	40.83
				Mines and quarries	0.15
22(2)	Natural	2.23	34	Natural	1.11
	Degraded Vegetation	5.21		Degraded Vegetation	79.40
	Cultivated, irrigated	0.90		Cultivated, irrigated	122.14
24	Natural	0.70	31	Degraded Vegetation	13.11
	Degraded Vegetation	3.42		Cultivated, irrigated	81.40
	Cultivated, irrigated	1.17		Urban industrial/transport	1.20
25	Natural	0.35	19	Natural	7.50
	Cultivated, irrigated	0.81		Degraded Vegetation	339.21
	Degraded Vegetation	2.04		Cultivated, irrigated	381.10
26	Natural	0.23	27	Degraded Vegetation	302.87
	Degraded Vegetation	1.88		Cultivated, irrigated	547.16
	Cultivated, irrigated	5.04		Urban industrial/transport	0.91
27	Degraded Vegetation	27.36	38	Natural	9.27
	Natural	18.24		Degraded Vegetation	140.12
				Cultivated, irrigated	114.02
28	Cultivated, irrigated	1.63	42	Natural	19.34
	Forest Plantations	0.90		Degraded Vegetation	89.20
	Natural	1.79		Cultivated, irrigated	182.26
	Degraded Vegetation	6.46		Urban industrial/transport	2.41
29	Natural	2.67	35	Urban industrial/transport	0.86
	Degraded Vegetation	4.75		Natural	9.31

Wetland number	Landcover in wetland	Area of wetland LC (ha)	Catchment FID	Landcover in catchment	Area of catchment LC (ha)
	Cultivated, irrigated	3.56		Degraded Vegetation	4.79
				Cultivated, irrigated	175.07
33	Natural	3.43	40	Urban industrial/transport	0.50
	Degraded Vegetation	6.57		Degraded Vegetation	10.26
	Cultivated, irrigated	2.67		Cultivated, irrigated	139.48
	Urban industrial/transport	0.09			
35	Cultivated, irrigated	5.60	27	Degraded Vegetation	406.99
	Natural	0.50		Cultivated, irrigated	436.47
	Degraded Vegetation	1.99		Natural	3.45
36	Natural	2.70	41	Cultivated, irrigated	533.68
	Degraded Vegetation	29.44		Degraded Vegetation	68.19
	Urban industrial/transport	0.13		Urban industrial/transport	2.85
38	Natural	2.72	59	Natural	3.44
	Degraded Vegetation	9.97		Degraded Vegetation	272.21
				Cultivated, irrigated	98.66
39	Natural	4.92	57	Cultivated, irrigated	65.93
	Degraded Vegetation	13.96		Natural	39.96
	Cultivated, irrigated	1.58		Degraded Vegetation	108.97
				Urban industrial/transport	1.67
40	Natural	4.87	38	Natural	8.36
	Cultivated, irrigated	0.25		Degraded Vegetation	190.72
	Degraded Vegetation	2.09		Cultivated, irrigated	102.72
42	Natural	5.72	48	Natural	15.36
	Degraded Vegetation	10.11		Degraded Vegetation	53.74
				Cultivated, irrigated	265.07
44	Natural	1.23	45	Urban industrial/transport	0.50
	Degraded Vegetation	5.64		Degraded Vegetation	87.53
				Cultivated, irrigated	51.10
46(1)	Degraded Vegetation	43.43	53	Degraded Vegetation	161.01
	Natural	4.60		Cultivated, irrigated	360.89
				Natural	7.26
				Urban industrial/transport	0.81

Wetland number	Landcover in wetland	Area of wetland LC (ha)	Catchment FID	Landcover in catchment	Area of catchment LC (ha)
46(2)	Natural	4.48	69	Cultivated, irrigated	64.57
	Degraded Vegetation	13.92		Degraded Vegetation	53.92
	Urban industrial/transport	0.09		Natural	69.84
				Urban industrial/transport	1.17
46(3)	Cultivated, irrigated	0.42	70	Degraded Vegetation	41.58
	Degraded Vegetation	8.26		Cultivated, irrigated	87.99
	Natural	6.95		Natural	89.81
47	Degraded Vegetation	2.53	60	Natural	40.95
	Natural	2.38		Degraded Vegetation	199.50
				Cultivated, irrigated	116.62
48	Natural	0.87	58	Natural	5.43
	Degraded Vegetation	7.03		Degraded Vegetation	145.88
				Cultivated, irrigated	31.79
50	Mines and quarries	0.09	47	Cultivated, irrigated	494.19
	Natural	0.84		Degraded Vegetation	258.43
	Degraded Vegetation	8.27		Mines and quarries	13.08
	Cultivated, irrigated	2.11			
51	Degraded Vegetation	3.50	52	Natural	35.39
	Natural	1.29		Degraded Vegetation	60.94
				Cultivated, irrigated	93.89
52	Degraded Vegetation	10.20	47	Cultivated, irrigated	494.19
	Natural	0.79		Degraded Vegetation	258.43
	Cultivated, irrigated	3.58		Mines and quarries	13.08
	Urban industrial/transport	0.06			
53(1)	Natural	1.52	61	Natural	3.91
	Degraded Vegetation	8.53		Degraded Vegetation	154.04
	Cultivated, irrigated	0.24		Urban residential- high density	33.61
	Urban residential- high density	0.06		Urban industrial/transport	2.31
				Cultivated, irrigated	25.79
53(2)	Degraded Vegetation	7.96	67	Natural	0.28
	Natural	1.19		Degraded Vegetation	62.16

Wetland number	Landcover in wetland	Area of wetland LC (ha)	Catchment FID	Landcover in catchment	Area of catchment LC (ha)
				Cultivated, irrigated	256.89
				Urban industrial/transport	4.52
53(3)	Degraded Vegetation	7.50	68	Degraded Vegetation	15.67
	Natural	1.23		Cultivated, irrigated	148.60
56	Degraded Vegetation	13.08	65	Cultivated, irrigated	143.24
	Natural	1.15		Degraded Vegetation	63.74
	Urban residential- high density	0.35		Urban industrial/transport	4.82
				Urban residential- high density	21.20
				Mines and quarries	1.42
57	Forest Plantations	3.87	66	Urban residential- high density	3.82
	Urban residential- high density	0.55		Urban industrial/transport	2.67
	Degraded Vegetation	14.72		Natural	1.28
	Natural	0.33		Degraded Vegetation	100.43
				Cultivated, irrigated	47.32
58	Degraded Vegetation	18.84	64	Natural	13.95
	Natural	4.08		Forest Plantations	1.22
	Cultivated, irrigated	1.23		Degraded Vegetation	127.04
				Cultivated, irrigated	168.63
62	Natural	0.60	71	Mines and quarries	1.97
	Degraded Vegetation	15.52		Degraded Vegetation	287.55
	Cultivated, irrigated	0.77		Natural	72.26
				Cultivated, irrigated	431.33

Table **8.3**: Magnitude of impact scores for each impact in wetlands and their sub-catchments in the upper Goukou River Quaternary catchment

Wetland	Catchment Impacts				Wetland Impacts			
	Catchment Area (excl wet)	Increased water inputs	Decreased water inputs	Magnitude: catchment impacts	Wetland Area	Increased water use	Reduced surface roughness	Flow impediment
0	389.6302	1.3589	1.5483	-0.1894	46.3698		0.6004	
1	271.6481	1.6821	1.2404	0.4418	45.3519	3.5066	0.3261	
2	399.7475	1.2400	0.1364	1.1035	53.2525		0.8343	
3	268.2885	0.6792	3.4315	-2.7522	19.7115		2.3552	
4	449.7871	0.4169	3.0289	-2.6120	27.2129		2.7589	
5	316.3642	1.5903	2.0802	-0.4899	33.6358		1.1996	
6	634.8581	1.1151	3.0090	-1.8939	49.1419		1.9600	
8	162.2255	2.3289	1.1079	1.2210	9.7745		1.8710	
9	608.9804	0.7461	3.7109	-2.9648	44.0196		2.6385	
10	340.4272	1.4353	1.8968	-0.4615	9.5728		2.8551	
11	353.9082	1.1203	3.1236	-2.0033	5.0918		3.5779	
12	101.5949	1.0819	3.1244	-2.0425	6.4051		2.5063	
13	779.8466	1.6264	2.1518	-0.5254	6.1534		3.2389	
14	419.8055	1.5516	2.4784	-0.9268	5.1945		2.3069	
16	165.4472	2.0058	1.6432	0.3626	6.5528		1.5700	
17	850.9435	1.0774	3.2150	-2.1376	4.0565		4.8187	0.0669
18	148.5265	0.6246	4.0525	-3.4278	3.4735		3.1189	
21	168.5045	0.6459	3.9167	-3.2709	2.4955		2.6284	
22(1)	138.6729	2.0866	1.4723	0.6143	5.3271		1.8000	
22(2)	202.6503	1.1755	3.0136	-1.8381	8.3497		1.8736	
24	95.7104	0.5240	4.2522	-3.7282	5.2896		3.0459	
25	727.8007	1.3982	2.6181	-1.2199	3.1993		3.1748	
26	847.8456	1.0813	3.2268	-2.1454	7.1544		4.3122	
27	263.4051	1.5958	2.1643	-0.5685	45.5949		1.8000	
28	293.2088	0.9867	3.1081	-2.1214	10.7912	0.7535	2.5534	
29	190.0299	0.1162	4.6065	-4.4903	10.9701		2.9193	
33	150.2419	0.2351	4.6418	-4.4067	12.7581		2.6535	0.0338
35	846.9015	1.4417	2.5769	-1.1352	8.0985		4.1965	
36	604.7283	0.3808	4.4126	-4.0318	32.2717		2.7731	0.0202
38	374.3055	2.1817	1.3179	0.8639	12.6945		2.3573	
39	216.5321	1.5791	1.5225	0.0565	20.4679		2.4329	
40	301.7998	1.8959	1.7018	0.1940	7.2002		1.0400	
42	334.1719	0.4824	3.9661	-3.4837	15.8281		1.9159	
44	139.1317	1.9196	1.8365	0.0831	6.8683		2.4622	
46(1)	529.9648	0.9251	3.4048	-2.4797	48.0352		2.7126	
46(2)	189.5048	0.9094	1.7036	-0.7942	18.4952		2.3029	0.0252
46(3)	219.3749	0.5686	2.0054	-1.4368	15.6251		1.7195	
47	357.0806	1.6761	1.6330	0.0431	4.9194		1.5458	
48	183.0939	2.3902	0.8682	1.5220	7.9061		2.6683	
50	765.6967	1.0980	3.2270	-2.1291	11.3033		3.1979	
51	190.2117	0.9611	2.4679	-1.5068	4.7883		5.9249	
52	762.3788	1.1027	3.2411	-2.1383	14.6212		2.1276	0.0195
53(1)	219.6558	2.9636	0.5870	2.3766	10.3442		2.6265	
53(2)	323.8573	0.7015	3.9662	-3.2647	9.1427		2.6106	

53(3)	164.2712	0.2861	4.5231	-4.2370	8.7288		2.5778	
56	234.4143	1.4831	3.0552	-1.5721	14.5857		2.8594	
57	155.5208	2.2148	1.5214	0.6933	19.4792	1.7886	2.4660	
58	310.8468	1.2260	2.7479	-1.5219	24.1532		2.5959	
62	793.1109	1.1001	2.7192	-1.6191	16.8891		2.9848	

Table 8.4: Ecosystem functionality with respect to toxicant removal of wetlands in the upper Goukou River Quaternary catchment based on catchment impacts

Catchment Impacts					
Wetland	**Water input decrease**	**Functionality Score**	**Wetland**	**Water input increase**	**Functionality Score**
29	4.490270984	3.291362062	53(1)	2.376645779	3.5
33	4.406683229	3.303064348	48	1.522043634	3.5
53(3)	4.236953361	3.326826529	8	1.220966802	3.5
36	4.031811116	3.355546444	2	1.103535857	3.5
24	3.728221802	3.398048948	38	0.863853443	3.5
42	3.483652318	3.432288675	57	0.693349938	3.5
18	3.427820618	3.440105113	22(1)	0.614282704	3.5
21	3.270850511	3.462080928	1	0.441771174	3.5
53(2)	3.264677526	3.462945146	16	0.362563646	3.5
9	2.964818874	3.5	40	0.194026471	3.5
3	2.752225682	3.5	44	0.083061912	3.5
4	2.611950187	3.5	39	0.05654267	3.5
46(1)	2.479697312	3.5	47	0.043114398	3.5
26	2.145449312	3.5			
52	2.138347945	3.5			
17	2.137638702	3.5			
50	2.129082103	3.5			
28	2.121400927	3.5			
12	2.042490873	3.5			
11	2.003250504	3.5			
6	1.893948742	3.5			
22(2)	1.8381315	3.5			
62	1.619134298	3.5			
56	1.572056423	3.5			
58	1.52187502	3.5			
51	1.506803551	3.5			
46(3)	1.436818114	3.5			
25	1.219917101	3.5			
35	1.135177798	3.5			
14	0.926790888	3.5			
46(2)	0.794200516	3.5			
27	0.568524452	3.5			
13	0.52541051	3.5			
5	0.489885455	3.5			
10	0.461484893	3.5			
0	0.189386192	3.5			

Table 8.5: Ecosystem functionality with respect to toxicant removal of wetlands in the upper Goukou River Quaternary catchment based on wetland impacts

Wetland Impacts							
Wetland	**Increased water use**	**Functionality Score**	**Reduced surface roughness**	**Functionality Score**	**Flow impediment**	**Functionality Score**	**Resolved onsite functionality**
0			0.6004	3.3919			3.3919
1	3.5066	3.5000	0.3261	3.4413			3.4413
2			0.8343	3.3498			3.3498
3			2.3552	3.0761			3.0761
4			2.7589	3.0034			3.0034
5			1.1996	3.2841			3.2841
6			1.9600	3.1472			3.1472
8			1.8710	3.1632			3.1632
9			2.6385	3.0251			3.0251
10			2.8551	2.9861			2.9861
11			3.5779	2.8560			2.8560
12			2.5063	3.0489			3.0489
13			3.2389	2.9170			2.9170
14			2.3069	3.0848			3.0848
16			1.5700	3.2174			3.2174
17			4.8187	2.6326	0.0669	3.5000	2.6326
18			3.1189	2.9386			2.9386
21			2.6284	3.0269			3.0269
22(1)			1.8000	3.1760			3.1760
22(2)			1.8736	3.1627			3.1627
24			3.0459	2.9517			2.9517
25			3.1748	2.9285			2.9285
26			4.3122	2.7238			2.7238
27			1.8000	3.1760			3.1760
28	0.7535	3.5000	2.5534	3.0404			3.0404
29			2.9193	2.9745			2.9745
33			2.6535	3.0224	0.0338	3.5000	3.0224
35			4.1965	2.7446			2.7446
36			2.7731	3.0008	0.0202	3.5000	3.0008
38			2.3573	3.0757			3.0757
39			2.4329	3.0621			3.0621
40			1.0400	3.3128			3.3128
42			1.9159	3.1551			3.1551
44			2.4622	3.0568			3.0568
46(1)			2.7126	3.0117			3.0117
46(2)			2.3029	3.0855	0.0252	3.5000	3.0855
46(3)			1.7195	3.1905			3.1905
47			1.5458	3.2218			3.2218
48			2.6683	3.0197			3.0197
50			3.1979	2.9244			2.9244
51			5.9249	2.4335			2.4335
52			2.1276	3.1170	0.0195	3.5000	3.1170
53(1)			2.6265	3.0272			3.0272
53(2)			2.6106	3.0301			3.0301

53(3)			2.5778	3.0360			3.0360
56			2.8594	2.9853			2.9853
57	1.7886	3.5000	2.4660	3.0561			3.0561
58			2.5959	3.0327			3.0327
62			2.9848	2.9627			2.9627

Table 8.6: Final scores and hectare equivalents of ecosystem functionality with respect to toxicant removal of wetlands in the upper Goukou River Quaternary catchment

Wetland	Wetland Impacts: Overall functionality	Catchment Impacts: Overall functionality	Final functionality score	Current functional Ha equiv	Historical functional Ha equiv	Percentage decrease in functionality
0	3.392	3.50	3.392	39.321	40.574	3.09
1	3.441	3.50	3.441	39.017	39.683	1.68
2	3.350	3.50	3.350	44.597	46.596	4.29
3	3.076	3.50	3.076	15.158	17.248	12.11
4	3.003	3.50	3.003	20.433	23.811	14.19
5	3.284	3.50	3.284	27.616	29.431	6.17
6	3.147	3.50	3.147	38.665	42.999	10.08
8	3.163	3.50	3.163	7.730	8.553	9.62
9	3.025	3.50	3.025	33.291	38.517	13.57
10	2.986	3.50	2.986	7.146	8.376	14.68
11	2.856	3.50	2.856	3.636	4.455	18.40
12	3.049	3.50	3.049	4.882	5.604	12.89
13	2.917	3.50	2.917	4.487	5.384	16.66
14	3.085	3.50	3.085	4.006	4.545	11.86
16	3.217	3.50	3.217	5.271	5.734	8.07
17	2.633	3.50	2.633	2.670	3.549	24.78
18	2.939	3.44	2.939	2.552	3.039	16.04
21	3.027	3.46	3.027	1.888	2.184	13.52
22(1)	3.176	3.50	3.176	4.230	4.661	9.26
22(2)	3.163	3.50	3.163	6.602	7.306	9.64
24	2.952	3.40	2.952	3.903	4.628	15.66
25	2.929	3.50	2.929	2.342	2.799	16.33
26	2.724	3.50	2.724	4.872	6.260	22.18
27	3.176	3.50	3.176	36.202	39.896	9.26
28	3.040	3.50	3.040	8.202	9.442	13.13
29	2.975	3.29	2.975	8.158	9.599	15.01
33	3.022	3.30	3.022	9.640	11.163	13.65
35	2.745	3.50	2.745	5.557	7.086	21.58
36	3.001	3.36	3.001	24.211	28.238	14.26
38	3.076	3.50	3.076	9.761	11.108	12.12
39	3.062	3.50	3.062	15.669	17.909	12.51
40	3.313	3.50	3.313	5.963	6.300	5.35
42	3.155	3.43	3.155	12.485	13.850	9.85
44	3.057	3.50	3.057	5.249	6.010	12.66
46(1)	3.012	3.50	3.012	36.167	42.031	13.95
46(2)	3.085	3.50	3.085	14.267	16.183	11.84
46(3)	3.190	3.50	3.190	12.463	13.672	8.84
47	3.222	3.50	3.222	3.962	4.304	7.95
48	3.020	3.50	3.020	5.969	6.918	13.72
50	2.924	3.50	2.924	8.264	9.890	16.45
51	2.434	3.50	2.434	2.913	4.190	30.47
52	3.117	3.50	3.117	11.394	12.794	10.94
53(1)	3.027	3.50	3.027	7.829	9.051	13.51
53(2)	3.030	3.46	3.030	6.926	8.000	13.43
53(3)	3.036	3.33	3.036	6.625	7.638	13.26

56	2.985	3.50	2.985	10.886	12.762	14.71
57	3.056	3.50	3.056	14.883	17.044	12.68
58	3.033	3.50	3.033	18.313	21.134	13.35
62	2.963	3.50	2.963	12.509	14.778	15.35
TOTAL				**638.7785318**	**716.928275**	

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APPENDIX 1

AN EVALUATION OF HEALTH AND ECOSYSTEM SERVICES PROVISION OF WETLANDS ON THE EKUBO ESTATE, PORT EDWARD, KWAZULU-NATAL

A1.1 Introduction

In general there is a strong link between the provision of ecosystem services and ecosystem health, and there are local and global initiatives to protect and restore ecosystem health for the benefit of human well-being (Millennium Ecosystem Assessment, 2005). In South Africa, both wetland health and the provision of ecosystem services are viewed as the key elements of wetland management and protection, and the State is currently spending between R50 million and R100 million per annum on rehabilitating wetlands in order to improve wetland health and functioning. The challenge is to develop tools that enable rapid assessment of these features of wetlands in order to develop strategic approaches that are sustainable.

This study was undertaken to determine the relationships between human impacts on wetlands, which can be assessed using the recently developed tool WET-Health (Macfarlane *et al.,* 2008), and the delivery of ecosystem services by wetlands, which can be assessed using the recently developed tool WET-EcoServices (Kotze *et al.,* 2008). The reason that this study was undertaken was to improve our understanding of the nature of the relationships between human impacts and the delivery of ecosystem services in the following respects:

- Are there relationships between human impacts on wetlands and their provision of ecosystem services, and if so, to what extent do these differ for different ecosystem services?
- Given that impacts to wetlands are likely to negatively affect the delivery of ecosystem services:
    - Are the relationships linear over a range of magnitudes of impact (A; Figure A1.1)?
    - Does the delivery of ecosystem services decline rapidly with small impacts such that once impacted, large impacts do not have a big effect (B; Figure A1.1)?
    - Are wetlands resilient in the face of small impacts followed by a rapid decline in the delivery of ecosystem services once the wetland has been severely impacted (C; Figure A1.1)?

Is there an increase in the provision of ecosystem services with small impacts followed by a rapid decrease (D; Figure A1.1)?

- Do the relationships provide an indication of the provision of ecosystem services of healthy wetlands (when the y-intercept is 0) irrespective of the type of impact?

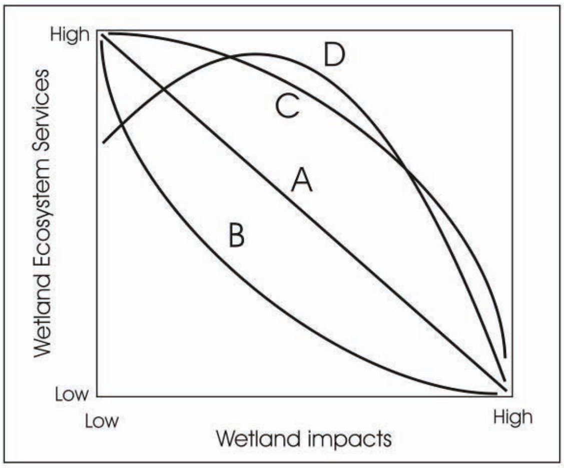

Figure A1.1: Likely trends in the delivery of ecosystem services in relation to impacts to wetlands.

The approach that was adopted was to assess the current hydrological health and provision of ecosystem services of a number of wetlands on a single property, the Ekubo Estate, on the South Coast of KwaZulu-Natal. The advantage of the Ekubo site was the presence of a relatively large number of wetlands (9 hydrogeomorphic (HGM) units) of a single HGM type (unchannelled valley-bottom wetlands) and with a single type of impact – excavation of drains to make wetland areas suitable for growth of sugar cane. Therefore, the HGM unit type and the nature of disturbance were constant, but the range of wetland health characteristics were variable. Thus the effects of variation in the type of HGM unit and type of impact were eliminated, and the only variation measured was the response of a range of ecosystem services to artificial drainage, which varied with respect to the intensity of this impact between wetlands.

In both the assessment of wetland health (using WET-Health) and the provision of ecosystem services (using WET-EcoServices), the more detailed, field based, Level 2 assessments, were undertaken in order to gain insight into the effects of individual factors on the provision of ecosystem services. For the purposes of this study, for reasons given in the main report, only indirect ecosystem services were assessed as follows:

- Flood attenuation;

- Streamflow regulation;
- Sediment trapping;
- Phosphate trapping;
- Nitrate removal; and
- Toxicant removal.

A1.2 Study site

The Ekubo Wetlands are situated on the property of the Ekubo Estate several kilometres north of Port Edward. The wetlands on the site (Figure A1.2) vary in size from less than 1 ha to nearly 8 ha (Table A1.1).

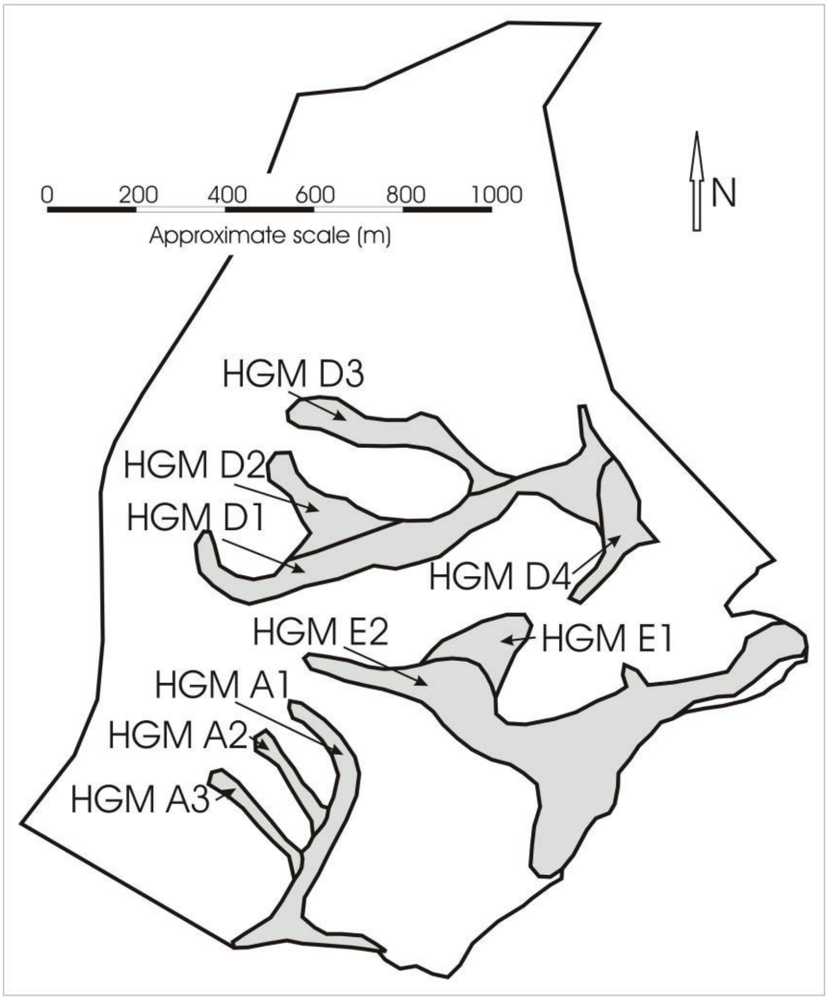

Figure A1.2: Map of the Ekubo Wetlands showing the approximate extent of HGM units assessed as part of this study.

Table A1.1: HGM Unit codes and their extent

HGM Unit	Area (ha)	Longitudinal slope (%)
A1	2.326	7.2
A2	0.633	11.8
A3	0.713	12.8
D1	7.323	5.0
D2	1.167	8.3
D3	2.194	6.5
D4	0.384	11
E1	0.767	4.9
E2	7.793	2.3

Although the wetlands were small they had very steep longitudinal slopes for their size such that they are likely to be vulnerable to erosion (Figure A1.3: see Macfarlane *et al.,* 2008 for discussion of vulnerability to erosion).

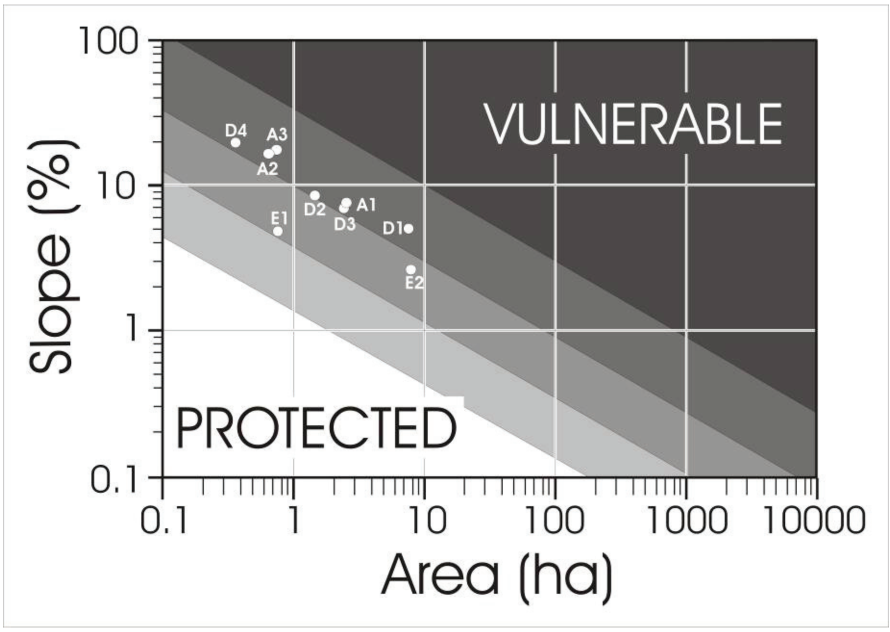

Figure A1.3: Relationship between wetland longitudinal slope and area for HGM units on the Ekubo Estate (from Macfarlane *et al.,* 2008).

A1.3 Methods

A1.3.1 Assessment of wetland health

Wetland health refers to the deviation of a wetlands present environmental state from the natural condition. The WET-Health tool (Macfarlane *et al.,* 2008) attempts to measure deviation from the natural reference condition for hydrology, geomorphology and vegetation. The tool is structured such that a low score (close to 0) provides an indication of good health, while a high score (close to 10) provides an indication of poor health. For the purposes of this study only hydrological health was assessed as it is recognized as the most important determinant of the present ecological state of a wetland (Mitsch and Gosselink, 2007).

A1.3.2 Assessment of ecosystem services

The assessment of ecosystem services is based on a series of characteristics of wetlands that affect the flow of water into, through and from a wetland, since the pattern of water flow through a wetland affects its residence time, the potential for interactions between water and wetland plants and the substrate (Kotze *et al.,* 2008). The assessment of the provision of wetland ecosystem services as described in WET-EcoServices is based both on the likely “effectiveness” of the wetland in providing a particular ecosystem service (i.e. on wetland characteristics) as well as the “opportunity” to provide such ecosystem services, which indicates whether the conditions exist in the catchment to exploit this effectiveness. For example, a wetland might have characteristics that make it very effective in attenuating floods, but if the catchment does not receive rainfall events that produce floods, the wetland might not ever provide this function in reality. The assessment of ecosystem services in this study examined the characteristics of the wetland only (i.e. we measured “effectiveness” only and not “opportunity”) such that the results could be translated to wetlands other than those examined in this study.

WET-EcoServices scores the effectiveness of wetlands to provide a particular ecosystem service on a scale of 0 (ineffective) to 4 (as effective as any wetland can be expected to be).

A1.4 Results

A1.4.1 Wetland health

Health scores varied from 0 (unmodified, natural) to 6 (largely modified) as shown in Table A1.2. Hydrogeomorphic units A1, A2 and A3 had not been drained artificially and scored 0, reflecting that they were unmodified and close to the natural reference condition (Health Category A). HGM units E1 and E2 were largely natural despite efforts to drain them (Health Category B), since due to their very shallow longitudinal slopes the drains were ineffective. In contrast, the HGM units of wetland D were moderately, to largely modified, due to their steep longitudinal slopes that resulted in the drains being very effective in leading runoff away from the wetland. HGM units D1, D3 and D4 were moderately modified (Health Category C), while HGM unit D2 was largely modified with a health score of 6.0 (Health Category D).

Table A1.2: An evaluation of the health of wetlands on the Ekubo Estate as estimated using WET-Health (Macfarlane *et al*., 2008)

HGM unit	**A1**	**A2**	**A3**	**D1**	**D2**	**D3**	**D4**	**E1**	**E2**
Hydrological health score	0.0	0.0	0.0	3.0	6.0	3.0	3.5	1.0	1.0
Hydrological health category	A	A	A	C	D	C	C	B	B

A1.4.2 Wetland ecosystem services

All the wetlands evaluated were found to be effective in supplying a number of ecosystem goods and services, although the degree to which each benefit was supplied, varied (Table A1.3).

The first of the functions that was evaluated was flood attenuation, with all wetlands scoring moderately high (from 2.2 to 2.5) since water flows laterally across the valley-bottom wetlands before arriving at the gully and draining from the wetland. However, WET-EcoServices makes no attempt to evaluate the effects of natural streams or artificial drains (or gullies) on the flood attenuation function of wetlands, such that all scores for flood attenuation are based on wetland characteristics other than this factor. Hence, the scores for flood attenuation are similar for all wetlands since for all factors other than the size and extent of artificial drains, they are remarkably similar.

Streamflow regulation varied from less than 2 to almost 2.5 such that these wetlands are moderately effective with respect to the provision of this ecosystem service.

The sediment trapping function of these wetlands was low (scores varied between 1.1 and 1.7) despite having characteristics that would be considered to favour sediment trapping, such as diffuse flow of water, dense vegetation cover and moderate flood attenuation functionality. This ecosystem service is evaluated on the basis of just a few characteristics in WET-EcoServices, with a key characteristic being the presence of direct evidence of sediment deposition. Only those HGM units with moderately impacted catchments had eroded catchments, which resulted in direct evidence of sediment deposition – which is not a feature of the wetlands themselves. If this characteristic is omitted, then the scores for sediment trapping are similar to the scores for flood attenuation.

Phosphate trapping scores were high for all wetlands with scores between 2.5 and 3.3, while scores for nitrate removal were very high, varying between 3.2 and 3.8. Scores for toxicant removal were also high, varying between 2.7 and 3.2.

Table A1.3: The provision of a number of ecosystem services by wetlands on the Ekubo Estate as estimated using WET-EcoServices (Kotze *et al.,* 2008)

	Hudrogeomorphic unit								
Ecosystem service	**A1**	**A2**	**A3**	**D1**	**D2**	**D3**	**D4**	**E1**	**E2**
Flood attenuation	2.2	2.2	2.2	2.3	2.2	2.2	2.2	2.5	2.3
Streamflow regulation	2.4	2.4	2.2	2.0	1.8	2.0	2.2	2.4	2.2
Sediment trapping	1.1	1.1	1.1	1.7	1.1	1.6	1.1	1.3	1.2
Phosphate trapping	3.3	3.3	3.3	2.7	2.5	2.6	3.3	2.8	3.0
Nitrate removal	3.8	3.8	3.8	3.2	3.2	3.2	3.8	3.2	3.6
Toxicant removal	3.2	3.2	3.2	2.7	2.7	2.7	3.2	2.7	3.0

A1.5 Discussion: relationships between ecosystem services and health

The relationships between the delivery of ecosystem services and health for the range of ecosystem services assessed are presented in Figure A1.4. In general there was a negative relationship between impacts to wetlands and the delivery of ecosystem services, and the relationship was generally linear. In some cases the relationship was curvilinear (second order polynomial) such that at intermediate levels of human impact, the delivery of ecosystem services was greatest, but as impacts increased there was a rapid decline in the provision of ecosystem services.

HGM units in wetland E scored highest with respect to **flood attenuation** (scores from 2.3 to 2.5) due to their very shallow longitudinal slopes, while the other HGM units scored fairly consistently at approximately 2.2 to 2.3 (Figure A1.4a). As mentioned previously, WET-EcoServices scores characteristics other than the effects of natural streams or artificial drains (or gullies) on flood attenuation function. This is viewed as a shortcoming and based on this analysis we suggest that there would have been a greater decline in ecosystem functionality with respect to flood attenuation, which is partly determined by the extent and size of drains or gullies, and also on the shape of wetlands – since linear wetlands would be more seriously impacted by this activity than circular ones. Nevertheless, for this HGM type the value of this analysis lies in the determination of the y-intercept, which would be expected to be close to 2.2.

With respect to **streamflow regulation**, healthy wetlands such as HGM units A1, A2, A3, E1 and E2 generally scored higher (2.2 to 2.4) than impacted wetlands such as D, which scored lowest (1.8 to 2.2; Figure A1.4b). Artificial drains lower the water table generally and reduce the duration of water supply from wetlands to downstream areas such that with increasing impacts the effectiveness for the provision of this ecosystem service declined.

In the case of **sediment trapping**, healthy wetlands (A1, A2, A3) and highly impacted wetlands (D2 and D4) scored poorly for sediment trapping (Figure A1.4c). However, those wetlands that had been impacted to an intermediate extent scored highest (D1 and D3). This is linked largely to the functionality of wetlands with respect to flood attenuation.

There was a general decrease in the effectiveness of wetlands with respect to **phosphate trapping** with increased wetland impacts since the most effective was wetland A followed by wetland E, while wetland D scored the lowest (Figure A1.4d). There were similar decreases in the effectiveness of **toxicant** (Figure A1.4f) and **nitrate removal** (Figure A1.4e).

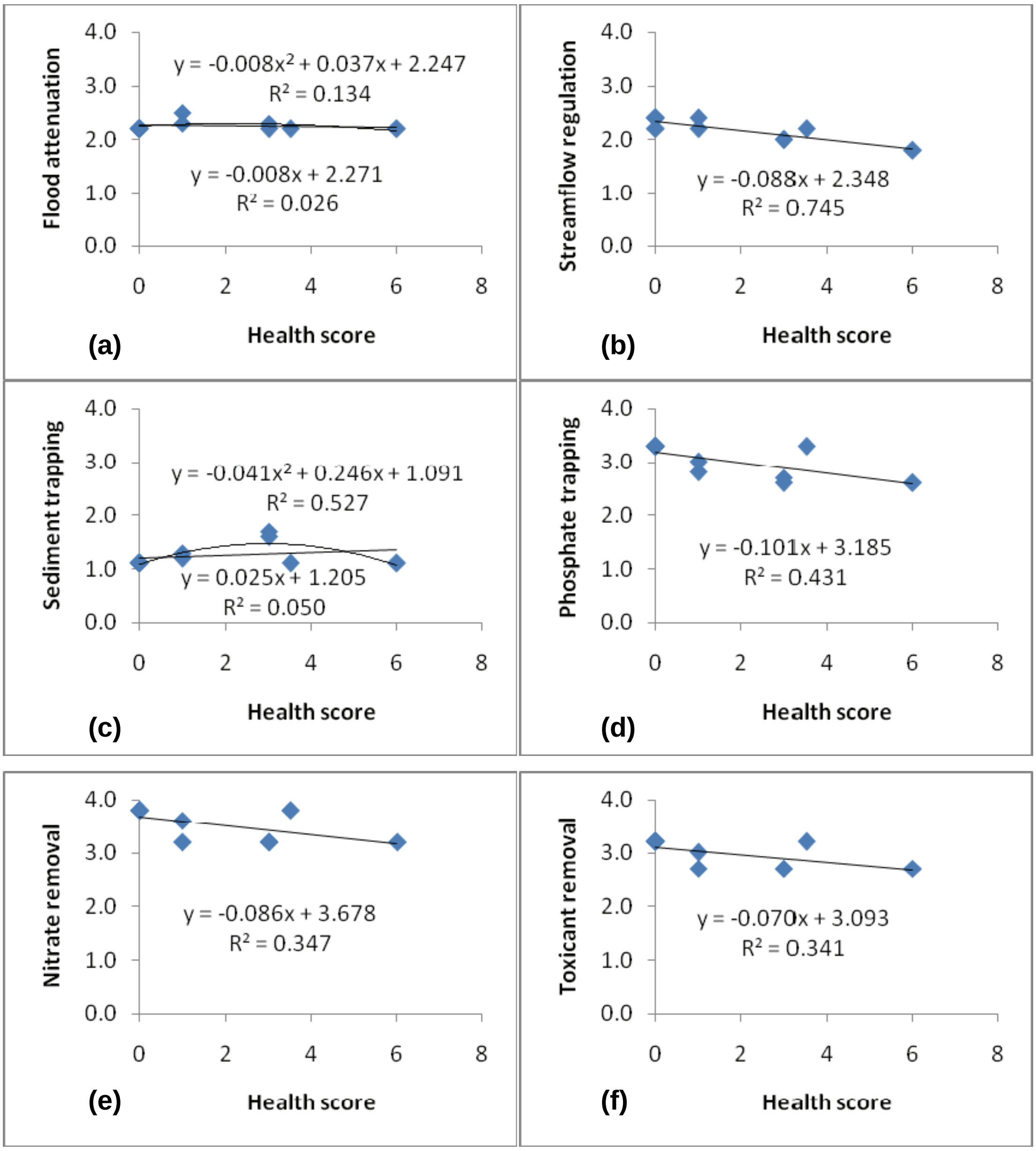

Figure A1.4: Relationships between the delivery of a range of ecosystem services and degree of human impact caused by artificial drainage on the Ekubo Estate. Note that unimpacted wetlands have a low score (close to 0) and critically impacted wetlands have a high score (close to 10).

The relationships between the provision of ecosystem services and wetland health provide a basis for interpreting the provision of ecosystem services for wetlands in an unimpacted state (Table A1.4).

Table A1.4: The effectiveness of provision of ecosystem services for unimpacted wetlands on the Ekubo Estate given the impacts of artificial drains on wetland functionality

Ecosystem service	y-intercept
Flood attenuation	2.2
Streamflow regulation	2.3
Sediment trapping	1.1
Phosphate trapping	3.2
Nitrate removal	3.7
Toxicant removal	3.1

A1.6 Conclusions

This study demonstrates that individual HGM units differ in terms of the level of delivery of different ecosystem services. It also illustrates the level of delivery of ecosystem services in valley-bottom wetlands generally as inferred from the y-intercept score. In this respect valley-bottom wetlands seem to perform very effectively with respect to toxicant removal, followed by phosphate removal and nitrate removal. They perform moderately effectively with respect to flood attenuation and streamflow regulation, and poorly with respect to sediment trapping.

In addition to this, the present study provides qualitative insights into the nature of the relationships between the provision of ecosystem services and the magnitude of impacts to wetlands. In general there is a negative relationship between the delivery of ecosystem services and human impacts, but some ecosystem services seem to respond in a linear fashion whereas others respond such that moderate levels of disturbance increase the level of delivery of ecosystem services followed by a decline with serious levels of impact. In this regard the range of impacts studied at the Ekubo Estate were from unmodified to largely modified systems. It would have been useful to examine the response of wetlands over a greater range of impact scores. Nevertheless, the qualitative insights gained from this study suggest that with greater and greater levels of impact the delivery of ecosystem services would decline at increasing levels, such that wetlands seem fairly resilient to small impacts, but that as impacts increase the delivery of ecosystem services declines increasingly. Therefore, relationships C and D (Figure A1.1) prevail in wetland ecosystems.

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