Understanding spatial patterns of dispersal and deposition of fine sediment and adsorbed phosphates in the Wiesdrift Wetland on the Nuwejaars River, Cape Agulhas

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ABSTRACT

River catchments in agricultural areas are strongly influenced by runoff from cultivated or grazed fields, and nutrient loading of these fields can result in large quantities of nitrates and phosphates being transported to rivers in surface runoff. In intensively farmed areas, nutrient loading is often so high that large quantities of nitrates and phosphates are transported to streams in surface runoff. Within these areas, strips of natural riparian vegetation and wetlands are critical in providing nutrient uptake functions that can reduce the load entering streams. A wetland can be a source, sink or transformer of nutrients, where fine sediments such as silt and clay have the ability to store and trap considerable amounts of phosphorus through adsorption and precipitation processes. Therefore, the determination of phosphorus adsorbed to fine sediment is important in understanding the role and value of wetlands in agricultural landscapes, and is the main focus of this study.

The aim of the study is to evaluate an indicator-based approach, *WET-EcoServices*, to assess wetland sediment and phosphate trapping, through comparison with field survey data. The study focuses on spatial analysis and field survey of three Hydrogeomorphological (HGM) units classified for the Wiesdrift wetland on the Nuwejaars River, Cape Agulhas. The three HGM units are classified as: a floodplain wetland at the inlet of the system, a channelled valley-bottom wetland towards the middle part of the system and a floodplain wetland towards the outlet of the system. In-field observations were recorded for hydrogeomorphic and vegetation characteristics for each HGM Unit. AstroTurf mat sediment samples, grabbed channel bed and floodplain sediment samples were analysed for particle size and orthophosphate concentrations, while suspended sediment masses were recorded from three pairs of time-integrated sediment samplers located near the inlet, near the middle, and near the outlet of the wetland. Statistical analysis showed that orthophosphate concentrations are associated with fine sediment. Thus, the orthophosphate concentrations follow the distribution of silt on the Wiesdrift wetland.

The dominant vegetation along transect 2, at which the highest concentrations of orthophosphate was found, is occupied by *Typha capensis* and *Cyperus textilis*. The percentage of fine sediment (silt) ranged between 0-37%, where the remaining percentage was sand. There was also a significant positive correlation between orthophosphate concentration and silt (Spearman's rank-order correlation: $r_s = 0.692$, $N = 70$, $P < .001$). The largest total sediment amount was found at Outlet 1 and Outlet 2 in the HGM unit 3 of the Wiesdrift wetland, with a value of 0.653 g. Overall, orthophosphate concentrations ranged between 0 mg/kg and 31320 mg/kg within the Wiesdrift wetland. *WET-EcoServices* determines an average score for phosphate trapping from on-site indicators such as hydrological zones, vegetation structure and soil texture/permeability. The

dispersal of fine sediment and associated adsorbed phosphate is more complex than can be determined by a tool like *WET-EcoServices* because the tool captures the long-term mean conditions of a wetland system that determines the overall uptake of phosphates over extended time periods, thus future wetland assessments is recommended to take place over a longer period than this study. However, the field results of orthophosphate distribution are generally consistent with the findings from *WET-EcoServices*, further motivating for the use of the tool in wetland management applications.

DECLARATION

I declare that '*Understanding spatial patterns of dispersal and deposition of fine sediment and adsorbed phosphates in the Wiesdrift Wetland on the Nuwejaars River, Cape Agulhas'* is my own work, that it has not been submitted for any degree or examination in any other university, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name: Tashveera Jagganath **Date: 25/03/21**

Signed: ....

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Chapter 1: Introduction

1.1 Background of the study

Agricultural lands in river catchments contribute great amounts of rainfall to adjacent streams and rivers. In farm areas, like the Cape Agulhas region, high concentrations of nitrates and phosphates are known to contribute to nutrient loads in streams from surface runoff. Wetlands are critical in providing nutrient uptake functions that can reduce the load entering streams (Decamps *et al*., 2004).

Globally, wetlands have the ability to remove nutrients from water passing through the system through the uptake of nutrients for plant growth and microbial conversions (Verhoeven *et al*., 2006). Many studies (Johnston *et al*., 1990, Johnston *et al*., 1991; Zedler, 2003, Hogan *et al*., 2004) at the study site scale show that wetlands provide a service to improve the quality of water and give rise to rehabilitation and creation of wetlands (Verhoeven *et al*., 2006). Using the Cape Agulhas as a case study, the study place focus on spatial patterns of dispersal and deposition of fine sediment and adsorbed phosphates on the Wiesdrift Wetland.

Phosphorus (P) cycling in wetlands occur through several ecosystem components, which involves the interaction between soil and water (Figure 1.1). Atmospheric inputs of P are relatively low and most P enters a wetland from surface flow, either through flooding or runoff from adjacent terrestrial land. Abiotic processes of interaction include between wetland soil, sediment and water play a role in regulating the cycle of phosphorus (Reddy *et al.*, 2010).

Forms of soluble and insoluble P cycle through the environment at different rates and time, whereby phosphorus can occur as particulate P, dissolved P in the environment (Reddy and DeLaune, 2008; Mitsch and Gosselink, 2015). In wetlands, inorganic and organic particulate P is associated with clay particles and biological material including bacteria that has decomposed and vegetation. Dissolved inorganic P is considered readily bioavailable (i.e. orthophosphate, soluble reactive P), whereas dissolved organic P will need to be transformed to inorganic P for use by plants (Mitsch and Gosselink, 2015).

Wetland P retention capacities depend on both biotic and abiotic processes (Currie *et al*., 2017). Biotic processes include incorporation of P into vegetation, plankton, and microorganisms. Abiotic retention processes include sedimentation, accretion, adsorption onto soil surfaces, precipitation, and the exchange of P between the soil and the water column (Currie *et al*., 2017). A considerable amount of P carried into the wetland system is by a fine sediment such as clay, in which the phosphorous is adsorbed to clay particles and follows sediment pathways of sedimentation and resuspension and in which P predominantly occur as particulate phosphorus (PP) (Eastman *et al.*, 2010; Mitsch and Gosselink, 2015).

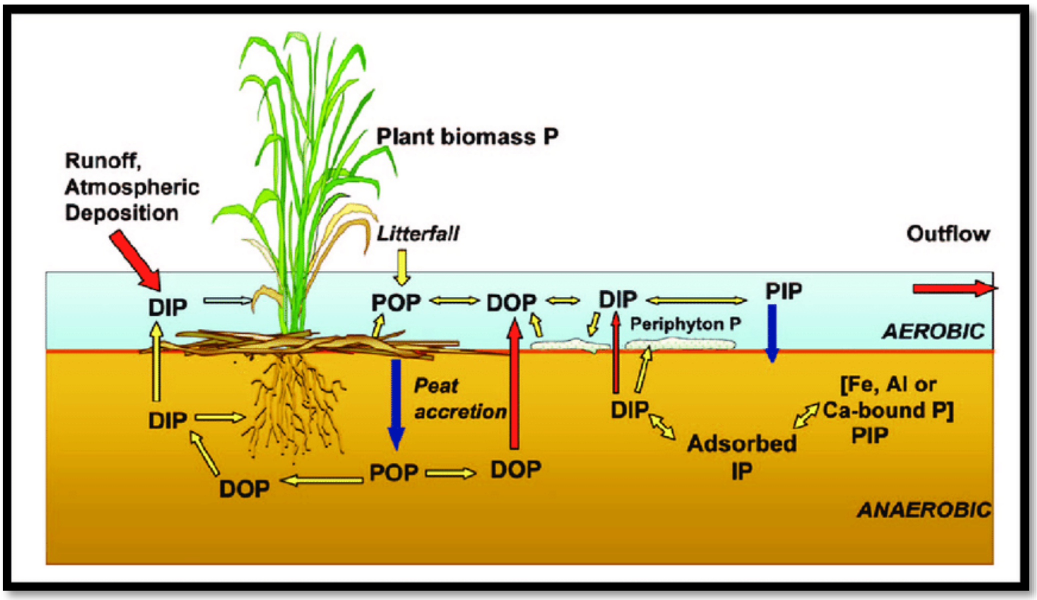


Figure 1.1: Showing the phosphorus cycle in a wetland system (Reddy *et al*., 2010).

1.2 Rationale

An estimation between 35-50% of wetlands are experiencing degradation in South Africa, most of these wetlands are highly threatened and not protected (Swanepoel and Barnard, 2007, Van Deventer *et al*., 2019). When South Africa's water resources are being examined, it is essential to identify that there is a link between water and other environmental processes such as evaporation and rainfall which then connect with surface water bodies (Swanepoel and Barnard, 2007). Therefore, wetlands play an important role in the cycle of water and are required to prevent ecosystems from deteriorating further (Swanepoel and Barnard, 2007; Kotze *et al*., 2009).

Sediments play a fundamental role in the aquatic ecosystem, in providing habitats for many aquatic organisms, such as areas for feeding, spawning and rearing (Wondim and Mosa, 2015). Therefore, the quality of sediment and associated sediment nutrients is important to understand and can further provide insight into restoration strategies for the biological integrity of water bodies, and the improvement of wellbeing for aquatic life and human health. In addition to water sampling, the need for sediment analysis is vital in evaluating qualities of the total ecosystem of a body of water (Wondim and Mosa, 2015).

Phosphorus cycling includes various transformations in the river system which converts phosphorus for plant growth and for microbial processes as well as phosphorus adsorption/desorption processes while sediment enters a river channel and settles on the river bed (Reddy *et al*., 2010).

Phosphorus and nitrogen is necessary for biological systems (such as increased crop productivity at a farm land). However, high levels of phosphorus and nitrogen can cause significant eutrophication of water bodies (Millennium Ecosystem Assessment, 2005). Another source of pollution may include the runoff of storm water surrounding areas in an urban setting, poor sanitation facilities in rural areas and the runoff of livestock manure to surrounding water bodies contribute to contamination of a river system/water body (US EPA, 2002; Millennium Ecosystem Assessment, 2005). The expansion of urban areas and agricultural practices has greatly increased the use of phosphorus in "excessive amounts" stressing aquatic ecosystems to the point of eutrophication (Howell, 2010).

Therefore, understanding how sediment-associated nutrients are spatially dispersed in relation to local hydrology and geomorphology is important (Lambert & Walling, 1987; Walling *et al.*, 2003; Middelkoop, 2005). In order to make decisions on how to properly manage and monitor wetlands in an ecologically sustainable manner, it is important to evaluate such wetland functions that control the exchanges of nutrients and sediments between rivers and adjacent floodplain wetlands. The following study will investigate the abiotic retention process of the Wiesdrift wetland's capacity to retain orthophosphate through the adsorption onto fine soil surfaces. It is important to understand how wetlands provides good and services to their surrounding communities (Malan and Day, 2005; Van Deventer *et al*., 2019). Many populations in South Africa directly depend on the ecosystem services that wetlands provide, which motivates for the development of tools, such as *WET-EcoServices*, that can help place a value on the benefits that wetlands supply to people in communities (Malan and Day, 2005). Malan and Day (2005) further add that indigenous knowledge of wetland functioning, benefits and wise uses need to be evaluated and preserved, thus motivates the use of *WET-EcoServices* in the study.

1.3 Aim

The aim of the study is to evaluate an indicator-based approach to assessing wetland sediment and phosphate trapping, through comparison with field survey data, using the Wiesdrift wetland at Cape Agulhas as a case study.

1.4 Objectives

- To classify hydrogeomorphic (HGM) units (refer to page 18 for definition), and document, describe and map spatial variation in hydrogeomorphic and vegetation characteristics across the Wiesdrift wetland, through spatial analysis and a field survey;
- To determine the spatial variation in sediment and adsorbed phosphate deposition across the HGM units identified above, through a field survey;

- To assess spatial variation in sediment and phosphate trapping across the HGM units identified, using the rapid assessment tool, *WET-EcoServices*, and;
- To compare and explain differences in the results of field survey and rapid assessment approaches.

1.5 Study overview

The overall purpose of the research is to assess the extent to which fluvial dispersal processes influence the spatial distribution of fine sediment and adsorbed phosphates across the Wiesdrift wetland, and how wetland characteristics influence the interaction between fine sediment and adsorbed phosphates across the wetland. It has been established that wetland-river interactions can be inferred from landform types, hydrological characteristics and hydrodynamics of a wetland (Ollis *et al*., 2013). This study aims to advance understanding of what is expected from a floodplain wetland in a dryland setting in terms of the wetland's ability to attenuate floods, trap sediments and adsorb phosphates. The extent of a wetland's ability to trap fine sediments is determined by the presence of vegetation and the fluvial dispersal processes for water and sediment across the wetland, among other factors (Ellery *et al*., 2010). In order to make decisions on how to properly manage and monitor wetlands in an ecologically sustainable manner, it is important to evaluate such wetland functions that control the exchanges of nutrients and sediments between rivers and the adjacent hydrogeomorphic (HGM) units.

Chapter 2: Literature review

2.1 Introduction

Chapter 2 provides a critical review of literature that informs the role of wetland hydrogeomorphology in sediment and associated phosphate assimilation, and the tools used to evaluate sediment and phosphate-associated wetland ecosystem services.

2.2 Wetlands

Wetlands are known to be one of the most biologically diverse and productive ecosystems supporting a wide variety of biodiversity (Tooth *et al*., 2015). In very large wetlands, such as river floodplains, internal spatial variation in characteristics, processes and species composition can be great (National Research Council, 1995).

Some or individual wetlands are directly associated with specific societal values, such as the attenuation of floods which acts as a function; and the seasonal storage of water which acts as a value. This association between a function of a wetland and the value of a wetland places importance on managing a wetland for its future wellbeing and the wellbeing of society in general (National Research Council, 1995).

Due to difficulties in describing wetland classification, there have been issues when comparing wetland types from one country with those in another country due to different classification systems that are used (Blackwell and Pilgrim, 2011). Many countries have national wetland terminology that are only understood by local wetland specialists in their country (Blackwell and Pilgrim, 2011).

Wetlands are areas that are occupied with water intermittently or continuously allowing for plant growth and biological activity on the wetland (Tooth and McCarthy, 2007; Millennium Ecosystem Assessment, 2005). At a global scale, wetlands are commonly found in humid regions, however, wetlands may also occur in drylands (Tooth *et al*., 2015). In dryland regions such as South Africa, wetlands are not expected to be primarily dependant on rainfall due to temporal variability and high evaporation rates in these areas. Instead, wetlands in drylands are commonly associated with close proximity to rivers, along with a combination of positive surface water balances (Tooth *et al*., 2015).

Wetlands have been recognized for various socioeconomic benefits that can be both direct (cultural and provisioning benefits) and indirect (regulating and supporting benefits). Direct benefits include: biodiversity conservation, water for human consumption and domestic use, water for agricultural purposes and recreational activities while indirect benefits include attenuation of floods, regulating the stream flow, trapping of sediment, assimilation of nutrients, erosion preventative measures and storage of carbon (Millennium Ecosystem Assessment, 2005; Kotze *et al*., 2009).

Despite such abovementioned wetland benefits, wetlands are still undergoing degradation in South Africa despite the existing legislation and national policies that have been implemented by government (Ellery *et al*., 2009, Skowno *et al*., 2019). The undergoing degradation is said to be as a result of anthropogenic land uses such as the conversion of natural wetlands into farmlands, eutrophication, sedimentation, filling, erosion, as well as natural influences that may be driven by geomorphic threshold behaviour or a response to Holocene climate change (Leberger *et al*., 2020). Therefore, it is important to assess wetland environmental systems in order to facilitate monitoring management and rehabilitation outcomes (Fischer and Acreman, 2004; Day and Malan, 2010).

2.3 HGM classification

Wetlands are divided based on each wetland's characteristic. Classifying wetlands provide an easier system for the management conservation practices (Jones, 2002). The hydrogeomorphic (HGM) approach to wetland classification is created based on the characteristics of wetland hydrology and geomorphology, and are regarded as two important drivers for precise wetland functions (Brinson, 1993; Ollis *et al*., 2013; Mitsch and Gosselink, 2015).

The hydrogeomorphic (HGM) unit and its hydrological regime highlights that inland aquatic ecosystems are strongly influenced by the HGM characteristics and the hydrological regime of the ecosystem (Ollis *et al*., 2013). HGM characteristics are interdependent (National Research Council, 1995), whereby HGM units are distinguished based on landform types (defines the shape and localised setting of the aquatic ecosystem), hydrological characteristics (describes the nature of water movement into, through and out of the aquatic ecosystem) and hydrodynamics (describes the direction and strength of flow through the aquatic ecosystem) (Ollis *et al*., 2013).

There are seven types of HGM units recognised for inland systems, and these are described as follows: river, channelled valley-bottom wetland, unchannelled valley-bottom wetland, floodplain wetland, depression, seep and wetland flat (Ollis *et al*., 2013). However, Kotze (2009) provides tools for the assessment of ecosystem services for the six HGM units provided in Table 2.1 (Kotze *et al*., 2009).

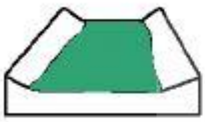
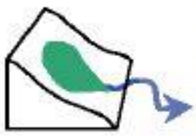
As in the case with all wetlands, the form of a particular floodplain depends upon the hydrological regime of influent waters and the local topography (Rogers, 1984). The hydrological regime describes the behaviour of that water within the system and underlying soil (Ollis *et al*., 2013). The hydrological regime directly affects its physical, chemical and biological characteristics and the overall functioning of rivers, wetlands and open waterbodies. Rivers are categorised according to their frequency and duration of flow, while wetlands are categorised according to their hydroperiod (Ollis *et al*., 2013). The decrease in flow rate of water moving onto the graded river course results in an accumulation of water, which results in overspills of river banks during high flow periods (Rogers, 1984).

According to Ollis *et al*. (2013), a floodplain wetland is a surface formed by alluvial river deposits that are found along river terraces. These terraces can become flooded overtop during a moderate peak flow event. Ollis *et al*. (2013) describes a channelled valley-bottom wetland as a wetland with a river channel running through it, with distinct floodplain wetland characteristics. By default, wetland areas adjacent to river channels in the lowland river zone or the upland floodplain river zone should be classified as 'floodplain wetlands'. On the other hand, wetlands that experience periodic inundation due to overtopping of the channel bank should be classified as 'channelled valley-bottom wetlands'.

In the absence of long-term hydrological records (as is common in non-perennial systems), soil morphology and vegetation can be used as indicators of the hydrological regime of a wetland (Ollis *et al*., 2013). Soil morphology characteristics indicate long-term hydrological conditions, while vegetation within a wetland indicates recent conditions (Ollis *et al*., 2013).

Wetland vegetation groups (e.g. National Freshwater Ecosystem Priority Areas Wetland Vegetation Groups) can be used as a spatial framework for the classification of wetlands at a national and regional scale, and conservation planning and wetland management initiatives (Ollis *et al*., 2013). When delineating a wetland, vegetation indicators can be described as the group of plant species that dominate the plant community and are used to identify different wetland types (Bedford *et al*., 1999; Collins, 2005). This method is supported and carried out by wetland specialist in the United States, whereby dominant plant species are used to characterise wetland classification (Cowardin *et al*., 1979).

Table 2.1: Wetland hydrogeomorphic (HGM) types typically supporting inland wetlands in South Africa (Kotze *et al.,* 2009).

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 with a channel		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 without a channel		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 channel		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.	*/ ***	*/ ***

Water source: *	Contribution usually small	
***	Contribution usually large	 Wetland
*/ ***	Contribution may be small or important depending on the local circumstances	
*/ ***	Contribution may be small or important depending on the local circumstances.	

2.4 Sediment distribution

Variations in the quantity and quality of sediment deposited in the floodplain are a result of local factors, such as flood characteristics, distance to the channel, sediment load, sediment texture, water velocity, floodplain morphology, vegetation cover on the floodplain and wind erosion (Knighton, 1998; Hupp, 2000, Datry *et al*., 2014, Mitsch and Gosselink, 2007, Ellery *et al*, 2010; Rogers, 1984).

2.4.1 Flood characteristics

The amount of water in the system of non-perennial rivers can impact concentrations of chemical constituents and physical variables in the river, such as the concentrations of solutes (salts, toxins), nutrients (Von Schiller *et al*., 2011) and water temperature (Russouw *et al*, 2005; Day *et al*., 2019).

When the streamflow of a river is reduced, sediments settle in the river channel. This reduced streamflow may cause a change in nutrient levels since nutrients can desorb into the water column (Day *et al*., 2019; Mosley, 2015). According to Day *et al*, (2019), lowered concentrations of dissolved nutrients (during the drying phase of the hydrological cycle) would be as a result of low levels of surface run-off, increased microbial activity due to longer residence times of the water.

Kaase and Kupfer (2016) states that the amount of sediment delivered to a wetland depends on how muvh water usually flows between the river and the floodplain wetland. Sources of sediment nutrient in the wetland system may be from sediment from stream and river channels that are either dissolved in water or/adsorbed onto fine sediment such as silt (Phillips, 1989). Hupp *et al*. (2009) states that floodplains that receive significant streamflow tend to receive large amounts of nutrients and toxins accompanied with sediment. Floodplains may be at risk to excess sediment if fluvial processes within a river system was altered by human activity, e.g., dam construction and channelization (Hupp *et al*., 2009). And as a result, the long-term impacts from such human activities is poorly understood and perhaps also under appreciated as floodplain sediment trapping is essential (Hupp *et al.*, 2009).

Tsheboeng *et al*. (2014) had studied the influence of hydroperiod variation on soil nutrient content in the Okavango Delta seasonal floodplains. Soil samples that were collected from zones of homogenous vegetation cover after low and high floods and analysed for pH, Na, Mg, Ca, K and P content. The findings concluded that Na, K, Mg, P and pH levels in soils were significantly different after comparing low flood data with high flood data (Tsheboeng *et al*., 2014). Tsheboeng *et al*. (2014) found that P content was significantly higher in all zones after high flood than after low flood. Flooding depth and duration increased in all vegetation zones during high flood.

Lambert and Walling (1987) findings support that of Kaase and Kupfer (2016), in which they compared floodplain and storm sediment in order to investigate deposition within the lower reaches of the River Culm in the United Kingdom. Their findings showed that fine sediment derived from suspended sediment are located further down of the study reach than that of course sediment. Lambert and Walling (1987) stated that more than 50% of clay were found during inundation, while silt and sediment deposited on the floodplain exceed suspended sediment by 17%, showing that nutrient and contaminants are far greater in deposited sediment than in suspended sediment. The differences in particle size, such that nutrient and contaminant concentrations in sediment are particle size dependent and are frequently higher in the fine silt and clay fractions.

Nicholas and Walling (1997) modelled flood hydraulics and overbank deposition rates and deposit grainsize distribution rates on river floodplains. The model is shown to predict complicated floodwater inundation sequences and patterns of suspended sediment dispersion and deposition, as a product of topography of the floodplain. They found that the hydraulic patterns affect overbank deposition amounts by controlling the frequency of inundation and the magnitude of local suspended sediments concentrations. Whereby, high concentrations of suspended sediments and bank deposition were strongly influenced by longitudinal convective currents. Whereas, low concentrations of suspended sediments were strongly influenced by diffusive mechanisms (where convective currents are weak).

Gretener and Strömquist (1987) conducted a study, on the recent deposition in the lower river, in which the present sedimentation rate and observed spatial variation in deposition were estimated using sediment traps. Estimation was based on total deposition in the area by comparing upstream and downstream transport data, through the use of Sundborg's sedimentation formula (based on particle size) and by observing sedimentation on sediment traps. Gretener and Strömquist (1987) found that deposition in the area was between 115-375 tonnes, in which sedimentation along the profiles displayed a lateral grain size differentiation typical of sedimentation by overbank deposition in a low gradient river and a spatial variation in deposition.

2.4.2 Distance to the channel

Floodplain deposition is an important process of storage in cycling of sediment, nutrients and contaminants in river basins. Without artificial flood protection on the floodplain, sedimentation amounts tend to decrease exponentially with increasing distance to the river. This may be because at locations further away from the river channel, less sediment is available for deposition due to exhaustion of suspended matter (Thonon *et al*., 2007). In addition, the transportation of sediment may be lower due to the slower velocity of water further away from the source/river channel.

Kaase and Kupfer (2016) states that floodplains located directly along the Congaree and Wateree Rivers, were found to have the highest sediment accumulated. According to Kaase and Kupfer (2016), thicknesses and grain sizes of sediment should become finer with increase to distance in river channel. However, topography of the floodplain makes the understanding of flow patterns, sediment deposition rates and grain-size distribution more difficult to understand. These findings were supported by Pierce and King (2008).

Pierce and King (2008) found that heavier and coarser particles occurred closer to the river channel as fine sediment further away from the channel settle in slow-moving or standing water. The transport and deposition of sediment varied because of local factors, such as how frequent floods occur, distance to the channel, load and texture of sediment, velocity of water, morphology of the floodplain, and vegetation cover. Alluvial systems make it possible for sediment deposited in floodplains to be reworked over time, resulting in potential future river management problems (Walling and He, 1998; Pierce and King, 2008). These finding agree with other studies, but also recognize that how flood hydraulics and typography of floodplain interact with each other play a major role in sediment deposition on a floodplain (Pizzuto, 1987; Middelkoop and van der Perk, 1998; Grenfell, 2012).

In the lowland portion of Willow Slough (Florsheim *et al*., 2011), the residence time of fine sediment within the channel generally appears short (due to the increase in channel transport and the absence of surface roughness). Land cover and landform, such as vegetation, can cause backwater reductions in flow strength and promote sediment storage. Florsheim *et al*. (2011) states that by removing vegetation on Willow Slough channels will cause the deposition of fine particles to decrease. The dams were responsible for trapping silt sediment, until the dams were removed and winter storm flows transported the sediment through the system (Florsheim *et al*., 2011). Bank erosion, as a result of storms, contributed to carbon and metals from both upland and lowland areas Florsheim *et al*. (2011). The source of sediment is less likely to be from bed and bank erosion but from possible irrigation sediment from surface erosion of lowland fields (Florsheim *et al*., 2011). Florsheim *et al*. (2011) concluded that low-lying agricultural areas, like Willow Slough, are most likely to contribute to negative impacts of phosphorous and pesticides on agricultural areas.

2.4.3 Sediment load and texture

Fondriest Environmental, Inc. (2014) divides sediment from rivers into two parts: wash load (which contained fine suspended particles smaller than 0.062 mm) and bed material load. This amount of fine particles depends mainly what the river bed was composed of and how the bed material would be transported downstream. On the other hand, bed material load may move either as temporarily suspended load or as bed load. The rate at which sediments accumulate within a river system depends mainly on the amount of sediment available in the catchment and the linkage between the river channel and the catchment (Fondriest Environmental, Inc., 2014).

2.4.4 Water velocity

McCarthy (2000) defines a wetland's capability to impede flows would be much greater if the wetland was already flooded prior to a flood event (as opposed to a dry wetland), such as an HGM located in an area known for seasonal or permanent rain.

2.4.5 Floodplain morphology

The ability of wetlands to trap sediments is largely related to the velocity of water flowing from steeper catchments into gently sloping wetland basins, which results in deposition of sediment as velocity of water becomes reduced (Ellery *et al*., 2010). This is particularly the case for floodplains where sediment is trapped during both low flows (e.g. point bars present within meandering channels) 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 (Ellery *et al*., 2010). The load of silt and organic detritus carried by flood waters is a major factor determining floodplain topography (Rogers, 1984).

Given that the transfer of suspended sediment to, and its deposition on, the floodplain is affected by the interaction of channel and overbank flows, and that such interaction varies with channel planform, the deposition pattern may similarly be expected to vary with planform (Day *et al*., 2019). It may also therefore be transformed by engineering proceses, for example through channel straightening or through returning previously straightened channels to a more natural meandering state (Day *et al*., 2019). However, there is a lack of quantitative data on deposition patterns which can be used in the development of guidelines for channel engineering, floodplain management and the construction of mathematical sediment deposition models (Bathurst *et al*., 2002). Bathurst *et al.* (2002) conducted two experiments in concentrated sediment amounts were found along channel banks in a straight wide channel, while the 'berm' formed further from the channel during a larger flow. An experiment was conducted which showed that deposition occurred across a wide meandering channel on floodplains adjacent to such channels, with high levels of deposition downstream of the meander, just past the bend apex. Bathurst *et al*. (2002) states that these flume results match the real-world field data, whereby the results from Bathurst *et al*. (2002) followed the deposition pattern of fine sediments which describe near-bank deposition, in which particle size decreases as distance from the channel increases.

2.4.6 Vegetation cover

Vegetation plays an important role in the functioning of wetlands (Cronk and Fennesey, 2001). Wetland plants in substrate can be deficient in oxygen and as a result of a change in the chemistry of the soil (Cronk and Fennessy, 2001). Wetland plants are herbaceous plants, that can be found floating or submerged (e.g. water lilies), with many commonly known plants such as sedges and grasses to be emergent in wetland habitats. Wetland vegetation have the ability to slow the flow of water and improve water quality. The vegetation traps nutrients, pollutants, and sediments by "sequestering them in their tissues and generally they trap sediments in an anoxic environment where anaerobic bacteria reduce many nutrients to a gaseous form" (Cronk and Fennessy, 2001). Therefore, wetland plants play a vital role in providing a flood attenuation, avoiding the surplus nutrients to create a harmful environment for aquatic plants and animals as well as provide insight to the health of a wetland.

Vegetation plays a role in both the deposition of sediment and inorganic phosphorus, such as orthophosphate, on the wetland floodplain. Vegetation increases sedimentation through a combination of reduced turbulence and reduced water velocity (Braskerud, 2001). At low rates, preferential flow through the wetland may be created and result in the hydraulic efficiency to decrease (Fennessey *et al*, 1994). Braskerud (2001) found that clay content increased from inlet to the outlet because sediments coarse sediments settle first. Whereas, vegetation long/short-term uptake of inorganic phosphates, such as orthophosphates, depend on plant type and associated characteristics (such as age and nutrient status) (Rogers, 1983; Reddy *et al*,1999). Short term storage refers to "when the vegetation decomposes and long-term storage usually occurs when the phosphorus is trapped within the plant structure" (Rogers, 1983; Reddy *et al*., 1999).

The production of macrophytes enhances sedimentation, which as a result also enhances the removal of phosphates, and in addition, the removal of phosphates by sediment is greater in wetlands with low water velocities and high hydraulic roughness. This is as a result of low water velocity that equates to a longer suspension time, allowing for a higher amount of phosphorus to be adsorbed by the sediments due to factors such as biological uptake of phosphorus in the overlying water or temporary sediment adsorption (Rogers, 1983). Higher hydraulic roughness within a wetland allows for better opportunities for sedimentation to occur (Turpie *et al*., 2010).

Similarly, Lintern *et al*. (2018) found that land cover and land use influence how suspended sediment, nutrients and toxins are delivered from water bodies to the wetland. A decrease in channel and surface roughness can result in decrease in vegetation cover thus increasing delivery of suspended sediments. It was found by Lintern *et al*. (2018) that when surface roughness is decreased, overland runoff velocity, sediments and nutrients within surface flow will be lost by sedimentation or by biogeochemical processes before reaching the waterbody downstream.

Braskerud (2001) determined the influence that constructed wetland vegetation can have in order to retain soil particles from 'arable' land. Soil particle retention was measured using "water flow-proportional sampling systems at the inlet and outlet of the wetland, sedimentation traps, and sedimentation plates in four small constructed wetlands over a period of 5 years". Braskerud (2001) results show that macrophytes stimulate the retention of sediment by increasing the hydraulic efficiency once preferential flow of water is reduced. Braskerud (2001) concluded that vegetation causes a positive impact on sediment deposition and avoids sediments from becoming suspended again in the water column.

Malan and Notten (2003) wrote an article which states that "*Cyperus textilis* is found in the southern part of South Africa, from Piketberg in the Western Cape to southern KwaZulu-Natal, where it grows along river banks and streams, in pools, dams or marshes, in wet ravines and even in coastal wetlands and brackish estuaries". Voigt (2007) reported that "*Typha capensis* is synonymous with most large as well as small freshwater bodies". *Typha capensis* is found in perennial regions of South Africa, which can be identified as 'leafy aquatic plants' with 'distinctive velvety-brown flower-spikes' (Voigt, 2007). Bulrushes, found globally and locally, are most common in aquatic habitats that are occupied by either standing or slow-flowing waters. Marshes, stream banks, dams and lakes are most commonly inhabited by *Typha capensis* (Voigt, 2007).

2.4.7 Wind erosion

Weinan and Fry (1996) states that "the transport of eroded soil materials implies a process whereby the eroded soil material is entrained into and moved within the air flow by surface creep, saltation, and suspension". According to Roose (1996), "aridity of climate, soil texture, soil structure, state of the soil surface, vegetation and soil moisture are all factors that affect the extent of wind erosion". Wind erosion can take place in areas that experience high percentage of rainfall after a dry period (more than six months without rain). The vegetation of the area changes from savannah to steppe, with patches of bare soil and wind that travels at least '20 km/in or 6 m/s' over dry soils resulting in wind erosion. Roose (1996) states that "coarse sand and gravelly or rocky soils are also more resistant, since the particles are too heavy to be removed by wind erosion" while "loamy sand, rich in particles between 10 and 100 microns in size, is the most vulnerable soil to wind erosion, while clayey soil is much better-structured and more resistant to wind erosion". Soil that has organic matter, iron and free aluminium, lime on the surface will be prone to wind erosion. Roose (1996) also states that vegetation and crop residues play a role in decreasing wind-speed at ground level, while moisture in the sand allows for cohesion of sand and loam, temporarily preventing the soil from wind erosion (Roose, 1996).

The rate at which sediment can be transported by wind is dependent on the amount of sediment available, grain size, and lastly the strength of the wind. Vandenberghe (2013) states that "sediments may be deposited and reworked by alternating wind and water". The grain size of channel sediment depends on flow energy of the river within the channel, whereby the finer-grained sediment become settled suspension material (Vandenberghe, 2013). Depositional mechanisms may accompany aeolian transport and sedimentation. Vandenberghe (2013) found that when aeolian sediment is deposited in a lake, fine sediment begins to settle in the standing water of abandoned pools, resulting in high content of clay and fine silt sediment. Whereas, sand and coarse silt are derived from the bed transport sediment. Vandenberghe (2013) describes wind strength by "the circulation pattern of the surrounding air and includes both horizontal velocity and turbulent movements".

2.5 Phosphorus in the wetland ecosystem

2.5.1 Phosphorus cycle

Phosphorus is an important nutrient for the growth of plants and is commonly found as phosphate (Pradhan and Pokhrel, 2013; Mitsch and Gosselink, 2015). Phosphorus can be in the form of dissolved inorganic phosphorus (DIP), dissolved organic phosphorus (DOP), particulate organic phosphorus (POP) and particulate inorganic phosphorus (PIP) (Figure 1) (Mitsch and Gosselink, 2015). However, phosphorus is only known for being bioavailable in the form of DIP, also referred to as orthophosphates, and occurs in a sedimentary cycle rather than in gaseous cycles (Mitsch and Gosselink, 2015; Reddy *et al*., 1999, de Vicente, 2021).

Soluble reactive phosphorus (SRP) is often used as indicators of the biologically available phosphorus in the form of phosphates. Mitsch and Gosselink (2015) states that "dissolved organic phosphorus and insoluble forms of organic and inorganic phosphorus are generally not biologically available until they are transformed into soluble inorganic forms". The sorption of phosphorus onto clay particles requires negatively charged phosphates to bond to positively charged edges of the clay and substitute phosphate for silicate in the clay matrix (Mitsch and Gosselink, 2015). This is common in riparian and coastal wetlands where phosphorus enters the wetland through adsorption to the fine sediment that later either undergo sedimentation or resuspension making phosphorus available to wetland plants (Mitsch and Gosselink, 2015).

2.5.2 Phosphate distribution

The concentration of chemicals and minerals vary in runoff and streamflow is caused by the following factors: Groundwater influence, climate, geographic effects, streamflow/ecosystem effects and human effects (Mitsch and Gosselink, 2015).

2.5.2.1 Groundwater influence

In cases where soil and rock weathering occur, through dissolution and redox reactions, changes in chemical composition can cause a water flowing through fractures or formations to change chemical composition, thereby playing a role in how the sediment in the water react when reaching waterbodies downstream (Mitsch and Gosselink, 2015).

2.5.2.2 Climate

The quality of surface water depends on the climate in the area, which include precipitation and evapotranspiration (Mitsch and Gosselink, 2015). In regions that are dry, there is a high concentration of salts in surface water, as opposed to humid regions. Wetland vegetation is also dependent on the climate for the growth and plant cover within the wetland, with indirect influence on soil moisture and the ability for the soil to erode on the wetland (Roose, 1996; Mitsch and Gosselink, 2015).

2.5.2.3 Geographic effects

Depending on "size of the watershed, the steepness or slope of the landscape, the soil texture, and the variety of topography", wetlands upstream play a role in the quality of water downstream (Mitsch and Gosselink, 2015). Whereby, low concentration of eroded insoluble material found in dissolved substances in surface water, whereas in water passing through the ground are found to have a high concentration of dissolved substances and low levels of suspended material (Mitsch and Gosselink, 2015).

2.5.2.4 Streamflow/ecosystem effects

The National Research Council (1995) states that phosphorus is carried in "wetlands by precipitation, overbank flow from streams and movement of surface and groundwater". The quality of surface water in changes according to the seasons experienced in the wetland. In general, high streamflow tends to have a low concentration of dissolved material and a low streamflow tend to have a high concentration of dissolved material (Mitsch and Gosselink, 2015, de Vicente, 2021).

Once there is an increase in primary production of nutrients and decomposition, nutrient cycling is rapid (National Research Council, 1995). An example of such instances can occur when a wetland experiences a 'pulse hydroperiod' and as a result rainfall contributes to streamflow that does not meet with wetland soil and subsurface minerals. Where a wetland experiences a high flow, high concentrations of sediment can be found in surface water (Mitsch and Gosselink, 2015, de Vicente, 2021). In cases where water moves from the ground to the surface and contributes to streamflow, one would expect to find higher concentrations of dissolved materials and sediments.

Therefore, a wetland can be a source, sink or transformer of nutrients, and a wetland can perform different functions for different nutrients, in which the wetland can act as a sink for nutrients like phosphorus, nitrogen and organic carbon (National Research Council, 1995; Reddy *et al*., 2010).

2.5.2.5 Human effects

Sewage run-off, urbanization and runoff from agricultural land significantly modifies the chemical composition of streamflow and groundwater that reach wetlands by changing the concentrations of sediments and nutrients such as phosphorus and nitrogen (Mitsch and Gosselink, 2015, Stapanian *et al*., 2016). Higher concentrations of nutrients are expected from farmland runoff than runoff from urban areas.

2.5.2.6 Runoff from adjacent lands

As a result of human affects (Mitsch and Gosselink, 2015), the transfer of phosphorus occurs through surface runoff from agricultural lands that bound to sediment and dissolves in the water (Sharpley *et al*., 2003). Eroded soil and organic material during flow events are made up of about 80% of phosphorus (generally dissolved phosphorus) which was carried by surface runoff from agricultural land and bounded to sediment (Sharpley *et al*., 1992).

2.6 *WET-EcoServices* assessment

The wetland benefits included in *WET-EcoServices* (Table 2.2) are described by Kotze *et al*. (2009) to be "considered most important for South African wetlands, and can be readily and rapidly described". *WET-EcoServices* is a rapid assessment tool for determining the services wetlands supply to the ecosystem. The process of applying *WET-EcoServices* starts with characterisation of the wetland, based on interpretation of aerial imagery and individual desktop assessment (Level 1). Thereafter, a field assessment is conducted based on the 15 benefits and a list of characteristics that is relevant to a particular benefit. In turn, the user is able to identify any threats and opportunity to further enhance a benefit associated with the assessed wetland (Kotze *et al*., 2009). *WET-EcoServices* is designed specifically for inland palustrine wetlands (e.g. marsh or floodplain) (Kotze *et al*., 2009).

Kotze *et al.* (2009) states that *WET-EcoServices* aims to "assist decision makers, government officials, planners, consultants and educators in undertaking quick assessments of wetlands, in order to reveal the ecosystem services that wetlands supply", allowing for better decision-making and planning. Kotze *et al.* (2009) groups the assessed ecosystem services based on how effective it is in supplying a benefit to the wetland; and 'opportunity' for the wetland to supply an ecosystem service (Kotze *et al*., 2009).

Since this study was conducted using the *WET-EcoServices* version 1 (published in 2009), *WET-EcoServices* version two has been released with assessment techniques for non-riparian wetlands (not made available in version one) and some indicators/characteristics were replaced to assess more significant aspects of wetland characteristics (Kotze *et al*., 2020).

Table 2.2: Ecosystem services included in, and assessed by, *WET-EcoServices* (Kotze *et al.*, 2009).

				Ecosystem service	Description
Ecosystem services supplied by wetlands	Indirect benefits	Regulating and 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
	Direct benefits	Biodiversity maintenance[2]			Through the provision of habitat and maintenance of natural process by the wetland, a contribution is made to maintaining biodiversity
		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

2.6.1 Flood attenuation

The role that wetlands play in flood control varies with landscape setting and antecedent hydrological conditions. For example, wetlands located in upper reaches of some river basins can act as sponges through the absorption of rainfall, where water infiltrates into the soil, in turn decreasing the rate of runoff that flows into downstream waterbodies, but this depends on whether wetlands have the hydrological capacity to absorb rainfall prior to an event (Bullock and Acreman, 2003).

Vegetation and topographic setting of a wetland play an important role in flood attenuation (Kotze *et al*., 2009). The attenuation of floods 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 (Ellery *et al*., 2010). The presence of depressions and pore spaces in soil while the wetland is dry, result in wetlands being able to retain a large volume of water. Dense vegetation cover causes friction on the wetland surface which slows the passage of water through the wetland (Ellery *et al*., 2010). 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 from the stream without easily re-entering it (Ellery *et al*., 2010).

At the start of a season the soils on the floodplain become saturated, while later in the season flood attenuation capacities become reduced. Floodplains lower the rate at which runoff would flow from a floodplain area because water and its associated minerals and nutrients would be lost through evapotranspiration. However, phosphorus tends to be significant in trapping phosphate because the phosphate strongly bounds to fine particles (Kotze *et al*., 2009).

Floodplains have been useful flood management practices, such as in the case of the world's largest rivers, including the Mississippi (Bedinger, 1981) and Rhine Rivers (Baptist *et al*., 2004). It was also established that the degree of attenuating a flood along a river is related to the channel size, roughness of river bed and the sinuosity of the river channel (Rameshwaran and Willets, 1999).

Channelled valley-bottom wetlands are characterized by narrow, steep gradient channels, with low amounts of sediment deposition and are therefore expected less of trapping sediment and attenuating floods (Kotze *et al*., 2009).

Floodplain wetlands move water over the banks causing water to spill over a lower gradient area, which prevents floodwater to reach channel capacity (Williams *et al*., 2012; Rogers, 1984). Floodplains are known to receive input of water from either surface water or groundwater. Surface water includes rivers and usually water from a river source, as a result of overbank flow after a flood event, and will often inundate floodplains intermittently. The water that travels from a river channel to the floodplain becomes temporarily stored on the rough floodplain surface. This surface is occupied by a complex of depressions, pools and old river channels that are accompanied by hydric soils (Williams *et al*., 2012). The stored water then may be released to a low gradient area located on an adjacent plain. It is reported that the flood attenuation on floodplains will vary hydrologically (water levels) and physically (gradient, surface area, hill slope) across different wetlands systems. In addition, a floodplain that is characterised with both high vegetation cover and soils that are not saturated will help in temporary storing water while large rates of evapotranspiration will also potential play a role in reducing catchment runoff (Williams *et al*., 2012).

A case study (Ellery *et al*., 2010) assessed wetlands on the Ekubo estate by using the *WET-EcoServices* tool to further understand the relationship between human impacts and the delivery of ecosystem services by wetlands within the estate. The Ekubo estate was located on the South coast of KwaZulu-Natal and was highly favourable to the presence of wetlands, whereby a single HGM Type (unchannelled valley-bottom wetlands) was represented by 9 HGM units. The wetlands had been subject to excavation of drains to make the wetland areas suitable for growth of sugar cane. The case study placed focus on only indirect ecosystem services ("Flood attenuation, Streamflow regulation, Sediment trapping, Phosphate trapping, Nitrate removal and Toxicant removal"). Based on the *WET-EcoServices* results for the Ekubo estate wetlands, the study concluded that the valley-bottom wetlands assessed were 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. In terms of the results for sediment trapping within the Ekubo estate wetlands, it was found that 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 (Ellery *et al*., 2010). However, 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 (Ellery *et al*., 2010).

In the case of phosphate trapping within the Ekubo estate wetlands (Ellery *et al*., 2010), it was concluded that the function of phosphate trapping within wetlands is similar to its sediment trapping function, in which phosphorus may be adsorbed to sediment, or it may be present in a dissolved form and be taken up by plants or involved in sorption reactions with soil or organic matter depending upon geochemical circumstances. Nonetheless, the large proportion of diffuse flow associated with valley-bottom wetlands made the assessed HGM type 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. Therefore, the study found that floodplains are considered to be less effective than valley-bottom wetlands in carrying out this function.

Verhoeven *et al*. (2006) evaluated the how wetlands were used in water quality management agricultural catchments and how nutrients were stored in wetlands contributing to 'nutrient overloading'. Verhoeven *et al*. (2006: p102) found that the potential for wetlands to improve the quality of water in surface water systems is only recognized "in catchments with a minimum area of wetlands relative to total catchment size". Verhoeven *et al*. (2006: p102) concluded that it is important to maintain a good water quality standard by ensuring that '2-7%' of a catchment be occupied by a wetland habitat. It was suggested that in order for a desired level of environmental quality to be met, the use of fertilizers need to be reduced, rehabilitation of wetlands need to be made a priority based on significant hydrological research.

2.6.2 Sediment trapping

The trapping of sediments by wetlands is largely related to the velocity of water flowing from steeper catchments into gently sloping wetland basins, which results in deposition of sediment as velocity of water becomes reduced (Ellery *et al*., 2010). This can be observed for floodplains where sediment is trapped during both low flows (in point bars present within meandering channels) 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 (Ellery *et al*., 2010). The load of silt and organic detritus carried by flood waters is a major factor determining floodplain topography (Rogers, 1984).

The amount of water passing through a non-perennial river influences the temperature of water and the amount of chemicals, nutrients and toxins (Rossouw *et al*., 2005; Von Schiller *et al*., 2011; Datry *et al*., 2016). When turbulence slows down due to a slow flow of water in the river channel, nitrogen and phosphate concentrations decrease. This occurs while the river system experiences a dry period, whereby surface run-off is little to none, denitrification processes take place via plants and algae (Mosley, 2016).

Similarly, river banks in reservoirs tend to become dry in areas experiencing a semi-arid climate. Once flood gate are open, nitrogen, phosphate and carbon become wet again and begin to mineralize/dissolve back into flowing water (Gunkel *et al*., 2015). Therefore, one can expect high concentrations of solutes and suspended sediments once water flows through the river system after a dry period (Datry *et al*., 2014). However, once flooding begins again over a dry, accumulated sediment can be lost from the non-perennial river due to high velocity of water passing through the channel (Powell *et al*., 1996).

2.6.3 Phosphate removal by wetlands

The ability of a wetland to remove/retain phosphate is based on various wetland characteristics and processes (such as sedimentation, adsorption of phosphate by soil and plant uptake of phosphorus) (Uusi-Kamppa *et al*., 2000; Havens *et al*., 2004). Such processes are either microbial-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 (Ellery *et al*., 2010). Some case studies reported that there was a 'positive correlation' between nutrient concentration (such as nitrogen and phosphorus) in rivers located in Finland and Southern Ontario (Sliva & Dudley, 2001; Varanka *et al*., 2015; Lintern *et al*., 2018).

Long term and short term storage of phosphate plays a role in how phosphate will be used by soil/organic matter and vegetation. Phosphate may become adsorbed to fine sediment, transform to dissolved phosphate in flowing water or remobilize to downstream water bodies as long-term storage (Rogers,1983; Richardson, 1985; Reddy *et al*., 1999). In cases where phosphorus is taken up by plants to maintain plant growth, particulate phosphorus need to undergo transformation so that it is made available to plants. The particulate phosphorus becomes adsorbed to sediment particles, preventing an extreme state of eutrophication (Maynard *et al.*, 2009, Li *et al*., 2013).

Beven *et al.* (2005) stated that the movement of sediment on hill slopes may be very dependent on the how much or how often rainfall occurs over a catchment, and sediment fluxes may be both supply limited and transport limited. It is rare, however, that any consideration is given to magnitude/frequency characteristics in the delivery of nutrients to stream channels, partly because there are only a few studies where adequate measurements of storm-related concentrations are available over sufficiently long time periods (Beven *et al*., 2005). This may be an important controlling factor for delivery of both particulate and dissolved P (Figure 2.1).

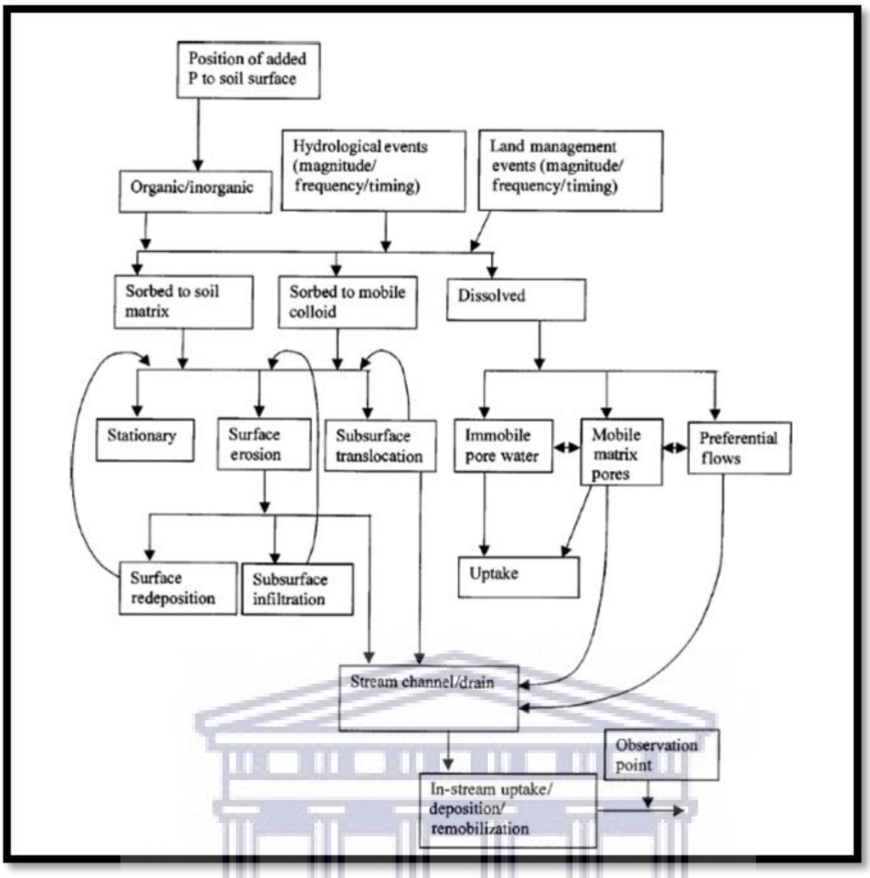


Figure 2.1: Pathways of P delivery to stream channels (Beven *et al*., 2005).

Wetlands are known to be constructed in agricultural areas because of their ability to maintain phosphate and sediment that are transported from the surrounding catchment (Geranmayeh *et al*., 2018). Sediment deposition describes the settling of sediment particles on the wetland bed and tends to increase with velocity of water lowers, increasing water retention in wetlands. Therefore, sedimentation rates are expected to be much higher in larger wetlands (Geranmayeh *et al*., 2018). However, small wetlands, such as in Norway, found in large catchments tend to have a low ability to remove sediments as a result of a high hydraulic load. The sediments from the small catchments become resuspended and transported downstream. Wetlands in Norway are often constructed downstream of agricultural developments to prevent sediment and nutrient loss in an attempt to avoid any possible negative impacts these pollutants may have on the quality of the lake waters downstream (Sveistrup et al., 2008; Figure 2.2).

Excessive amounts of phosphate transported via runoff from adjacent agricultural lands may cause a limitation to growth of freshwater ecosystems. Freshwater ecosystems become altered as eutrophication takes place, changing how the ecosystem functions (Maynard *et al*., 2009). McDowell *et al*. (2001) suggests that management practices are important to address the problems faced from excess phosphorus meeting water bodies, as these areas will soon become a ‘critical source area’.

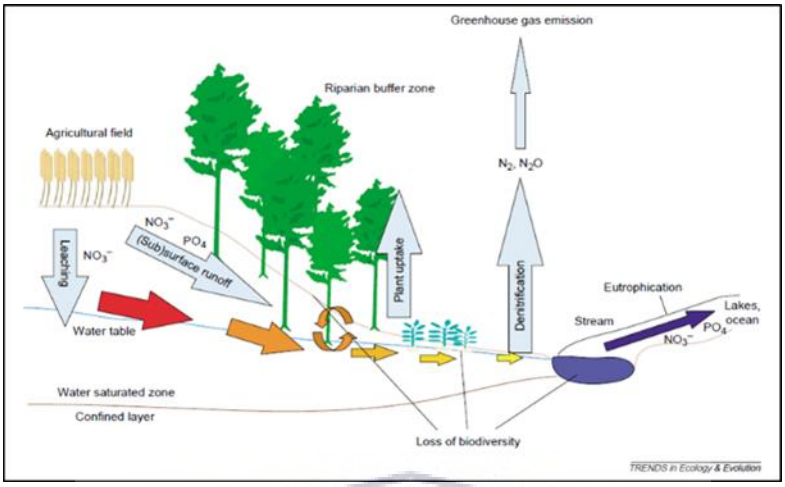


Figure 2.2: Cross-section of a riparian wetland showing hydrological fluxes, nutrient processes and environmental impacts of nutrient loading. Thicker arrows with warmer colours indicate a higher nutrient loading rate (Verhoeven *et al*., 2006).

2.7 Qualitative and quantitative assessment

Due to how costly environmental monitoring can become, a need for simple and efficient monitoring methods were required (U.S. EPA, 2008). In the recent years, several methods, such as complex gravimetry, colorimetry, spectrophotometry, atomic absorption spectrometer, flow-injection spectrophotometry, ion chromatography and also HPLC, have been developed to monitoring the phosphate levels in the natural water. Some of these methods offer disadvantages such as requiring complicated and expensive equipment and few of these are also involving the extraction procedures, thus limiting the practice method in the common laboratory (Habibah *et al*., 2018).

Phosphate determination by the molybdovanadate method determines phosphate directly as orthophosphate/reactive phosphorus (Pradhan and Pokhrel, 2013). The phosphate determination by molybdovanadate method in conjugation with the use of a UV-visible spectrophotometer. This method is simple to carry out and can be done in the laboratory. Pradhan and Pokhrel (2013) describes the method as a combination of reactive phosphorus and molybdate to create a ‘phosphomolybdate complex’. This mixture then reacts with the reagent to form a ‘vanadomolybdophosphoric acid’. The phosphorus concentration can be identified according to how intense the yellow acid looks to the naked eye. The method is simple and cheap compared to other methods, and does not require a long reaction time. The method is based on Lambert-Beer's law, in which the concentration of phosphate can range between 0.1-11 ppm (Pradhan and Pokhrel, 2013).

In terms of wetland assessment, rapid methods require is cost saving and provides a fast method of acquiring data for sample collection and data analysis (Fenessey *et al.*, 2007). Furthermore, there is also a developing appreciation for wetlands and important role it has in South Africa (Malan and Day, 2005). Many populations in South Africa directly depend on the ecosystem services that wetlands provide, which motivates for the development of tools, such as *WETEco-Services* (Malan and Day, 2005), thus motivates the use of *WETEco-Services* in the study for further understanding of the wetlands ability to trap sediment and adsorbed phosphate.

2.8 Conclusion

While there are studies on floodplains in drylands, previous literature found that there is an importance for further research in wetland ecosystems, most pertaining to sediment and nutrient dispersal and deposition in wetland systems and for non-perennial rivers. Therefore, this study will focus on three ecosystem services, namely flood attenuation, sediment trapping and phosphate trapping that play a role in the distribution of phosphate within a wetland system.

Chapter 3: Study area and methods

3.1 Introduction

This chapter provides a detailed description of the study area and methods that were used for data collection and data analysis.

3.2 Study area

3.2.1 Study area description

The Wiesdrift wetland is found within the Cape Agulhas region (Figure 3.1) of the Western Cape, South Africa. The Wiesdrift wetland can be described as a seasonal floodplain wetland of the Nuwejaars River, located approximately 150 km east of Cape Town. The Nuwejaars River originates in the Bredasdorp Mountains, north-east of Elim and flows in a south-easterly direction, approximately 25 km from Elim, into the Soetendalsvlei (one of South Africa's largest freshwater coastal lakes), and flows out as the Heuningnes River to the Heuningnes estuary at De Mond, a protected Ramsar wetland site (i.e. The Convention on Wetlands of International Importance, more commonly known as the Ramsar Convention) (Russel and Impson, 2006). The Nuwejaars River can be described as a seasonal, non-perennial stream that receives high flows during the wet winter season between May and August and low to no flows in summer between October and April, with longer periods of no flow associated with meteorological droughts. The river begins to meander as it moves from its upper reaches to the lowlands of the Agulhas Plain, forming large floodplain wetlands such as the Wiesdrift wetland system with an average elevation of 11 meters above sea level.

3.2.2 Local climate

The study area experiences a Mediterranean-type climate, characterised by hot dry summers (temperatures ranging between 20-30°C) and cold wet winters (temperatures ranging between 12-18°C). The annual average rainfall for the catchment ranges between 400 mm/year in the east to 500 mm/year in the west (Herdien *et al*., 2005). Rainfall is higher on the south faces of the headwater mountains than on the north facing slopes as a result of rain-bearing winds that move from the west or south west (Bickerton, 1984). Annual evaporation is about 1445 mm (Middleton and Bailey, 2005; Bailey and Pitman, 2016).

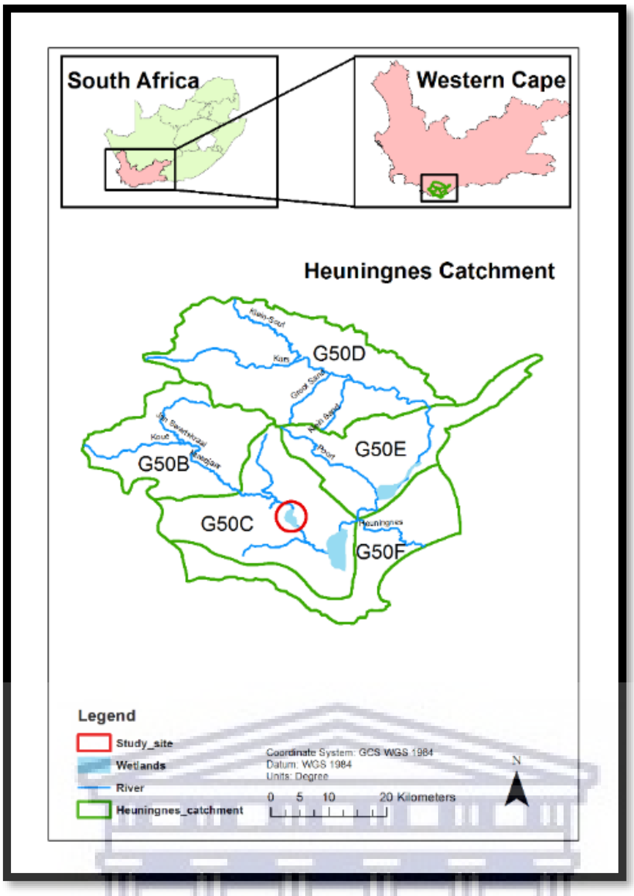


Figure 3.1: Study area within the Heuningnes Catchment.

3.2.3 Geology

The Heuningnes Catchment (Figure 3.2) is characterized by undulating topography in the northern part while the southern and south-eastern areas are predominately gently sloping areas. Surface water drains towards the coast in the south from areas of high elevation to areas of lower elevation. The Malmesbury Group and Cape Granite Suite are local basement rocks and are overlaid by the Table Mountain and Bokkeveld Groups. The coastal mountains of the Nuwejaars River Catchment comprise of Cape Fold Belt Table Mountain Group sandstones and quartzites. At the foothills of these mountains are undulating surfaces mainly made up of Bokkeveld Group shales (Bickerton, 1984; Johnson *et al*., 2006).

The Agulhas Plain occupies the geomorphic province, Southern Coastal Lowlands. Around Arniston and Stilbaai, karstic deranged drainage pattern (which lies on soluble marine limestone) are found to have numerous enclosed hollows have been produced by solution weathering (Partridge *et al*., 2010).

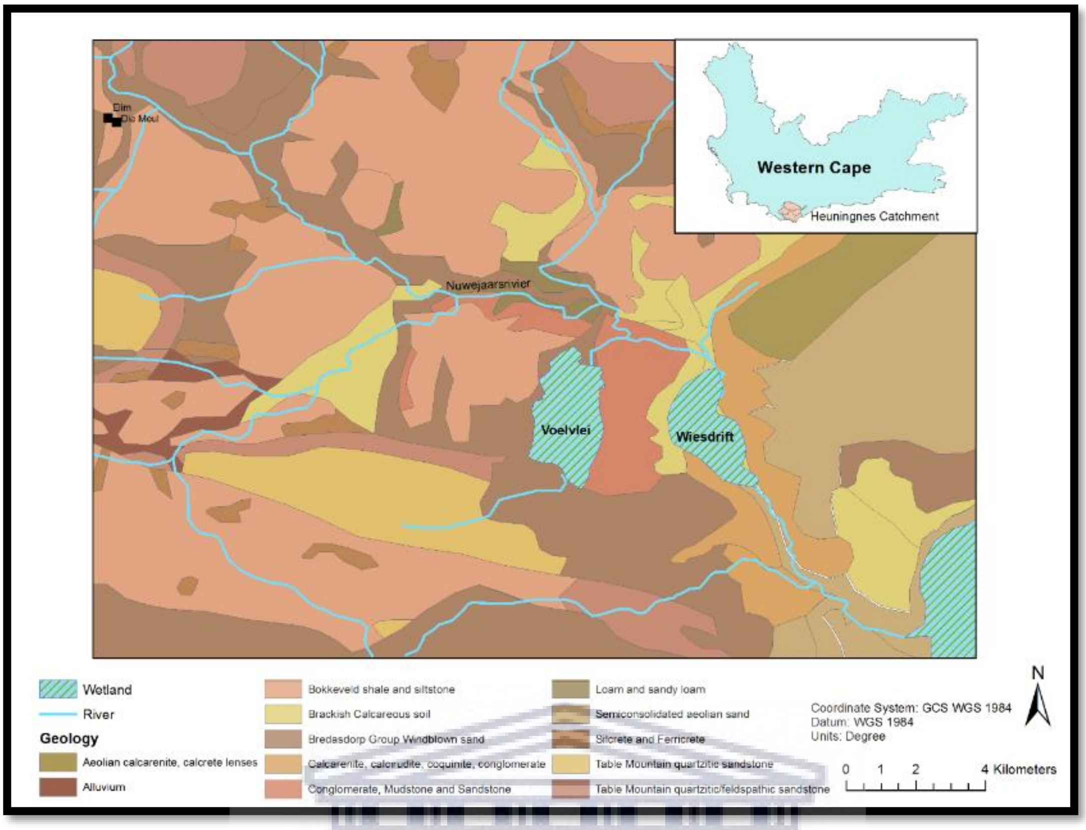


Figure 3.2: Geology associated with the Wiesdrift Wetland.

3.2.4 Drainage pattern

The Heuningnes catchment has one major river known as the Heuningnes River, which is fed by two tributaries; the Kars River and the Nuwejaars River (Figure 3.3). The present study places a focus on the Nuwejaars River. The Nuwejaars River has five tributaries namely the Koue, Wolwegatskloof, Jan Swartskraal, Boskloof and Uintjieskuil (Bickerton. 1984). When the Soetendalsvlei Lake overflows, it then confluences with the Kars River downstream, in turn forming the Heuningnes River. The upper segments of the Nuwejaars and the Kars River have been identified as priority rivers for conservation purposes (Heirden *et al*., 2005; Nel *et al*, 2011; Skowno *et al*, 2019). Water quality is considered to be better in the headwaters than the quality of water downstream (River Health Programme, 2011). Wetlands are commonly found along the Nuwejaars River, which are linked to adjacent streams. The development of the wetlands is partly due to the low gradient of the area. Some smaller ephemeral pans in the lower part of the Nuwejaars River are mostly fed by small local channels and are usually flooded during winter rainfall but dry up during summer.

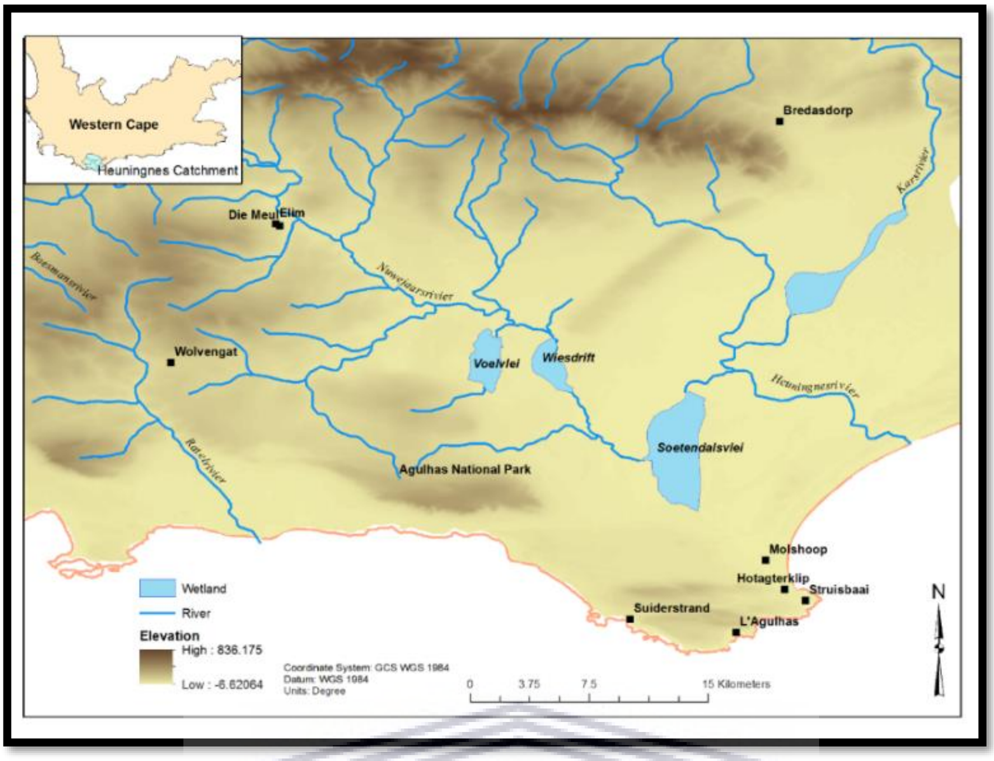


Figure 3.3: Study area showing the associated rivers, wetlands and towns.

3.2.5 Vegetation

Some parts of the catchment (Figure 3.4), such as Jan Swartskraal have been invaded by various alien *Acacia, Eucalyptus* and *Pinus* species, and as a result have led to the farmers in the Jan Swartskraal catchment attempting to rehabilitate the lands by clearing invasives and replanting natural fynbos. Mountainous regions in the northern part of the catchment are largely covered by natural fynbos and invasions of woody alien vegetation which decreases downstream. The Elim and Voëlvlei regions are largely covered in natural fynbos. Moderately tall, dense restioid, ericoid-leaved and proteoid shrublands are supported by the low mountains, undulating hills and moderately undulating plains on deep acid sands overlying Table Mountain sandstones near Elim (Rebelo *et al*., 2006). Fragmented outliers of the shale renosterveld are found on the southern part of the Agulhas Plain between Soetendalsvlei and Waskraalsvlei. Moderately undulating plains and pans in the southern part of the Agulhas Plain are surrounded by medium dense cupressoid and small leaved, low to moderately tall grassy shrubland, usually dominated by renosterbos (Rebelo *et al*., 2006).

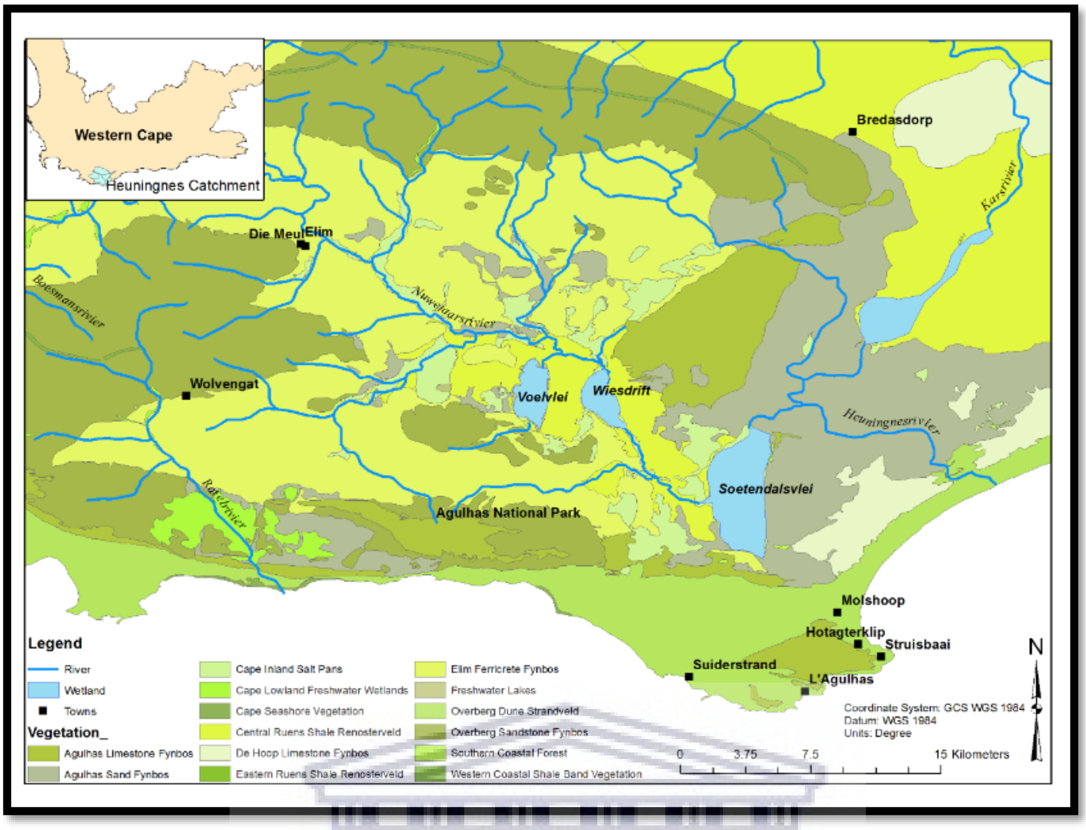


Figure 3.4: Map showing vegetation in the study area (National vegetation types from Vegetation Map of South Africa, Lesotho and Swaziland, 2012; Dayaram *et al*, 2017).

3.2.6 Land use

Most of the catchment (Figure 3.5) is used for pastures, cattle farming, raising of livestock, livestock grazing and crop farming such as wheat and canola. A dairy farm is located close to the town of Elim (Figure 7) and is found on the bank of the lower part of the Nuwejaars River, just downstream of the Wiesdrift floodplain wetland (Dayaram, *et al*., 2017). Currently 23ha of irrigated pastures is in use (Nieuwoudt, 2010).

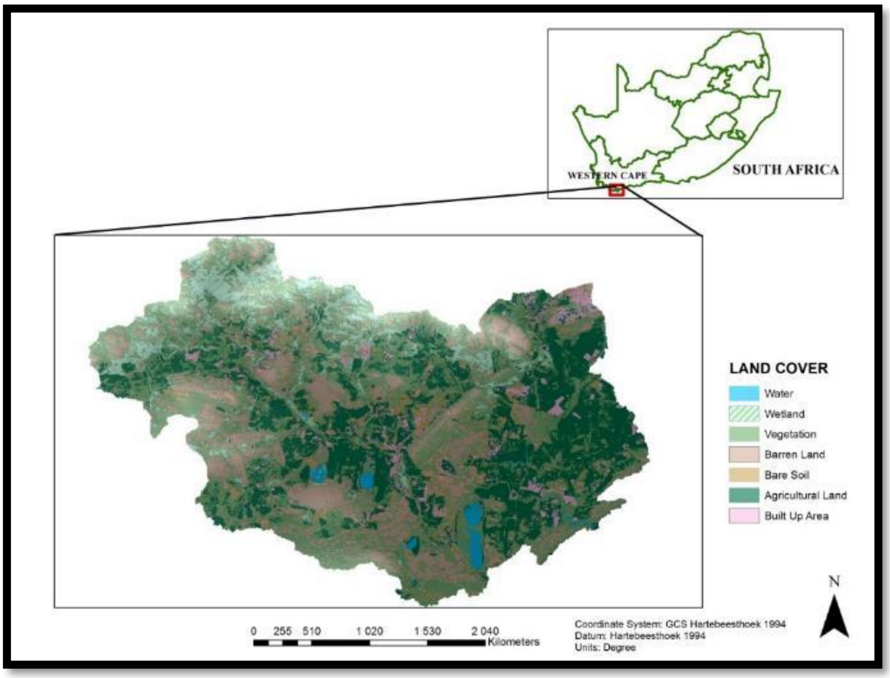


Figure 3.5: Showing the land use of the catchment (South African National Land Cover (SANLC), 2018).

3.3 Data collection

Data collection methods include those supporting a *WET-EcoServices* assessment, as well as field campaigns and laboratory analysis for sampling and measurement of associated P concentrations.

3.3.1 Wetland assessment using *WET-EcoServices*

While there are a number of previously developed tools used to assess wetland ecosystems, none of these were directly transferable to South African environments (Kotze *et al*., 2009). Many of the previous wetland functional assessment techniques were developed according to wetlands situated in more developed parts of the world. *WET-EcoServices* provides an assessment tool in agricultural settings, where it is important to understand the regulatory role of wetlands in water quality (Kotze *et al*., 2009). The data collection includes the assessment of the Wiesdrift wetland by using the *WET-EcoServices Tool.*

3.3.1.1 *WETEco-Services* desktop survey

The desktop assessment (also known as Level 1) includes the classification of the Wiesdrift wetland according to the HGM type (Brinson, 1993) based on geomorphic setting and patterns of flowing water through a wetland (Macfarlane *et al*., 2009). The HGM classification is based on information found on aerial photographs and topographic maps (Kotze *et al*., 2009). Floodplains are characteristically associated with attenuation of floods and the trapping of sediments (Kotze *et al*., 2009). The National Wetland map 5 data (van Deventer *et al*., 2019) was considered, but needed improvement to inland wetlands and therefore the reason for delineating the Wiesdrift Wetland as a study site.

3.3.1.2 *WET-EcoServices* field assessment

The field assessment (also known as Level 2) is carried out to ground truth information that has been observed during the desktop survey. The field assessment of the wetland is based on a number of characteristics of the hydrology, geomorphology and vegetation (Kotze *et al*., 2009). The assessment is categorised between a catchment unit, on-site features and on-site users of provisioning and cultural services. The assessment of the Wiesdrift Wetland only focused on the first two categories, catchment unit and on-site features.

3.3.2 Collection of sediment samples for orthophosphate analysis

Floodplain deposited sediment was collected using AstroTurf mats over one wet season (view Figure 3.7 for sample locations). The AstroTurf mats collected following field deployment were left to air-dry and the mass of each usable mat was recorded. Samples were collected following a stratified sampling approach along six transects oriented perpendicular to the wetland thalweg. Ten Astroturf mats were installed on each transect to sample flood deposition over the 2018 wet season. In addition, surface sediment samples were collected at each mat installation site using an Eijkelkamp gauge corer. River suspended sediment was sampled in the river channel at the inlet, middle and outlet of the wetland using time-integrated pipe suspended sediment samplers, installed at a height above the bed equal to 0.4 bank-full flow depth (Phillips *et al*., 2000). These samplers do not provide information on suspended sediment concentrations, but provide a measure of the relative difference in fine-sediment throughput at different points within the wetland, and thus a measure of whether sediment is being retained within the wetland. Cross-sections were surveyed across the Wiesdrift floodplain wetland for each HGM unit using a Differential Global Positioning System (DGPS) (see Figure 3.6). The cross sections describe the connectivity between the river structure and the floodplain. It is understood that connectivity between channels and adjacent floodplains prevents movement between each other, therefore playing a role in altering the transport of material within a river system (Fryirs *et al*., 2007).

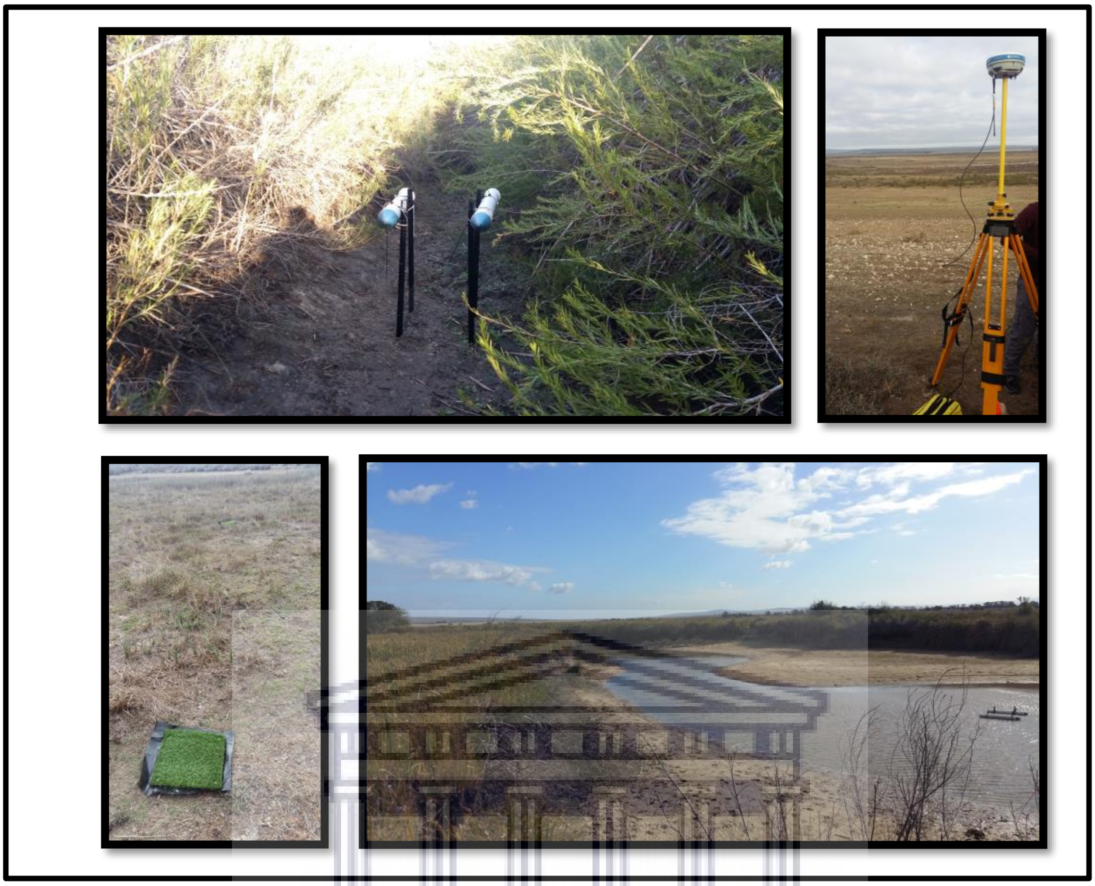


Figure 3.6: Equipment used in the field. Date: 9 May 2018. Images by: Tashveera Jagganath.

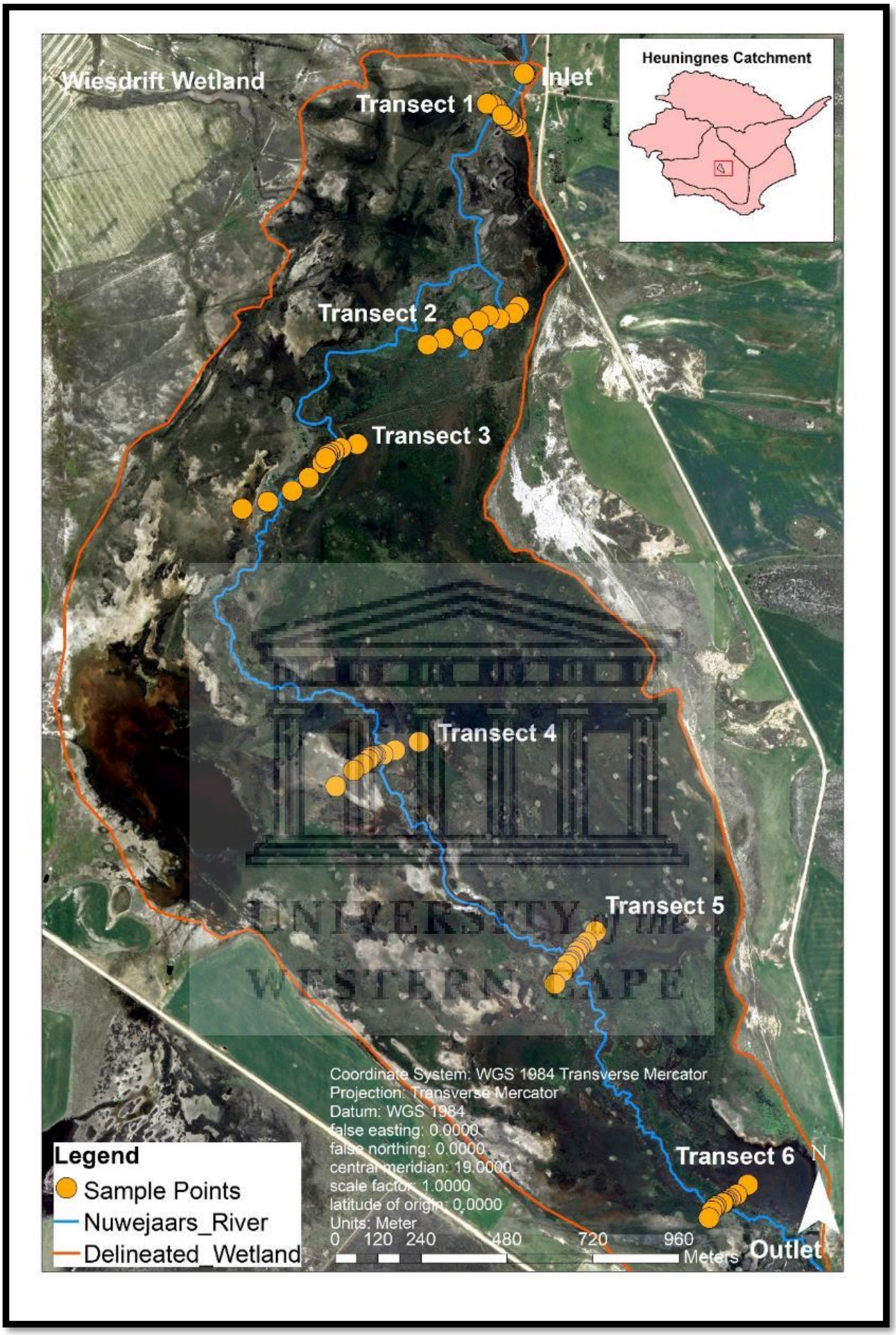


Figure 3.7: Study site with sample points and delineated wetland boundary.

3.4 Data analysis

3.4.1 Introduction

The data analysis methods include the use of the rapid assessment tool known as *WET-EcoServices* and the analysis for phosphate concentrations within sediment by following the molybdovanadate method, as well as the use of Spearman's Rank Correlation (statistical analysis) to investigate the relationship between orthophosphate concentration and particle size of sediment.

3.4.2 *WETEco-Services* analysis

Analysis of the wetland included the review of the results observed from the desktop description of the wetland, with respect to the individual HGM types and their characteristics. Individual assessments were conducted for each HGM type (see Appendix A, Table A1 for categorised assessment). The on-site assessment was carried out during the dry season (January 2019) and desktop analysis of multiple characteristics was carried out for characteristics that seemed relevant to the ecosystem service in terms of flood attenuation, sediment trapping and phosphate trapping. A score (ranging from 0 - 4) is used to identify and gather information about each wetland characteristic.

According to Kotze *et al*. (2009), in order to obtain an overall rating for the particular wetland benefit, *WET-EcoServices* purposefully avoided complicated weighting systems, and is based on an average score (Kotze *et al*., 2009). Where there were characteristics relating to effectiveness and opportunity, an average is calculated for each of these two groups. For the analysis of flood attenuation, sediment trapping and phosphate removal, the assessed ecosystem service was given scores based on the characteristics that are important for provision of each ecosystem service provided by each HGM unit, based on the *WET-EcoServices* assessment rationale and the method assigned for each characteristic (see Appendix A, Table A2 - A4).

3.4.3 Particle size pre-treatment and analysis

Surface samples collected during field campaign 1 were stored in a freezer. In preparation for particle size analysis, the samples were defrosted and were placed in beakers to dry in an oven for 24 hours at 105°C. Thereafter, each sample was crushed using a pestle and mortar, and thereafter placed in plastic bags. Sediment samples were sieved through a 2.0 µm and approximately 30g of sediment were weighed into a beaker. The sample was taken to the fume hood, where 30ml of Hydrogen peroxide (H_2O_2) were added to the beaker and further 10ml increments were added once frothing receded. This was done in order to digest all organic carbon in the soil sample. The beaker was then removed from the fume hood and 6 ml of Hydrochloric acid (HCl) was added to the soil sample in the beaker to disperse metallic binding agents, with a few drops of deionised water added to the sample to avoid drying. Once cooled down, the fluid mixture of sediment and chemicals was filtered in order to separate the sample and the waste. Lastly, filtered sediment was transferred into a 1000 ml graduated glass cylinder glass, with a 100 ml addition of dispersing agent and then sealed with a stopper. This procedure was repeated for all sediment samples (See Appendix B, Table B1).

The sample cylinder for each sample was topped up to 1000 ml with deionised water, capped with a rubber stopper and agitated by inverting 10 times to suspend all dispersed material, and then fitted with a Pario pressure-transducer particle size analyser, which determines the particle size distribution following Stokes Law.

Significant relationships between variables were also determined using Spearman's rank-order correlation analysis (Free Statistics Software: version 1.2.1). Spearman's rank correlation was used to investigate if there were any relationship between the orthophosphate concentration and particle size of sediment (i.e. silt and sand) (see Appendix B, Table B1). This correlation was used because Spearman's test is a nonparametric test used when data is measured at the ordinal level, or when the data for one or both of the variables is not normally distributed.

3.4.4 Phosphate extraction and analysis

Surface samples collected during field campaign 1 were stored in a freezer. In preparation for phosphate analysis, the samples were defrosted and were placed in beakers to dry in an oven for 24 hours at 105°C. Thereafter, each sample was crushed using a pestle and mortar and placed in plastic bags. Sediment samples were sieved through a 125 μm sieve to remove coarse organic fragments and approximately 0.5 g of prepared sediment was weighed accurately into a labelled 50ml centrifuge tube. Thereafter, 40 ml of 1.0 M Hydrochloric Acid (HCl) was added to each tube. A 'blank' was created by adding 40 ml 1.0 M HCl to an empty tube, whereby the sample followed the same procedure as those of sediment samples. After shaking, the tubes were then centrifuged at 2500 RPM for 15 minutes. The supernatant was then transferred to a labelled 250 ml storage bottle. Thereafter, 40 mL of 1.0 M Sodium Hydroxide (NaOH) was added to each tube. The tubes were shaken to disaggregate the sample. The samples were shaken again for 4 hours. Afterwards, samples were centrifuged at 2500 RPM for 15 minutes. And the supernatant transferred to the respective storage bottle. A further 40 ml of 1.0 M NaOH was added to each tube. Once again, the tube was shaken to disaggregate sample. The samples were shaken by hand and the lids of the tubes were loosely applied before being placed in the oven at 90°C for approximately 16 hours (i.e. overnight). After the samples were taken out of the oven, they were centrifuged at 2500 RPM for 15 minutes and the supernatant added to the relevant bottle. Using a pipette, 6 ml of concentrated HCl were added to each sample in the storage bottle. The contents of the 250 ml storage bottle were then transferred to a 200 ml volumetric flask and the volume of the flask was filled to the 200 ml mark using deionised water. The same was done for the 'blank' sample. Thereafter, the samples were stored for analysis. The analysis for extractable orthophosphate was conducted using a spectrophotometer DR 6000 (Hach brand) (Figure 3.8). The concentration of orthophosphate, for each sample, was obtained by following the molybdovanadate method (which has a 95% confidence level). Thereafter, the concentration of extractable orthophosphate was calculated using the measured concentration of orthophosphate, mass of sediment extracted and the volume of extract (see Appendix C, Table C1).

Concentration of extractable Orthophosphate from sediment (mg/kg)

$$= \frac{\textbf{Concentration in (mg/L) x Volume of extract (L)}}{\textbf{Mass of sediment extracted (kg)}} \quad (1)$$

Where:

The concentration in mg/L is the value measured

The volume of the extract was 0.2L

The mass of sediment extracted was 0.0005kg

3.4.5 Suspended sediment sample preparation and analysis

The suspended sediment samples collected by the time-integrated pipe samplers were filtered using filter paper and a beaker. The filter paper was weighed before and after the filtering process. Thereafter, the filtered sediment was dried in a drying oven for 24 hours at 105°C. Mass of dry sediment samples were recorded and compared.

A full data analysis for the suspended sediment samples were not possible as there was insufficient amount of sediment available to carry out phosphate analysis or particle size analysis. Thus, a comparison between the mass of sediment at each location along the river channel was possible only.

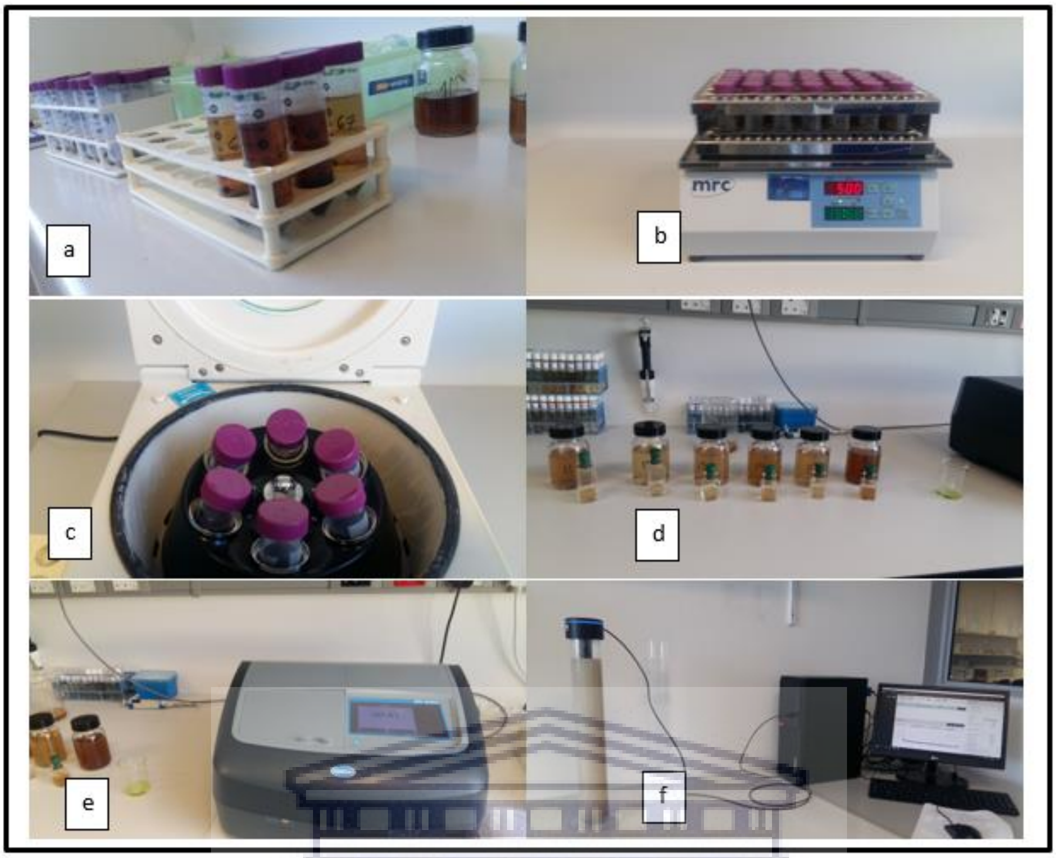


Figure 3.8: Showing laboratory equipment used during the data-analysis phase (a) samples before being shaken, (b) samples prepared for shaking, (c) samples in the centrifuge, (d) samples prepared for P-analysis, (e) spectrophotometer DR 6000 and (f) Pario pressure-transducer particle size analyser.

Chapter 4: Results

4.1 HGM classification, vegetation characteristics, sediment and phosphate spatial variation on the Wiesdrift Wetland

4.1.1 Classification of HGM units and spatial variation in HGM and vegetation characteristics

Based on the hydrological and geomorphic features of the wetland, the Wiesdrift wetland system was classified into three HGM Units (Figure 4.1), according to the HGM types (Kotze *et al*., 2009): floodplain (HGM 1) located at the inlet of the wetland system, a channelled valley-bottom (HGM 2) wetland located along the middle of the wetland system and a floodplain (HGM 3) located close the outlet of the wetland system. Based on aerial photos and surrounding agricultural land use, there is a moderately high contribution of catchment land uses to increasing sediment inputs from the natural condition. There are a number of farms upstream (Figure 8) that could contribute to phosphate supply through the use of fertilizers used for crops, as well as the dairy at Elim with pastures for dairy herds that connect directly to the banks of the Nuwejaars River.

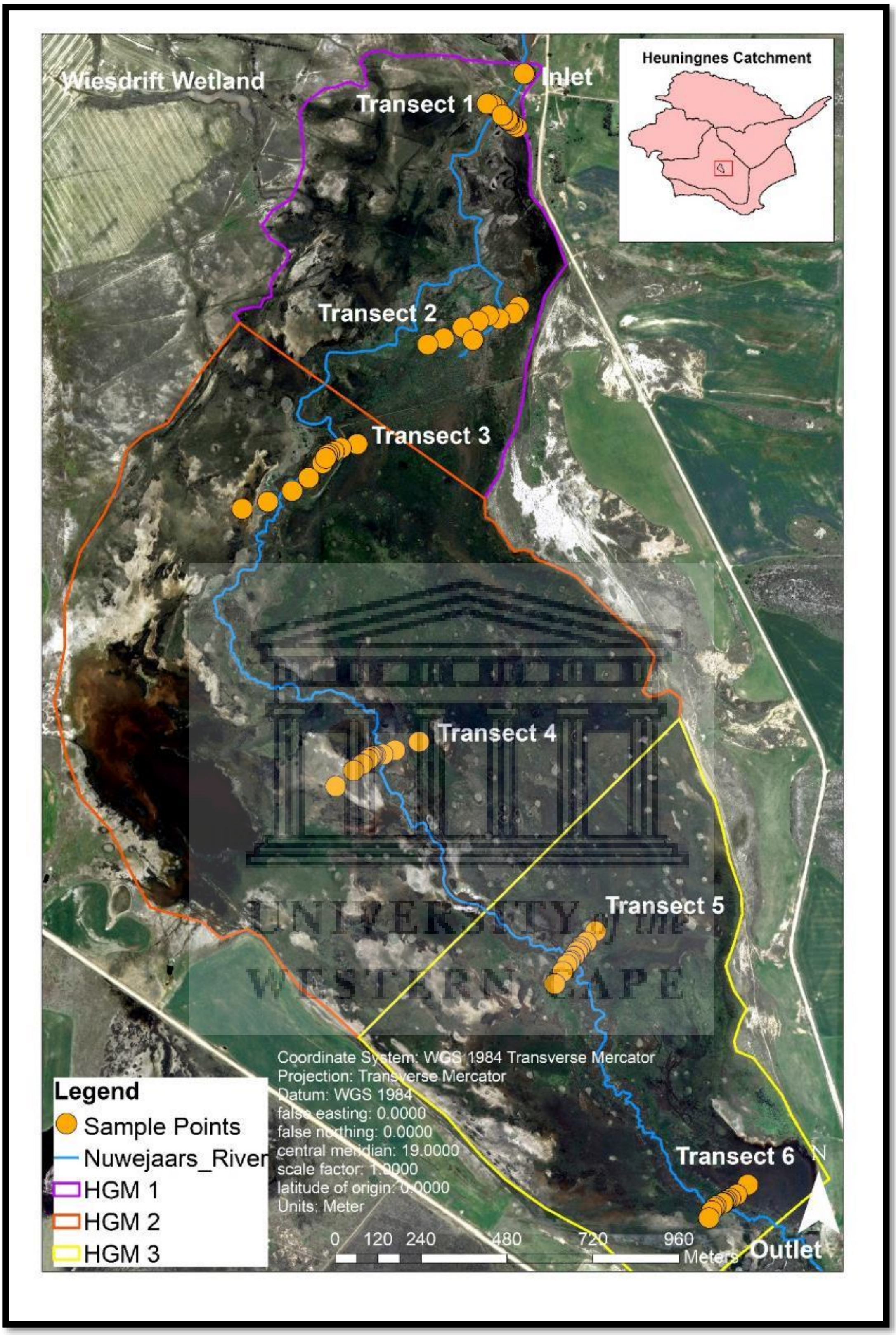


Figure 4.1: Delineated HGM Units on the Wiesdrift wetland.

4.1.2 Floodplain characteristics

Floodplain characteristics were recorded based on dominant vegetation, surface roughness, soil texture and permeability of soil, as well as observed characteristics at each AstroTurf mat sampling point (see Appendix A, Table A5).

Between Astroturf mats 1 and 2 (Transect 1), *Sarcocornia* sp. was observed along with *Cyperus textilis, Stenotaphrum secundatum* and *Hemathria altissma* that was dominant on sandy loam textured soil with moderate permeability. Between Astroturf mats 3-5, the dominant vegetation included *Salicorna* sp., *Sporobolus virginia* and *Triglochin* sp. with soil texture and permeability that was the same along Astroturf mats 1 and 2. Astroturf mats 6-10 had the presence of *Cyperus textilis, Stenotaphrum secundatum* and *Juncus kraussii* as observed dominant vegetation for the area with soil texture and permeability that was the same along Astroturf mats 1-5. No signs of overbank activity were observed. However, some signs of windblown sediment were observed along Astroturf mats 6-10.

Along Astroturf mats 11-14, *Cyperus textilis*, *Cyperus fastigiatus*, *Phragmites australis* and *Phalaris arundinacea* were observed as the dominant vegetation for the area, the presence of *Eleocharis limosa* was found to be dominant for the area where Astroturf mat 15 was located. *Cyperus textilis*, *Cyperus fastigiatus* and *Phragmites australis* were found to be the dominant vegetation surrounding Astroturf mats 16 and 18. *Cliffortia strobilifera* were the dominant vegetation surrounding Astroturf mat 17, while *Searsia* sp. and *Elegia tectorum* were dominant vegetation around Astroturf mats 19, and *Sporobolus virginicus* and *Elegia tectorum* were observed around Astroturf mat 20. Loam textured soil with moderately low permeability were observed along Astroturf mats 11-15, whereby signs of a flood-out, sediment deposition and the presence of an alluvial ridge were observed. Cemented alluvium textured soil with low permeability were observed along Astroturf mats 16-20, in which these samples were no longer being used for analysis as the Astroturf mats were blown over by strong winds. Dominant vegetation surrounding Astroturf mat 21 included: *Cyperus textilis, Cyperus fastigiatus* and *Phragmites australis*; with sandy loam soil texture present, allowing for moderate permeability.

Astroturf mat 21 was found hidden by surrounding plants with deposition present. The dominant vegetation surrounding Astroturf mat 22 were found to be *Cyperus textilis* and *Helichrysum* sp., with loam soil texture that allows for moderately low permeability. Observed around the surrounding area where Astroturf mat 23 were placed was the *Eleocharis limosa* plant, found on loam textured soil with moderately low permeability. The salt tolerant, *Salicornia* sp., was once again observed along Astroturf mat 24, whereby clay/loam textured soil was observed. The dominant vegetation observed where Astroturf mat 25 was located included: *Eleocharis limosa* and *Agrostis* sp., in which the

Astroturf mat was not found and thus was excluded from the analysis. For Astroturf mat 26, *Cyperus textilis* and *Phragmites australis* were observed as the dominant vegetation for the area, with the presence of sandy loam textured soil allowing for moderate permeability. The dominant vegetation for Astroturf mat 27 was *Cyperus* sp., in which the soil texture and permeability was found to be sandy loam textured soil allowing for moderate permeability as well. It was observed that *Salicornia* sp. and *Sporobolus virginicus* was the dominant vegetation surrounding Astroturf mat 28, in which the mat was excluded from analysis as it was found blown over. The dominant vegetation for mat 29 was the short vygie *Disphyma dunsdonii*, which contributes to very low surface roughness for that part of the wetland. Dominant vegetation for Astroturf mat 30 included: *Sporobolus virginicus* and *Eleocharis limosa*. The presence of cemented alluvium with low permeability were observed along Astroturf mats 28-30.

Surrounding Astroturf mat 31 was the dominant *Cliffortia strobilifera* and *Elegia tectorum* plants, with loam textured soil and moderately low permeability. The dominant vegetation surrounding Astroturf mat 32 included: *Juncus kraussii*, *Elegia tectorum* and *Diplachne fusca*, with loam textured soil and moderately low permeability as well. The dominant vegetation surrounding Astroturf mat 33 was *Diplachne fusca*, with the presence of sandy loam textured soil allowing for moderate permeability. At Astroturf mat 34, it was observed that *Elegia tectorum* and *Diplachne fusca* were the dominant vegetation in the surrounding area. Due to the mat being blown over by wind, Astroturf mat 34 was excluded from analysis. Surrounding Astroturf mat 35, *Salicornia* sp. was once again observed as the dominant vegetation. The dominant vegetation for Astroturf mat 36 included: *Hemarthria altissima*, *Cliffortia strobilifera* and *Phragmites australis*, in which presence of deposition was observed on the mat and bark from surrounding plants having fallen on the mat as well. The dominant vegetation for Astroturf mat 37 was *Phragmites australis*, whereby signs of flooding over the mat were observed and bark from surrounding plants were observed also. Astroturf mats 36 and 37 had presence of loam textured soil with moderately low permeability. The dominant vegetation for Astroturf mat 38 included: *Phragmites australis* and *Juncus kraussii*, in which the mat was surrounding the old/abandoned channel and the presence of bark from surrounding plants were also found on the mat. The presence of sandy loam textured soil for Astroturf mat 38 allowed for moderate permeability.

The dominant vegetation observed at Astroturf mat 40 was *Eleocharis limosa* and *Agrostis* sp., while the dominant vegetation at Astroturf mat 41 was *Cynodon dactylon* and the dominant vegetation at Astroturf mat 42 was *Cynodon dactylon* and *Eleocharis limosa*. At Astroturf mat 43, the dominant vegetation included: Cynodon dactylon and Juncus kraussii. Along Astroturf mats 40-43, loam textured soil was observed. Astroturf mat 44 was surrounded by *Diplachne fusca* and *Eleocharis* *limosa,* while Astroturf mat 46 was surrounded by *Cyperus textilis, Phragmites australis* and *Helichrysum.* The dominant vegetation for Astroturf mat 47 included: *Cyperus textilis* and *Phragmites australis,* whereas the dominant vegetation observed for Astroturf mat 48 included: *Cyperus textilis, Phragmites australis* and *Helichrysum* sp. The soil texture for Astroturf mat 46 was sandy loam while soil texture for Astroturf mats 47 and 48 was observed as loam. Astroturf mat 49 (which was excluded from analysis) had one dominant species, *Stenotaphrum secundatum.* The dominant vegetation surrounding Astroturf mat 50 was *Eleocharis limosa* and *Elegia tectorum,* and soil texture was observed as silty loam/partially cemented.

Astroturf mat 51 had dominant vegetation observed as: *Typha capensis, Cyperus textilis and Cyperus fastigiatus,* with loam textured soil observed as well. The dominant vegetation observed for Astroturf mat 52 were: *Cyperus textilis, Cyperus fastigiatus* and *Phragmites australis,* with the presence of clay loam textured soil. The dominant vegetation observed for Astroturf mat 53 included: *Cyperus textilis* and *Phragmites australis,* while loam to clay loam textured soil was present. Astroturf mat 54 had dominant vegetation which included: *Typha capensis, Bolboschoenus maritimus* and *Cyperus textilis,* with loam to clay loam textured soils present. AstroTurf mat 55 could not be located and therefore surrounding dominant vegetation identification was not possible. The dominant vegetation observed around Astroturf mat 56 included: *Typha capensis* and *Eleocharis limosa,* while the dominant vegetation observed around Astroturf mats 57 and 58 were *Cyperus textilis* and *Phragmites australis.* The dominant vegetation surrounding Astroturf mats 59 and 60 were *Typha capensis* and *Cyperus textile.* Signs of floodover were present on Astroturf mat 59, while presence of mud cracks on Astroturf mat 60 proved that there was definite sediment deposition on the mat, as well as direct deposition on surrounding vegetation.

All three units had a high presence of vegetation cover, with low vegetation structure (in terms of height and robustness) in HGM 1 and HGM 3 and high vegetation structure in HGM 2. Figures 4.2 – 4.5 were some of the observations captured in the field, in which one can see the presence of mottling, dense vegetation surrounding the AstroTurf mat, plastic displaced from under the AstroTurf mat in Figure 4.4.

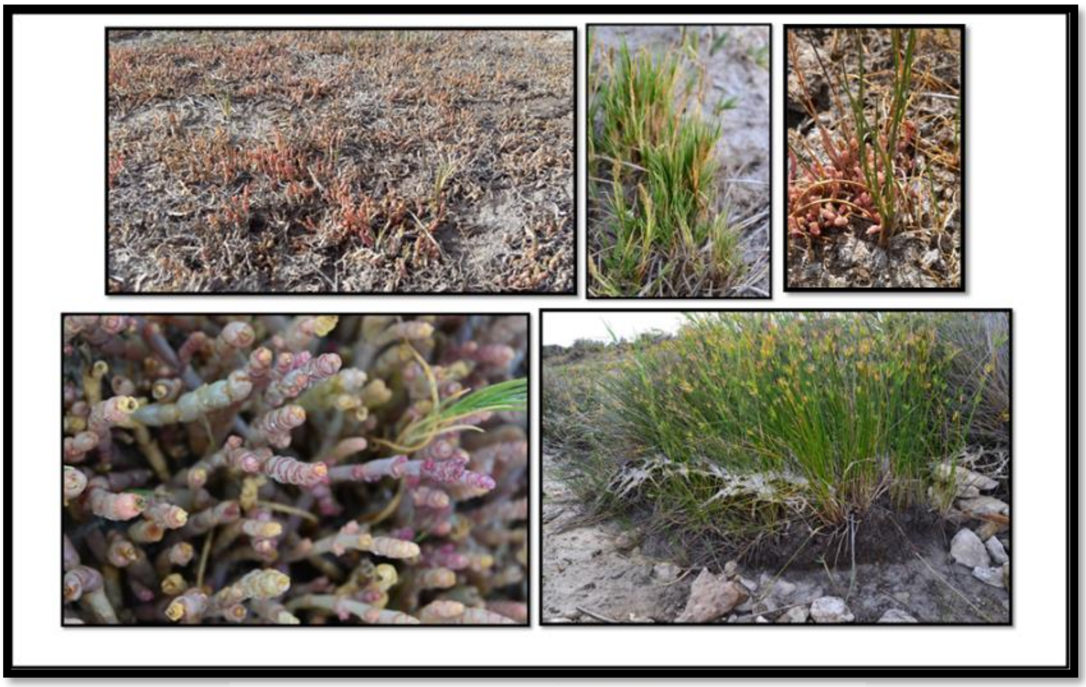


Figure 4.2: Vegetation observed in the field during on-site assessment (Field campaign 2). Date: 15 Jan 2019. Images by: Dr. Donovan Kotze.

Figure 4.3: Vegetation observed in the field during on-site assessment (Field campaign 2). Date: 15 Jan 2019. Images by: Dr. Donovan Kotze.

Figure 4.4: Samples observed during field campaign 2. Date: 15 Jan 2019. Images by: Dr. Michael Grenfell and Dr. Donovan Kotze.

Figure 4.5: Showing samples observed during field campaign 2. Bottom image is a demonstration of the 50 cm wetland soil taken with the auger to determine soil texture. Date: 15 Jan 2019. Images by Dr. Michael Grenfell and Dr. Donovan Kotze.

4.1.3 Spatial variation in sediment and adsorbed phosphate deposition across the HGM units identified above, through field survey

4.1.3.1 Cross-sections of transects along each HGM and field observations

Figures 4.6 – 4.10 show surveyed valley floor cross-sections for transects illustrated in Figure 4.1, as well as AstroTurf mat locations. All transects (Figures 4.6 - 4.10) are displayed from left to right across the valley floor. Figure 17 can be identified as a single-thread channel whereby the main river channel has a well-defined boundary between the floodplain vegetation and open water in the river channel. Upstream of the floodplain, the Nuwejaars River is confined to a shallow river channel, where the width of the floodplain (112 m in HGM 1) extends to 396 m across the valley floor in HGM 2 (Figure 4.7). The bank where AstroTurf mats 1- 5 are installed is 0.2 m higher than the bank where AstroTurf mats 6-10 are installed.

Anecdotal accounts from farmers suggested that the winter flood of 2018 was of limited magnitude, and entirely contained within the channel banks at Transect 1. There were signs of flooding in the form of woody debris found on the samplers within HGM 2. Downstream of HGM 2, the floodplain becomes narrower at a width of 187m (Figure 4.10).

Field visit observations confirmed that the wetland system had an abandoned/old channel which was separated by a floodout (lower end of HGM 1, transect 2) (see Table 4.1 for AstroTurf mat elevation and distance to the distributary channel along Transect 2), that was characterised by dense vegetation/reedbeds (such as *Phragmites australis*). Traditional neck cut-offs, where the channel pinches itself off forming well-defined oxbows, were identified within the study reach close to the low-moderate sinuosity river channel. The wetland system overall contains a complex network including oxbow lakes, pools and an abandoned channel.

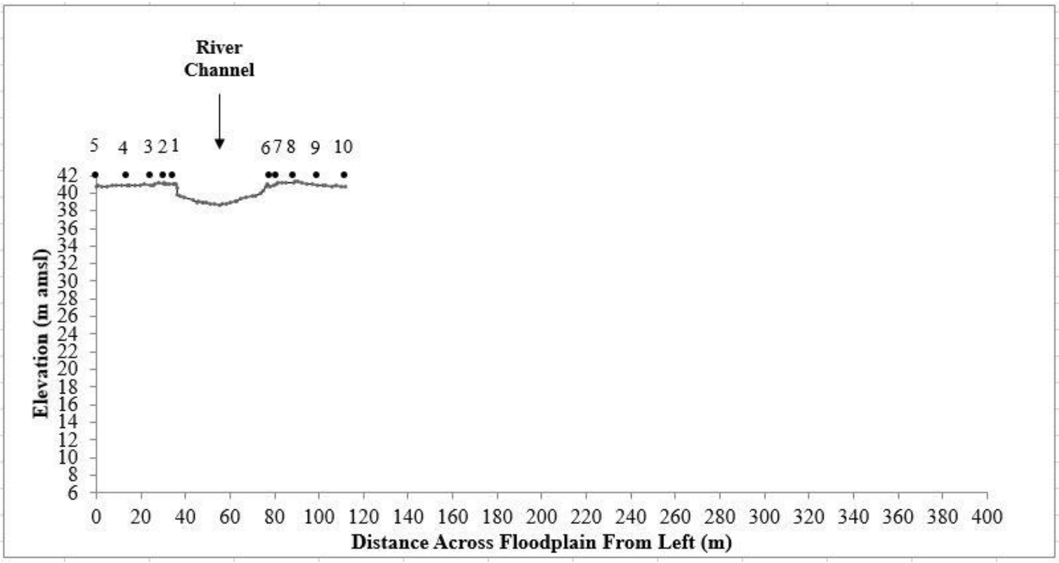


Figure 4.6: Cross-section along Transect 1 in HGM 1. Bullet points indicating location of AstroTurf mats (Metres above mean sea level).

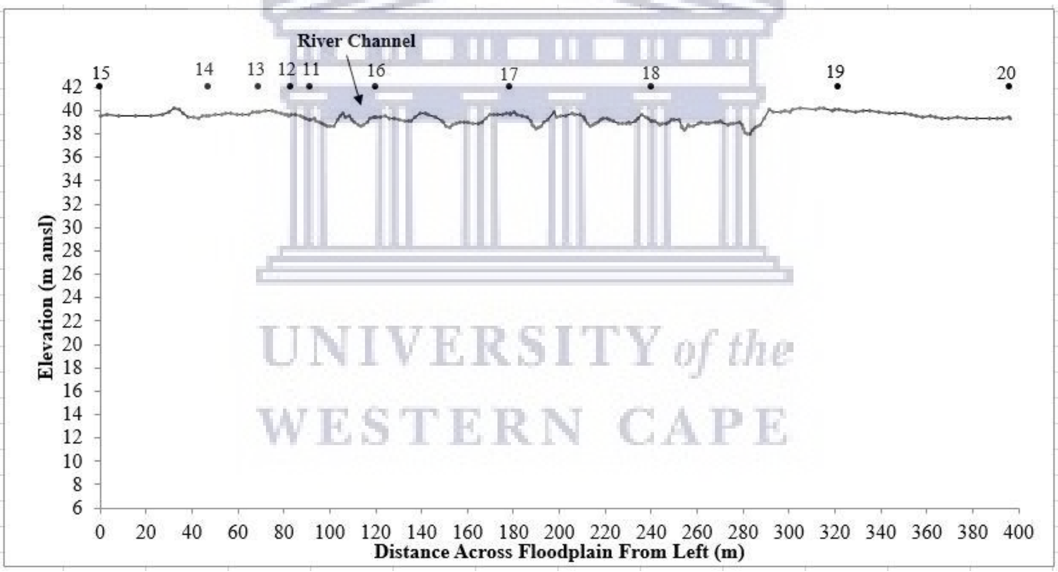


Figure 4.7: Cross-section along Transect 3 in HGM 2. Bullet points indicating location of AstroTurf mats (Metres above mean sea level), as well as the active channel and several oxbows (depressions in the transect line).

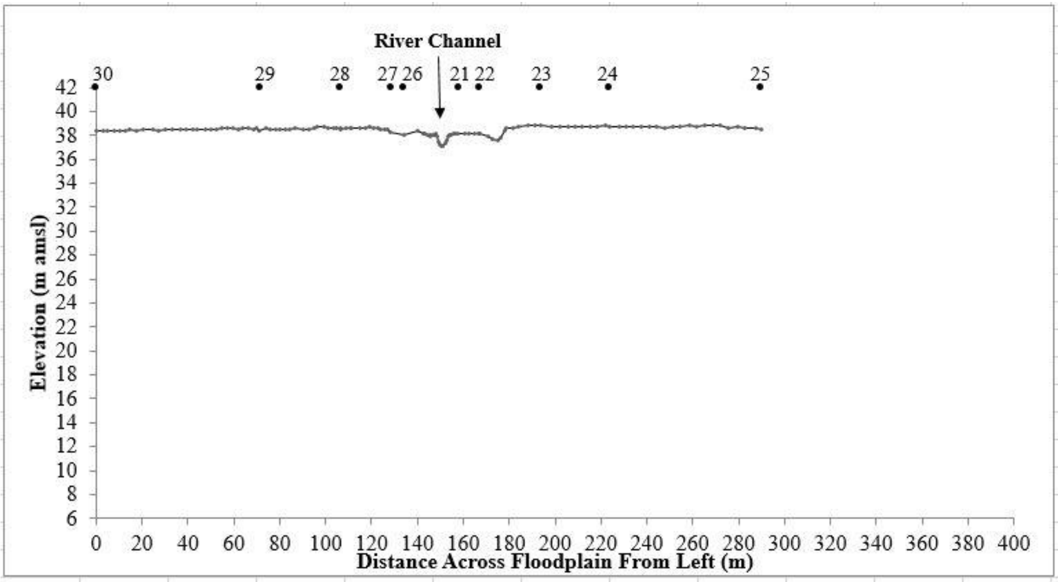


Figure 4.8: Cross-section along Transect 4 in HGM 2. Bullet points indicating location of AstroTurf mats (Metres above mean sea level).

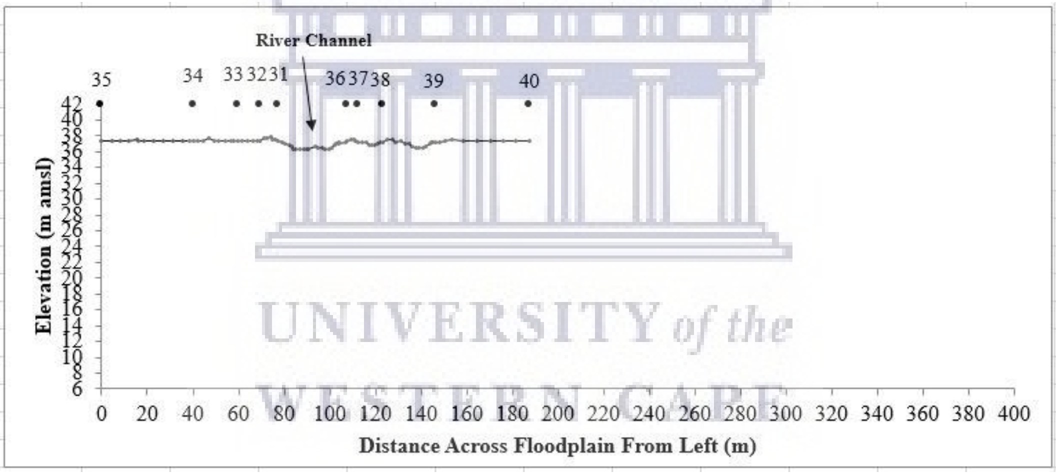


Figure 4.9: Cross-section along Transect 5 in HGM 3. Bullet points indicating location of AstroTurf mats (Metres above mean sea level), as well as the active channel and several oxbows (depressions in the transect line).

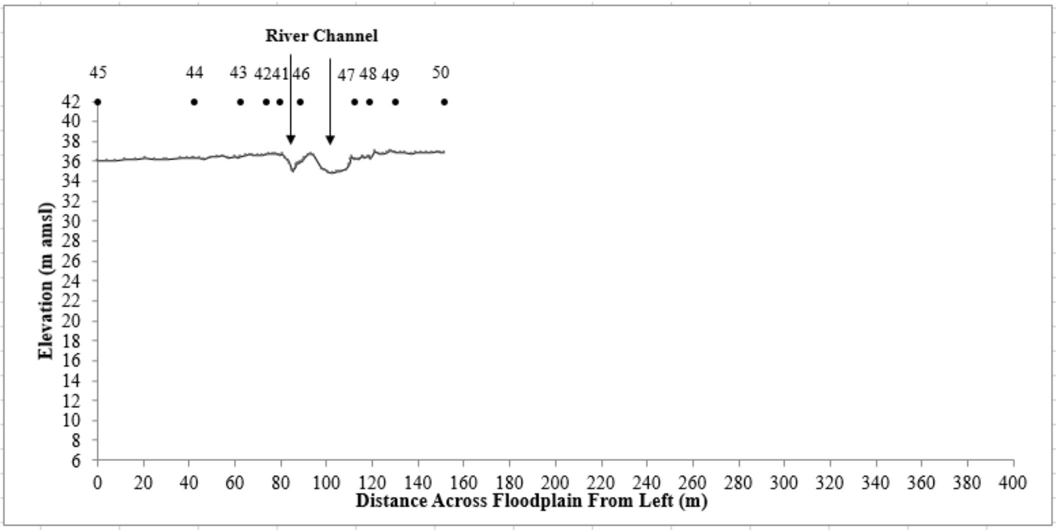


Figure 4.10: Cross-section along Transect 6 in HGM 3. Bullets points indicating location of AstroTurf mats (Metres above mean sea level).

Table 4.1: Elevation along Transect 2 in HGM 1 and distance from a distributary channel.

Transect 2	Distance from a distributary channel (m)	Elevation (m amsl)
AstroTurf mat 51	2.20	8.37
AstroTurf mat 52	1.99	8.70
AstroTurf mat 53	6.58	8.49
AstroTurf mat 54	33.49	8.55
AstroTurf mat 55	54.15	8.32
AstroTurf mat 56	68.17	8.26
AstroTurf mat 57	76.48	8.29
AstroTurf mat 58	110.26	8.06
AstroTurf mat 59	2.24	8.35
AstroTurf mat 60	0.68	8.36

4.1.3.2 Particle size distribution and orthophosphate concentrations adsorbed to fine particles

Little to no clay-sized sediment was found in all three HGM types as compared to the higher content of silt and sand across the Wiesdrift wetland system (Figure 4.13). The percentage of fine sediment, silt, ranged between 0-37%, where the remaining percentage was sand (Figure 4.15).

Spearman's rank correlation was used to investigate if there were any relationship between the orthophosphate concentration and particle size of sediment (i.e. silt and sand) (see Appendix B, Table B1). There was a significant positive correlation between orthophosphate concentration and silt

(Spearman's rank-order correlation: $r_s = 0.692$, $N = 70$, $P < .001$) (Figure 4.11). Whereas, there was a significant negative correlation between orthophosphate concentration and sand (Spearman's rank-order correlation: $r_s = -0.692$, $N = 70$, $P < .001$) (Figure 4.12). This illustrates that as grain size increases, the concentration of orthophosphate decreases in the Wiesdrift wetland. The results are consistent with findings by Rogers (1983), where fine sediments have the ability to store and trap considerable amounts of phosphorus through adsorption and precipitation processes.

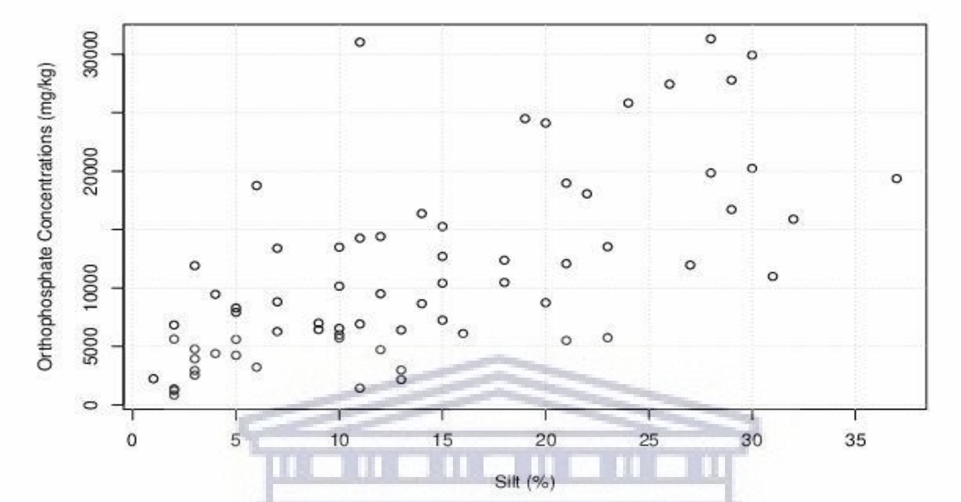


Figure 4.11: Scatterplot showing significant positive correlation between orthophosphate concentration (mg/kg) and silt (%).

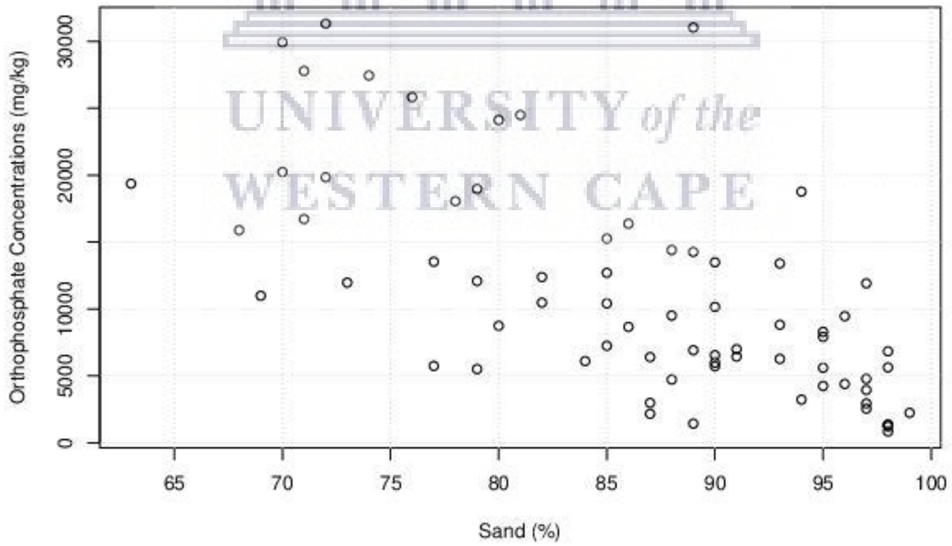


Figure 4.12: Scatterplot showing significant negative correlation between orthophosphate concentration (mg/kg) and sand (%).

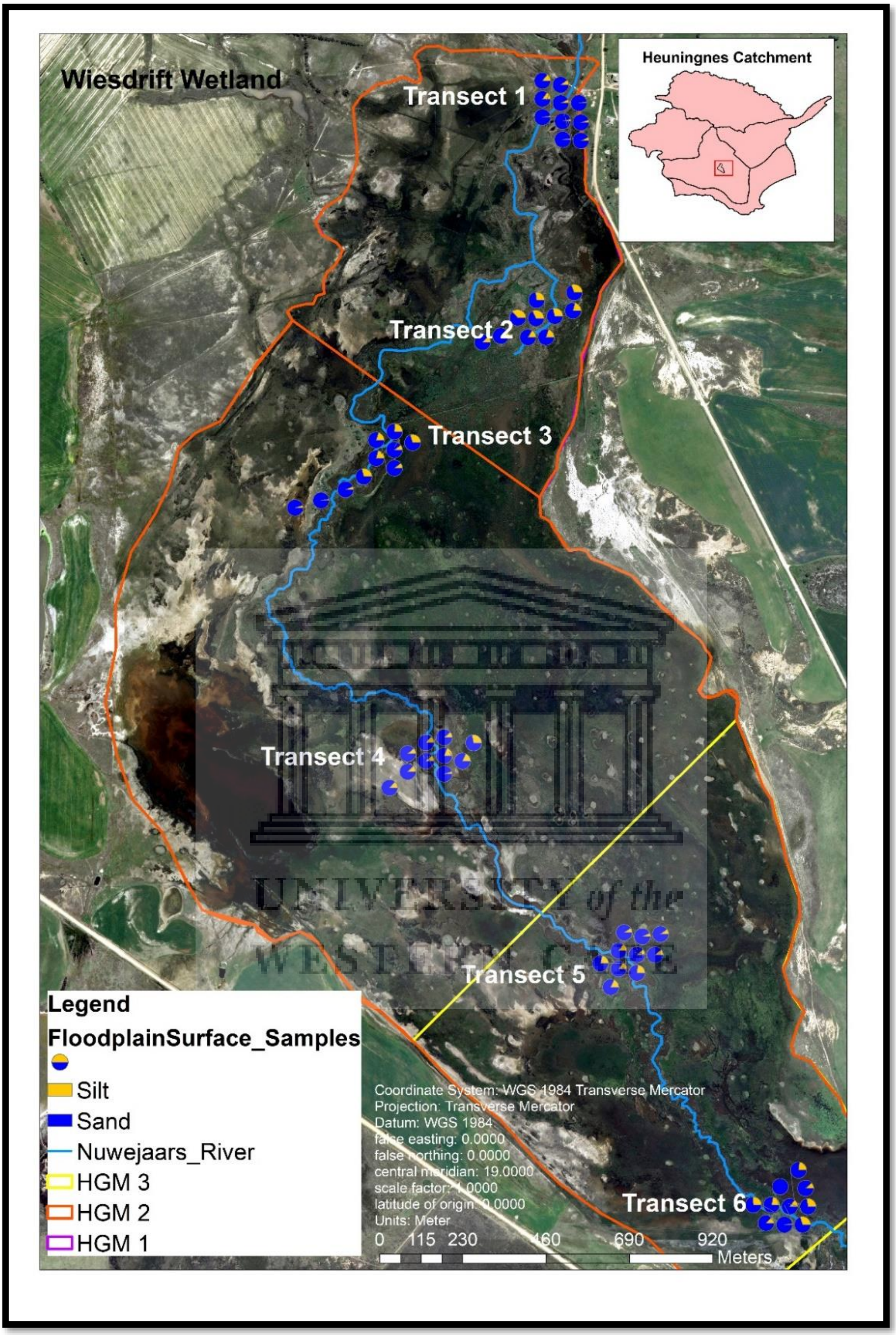


Figure 4.13: Sand (%) and Silt (%) found along Transects 1- 6 in grabbed sediment samples.

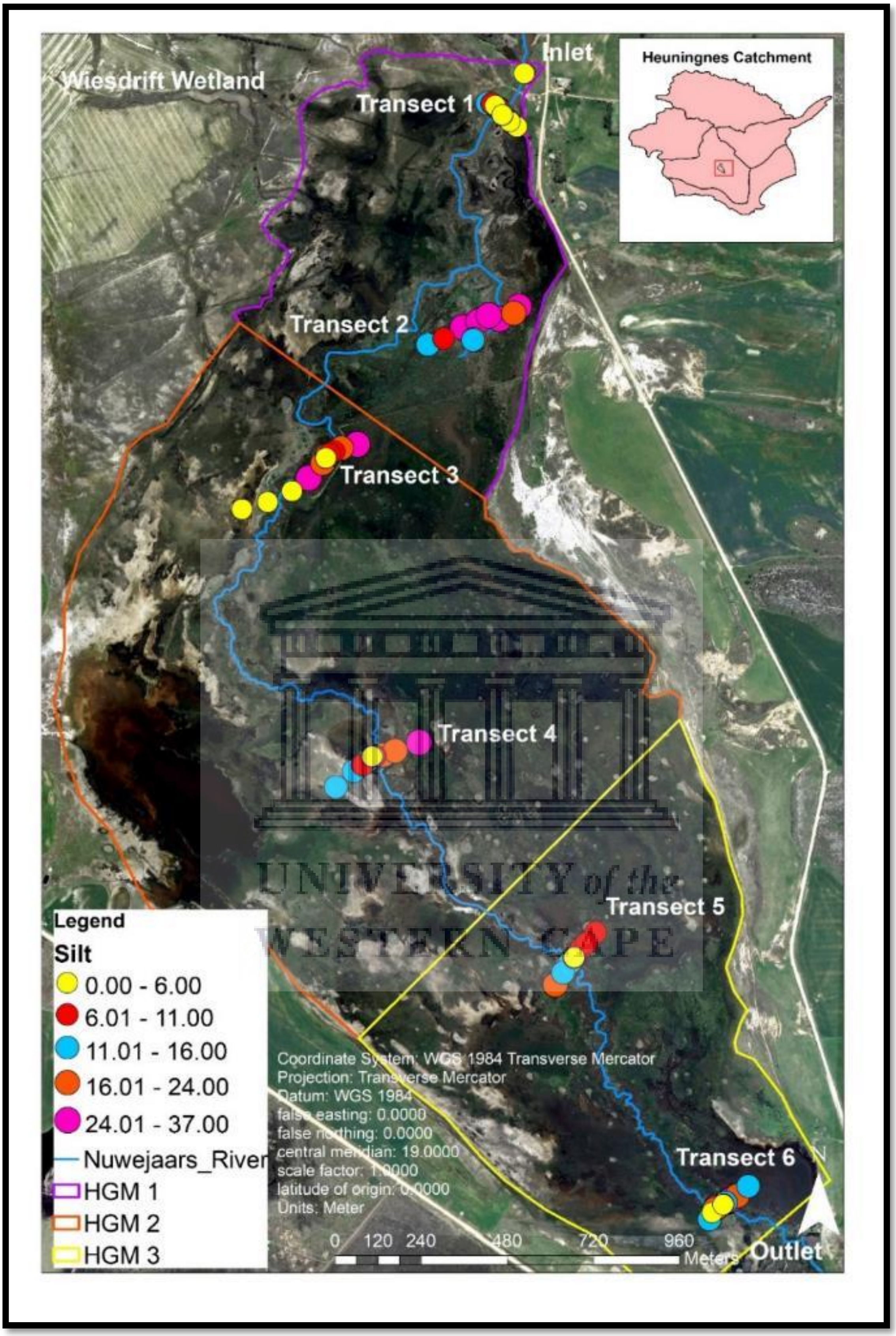


Figure 4.14: Silt (%) found along Transects 1- 6 in grabbed sediment samples.

4.1.3.3 Spatial variation in suspended sediment distribution along the river channel

Figure 4.15 displays a steady increase in the total amount of suspended sediment that was collected by the time-integrated sediment samplers, as the channel flows further downstream. At the inlet, which is located within HGM 1, the total amount of sediment collected by the two time-integrated samplers (Inlet 1 and Inlet 2 as a collective) was 0.358 g. Towards the middle of the wetland, one can see a slight increase in the amount of suspended sediment collected, with a total amount of 0.513 g (Mid-Channel 1 and Mid-channel 2). The largest total sediment amount was found at Outlet 1 and Outlet 2 in HGM unit 3, with a value of 0.653 g. This relationship was not expected, but is likely a consequence of the limited overbank connectivity of the river channel and floodplain during the relatively dry sampling period, which would have resulted in sediment throughput and even downstream accumulation dominating within the channel, with little to no overbank exchange.

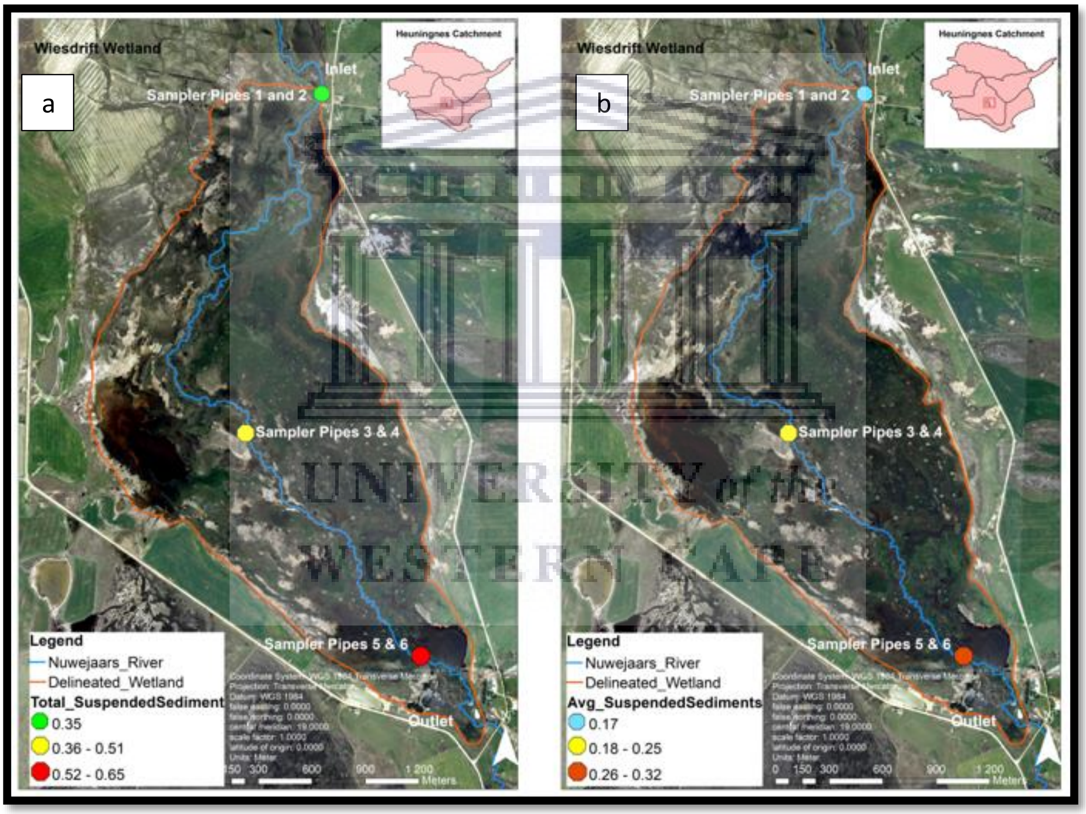


Figure 4.15: Showing total values (in grams) for suspended sediment (a) and average of the total values (in grams) for suspended sediment (b) at three points along the Nuwejaars River.

4.1.3.4 Spatial variation of phosphate in floodplain (grabbed) surface soil samples and channel bed soil samples

All floodplain surface samples and channel bed samples were analysed. With regard to orthophosphate concentration levels found in surface samples grabbed from the floodplain area and channel bed area, the measured concentrations varied. Overall, orthophosphate concentrations ranged between 0 mg/kg and 31320 mg/kg within the Wiesdrift wetland (Figure 4.16). Along transect 1, the highest reactive phosphorus measurement was found closest to the river channel, along the right bank (facing downstream) of the river (Figure 4.17). The lowest amounts of reactive phosphorus were found to be within the river bed samples. Transect 2 has concentrations along the right side of the distributary channel facing downstream between 394421 – 8818.90 mg/kg, 8819 – 14409 mg/kg and 14409.40 – 20238.09 mg/kg (Figure 17).

Higher concentrations were found along transect 3 with orthophosphate measurements ranging between 20238 - 31320 mg/kg (Figure 4.18). Similar to Transect 1, orthophosphate concentrations ranged between 394421 – 8818.90 mg/kg and 8819 – 14409 mg/kg for sample points along Transect 4 (Figure 4.18). And similar to Transect 4 (Figure 4.18), Transect 6 (on the right side bank facing downstream) show orthophosphate concentrations decreasing as one moves further away from the channel (Figure 4.19).

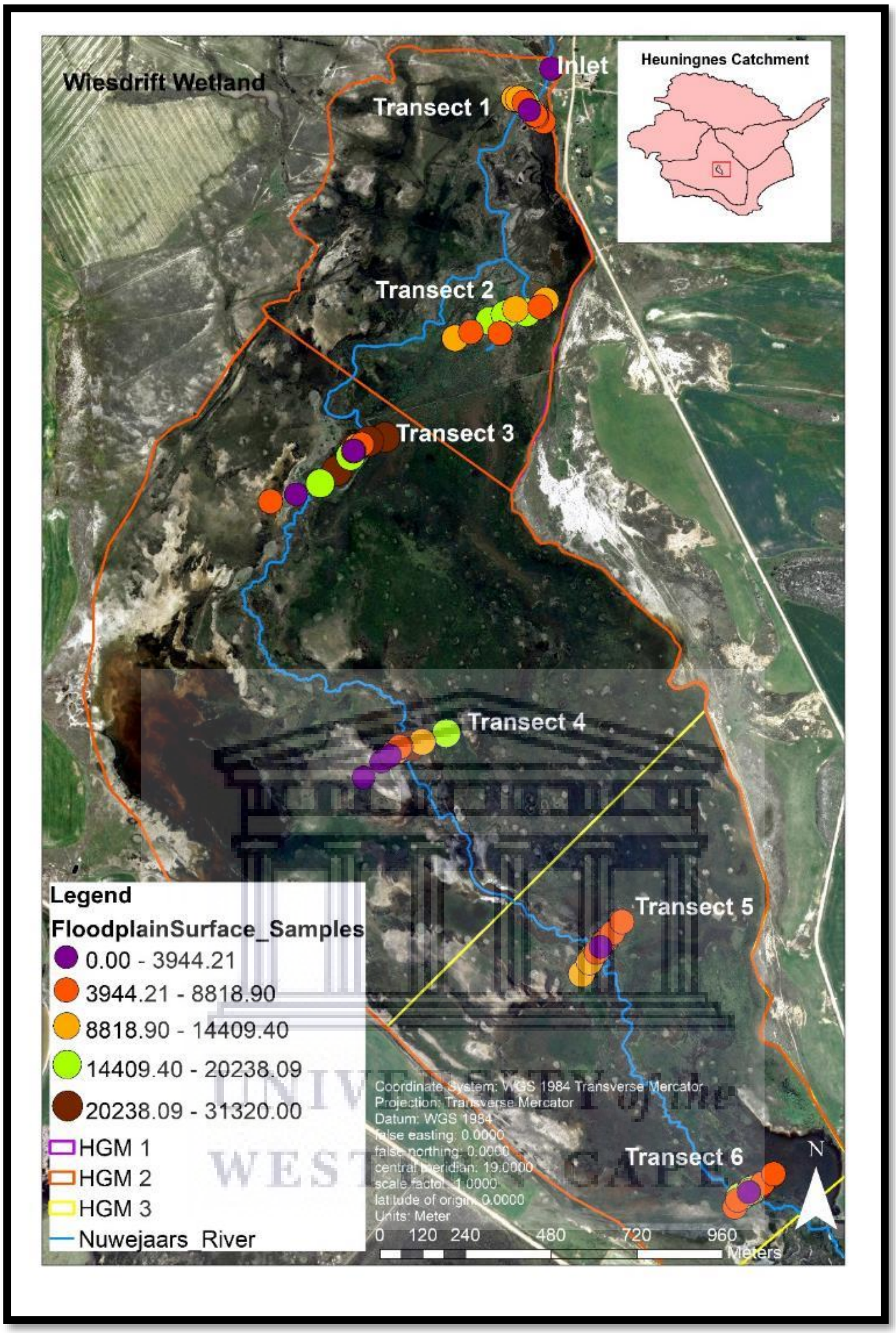


Figure 4.16: Spatial distribution of floodplain surface soil samples and channel bed soil samples indicating variation in orthophosphate concentrations (mg/kg).

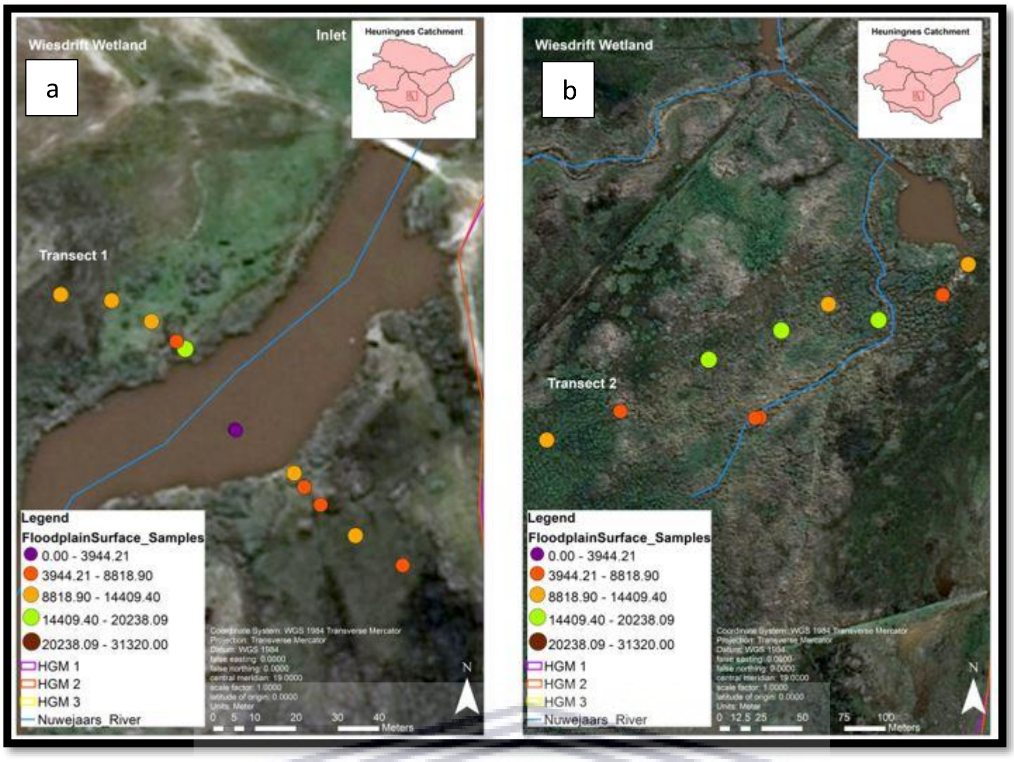


Figure 4.17: Spatial distribution of floodplain surface soil samples and channel bed soil samples (mg/kg) along Transect 1 (a) and Transect 2 (b).

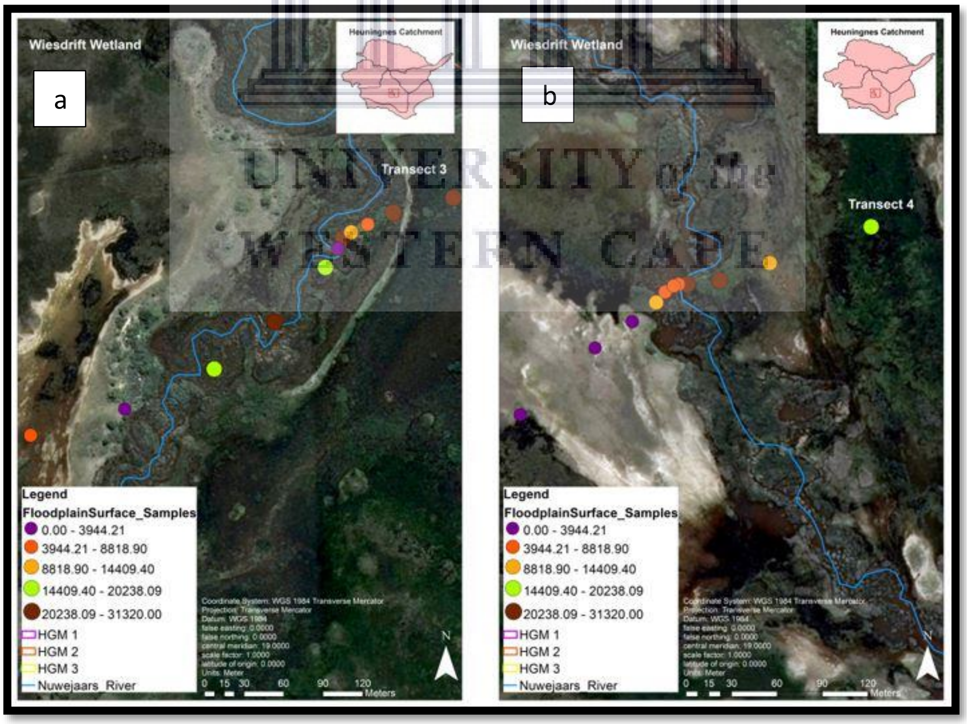


Figure 4.18: Spatial distribution of floodplain surface soil samples and channel bed soil samples (mg/kg) along Transect 3 (a) and Transect 4 (b).

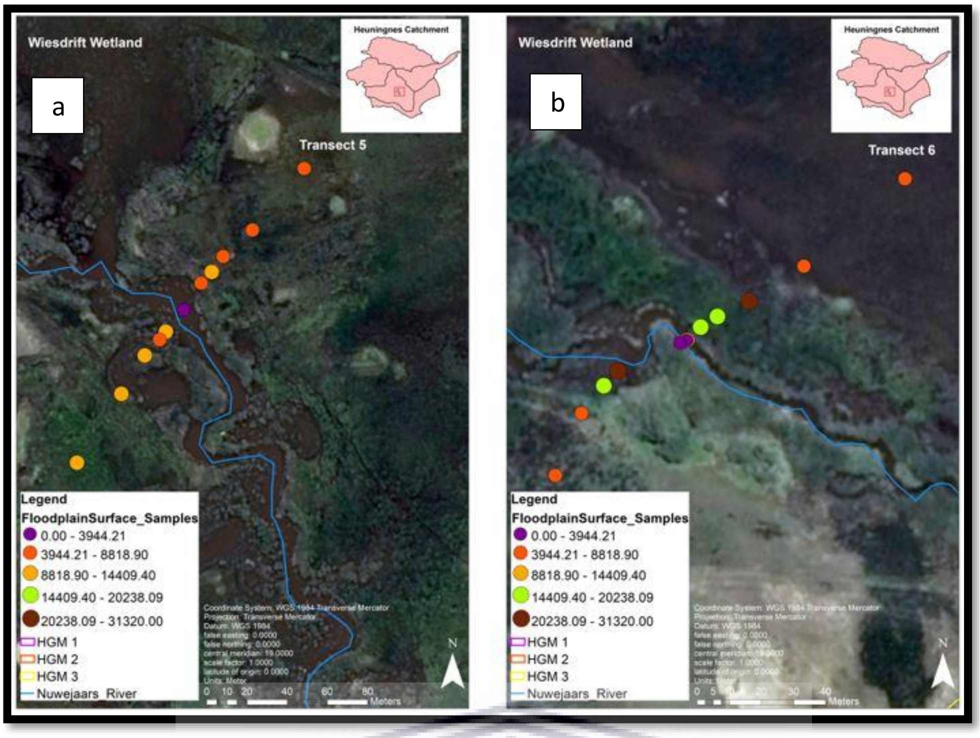


Figure 4.19: Spatial distribution of floodplain surface soil samples and channel bed soil samples (mg/kg) along Transect 5 (a) and Transect 6 (b).

4.1.3.5 Spatial variation of phosphate deposited on floodplain AstroTurf mats

Data is shown for AstroTurf mats that were found to have river-deposited sediment and were analysed accordingly since not all AstroTurf mats had deposited sediment found at the AstroTurf mat sample points. Depending on the gradient of the Wiesdrift wetland, the following values of orthophosphate concentration were found ranging between 1153.78 mg/kg to 30059.90 mg/kg (Figure 4.20).

Figure 4.21 show that high concentration of orthophosphate is found on AstroTurf mat 10 (right side bank facing downstream). However, a decrease in orthophosphate concentrations can be found further away from the river channel along AstroTurf mats 1-5 (left side bank facing downstream). This may be due to the high banks along the river channel where Transect 1 AstroTurf mats were installed (Figure 4.21), which prevents overbank spill. A higher concentration at AstroTurf mat 10 could be related to the relief of the floodplain, in which the Transect 1 AstroTurf mats were placed on an area of low relief.

Along Transect 2 (Figure 4.21), the highest concentration of orthophosphate is found closest to the floodout feature, whereas orthophosphate concentration decreases downstream of the floodout along the river channel. Orthophosphate concentration results from samples collected along transect 3 show that there is high orthophosphate present towards the middle of the wetland (Figure 4.22). However, mat 20, which is located furthest away from the river channel, display low concentrations of orthophosphate. High concentration of orthophosphate can be found closer to the river channel along transect 4, with concentration values ranging between 8087.64 to 30059.90 mg/kg (Figure 4.22).

Along transect 5 (Figure 4.22), orthophosphate concentrations seem to be decreasing further away from the channel on the left side bank (facing downstream) while the highest concentration is found closest to the river channel on the right side bank facing downstream of the river. Transect 6 (Figure 4.22) show that concentration of orthophosphate seems to increase from the right side of the bank to the left side of the bank (facing downstream of the river channel).

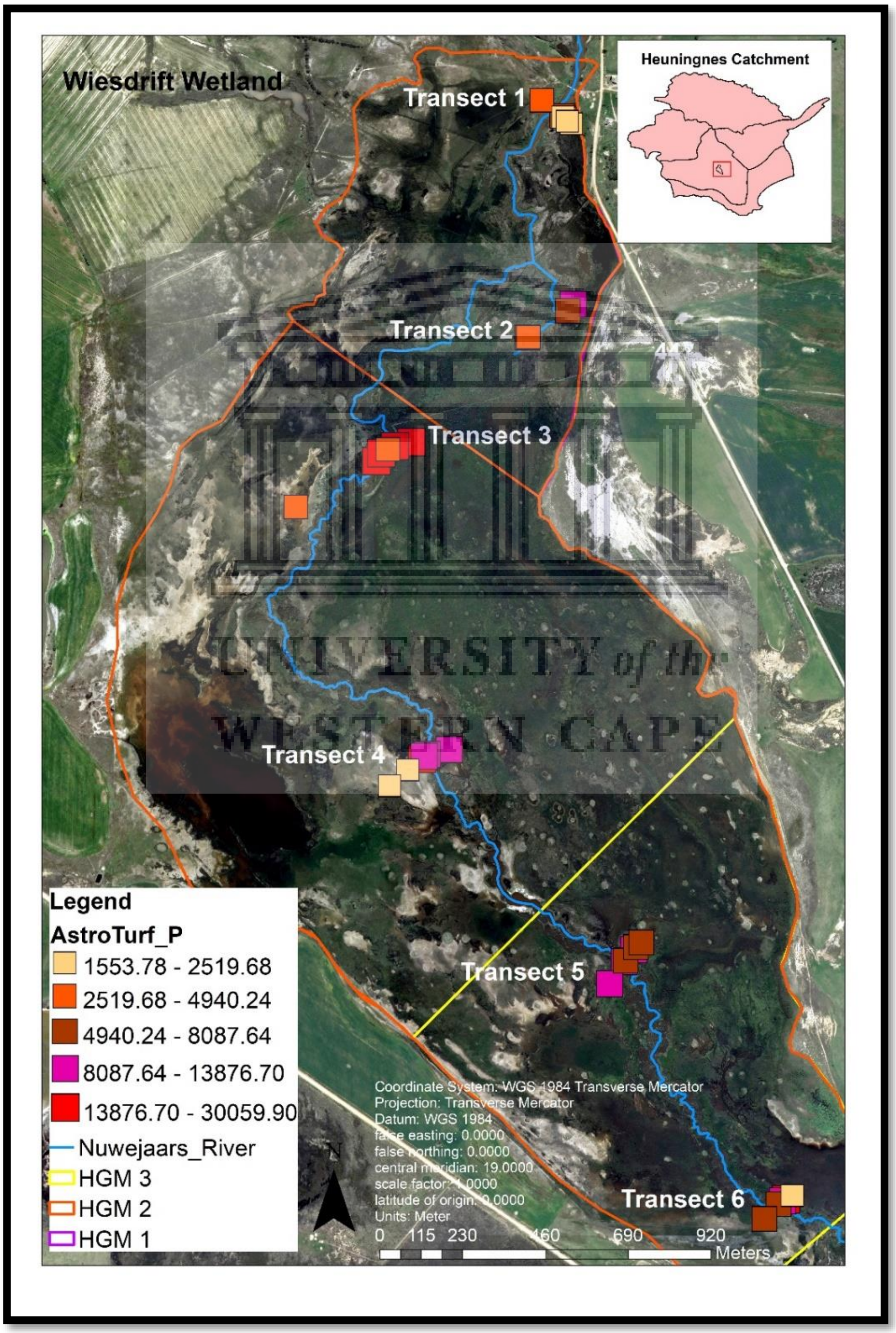


Figure 4.20: Spatial distribution of orthophosphates (mg/kg) deposited on AstroTurf mats.

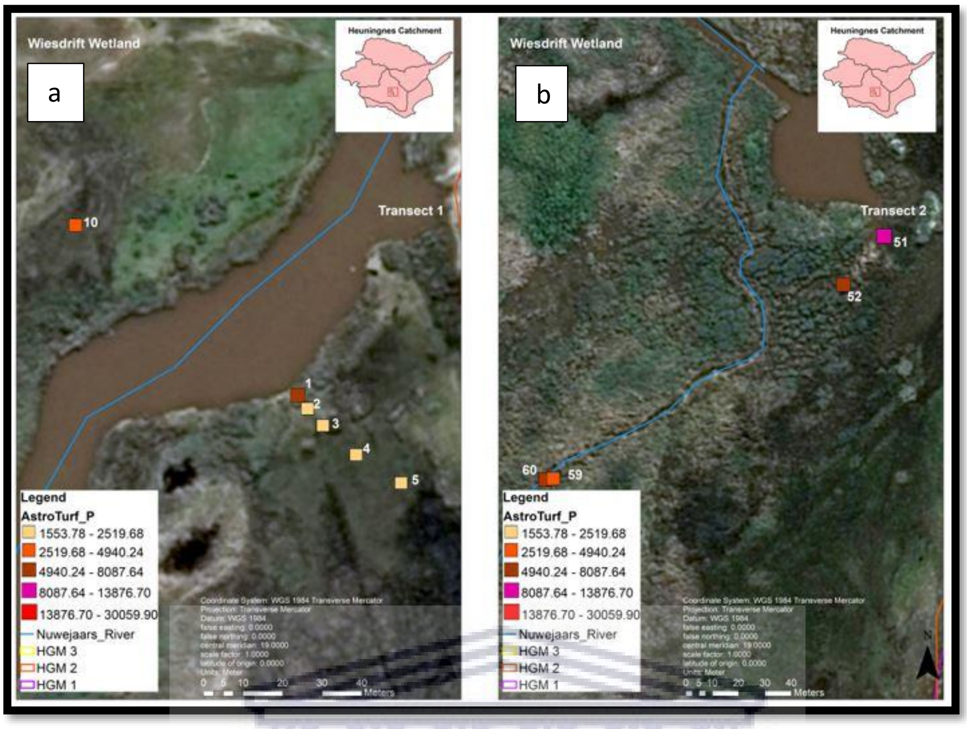


Figure 4..21: Orthophosphate concentrations (mg/kg) deposited on AstroTurf mats for Transect 1(a) and Transect 2 (b).

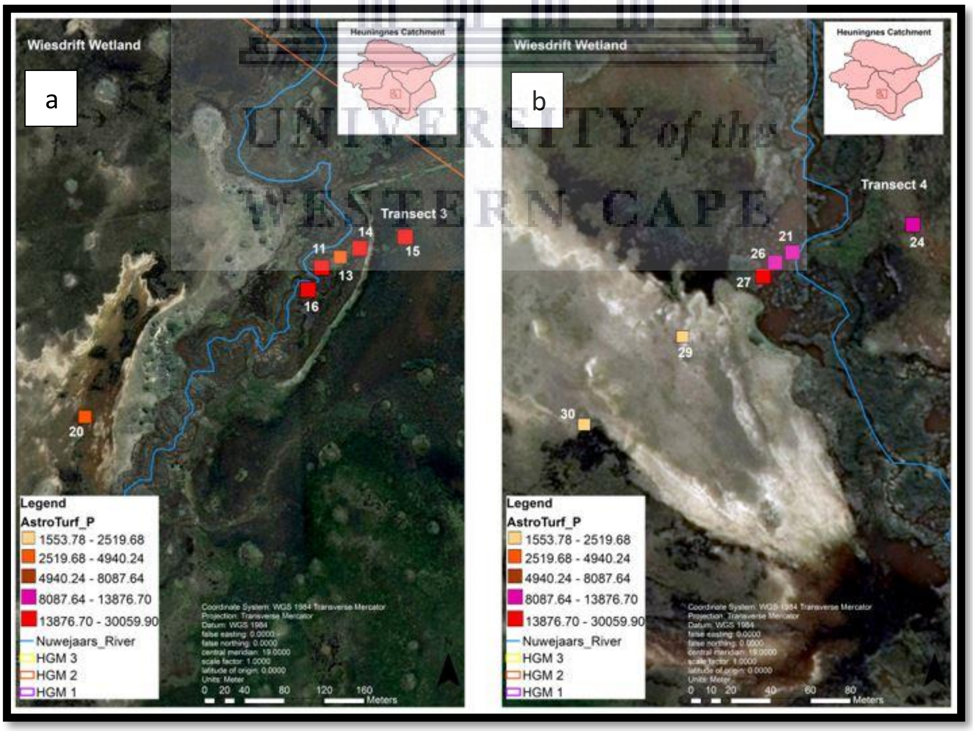


Figure 4.22: Orthophosphate concentrations (mg/kg) deposited on AstroTurf mats for Transect 3 (a) and Transect 4 (b).

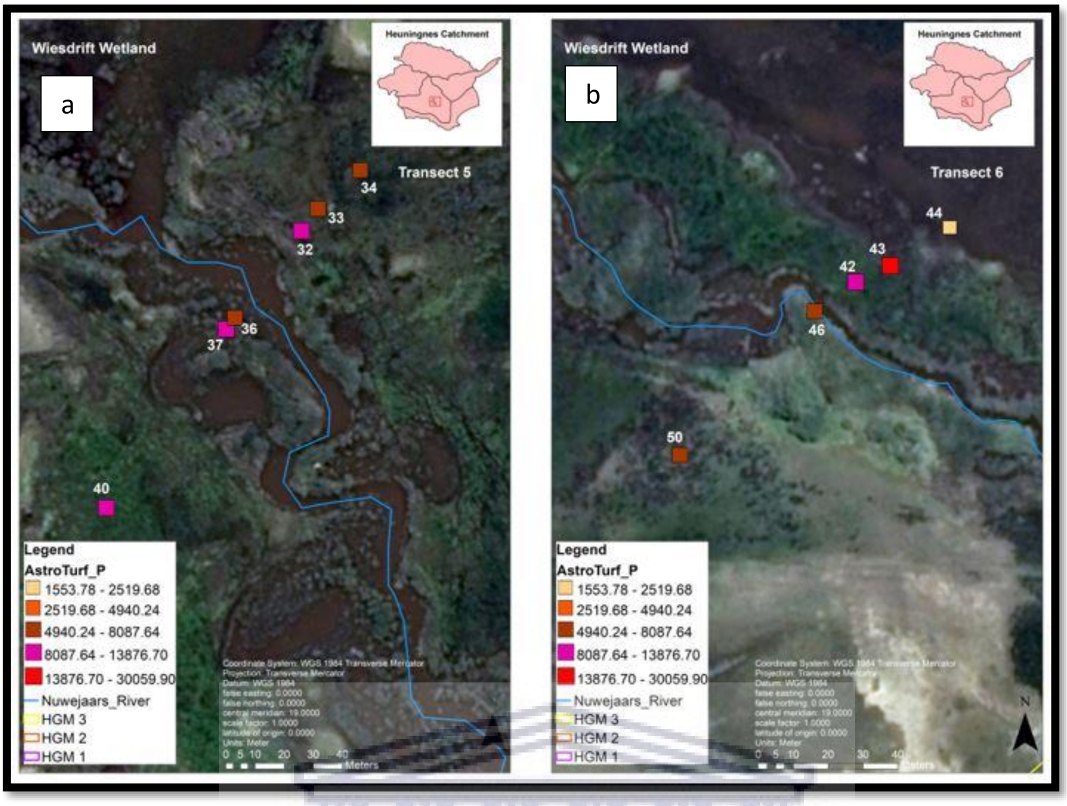


Figure 4.23: Orthophosphate concentrations (mg/kg) deposited on AstroTurf mats for Transect 5 (a) and Transect 6 (b).

4.2. Sediment and phosphate HGM variation using *WET-EcoServices*

Based on the *WET-EcoService's* assessment (Appendix A, Table A1), the Wiesdrift wetland is located within a large upstream catchment. The catchment is made up of gentle gradient slopes with moderate runoff of the soils in the catchment. The catchment can be categorised as a zone 1 (Macfarlane and Atkinson, 2015), which is identified as a catchment experiencing a low amount of rainfall.

Based on the *WET-EcoService's* on-site assessment (see Appendix A, Table A1) conducted in the field, all three HGM units had a moderately low sinuosity stream channel passing through the wetland; with HGM 1 and HGM 3 being strongly channelled, whereby low flows were entirely confined to the main channel of the river. HGM 2 was observed to be moderately channelled, with low flows predominantly confined to the main channel of the river with some diffuse flow occurring. In terms of soil saturation, HGM 1 and HGM 3 had a mix of seasonally and temporarily saturated soils, while HGM 2 was dominated by seasonally saturated soils. The frequency with which storm flows were spread across HGM 1 and HGM 3 is over a 1 to 5-year frequency, whereas the frequency with which storm flows are spread across the HGM 2 unit is categorised as more than once a year. HGM 1 and HGM 3 had a moderately abundant presence of depressions (based on the number of

Oxbox lakes identified within the HGM unit), whereas HGM 2 had an abundance of depressions present. In terms of soil properties, HGM 1 and HGM 3 soil could be described as fine textured soils with low permeability, whereas HGM 2 soil could be described as moderately fine textured soils. As observed, there was low direct evidence of recent sediment deposition in HGM 1 and HGM 3 and moderately low direct evidence of recent sediment deposition in HGM 2. Low direct evidence of erosion was observed in all three HGM units.

The average scores from the *WETEco-Services* assessment were used in order to determine sediment and orthophosphate variation by each HGM unit for the Wiesdrift wetland (Appendix A, Table A1). Scoring was completed for characteristics that contributed to the attenuation of floods (Table 4.2), the trapping of sediments (Table 4.3), and phosphate removal (Table 4.4); in order to determine potential variation in sediment and phosphate for each HGM unit.

Table 4.2: Characteristics contributing to attenuation of floods by each HGM unit.

Effectiveness: Flood Attenuation	**HGM Unit 1**	**HGM Unit 2**	**HGM Unit 3**
HGM unit size	0	1	0
HGM Unit slope	0	0	0
HGM Unit surface roughness	1	3	1
Presence of depressions	3	4	3
Frequency with which storm flows are spread across the HGM Unit	3	3	3
Sinuosity of the stream channel	1	1	1
Representation of different hydrological zones	2	3	2
Effectiveness Score	**1.4**	**2.1**	**1.4**
Opportunity: Flood Attenuation	**Score for HGM 1**	**Score for HGM 2**	**Score for HGM 3**

Average slope of the HGM unit catchment	0	0	0
Inherent run-off potential of soils in the HGM unit's catchment	2	2	2
Contribution of catchment land-uses to changing runoff intensity from the natural condition	3	3	3
Rainfall intensity	0	0	0
Opportunity Score	**1.3**	**1.3**	**1.3**
Overall score: Flood Attenuation	**1.3**	**1.7**	**1.3**

Table 4.3: Characteristics contributing to sediment trapping by each HGM unit.

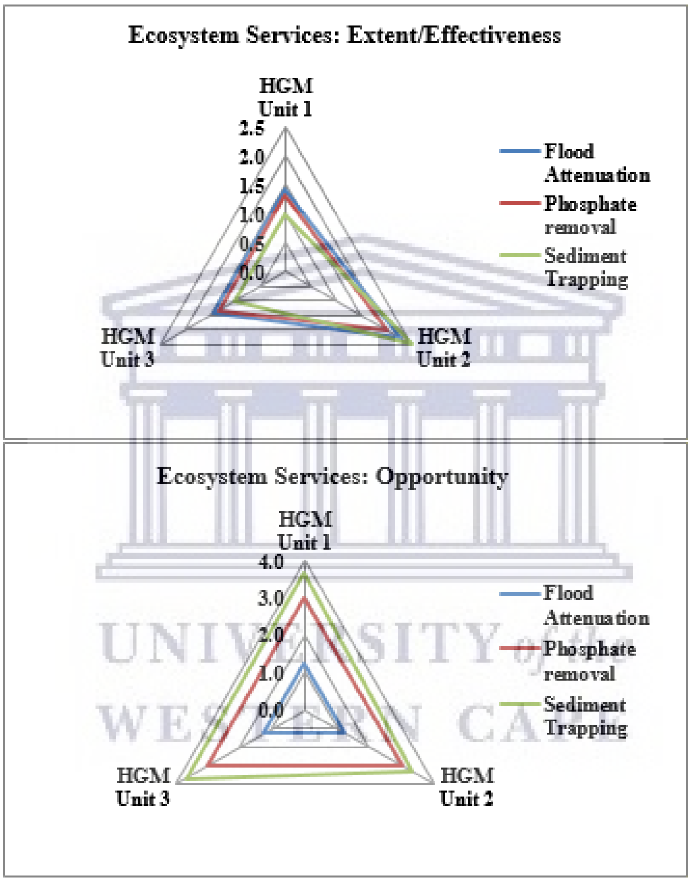
Effectiveness: Sediment trapping	**Score for HGM 1**	**Score for HGM 2**	**Score for HGM 3**
HGM units ability to attenuate floods	1	2	1
Direct evidence of sediment deposition in the HGM unit	1	3	1
Effectiveness score	**1**	**2.5**	**1**
Opportunity: Sediment trapping	**Score for HGM 1**	**Score for HGM 2**	**Score for HGM 3**
Extent to which dams are reducing the input of sediment to the HGM unit	4	4	4
Extent of sediment sources (i.e. disturbed or un-vegetated areas) delivering sediment to the HGM unit from its catchment	3	2	3

Presence of any important wetland or aquatic system downstream	4	4	4
Opportunity Score	**3.7**	**3.3**	**3.7**
Overall Score: Sediment Trapping	**2.3**	**2.9**	**2.3**

Table 4.4: Characteristics contributing to phosphate trapping by each HGM unit.

Effectiveness: Phosphate trapping	**Score for HGM 1**	**Score for HGM 2**	**Score for HGM 3**
Effectiveness in trapping sediment	1	2	1
Pattern of low flows within the HGM Unit	0	1	0
Extent of vegetation cover	3	3	3
Effectiveness score	**1.3**	**2.0**	**1.3**
Opportunity: Phosphate trapping			
Level of sediment input	3	3	3
Extent of potential sources of phosphate in the HGM units catchment	3	3	3
Effectiveness score	**3**	**3**	**3**
Overall score: Phosphate trapping	**2.2**	**2.5**	**2.2**

Comparing the results of each ecosystem service for each HGM unit (Figure 4.24), the channelled valley-bottom wetland unit (HGM 2) has a score rating of 2.3 which displays a moderately higher effectiveness at attenuating floods than the floodplains at HGM 1(score rating of 1.4) and HGM 3 (score rating of 1.4). HGM 2 is expected to have the lowest incidence of flows confined to the river channel, with a presence of high surface roughness contributing to a greater rate of flood attenuation. With high score ratings for sediment trapping (score of 2.5) and phosphate removal (score of 2), the channelled valley-bottom wetland (HGM 2) has a higher effectiveness at trapping sediment, thus contributing to a higher extent for the channelled valley-bottom wetland to remove phosphate. The opportunity to improve the flood attenuation within the wetland has a score of 1.3, which means that chances of improving the wetland based on characteristics listed in Tables 7, 8 and 9 are intermediate. In addition, the valley-bottom wetland scores showed that the HGM unit had a higher ability to remove phosphate when compared to the other two HGM units' scores (Figure 4.24).



Score:	<0.5	0.5-1.2	1.3-2.0	2.1-2.8	>2.8
Rating of the likely extent to which a benefit is being supplied	Low	Moderately low	Intermediate	Moderately high	High

Figure 4.24: A radar diagram displaying the effectiveness and opportunity of the three HGM Units identified within the Wiesdrift wetland system.

Chapter 5: Discussion

5.1 Sediment and phosphate distribution along the Wiesdrift wetland

The field survey reported on key hydrogeomorphological and vegetation features of the wetland, as well as the spatial variation of deposited fine sediment and adsorbed phosphate, and the longitudinal variation of suspended sediment throughput along the Nuwejaars River channel.

Local factors (such as "flood characteristics, sediment load, sediment texture, water velocity, floodplain morphology, vegetation cover on the floodplain and wind erosion") play a major role in the amount of phosphorus found bound to wetland sediment (Knighton, 1998; Hupp, 2000, Datry *et al*., 2014, Mitsch and Gosselink, 2007, Ellery *et al*, 2010, Rogers, 1984 and Roose, 1996).

Flows of the Nuwejaars River were largely confined to the river channel during the field sampling period, as flows are reduced, reducing or limiting the turbidity in water and the movement of sediment loads along the wetland, supporting findings from Mosley (2015).

The Nuwejaars River channel most likely accumulates sediment and associated phosphate during periods of low-flow and may lose sediment downstream towards HGM 2 during periods of higher flow, as the floodout and overbank deposition are activated. Similarly, the same deposition process could influence the higher amounts of nutrients and sediment found on the wetland within HGM 2 where it is found that flood attenuation is highly effective. This may be due to advected wetted fronts in which nutrients and minerals travel to water bodies at a lower gradient, similar to findings from Datry *et al*. (2014).

Spearman's Rank correlation (Figure 4.11) supports previous literature as results showed that the sampled transects have a significant positive correlation between fine sediment (silt) and P (i.e. orthophosphate) deposition, such that adsorbed phosphate concentration vary with the spatial distribution of silt deposition. This is not always associated with distance to the channel, and can vary with local floodplain topography and variations in vegetation cover (e.g. sparse cover of *Sarcocornia* sp. versus dense cover *of Cyperus textilis*).

Significant amounts of fine sediments can be found further away from the channel in stagnant water/water that moves at a slow rate (Thonon *et al*., 2007, Pierce and King, 2008, and Grenfell, 2012). This may be the case in the Wiesdrift wetland in which most of the course sediments found on the wetland is categorised as sand and the remaining fine sediment is found to be silt, although the spatial distribution of silt is locally quite complex. When comparing the percentage of silt found on the floodplain, the highest percentage can be found along Transect 2 which is occupied by a floodout system.

The floodplain morphology may also have an influence on the deposition pattern of sediment on the floodplain. On the floodplain of River Odense, for example, the highest deposition rates have been found at the outside of a meander bend. Similarly, at Wiesdrift the values of orthophosphate adsorbed to silt were found to be higher at sample points where AstroTurf mats are located on the outside bend of a large meander in Transect 4 resulting in overbank flow during peak flood periods that could be preferentially advect sediment that could be trapped in the dense vegetation along the floodplain (Figure 4.22).

Vegetation plays a role in both the deposition of sediment and inorganic phosphorus, such as orthophosphate, on the floodplains. The dominant vegetation along Transect 2, at which the highest concentrations of orthophosphate was found, is occupied by *Typha capensis* and *Cyperus textilis*. In cases where *Typha capensis* is known to be found in either stagnant or shallow slow-flowing water in wetlands (Voigt, 2007), it may play a role in increasing the sedimentation through a combination of reduced turbulence and reduced water velocity and thus decreasing the rate of resuspension (Braskerud, 2001). *Cyperus textilis* is also known to take up excess nitrates and phosphates from treated sewage (Malan and Notten, 2003). In combination with the mud cracks found on the AstroTurf mats, mottling found on the surface soil, as well as direct deposition of sediment on vegetation along Transect 2, may further the opportunity for sediment and orthophosphate to be filtered by the dominant vegetation along Transect 2 in the Wiesdrift wetland.

Data for suspended sediment distributed along the wetland was recorded over a single season, in which the wetland system did not experience any large overbank events during the time of sampling. However, all flows were essentially contained within the channel so it is possible that under confined channelled conditions the channel essentially acts as a canal and minor supply/throughput system (Mosley, 2015). Thus, the sediment samplers located closer to the outlet of the wetland have recorded higher suspended sediment amounts. In wetter years, it is expected that there would be more vegetation cover in the channel and on the floodplain, greater connectivity of overbank flows with the floodplain, and better retention of sediment within the floodplain and valley-bottom wetlands.

A factor that may also play a role in the Wiesdrift wetland system is the ability of sediment being transported through wind erosion. The Cape Agulhas region is known to experience strong, regular prevailing winds greater than 6 m/s (World Weather Online, 2021), thus contributing to the role of wind erosion in the study area (Roose, 1996). All of the sediment samples analysed for particle size analysis produced results that included both silt and sand percentages, where sand was found to be at a higher percentage than silt in all soil samples that were tested. The results from the particle size analysis together with in-field recordings of soil texture and observations made in the field provide an indication that sediment which settled on the floodplains of the Wiesdrift wetland system could be as a result of wind erosion reworked by aeolian processes. While in the field, indication of disturbance to the mats being displaced, with some mats turned over, show that wind erosion is very active on the floodplain of the wetland system, and could remove fine-grained sediments (Roose, 1996).

5.2 *WET-EcoServices*

Following the classification system of wetlands (Kotze *et al*., 2009), the Wiesdrift Wetland would currently be classified as three HGM units in the following down-valley sequence: floodplain wetland (HGM 1), channelled valley-bottom wetland (HGM 2) and floodplain wetland (HGM 3). Wetland characteristics (based from Kotze *et al*. (2009)) were assessed and in turn influenced the overall scores of each HGM unit's extent to attenuate floods, trap sediment and remove phosphates.

5.2.1 Flood attenuation

5.2.1.1 HGM size in relation to size of catchment

Kotze *et al*. (2009) states that the larger the wetland relative to its catchment, the greater will be its potential influence on flood-flows. Thus, based on the HGM Unit area, HGM 2 had a greater score of 1 (between 1 and 2%) as compared to HGM 1 and 3 with a score of 0 (<1%). In which HGM 2 occupied a bigger area of the Wiesdrift wetland, in turn having a greater influence in attenuating floods along the valley-bottom wetland. Findings from the channelled valley-bottom wetland in this study in the Wiesdrift Wetland further proves that such wetlands play an important role in trapping of sediment and associated nutrients due to the wetlands characteristics and is similar to findings from Ellery *et al*. (2010) in which *WET-EcoServices* results for the Ekubo estate wetlands found that the valley-bottom wetlands assessed were moderately effective at attenuating floods as they spread inflowing waters over a large area, slowing it down due to friction.

5.2.1.2 The contribution slope has to runoff in the HGM unit

The slope of all three HGM units had a score greater that 5%, influencing runoff from adjacent fields that may contribute to sediment deposition on the wetland. Slope of HGM 1 and HGM 3 may have resulted in a faster surface runoff and thus contributing less to attenuation of floods on the floodplain. In the case for steep slopes, water moves a lot faster allowing for a lower capability of a wetland to attenuate floodwaters (Kotze *et al*., 2009). To an extent, the floodplains on the Wiesdrift wetland do play a role in attenuating floods as addressed by Kotze *et al*. (2009) in *WET-EcoServices*, because Wiesdrift wetland vegetation showed signs of soil and organic matter present. Flood attenuation is likely to be high early in the season until the floodplain soils are saturated and the oxbows and other depressions are filled, although the field observations indicate that this will depend on the temporal pattern of overbank flooding.

5.2.1.3 Surface roughness of HGM unit

Given that HGM unit 2 had a score of 3 for surface roughness illustrates that the moderately high surface roughness presence on the channel valley-bottom wetland offer a high resistance to water flow. Dominant vegetation in HGM 2 included *Cyperus textilis*, *Cyperus fastigiatus*, *Phragmites australis, Phalaris arundinacea* and *Eleocharis limosa*. Dense reeds, such as the dominant vegetation found in HGM 2 may contribute to a higher frictional resistance to flowing water passing through the channelled valley-bottom wetland and thus allowing for a greater extent of the wetland in HGM 2 to attenuate floods. These findings regarding surface roughness in relation to HGM unit capabilities correspond with findings by Kotze *et al.* (2009).

5.2.1.4 Storm flow spread and frequency across the HGM unit

All three HGM units of the Wiesdrift Wetland experience a 1 to 5-year stormflow in which stormflows that are spread across all three HGM units may also influence sediment trapping (Kotze *et al*., 2009), and the regulating services strongly associated with the trapping of sediment and adsorbed phosphate on the Wiesdrift wetland. While stormflows may be experienced often by an HGM unit and are contained within the river channel, the effectiveness of the HGM unit in attenuating floods will be much lower and this can be expected for the three HGM units in the Wiesdrift wetland, based on the *WET-EcoServices* assessment (Kotze *et al*., 2009).

5.2.1.5 Sinuosity of the stream channel / flow patterns within the HGM unit

While stream sinuosity of the channel is categorised as moderately low, HGM 2 display characteristics of a moderately channelled wetland whereby low flows are predominantly confined to the main channel of the Nuwejaars River but some diffuse flows occur allowing for greater ability in trapping of sediment (Kotze *et al*., 2009). Whereas, the flow pattern of the floodplains in HGM 1 and HGM 3 can be described as strongly-channelled, with flows that are entirely confined to the main channel. Thereafter, the wetland stores water for longer allowing for chemicals and toxins to assimilate (Kotze *et al*., 2009). This may also be the case for phosphate to be trapped in sediment that are then deposited on the channel banks and become trapped in vegetation.

5.2.1.6 Representation of different hydrological zones

If a flood event occurs straight after one flood event ended on a wetland, then the capability of a wetland to contain flows from flood would be greatly lowered (McCartney, 2000). Thus a HGM unit that is dominated by areas that remain wet for most of the rainy season is more likely to be wet rather than dry zone with temporary rainfall.

HGM 1 and HGM 3 had a score of 3 which describes the hydrological zone as mix of seasonally and temporarily saturated soils, whereas HGM 2 has a hydrological zone dominated by seasonally saturated soils. Mottling found in the first 50 cm with an augur along Transect 2 in HGM 1 indicates that although the soil is dry at the time of assessment, it had been saturated for a long period quite recently (National Research Council, 1995). In addition, HGM 2 is occupied by dominant vegetation, such as *Cyperus textilis*, *Cyperus fastigiatus*, which are indicators of seasonally wet hydrological zones.

5.2.2 Sediment trapping and phosphate trapping

A slow runoff will allow for more time for sediment to be deposited or carried by runoff. If a wetland has a high ability to attenuate flood, it allows for sediment to be trapped by the wetland (Kotze *et al*., 2009).

Considering the average of the above-mentioned flood attenuating characteristics of HGM units 1, 2 and 3, the effectiveness of HGM 1 and HGM 3 is considered to be low, while HGM 2 has an intermediate effectiveness at attenuating floods. Therefore, the channelled valley-bottom wetland on the Wiesdrift wetland allow for trapping of sediment and adsorbed phosphates because it has a greater extent to attenuates floods.

If sediment can be observed during field data collection then it would show that the wetland vegetation is capable of trapping sediment (Kotze *et al*., 2009). Based on direct evidence of sediment deposition as an indication for the HGM ability to trap sediments (Kotze *et al*., 2009), the presence of mud cracks on AstroTurf mats proves that there has been definite sediment deposition on the mat, as well as direct deposition of sediment on surrounding vegetation can be seen for both HGM 1 and

HGM 2, however the extent to trap sediment is higher at HGM 2 because of low gradients and the high level of surface roughness due to the dense stands of reeds that offer resistance to flowing water.

While it is acknowledged that the pattern of low flows plays an important role in the deposition of sediment**,** sediments can be accompanied by toxic chemicals and nutrients making it crucial for wetlands to trap sediments and in turn remove pollutants that may pass through a wetland (Kotze *et al*., 2009). HGM 2 had an intermediate effectiveness in trapping sediment, while HGM 1 and HGM 3 have a moderately low effectiveness in trapping sediment. Therefore, it was expected that sediment and adsorbed phosphate found on the Wiesdrift wetland would be higher in HGM 2 than in HGM 1 and HGM 3.

5.3 Differences in the results of field survey and rapid assessment approaches

The phosphate determination by the molybdovanadate method determines phosphate directly as orthophosphate/reactive phosphorus, while the *WET-EcoServices* tool determines the wetland service delivery, such as the trapping of sediment and phosphate, based on effectiveness and opportunity scores.

Field survey results showed that orthophosphate concentrations are associated with fine sediment. Therefore, the orthophosphate concentrations follow the distribution of silt on the Wiesdrift wetland. This may be due to the channel landform and the presence of vegetation that occupies the banks of the Nuwejaars River channel. Similar characteristics played a role in the *WET-EcoServices* tool assessment, but characteristics were measured against a checklist.

Based on the results obtained for orthophosphate concentrations, using the *WET-EcoServices* rapid assessment tool, the effectiveness for the Wiesdrift wetland system to trap/remove phosphate by vegetation and fine sediment is more significant in the channelled-valley bottom wetland as opposed to floodplain wetlands upstream (closer to the inlet) and downstream (closer to the outlet) of the channelled valley-bottom wetland. Results from *WET-EcoServices* may not be a direct influence of the relationship between orthophosphates and fine sediment as it depends on the average score from on-site indicators such as hydrological zones, vegetation structure and soil texture/permeability. Consequently, the influence that fine sediment has on the distribution of orthophosphates can be affected by the supply scores based on HGM characteristics. The results of sediment-associated orthophosphate distribution are generally consistent with the findings from *WET-EcoServices (*Kotze *et al.*, 2009).

Chapter 6: Conclusion

6.1 Introduction

The results of this study confirm that both field survey and *WET-EcoServices* assessment and analysis of HGM characteristics, sediment load and texture, water velocity, floodplain morphology, vegetation cover and presence of wind erosion on the floodplain were the most important of the environmental variables measured accounting for the sediment and phosphate spatial distribution present in the Wiesdrift wetland system. A high level of phosphate concentration turnover is witnessed along the shallow gradient of the Wiesdrift Wetland and where high surface roughness occurs, with an existing relationship between fine sediment and orthophosphate concentrations observed in the Wiesdrift wetland. To an extent, the Wiesdrift wetland provides the potential to remove orthophosphates from water sources passing through it, although it is likely to vary from a long-term process perspective with variation in the flooding regime.

For future management implications based on *WET-EcoServices* opportunity scores (Figure 4.24), it is important to note that vegetation plays an important role in the trapping of sediment and associated nutrients, such as phosphate, thus clearing of vegetation for agricultural use, trampling by livestock while grazing and excessive burning, may cause a decrease in wetland vegetation cover and/or weakening in vegetation structure which will affect the delivery of ecosystem services provided by the Wiesdrift Wetland to attenuate floods, as well as store both sediment and phosphate. Where human-induced impacts in the catchment such as afforestation, alien infestation, abstraction for irrigation and the presence of dams occur, this could reduce the Wiesdrift Wetland's ability to attenuate floods. Flow regulation activities that reduce channel-floodplain connectivity may increase the rate of sediment and phosphate throughput, effectively bypassing the wetlands and posing a threat to important aquatic ecosystems downstream (e.g. Soetendalsvlei). In addition, reduced plant productivity will be as a result of reduced water inputs such that the uptake of dissolved phosphorus by plants will be reduced as well.

6.2 Limitations

Field sampling took place during a dry period, with limited overbank flow occurring. It is likely that this would have influenced the movement of sediment through the system, both within the channel (pipe-sampler results), and on the floodplain (AstroTurf mat sample results). Due to the low levels of rainfall received within the study area, a full data analysis for the suspended sediment samples were not possible as there was insufficient amount of sediment available to carry out phosphate analysis or particle size analysis. Further research would be needed to evaluate sediment-associated phosphate retention during wet periods of increased floodplain inundation. The results of this study provide some insight into dry period sediment dispersal, which is important for comparative purposes. On account of this, the dispersal of fine sediment is actually more complex than can be determined by a tool like *WET-EcoServices* because the *WET-EcoServices* assessment tool captures the long-term mean conditions of a wetland system (both dispersal and uptake of vegetation).

6.3 Recommendations

WET-EcoServices is useful as a rapid assessment tool, for applications that require information about the long-term general conditions of sediment and phosphate retention within a wetland, as well as required for accuracy assessments, verification of modelling data and systems dynamics. Some applications, such as the design of wetland rehabilitation interventions for sediment and phosphate removal, might require a greater level of detail, with frequent sampling campaigns, than that provided by the rapid assessment tool. The 'WET-EcoServices Version 2: A revised ecosystem services assessment technique' by Kotze *et al*., (2020) can be used for future research on wetland assessments. Understanding relationships between river channel planform/floodplain topography and sediment dispersal can assist in high-level assessments of sediment and phosphate trapping processes, thus further research is recommended.

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APPENDIX A: *Wet-EcoServices* assessment and floodplain characteristics

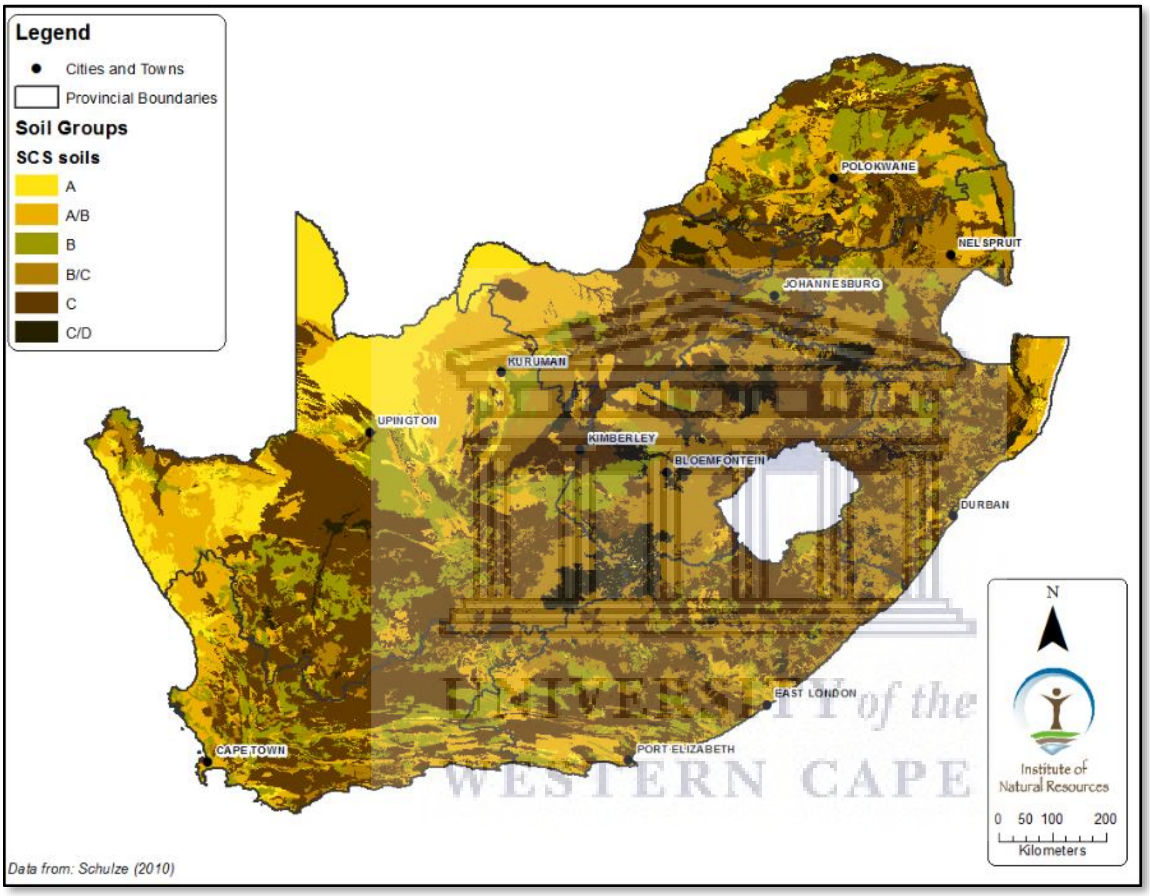
Table A1: Check sheet for Ecosystem Services (Kotze *et al*., 2009).

CATCHMENT CONTEXT OF THE ASSESSMENT UNIT **KEY: Upper Channel(U)/HGM 1, Middle Channel(M)/HGM2 and Downstream Channel (D)/HGM 3**					
CHARACTERISTICS SCORE:	**0**	**1**	**2**	**3**	**4**
EFFECTIVENESS OF THE HGM UNIT					
Size of the contributing upstream topographically-defined catchment.		Small local catchment (<10ha)	Moderately small upstream catchment (10-100ha)	Moderately large upstream catchment (100-1000ha).	**Large upstream catchment (>1000ha)**
Rationale: Whilst the importance of catchment size varies depending on the service being provided, wetlands with larger catchments are generally better located in terms of intercepting catchment runoff than headwater wetlands (Hansen et al. 2018). Thus, the size of the contributing upstream catchment is assumed to be relevant to all regulating services (except streamflow regulation, for which the relationship between catchment size and these services is poorly understood). Catchment size is also relevant to regulating services provided by riparian areas, although it is recognized that wetlands receive pollutants from the upstream catchment much more regularly than riparian areas which are typically only activated by flows from the main channel during high flow periods. Limitation: Note that this assessment is limited to the topographically defined catchment and therefore does not cater for water which is supplied by a regional aquifer that extends beyond the topographically defined catchment, e.g. as is common on coastal plain settings. As such, the benefit of wetlands in treating polluted water linked to any regionally connected groundwater source is not well addressed in this rapid method.					

Average slope of the Assessment unit's catchment	**Gentle gradient (<=10%); Low relief** **(U,M,D)**		**Moderate gradient (>10 – 20%); Moderate relief**		**Steep gradient (>20%); High relief**
Rationale. Given other factors being equal, the steeper the slope, the faster will be the runoff and the greater will be the runoff intensity, and therefore the greater will be the potential for floods and erosion. ***Method*.** Use a 1: 50 00 topographic map of the catchment to measure at least five to ten representative slopes in the catchment (depending on how heterogeneous the catchment) and calculate their average. Measure the horizontal distance between the lowest and highest contour on each slope and the vertical distance based on the number of contour lines in the slope and the contour interval, which in a 1: 50 000 scale map is 20 m. Remember that slope must be expressed as a percentage. For example, if the horizontal distance is 2000 m and the vertical distance is 60 m then the slope = 60 ÷ 2000 x 100% = 3%.					
Inherent runoff potential of the soils in the Assessment unit's catchment	**Low (A and A/B)**	**Mod low (B)**	**Moderate (B/C)** **(U, M, D)**	**Mod high (C)**	**High (C/D)**
Rationale: The higher the runoff potential of the soil, the slower will be the infiltration and the greater will be the runoff intensity (Schulze *et al.*, 1989). Changes in runoff intensity has implications for both flood attenuation and erosion control. *Method:* Use the following categories and consult the local Department of Agriculture office if you are unsure. Check also the Land Type Survey report for the area (e.g. Land Type Survey Staff, 1986) which includes data on soil texture. Refer to the map below showing the distribution of SCS Soil Groups A to D over South Africa at a spatial resolution of land type polygons (Schulze, 2010)					

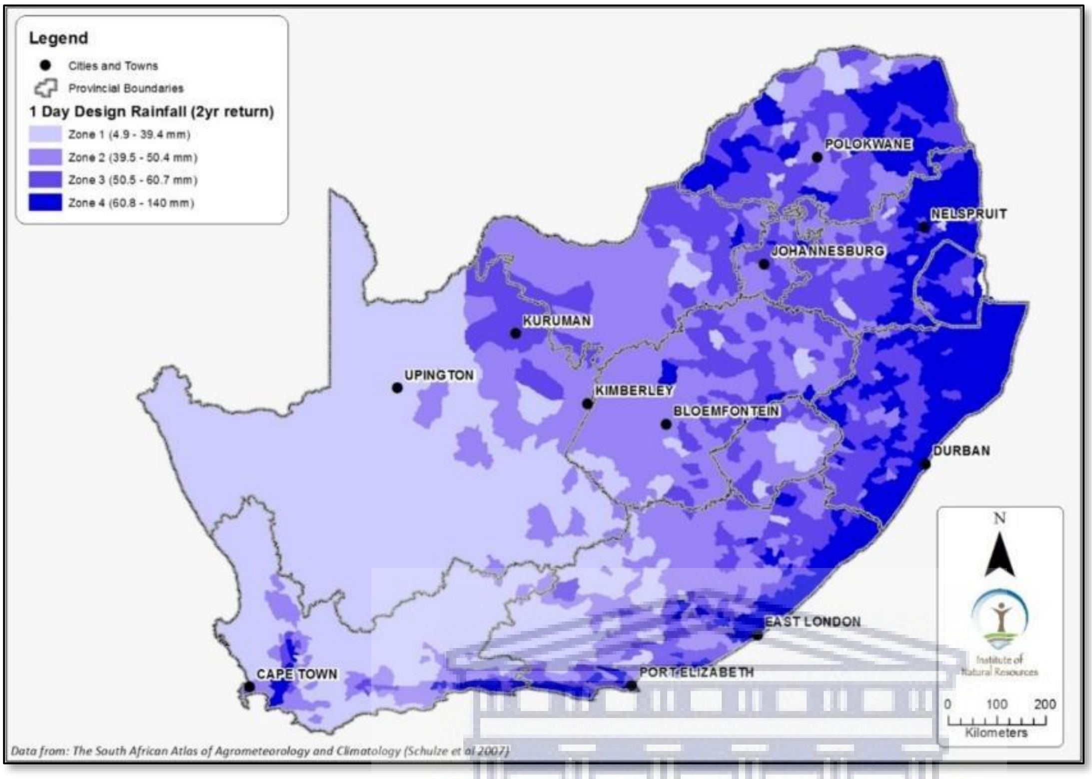
Low runoff potential	**Moderately low runoff potential**	**Moderately high runoff potential**	**High runoff potential**
Infiltration and permeability rates	Moderate infiltration rates, effective depth	Infiltration rate low. Permeability	Very slow infiltration and permeability rates. Clay soils

are high. Deep, well drained to excessively drained sands and gravels	and drainage. Moderately fine to moderately coarse textures. Permeability slightly restricted	restricted by layers that impede downward movement of water. Moderately fine to fine texture.	with high shrink/swell potential. Soils with permanent high water table or with clay pan or clay layer at or near surface or shallow soils over fairly impervious material.



Rainfall intensity	**Low (Zone 1) (U, M, D)**	**Moderately low (Zone 2)**		**Moderately high (Zone 3)**	**High (Zone 4)**
Rationale: Stormflows, which are directly relevant to flood attenuation and erosion control, result from rainfall. The rate or intensity of rainfall is usually more important than the total amount of rain. Rates are usually expressed in mm/hour(hr) or mm/24hr. From the map it can be seen that the level of intensity of storms varies widely across South Africa, from Rainfall zone 1 which has the lowest intensities to Rainfall zone 4 with the highest.					

Method: Determine the rainfall intensity zone based on the location of the wetland with reference to the adjacent map.



Rainfall intensity zones based on one day design rainfall over a two year return (adapted from Schulze, 2007 by Macfarlane and Atkinson 2015).

Contribution of catchment land-uses to increasing sediment inputs from the natural condition	Low	Mod low	Intermediate	**Mod high (U, M, D)**	High

Rationale: The greater the extent of catchment land-uses (e.g. cultivated lands and gravel roads) which increase sediment input in the Assessment unit's catchment and the closer these are located to the Assessment unit, the greater will be the likely increased supply of sediment to the Assessment unit. For example, where cultivated lands occupy 50% of the Assessment unit's catchment and some of these occur within 10 m of the Assessment unit the potential supply of sediment to the Assessment unit is likely to be high.

Method: Observe on maps and aerial photos and during the rapid visual appraisal the extent and location of sediment sources. Sources of sediment to consider include: cultivated lands, particularly those poorly conserved; actively eroding gullies and bare areas of veld, forestry plantations on steep slopes or where planting and extraction practices are poor; gravel roads, particularly where they are poorly designed. It is important that due account be taken of the effect that any dams may have in trapping the increased sediment if the dams are located between the sediment source and the Assessment unit. If a WET-Health assessment of the Assessment unit exists then refer to the end of the Water quality module to see the predicted degree to which suspended solids are likely to have been changed from the natural reference state of the Assessment unit.

Extent of phosphate sources in the assessment unit and associated catchment	Low	Mod low	Intermediate	**Mod high (U, M, D)**	High

Rationale: The greater the extent of phosphate sources (point source and non-point source) in the Assessment unit's catchment and the closer these are located to the Assessment unit, the greater will be the likely supply of phosphates to the unit and therefore the opportunity to enhance water quality (Adamus et al., 1987).

Method: Identify non-point sources of pollution by considering areas (>0.5 ha) of fertilized crop or pasture land, urban/industrial areas and areas (>0.5 ha) where the density of houses with septic tanks or pit latrines exceeds 6 houses per ha. Identify point sources by considering sewage or industrial outfalls, dairies, piggeries or feedlots. Speak to someone with good local knowledge about pollution sources, particularly point sources, which are often not visible on satellite images or aerial photographs or when the catchment is viewed from a distance. The local DWAS office may also have information concerning known pollution sources. If a WET-Health assessment of the Assessment unit exists then refer to the end of the Water quality module to see the predicted degree to which phosphates are likely to have been changed from the natural reference state of the Assessment unit.

Degree to which sediment, phosphates, nitrates &/or toxicants are intercepted by ecological infrastructure upslope/upstream of the Assessment unit		**High (U, M, D)**	Intermediate	Moderately low	Very low

Rationale: Upslope/upstream ecological infrastructure includes a vegetated buffer upslope of the Assessment unit and wetland/s and/or riparian areas upstream of the Assessment unit. Contaminant sources (including sediment, phosphates, nitrates & toxicants) lying upslope or upstream of the Assessment unit may potentially be intercepted by upslope/upstream ecological infrastructure, and the more extensive this ecological infrastructure, the greater its potential for interception of contaminants and therefore reducing the demand placed on the Assessment unit from a water quality enhancement perspective. However, it is very important to recognize that if contaminant loads are high, the ecological infrastructure is seldom able to achieve a high level of interception even when the extent of this infrastructure is high.

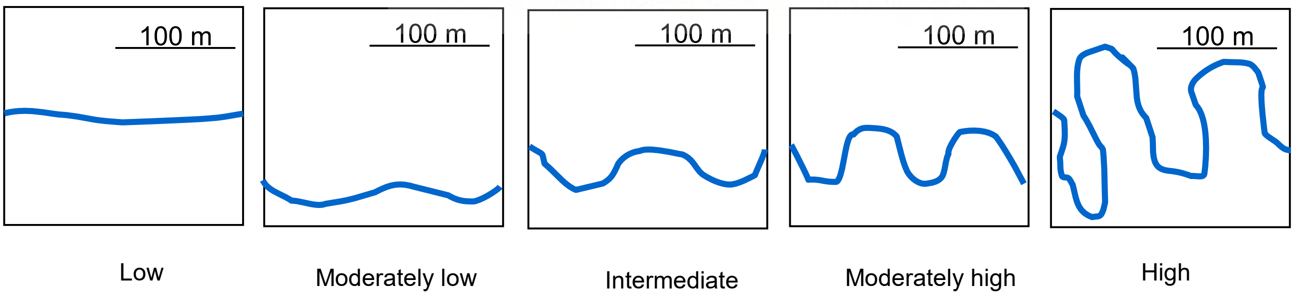
Method: Use recent satellite images or field observation to observe the extent of a vegetated buffer upslope of the Assessment unit and wetland/s and/or riparian areas upstream of the Assessment unit.

ON-SITE FEATURES OF THE ASSESSMENT UNIT

Sinuosity of the stream channel	Low	**Moderately low (U, M, L)**	Intermediate	Moderately high	High

Rationale: For a given longitudinal slope of the Assessment unit, the greater the sinuosity of the stream channel the more gentle the slope within the channel and therefore the slower will be the flow of water. This has implications for flood attenuation, sediment trapping and water quality enhancement.

Method: Identify based on interpretation of aerial photos which of the five sinuosity classes given below best describes the situation in the Assessment unit.



Note: Assessment units which do not have a channel should be scored the same as a High level of sinuosity

Flow patterns of low flows within the	**Strongly channelled: Low flows**	**Moderately channelled: Low flows predominantly**	Intermediate: Low flows approximately equally	Moderately diffuse: Flow is predominantly	Very diffuse: Flow is entirely or almost entirely diffuse, and if any

assessment unit	**entirely confined to a main channel** **(U,D)**	**confined to a main channel but some diffuse flow occurs, e.g. in weakly channelled sections of the unit** **(M)**	distributed as diffuse flow and within a channel	diffuse, but localized preferential flow path/s are evident	preferential flow paths are present they are very localised

Rationale: Much of a wetland's assimilation of pollutants, particularly those pollutants not carried by sediment, takes place during low flow periods. During these periods, waters are shallower and residency times in the wetland longer, which affords the wetland greater opportunity to assimilate pollutants contained in the water (Kadlec and Kadlec 1979; Hammer 1992). It is therefore important to determine this particular flow pattern. Some wetlands experience diffuse flow during both low flow and high flow periods, allowing for considerable contact. Conversely, other wetlands may experience diffuse flow under stormflow conditions but under low flow conditions water is contained within a small part of the wetland in the active channel, allowing for little contact between wetland and water. The flow pattern of low flows has implications for sediment trapping and water quality enhancement services.

Method: Determine the pattern of low flows based on field observation of landform, examination of aerial photos and local knowledge. In particular, take note of any stream channels, artificial drainage furrows, erosion gullies and other features which may confine low flows and therefore prevent these flows moving diffusely through the assessment unit. It is important to note that low flows refer not only to flows during the dry season but also to regular flows during the wet season, i.e. excluding stormflows. The active channel is the portion of a river/stream that is inundated at sufficiently regular intervals to maintain channel form (i.e. the presence of distinct bed and banks) and keep the channel free of terrestrial vegetation (Ollis et al. 2013). Active channels are typically filled during bankfull discharge (i.e. during the annual flood) except for intermittent rivers which do not flood annually (Ollis et al. 2013).

Current representation of different hydrological zones	Non-wetland	Dominated by temporarily saturated soils	**Mix of seasonally and temporarily saturated soils (U,D)**	**Dominated by seasonally saturated soils (M)**	Dominated by permanently saturated soils

Rationale: Hydrology is central to how wetlands and riparian areas function and supply services. Therefore the hydrological zones represented in the Assessment unit have a key influence over the supply of almost all regulating services considered, e.g. the assimilation of nitrates and toxicants and attenuation of floods, as well as some of the provisioning services, e.g. food for livestock. Method: It is very important to emphasize that the current situation is taken as that which occurs across all seasons in the year and not just as you see it on the particular day which you visit the wetland. The vegetation and the soil colour patterns should be examined as indicators of soil wetness over the seasons. The permanently saturated zone is typically dominated by tall sedges, reeds or bulrushes and the soils are typically grey, often with a sulphidic (rotton egg) smell. The seasonally saturated zone is typically dominated by medium height sedges and/or grasses and the soils are typically grey with many bright orange/yellow mottles, usually present close to the soil surface. The temporarily saturated zone is typically dominated by a mix of plants occurring predominantly outside of wetlands and hydric (water-loving) sedges and grasses, which are usually short growing. Non-wetland areas typically have brown soils and lack hydric plant species. It is important to also emphasize that the current situation may have been altered from the natural situation. For example, the area may have naturally been seasonally saturated, but drainage ditches or eucalypt trees in the unit have now reduced its level of wetness to temporary. In this case, the soils reflect the natural hydrological conditions under which they were historically formed rather than the current hydrological conditions. For more information refer to Kotze (1996) ["How wet is a wetland?"] and DWAF, 2006 [the DWAF guideline for delineating wetlands]). A soil auger and a Munsell colour chart will be required in order to examine colour patterns of the soil (e.g. purity of the colour and the presence of mottles) in the field as an indicator of hydrological zones.					
Frequency with which storm flows are spread across the Assessment unit		Never OR unit occurs within the active channel of a river (includes banks)	Occasionally but less frequently than every 5 years	**1 to 5 year frequency** **(U, D, M)**	**More than once a year** **(M)**

Rationale: The greater the frequency with which stormflows exceed the capacity of any channel/s passing through the Assessment unit and are spread across the Assessment unit, the greater will be the effectiveness of the Assessment unit in attenuating floods. Conversely, the greater the extent to which stormflows are contained within a channel passing through the Assessment unit, the lower will be the effectiveness of the Assessment unit in attenuating floods. The frequency with which stormflows are spread across the Assessment unit also influences sediment trapping, and the regulating services which are strongly associated with the trapping of sediment, e.g. phosphate removal.

Method: Use a rapid visual appraisal (look out for debris deposited by stormwater) and local knowledge. Pay particular attention to human modifications such as straightening, widening and deepening of the channel, and artificial levees, which serve to reduce the frequency with which flooding out of the channel takes place. Note also that incision of the natural stream channel may result in a floodplain/valley bottom no longer being actively flooded, even though the system developed under regular flooding in the past. In hillslope seepages and un-channelled valley bottoms, stormflows are generally spread across the unit, unless they have been cut off by human modifications.

Occurrence of depressions in the assessment unit	None	Present but few or remain permanently filled close to capacity	Intermediate	**Moderately abundant (U,D)**	**Abundant (M)**

Rationale: Depressions refer to hollows in the ground in which water may collect. Depressions are usually rounded in shape, but may also be elongate, as is characteristic of oxbow lakes. Depressions may greatly increase the detention storage capacity of the wetland, depending on the extent and depth of the depressions. However, those depressions that remain filled to near maximum capacity throughout the year are unlikely to retain floodwaters, even if deep. Thus, depressions primarily influence flood attenuation, and, in turn, sediment trapping, and the regulating services which are strongly associated with the trapping of sediment, e.g. phosphate removal.

Method: Determine the extent, depth and flooding history based on interpretation of maps, photos and/or satellite images, a rapid visual appraisal and on local knowledge.

Soil properties (permeability)	Very low: Fine textured soils with a hard surface or introduced hardened surfaces, e.g. tar roads	**Low: Fine textured sols with low permeability (e.g. clay loam and clay).** **(U, D)**	**Moderately low: Moderately fine textured soils (e.g. loam & sandy clay loam)** **(M)**	Moderate: Moderately textured soils (e.g. sandy loam) OR Shallow (<30cm) well-drained soils).	High: Deep (>30cm) well-drained soils (e.g. sand and loamy sand).

Rationale: Soil properties can have a bearing on the assessment unit's ability to attenuate floods, trap sediments and provide water quality enhancement services. In the case of flood attenuation and sediment trapping, soils with good drainage properties promote infiltration thus enhancing these services.

Method: Soil texture is used as the primary means of rating soil permeability, and for a rapid assessment this is approximated by wetting the soil and feeling it your hands to determine whether it is dominated by clay, sand or is an intermediate mix of the two, generally referred to as loam. It is important to note, however, that additional factors affect permeability. One of these is soil depth, with a slight refinement included in the assessment to cater for soils which are sandy and therefore have inherently high permeability but are shallow. The positive effects of vegetation on soil infiltration should also be acknowledged, including the following: (1) creation of soil pores as a result of root growth and (2) protecting the soil surface from raindrop impact, which would otherwise contribute to compaction of the soil surface and closure of natural soil pores. The score for fine textured soils may therefore be adjusted up by one class where vegetation is believed to have significantly improved infiltration rates.

Direct evidence of recent sediment deposition in the assessment unit	**Low** **(U, D)**	**Moderately low (M)**	Intermediate	Moderately high	High

Rationale: Direct evidence of sediment which has recently been deposited in the Assessment unit would indicate that the unit is currently trapping sediment. This has further implications for erosion control as well the regulating services which are strongly associated with the trapping of sediment, i.e. phosphate removal and toxicant removal.

<table>
<tr><td colspan="6">Method: Look for signs such as sediment which is covering plant litter or low growing plants. This may vary from a thin coating over the vegetation to complete burial of the vegetation. Look particularly in areas where there is a change from a steeper to a gentler slope and/or from channelled flow into diffuse flow. The occurrence of terrestrial and/or pioneer species may also alert you to areas where large amounts of sediment have been deposited.</td></tr>
<tr><td>Direct evidence of erosion in the assessment unit</td><td>High</td><td>Mod high</td><td>Intermediate</td><td>Mod low</td><td>Low
(U, M, D)</td></tr>
<tr><td colspan="6">Rationale: If there is currently a high level of active erosion in the assessment unit then this is taken as direct evidence that the unit is not effectively controlling erosion. It is, however, acknowledged that erosion may be an integral part of the natural dynamics of a wetland/riparian area, e.g. those characterized by geomorphological cycles of cut and fill, as described by Pulley et al. (2018).

Method: Use airphoto/satellite imagery interpretation to assist in the identification of erosion gullies and areas of bare soil. These should be checked in the field to see if there are signs of active erosion (e.g. sods of soil recently broken off the face of an erosion gully). The focus is on current erosion rather than erosion that occurred historically but which is now stable. If erosion observed in the Assessment unit is part of the natural dynamics of the unit and rather than from human impacts then omit this indicator. If a WET-Health assessment of the unit exists then refer to the Geomorphology module where the contribution of human impacts to erosion would have been assessed.</td></tr>
<tr><td>Extent of vegetation cover in the assessment unit</td><td>Low</td><td>Mod low</td><td>Intermediate</td><td>Mod high
(U, M, D)</td><td>High</td></tr>
<tr><td colspan="6">Rationale: Vegetation cover has important direct effects on wetland functioning, in particular by the protection it provides to the soil surface from erosion. In addition, it provides a course indicator of the extent to which the soil is occupied by roots, which in turn bind the soil and contribute to soil organic matter and microhabitat for microbes which assist in the assimilation of nitrates and toxicants.

Method: Cover refers to the extent of aerial cover over the entire year. Therefore it is best not to assess this indicator shortly after a fire as cover would have been temporarily reduced. Assign the assessment unit to one of the following five cover classes based on a visual appraisal of the canopy cover:</td></tr>
</table>

- Low cover: Predominantly bare soil; vegetation sparse or present for only short periods (i.e. periods less than 4 months)
- Moderately low cover: Partially covered with permanent vegetation but with extensive bare areas or predominantly well covered but with extended periods when predominantly bare soil (e.g. between establishment of annual crops)
- Intermediate: Reasonably well covered with permanent vegetation but with noticeable bare areas lacking vegetation
- Moderately high cover: Predominantly well covered with permanent vegetation but with small bare areas lacking vegetation (although aerial cover may be temporarily reduced following burning)
- High cover: Complete and permanent cover (although aerial cover may be temporarily reduced following burning)

Note: Even in a complete and permanent cover, there will often be a certain amount of bare ground visible, but this will be as many very small areas, generally less than 0.1 m^2.

Vegetation structure in terms of height and robustness	Very low	**Low (U, D)**	Intermediate	**High (M)**	Very high

Rationale: Vegetation structure is described primarily in terms of surface roughness, which is related to height and robustness of the vegetation. The greater the surface roughness of a wetland, the greater is the frictional resistance offered to the flow of water and the more effective the wetland will be in slowing down the movement of water through the wetland. This, in turn, contributes positively to attenuating floods and trapping sediment, together with phosphates and toxicants adsorbed to the sediment (Reppert et al., 1979; Adamus et al., 1987).

Method: Assign the assessment unit to one of the five classes below based on which class description best describes the situation in the unit. Note, sparse woody vegetation would generally be assigned to the Intermediate class. Where vegetation structure varies across the assessment unit, take the average condition. Where it varies during the year (e.g. in response to the growth cycles of plants) take the average condition during the wet season.

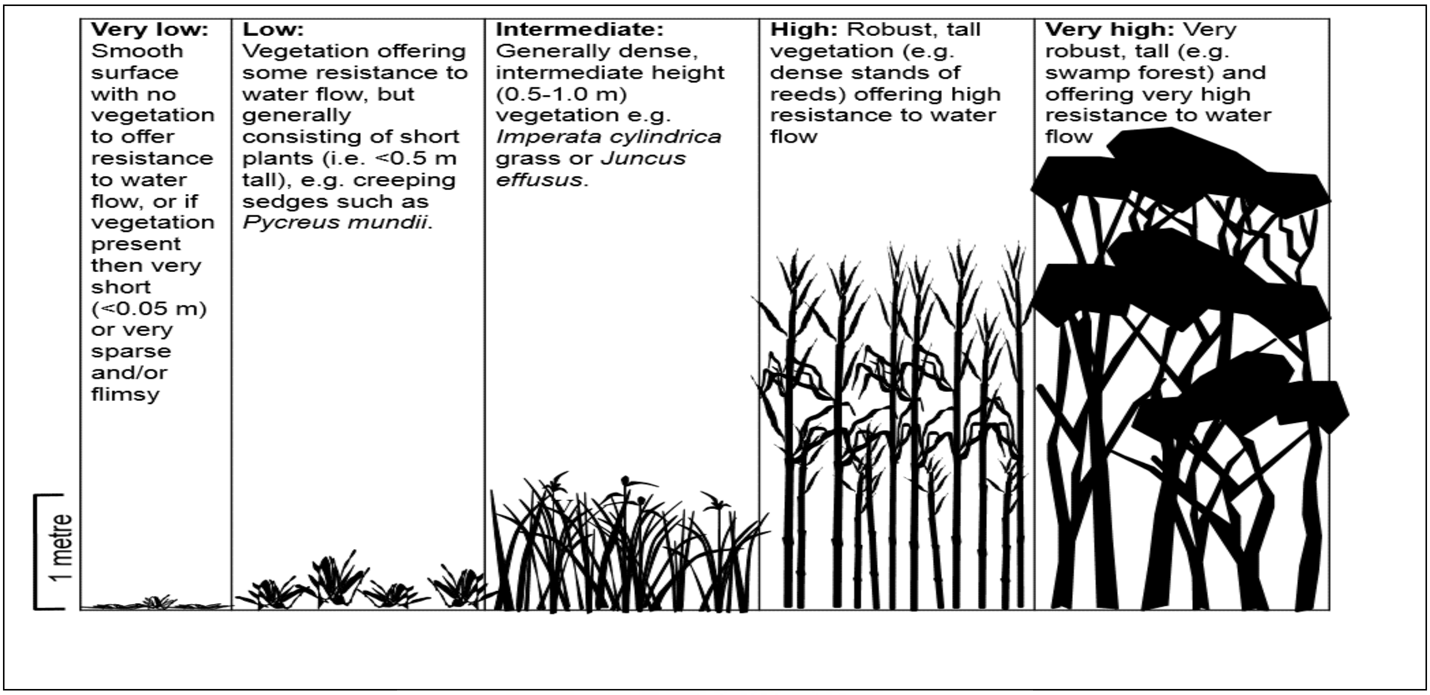

Very low: Smooth surface with no vegetation to offer resistance to water flow, or if vegetation present then very short (<0.05 m) or very sparse and/or flimsy
Low: Vegetation offering some resistance to water flow, but generally consisting of short plants (i.e. <0.5 m tall), e.g. creeping sedges such as *Pycreus mundii*.
Intermediate: Generally dense, intermediate height (0.5-1.0 m) vegetation e.g. *Imperata cylindrica* grass or *Juncus effusus*.
High: Robust, tall vegetation (e.g. dense stands of reeds) offering high resistance to water flow
Very high: Very robust, tall (e.g. swamp forest) and offering very high resistance to water flow
1 metre

Table A2: Characteristics assessed based on rationale and method that contribute to attenuation of floods (based from Kotze *et al*., 2009).

Effectiveness: Flood Attenuation	**Rationale**	**Method**
1. Size of HGM unit relative to the HGM unit's catchment	The larger the wetland relative to its catchment, the greater will be its potential influence on flood - flows.	The percentage area of the HGM unit's catchment occupied by the HGM unit = HGM unit area, in which the HGM unit's catchment area is multiplied by 100.
2. Slope of the HGM Unit	Given that the speed of water flow is directly influenced by slope, the more gentle the slope the greater will be the attenuating ability of the HGM unit.	The slope of the HGM unit should be expressed as a percentage (e.g. in a 1% slope for every 100m travelled horizontally, there is a vertical drop of 1m). Where slope varies across the HGM unit, take the average slope.
3. Surface Roughness of HGM Unit	The greater the surface roughness of a wetland, the greater is the frictional resistance offered to the flow of water and the more effective the wetland will be in attenuating the floods. The surface roughness of a wetland is	Thinking particularly in terms of the resistance offered to water flow by the vegetation, assign the HGM unit to one of the following classes:

	usually determined primarily by vegetation, but hummocks may also contribute significantly. Hummocks refer to small earth mounds covered in vegetation about 20-50cm in diameter and 50cm high, commonly found in wetlands at high altitudes (>1500m).	*Low:* smooth surface with little or no vegetation to offer resistance to water flow *Moderately low:* vegetation offering slight resistance to water flow, generally consisting of short plants (i.e. < 1m tall) *Moderately high:* robust vegetation (e.g. dense stand of reeds) or hummocks offering high resistance to water flow *High:* vegetation very robust (e.g. dense swamp forest) and offering high resistance to water flow *Note:* where roughness varies across the HGM unit, take the average condition.
4. Presence of depressions	Depressions (e.g. oxbow lakes) may greatly increase the detention storage capacity of the wetland,	Determine the extent, depth and flooding history based on

	depending on the extent and depth of the depressions. However, those depressions that remain filled to near maximum capacity throughout the year are unlikely to retain floodwaters, even if deep.	interpretation of maps and photographs, a rapid visual appraisal and on local knowledge.
5. **Frequency with which storm flows are spread across the HGM Unit**	The greater the frequency with which stormflows exceed the capacity of any channel/s passing through the HGM unit and are spread across the HGM unit, the greater will be the effectiveness of the HGM unit in attenuating floods. Conversely, the greater the extent to which stormflows are contained within a channel passing through the HGM unit, the lower will be the effectiveness of the HGM unit in attenuating floods.	Use a rapid visual appraisal (look out for debris deposited by storm water) and local knowledge. Check first if the wetland is connected to the drainage network. If not (i.e. the wetland is isolated from the drainage network, as is the case for many pans), then the wetland should not be considered to receive stormflows and should therefore score '0'. (Such isolated wetlands may nevertheless contribute indirectly to flood). If the HGM unit is connected, then consider the following features.

6. Sinuosity of the stream channel	For a given longitudinal slope of the HGM unit, the greater the sinuosity of the stream channel the more gentle the slope within the channel and therefore the slower will be the flow of water.	Identify based on interpretation of aerial photographs which of the five sinuosity classes given below best describes the situation in the HGM unit.
7. Representation of different hydrological zones	If a wetland is already flooded immediately before the arrival of a flood event, its capacity to detain these flows and thereby reduce the floodpeak would be lower than if the wetland were in a dry state. Thus, a HGM unit that is dominated by areas that remain wet for most of the rainy season (i.e. the permanent and seasonal zones) is more likely to be wet on the arrival of a flood event than a HGM unit which is dominated by the temporary zone.	Use effective indicators of long-term hydrology, namely soil and vegetation, because long-term data will generally be lacking. A soil auger and a Munsell colour chart will be required in order to examine colour patterns of the soil (e.g. purity of the colour and the presence of mottles) in the field as an indicator of long-term water regime.
Opportunity: Flood Attenuation	**Rationale**	**Method**

1. Average slope of the HGM unit catchment	Given other factors being equal, the steeper the slope, the faster will be the runoff and the greater will be the runoff intensity, and therefore the greater will be the potential for floods.	Use a 1: 50 00 topographic map of the catchment to measure at least five to ten representative slopes in the catchment (depending on how heterogeneous the catchment) and calculate their average. Measure the horizontal distance between the lowest and highest contour on each slope and the vertical distance based on the number of contour lines in the slope and the contour interval, which in a 1: 50 000 scale map is 20m. Remember that slope must be expressed as a percentage.
2. Inherent run-off potential of soils in the HGM unit's catchment	The higher the runoff potential of the soil, the slower will be the infiltration and the greater will be the runoff intensity	Determine runoff potential based on the following categories: • Low runoff potential: Infiltration and permeability rates are high. Deep, well drained to excessively drained sands and gravel.

		• Moderately low runoff potential: Moderate infiltration rates, effective depth and drainage. Moderately fine to moderately coarse textures. Permeability slightly restricted • Moderately high runoff potential: Infiltration rate low. Permeability restricted by layers that impede downward movement of water. Moderately fine to fine texture. • High runoff potential: Very slow infiltration and

		permeability rates. Clay soils with high shrink/swell potential. Soils with permanent high water table or with clay pan or clay layer at or near surface or shallow soils over fairly impervious material.
3. Contribution of catchment land-uses to changing runoff intensity from the natural condition	Land-use factors may have a very important influence on runoff intensity (Schulze, et al., 1989). Several land-use factors may increase runoff intensity: Poor conservation practices in cultivated lands (e.g. lack of contour tillage and contour banks, soil compaction) decrease infiltration and increase surface runoff, thereby increasing runoff intensity, while good conservation practices tend to prevent this. Poor veld condition diminishes infiltration and increases runoff intensity compared with natural	*For factors increasing runoff intensity:* examine the National Landcover data for the catchment (particularly in the case of large catchments not readily visible from the HGM unit during the field assessment) or undertake a reconnaissance in the field to identify land-uses such as those described above which decrease infiltration. *For factors decreasing runoff intensity:* look out for dams, particularly those which remain at a relatively low level for most of

	good condition veld. Hardened surfaces in the catchment resulting from buildings, roads, footpaths, parking lots and other such developments. The greater the extent of hardened surfaces, the smaller the area available for infiltration to take place and the greater the runoff intensity will be. If hardened surfaces are extensive, the effect will be considerable. Most industrial and commercial areas have a high extent of hardened surfaces due to the large buildings and their roofs and extensive roads and parking lots. Factors which may reduce runoff intensity include dams, particularly if they remain at relatively low levels for much of the time, and flood retention basins.	the time, and flood retention structures.

4. Rainfall intensity	Stormflows result from rainfall, with the rate or intensity of rainfall usually being more important than the total amount of rain. Rates are usually expressed in mm/hour(hr) or mm / 24hr. From the map it can be seen that the level of intensity of storms varies widely across South Africa, from Rainfall Zone I which has the lowest intensities to Rainfall Zone IV with the highest.	Determine the rainfall intensity zone based on the location of the wetland with reference to the adjacent map.

Table A3: Characteristics assessed based on rationale and method that contribute to sediment trapping (based from Kotze et al., 2009).

Effectiveness: Sediment trapping	Rationale	Method
1. Effectiveness of HGM unit in attenuating floods	The greater the extent to which sediment-laden runoff is slowed down, the greater will be the extent of deposition of the sediment carried by the runoff. Thus the greater the extent to which a wetland attenuates	Calculate the average for characteristics 1 to 7 of Table 4.1 to determine effectiveness in attenuating floods.

	floods (e.g. through high surface roughness), the more effective it will be in trapping sediment.	
2. Direct evidence of sediment deposition in the HGM unit	Direct evidence of sediment deposition would indicate that the HGM unit is currently trapping sediment.	Look for signs such as sediment deposited on litter or low growing plants. Look particularly in areas where there is a change from a steeper to a gentler slope and/or from channelled flow into diffuse flow. The occurrence of terrestrial and/or pioneer species may also alert you to areas where large amounts of sediment have been deposited.
Opportunity: Sediment trapping	**Rationale**	**Method**
1. Extent to which dams are reducing the input of sediment to the HGM unit	The greater the extent of dams and other structures in the HGM unit's catchment which act to detain sediment that would otherwise reach the wetland, the more limited would be the opportunity	Observe on maps and aerial photographs and during the field assessment the location of dams' in relation to the HGM unit. Now select that class given below which best describes the situation

	for the wetland to receive and trap sediment.	in the wetland's catchment in terms of the dams' effect in reducing sediment inputs.
2. Extent of sediment sources (i.e. disturbed or un-vegetated areas) delivering sediment to the HGM unit from its catchment	The greater the extent of sediment sources (e.g. cultivated lands and gravel roads) in the HGM unit's catchment and the closer these are located to the HGM unit, the greater will be the supply of sediment to the HGM unit. For example, where sediment sources occupy 50% of the HGM unit's catchment and some of these occur within 10 m of the HGM unit the potential supply of sediment to the HGM unit is likely to be high.	Observe on maps and aerial photographs and during the rapid visual appraisal the extent and location of sediment sources. Sources of sediment to consider include: cultivated lands, particularly those poorly conserved; actively eroding gullies and bare areas of veld, forestry plantations on steep slopes or where planting and extraction practices are poor; gravel roads, particularly where they are poorly designed. It is important that due account be taken of the effect that any dams may have in trapping the increased sediment if the dams are

		located between the sediment source and the wetland.
3. Presence of any important wetland or aquatic system downstream	If a wetland were providing any ecological service related to water supply and water quality (including sediment, phosphates, nitrates and toxicants), then this service would be of added value if there were an important downstream wetland or aquatic system benefiting from the service. The downstream system (including natural systems as well as storage dams) may be considered important for several reasons, including maintenance of biodiversity and the supply of water for human use.	Seek any important wetland or aquatic system for 8 km downstream of the HGM unit if the HGM unit's catchment is less than 5000 ha and if greater than 5000 ha then continue for 16 km downstream. Contact the relevant provincial nature conservation organization for information on wetlands and aquatic systems considered important for biodiversity conservation for the province or at a national level. Contact DWAF for information on aquatic systems important for human use.

Table A4: Characteristics assessed based on rationale and method that contribute to phosphate trapping (based from Kotze et al., 2009).

Effectiveness: Phosphate trapping	Rationale	Method

1. Effectiveness in trapping sediment	Phosphates and many toxicants are absorbed to sediments. Thus, the greater the extent to which wetlands traps new sediment, the greater will be the extent to which the wetland removes these associated pollutants. Phosphates are much less mobile than nitrogen in both the aerobic and anaerobic states, and therefore much less vulnerable to leaching. Although remobilisation of phosphorus may occur following inundation, which results in the development of anaerobic conditions, the phosphorus tends to soon become absorbed again (e.g. to iron hydroxides that form under anaerobic conditions).	Effectiveness in trapping sediment is the average of Characteristics 1 and 2 of Table 4.
2. Pattern of low flows within the HGM Unit	Much of assimilation by wetlands of pollutants, particularly those pollutants not carried by sediment,	Pattern of flows based on field observation of landform,

	takes place during low flow periods. During these periods, waters are shallower and residency times in the wetland longer, which affords the wetland greater opportunity to assimilate pollutants contained in the water. It is therefore important to determine this particular flow pattern. Some wetlands experience diffuse flow during both low flow and high flow periods, allowing for considerable contact. Conversely, other wetlands may experience diffuse flow under stormflow conditions but under low flow conditions water is contained within a small part of the wetland in the channel, allowing for little contact between wetland and water.	examination of aerial photographs and local knowledge.

3. Extent of vegetation cover	Vegetation cover is taken as a coarse indicator of above- and below-ground living biomass. The greater the biomass, the greater will be the provision of microhabitat and organic matter critical for soil microbes involved in the assimilation of nitrates, phosphates and toxicants. In addition, the greater the vegetation biomass, the greater will be the potential of the wetland to assimilate nitrates and phosphates through direct assimilation by the plants. It is recognized, however, that at the end of the growing season significant amounts of nutrients taken up by the plants may be lost through litterfall and subsequent leaching, although this is limited by the translocation of	HGM unit is assigned to one of the following five cover classes based on a visual appraisal of the canopy cover: Low cover: Predominantly bare soil; vegetation sparse or present for only short periods (i.e. periods less than 4 months), Moderately low cover: Partially covered with vegetation on a permanent basis or predominantly well covered but with brief periods when predominantly bare soil (e.g. when preparing for planting an annual pasture), Intermediate: Reasonably well covered with permanent vegetation but with noticeable bare areas lacking vegetation, moderately high cover: Predominantly well covered with permanent vegetation but with

	nutrients to the below-ground storage portions of the plant.	small bare areas lacking vegetation (although aerial cover may be temporarily reduced following burning) and, high cover: complete and permanent cover (although aerial cover may be temporarily reduced following burning).
Opportunity: Phosphate trapping	**Rationale**	**Method**
1. Level of sediment input	Sediment reduces the quality of water and provides sites of attachment for other pollutants, particularly phosphate and certain toxicants. Therefore, the greater the level of sediment input from the HGM unit's catchment, the greater will be the opportunity for the HGM unit to enhance water quality. In addition, the greater the extent of sediment sources (e.g. cultivated	Maps and aerial photographs were observed during the rapid visual appraisal the extent and location of sediment sources. Sources of sediment to consider include: cultivated lands, particularly those poorly conserved; actively eroding gullies and bare areas of veld, forestry plantations on steep slopes or where planting and extraction practices are poor; gravel roads,

	lands and gravel roads) in the HGM unit's catchment and the closer these are located to the HGM unit, the greater will be the supply of sediment to the HGM unit. For example, where sediment sources occupy 50% of the HGM unit's catchment and some of these occur within 10 m of the HGM unit the potential supply of sediment to the HGM unit is likely to be high.	particularly where they are poorly designed.
2. Extent of potential sources of phosphate in the HGM units catchment	The greater the extent of phosphate sources (point source and non-point source) in a wetland's catchment, the higher the likelihood that phosphate may be a problem in the river system, and the greater will be the opportunity for the wetland to trap these elements and therefore enhance water quality.	Identify non-point sources of pollution by considering areas (>0.5 ha) of fertilized crop or pasture land, areas (>0.5 ha) where the density of houses with septic tanks or pit latrines exceeds 6 houses per ha. Identify point sources by considering sewage or industrial outfalls, dairies, piggeries or feedlots. Contact

		your local DWAF office concerning known pollution sources.

Table A5: Field observations during field campaign 1 and 2

Mat No.	Dominant Vegetation	Surface Roughness	Soil texture/Permeability	Characteristics	Use/Not use for Analysis
Inlet					
1 2	*Cyperus textis, Stenotaphrum secundatum and Hemathria altissma*	Low	Sandy loam/Moderate	Is placed along a higher bank than mats 6 - 10	Use for analysis
3 4 5	*Salicorna* sp., *Sporobolus Virginia and Triglochin* sp.				
6 7 8 9 10	*Cyperus textilis, Stenotaphrum secundatum and Juncus kraussii*	Intermediate	Sandy loam/ Moderate	No signs of overbank activity, but shows some sign of wind-blown sediment	Use for analysis
Between Inlet and Mid-Channel					
11 12 13 14	*Cyperus textilis, Cyperus fastigiatus, Phragmites australis and Phalaris arundinacea*	Intermediate	Loam/ Moderately low	Signs of floodout, signs of sediment deposition and presence of alluvial wedge	Use for analysis
15	*Eleocharis limosa*				
16	*Cyperus textilis, Cyperus fastigiatus and Phragmites australis*	Low	Cemented Alluvium/Low	No plastic found under mat	Use for analysis
17	*Cliffortia strobilifera*				Use for analysis
18	Cyperus textilis, Cyperus fastigiatus and Phragmites australis			Have been blown over by wind	Exclude from analysis
19	*Searsia and Elegia tectorum*			Have been blown over by wind	Exclude from analysis

20	*Sporobolus virginicus and Elegia tectorum*				Use for analysis
Mid-Channel					
21	*Cyperus textilis, Cyperus fastigiatus and Phragmites australis*	Intermediate	Sandy loam/moderate	Deposition present and mat was buried by surrounding plants	Use for analysis
22	*Cyperus textilis and Helichrysum*	Intermediate	Loam		
23	*Eleocharis limosa*	Low	Loam		
24	*Salicornia* sp.	Low	Clay loam		
25	*Eleocharis limosa and Agrostis* sp.	Low	Loam/clay loam	Could not be located, mat may have been blown away	Exclude from analysis
26	*Cyperus textilis and Phragmites australis*	Intermediate	Sandy loam/moderate		Use for analysis
27	*Cyperus* sp.				
28	*Salicornia* sp. *and Sporobolus virginicus*	Low	Cemented Alluvium/Low	Mat found blown over	Exclude from analysis
29	*Vygie*	Very low			Use for analysis
30	*Sporobolus virginicus and Eleocharis limosa*	Low			
Between Mid-Channel and Outlet					
31	*Cliffortia strobilifera and Elegia tectorum*	Intermediate	Loam		Use for analysis
32	*Juncus kraussii, Elegia tectorum and Diplachne fusca*	Intermediate	Loam		Use for analysis
33	*Diplachne fusca*	Low	Sandy loam		Use for analysis
34	*Elegia tectorum and*	Low		Has been blown out and blown by wind	Exclude from analysis

	Diplachne fusca				
35	*Salicornia* sp.	Very low			
36	*Hemarthria altissima, Cliffortia strobilifera and Phragmites australis*	Intermediate	Loam	Presence of deposition on the mat, bark from surrounding plants found on the mat	Use for analysis
37	*Phragmites australis*		Loam	Signs of flooding over the mat, bark from surrounding plants found on the mat	Use for analysis
38	*Phragmites australis and Juncus kraussii*		Sandy loam	Mat was surrounding old channel, bark from surrounding plants found on the mat	Use for analysis
39				Mat had moved location, found ripped out due to windy conditions, found without plastic and was not pegged into the ground	Exclude from analysis
40	*Eleocharis limosa and Agrostis* sp.	Very low	Loam		Use for analysis
41	*Cynodon dactylon*	Low	Loam		Use for analysis
42	*Cynodon dactylon and Eleocharis limosa*	Low	Loam	Mole hill partially collapsed next to mat	Use for analysis
43	Cynodon dactylon and Juncus kraussii	Low	Loam		Use for analysis
44	*Salicornia* sp., *Triglochin bulbosa and Sporobolus virginia*	Very low	Clay loam		

45	*Diplachne fusca and Eleocharis limosa*	Low			
46	*Cyperus textilis, Phragmites australis and Helichrysum*	High	Sandy loam		Use for analysis
47	*Cyperus textilis and Phragmites australis*	High	Loam		Use for analysis
48	*Cyperus textilis, Phragmites australis and Helichrysum*	High	Loam	Mat found with one flap over covering the mat	Use for analysis
49	*Stenotaphrum secundatum*	Low		Mat found lying upside down	Exclude from analysis
50	*Eleocharis limosa and Elegia tectorum*	Intermediate	Silty loam/partially cemented		Use for analysis
Outlet					
51	*Typha capensis, Cyperus textilis and Cyperus fastigiatus*	High	Loam		Use for analysis
52	*Cyperus textilis, Cyperus fastigiatus and Phragmites australis*	High	Clay loam	Evidence of sediment deposition as there is presence of sediment deposited on surrounding vegetation, sediment deposited well on mat	Use for analysis
53	*Cyperus textilis and Phragmites australis*	High	Loam to clay loam		Use for analysis
54	*Typha capensis, Bolboschoenus*	High	Loam to clay loam	Mat flipped over, mottling in the soil	Exclude from analysis

	maritimus and Cyperus textilis			shows that there is iron oxide along the channel	
55				Mat could not be located	Exclude from analysis
56	*Typha capensis and Eleocharis limosa*	High		Mat has been trampled by animal	Exclude from analysis
57	*Cyperus textilis and Phragmites australis*	High		Mat could not be located	Exclude from analysis
58	*Cyperus textilis and Phragmites australis*	High		Mat could not be located	Exclude from analysis
59	*Typha capensis and Cyperus textilis*	High		Signs of floodover	Use for analysis
60	*Typha capensis and Cyperus textilis*	High		Presence of mud cracks on mat proves that there has been definite sediment deposition on the mat, as well as direct deposition on surrounding vegetation	Use for analysis

APPENDIX B: Particle Size Analysis Results

Table B1: Sample analysis results derived from (Pario) Particle Size Analyser

Sample	Total dry weight for PARIO (g)	Mass of particles in PARIO (g)	Mass of dispersant in PARIO (g)	Silt (%)	Sand (%)
1	30.09	29.60	2.446	2	98
2	30.03	29.11	0.5	2	98
3	30.00	27.21	0.5	3	97
4	30.06	27.76	0.5	4	96
5	30.02	24.84	0.5	5	95
6	30.00	23.11	0.5	10	90
7	30.02	29.00	0.5	2	98
8	30.03	29.15	0.5	2	98
9	30.01	26.12	0.5	6	94
10	30.00	26.92	0.5	3	97
11	30.00	23.03	0.5	4	96
12	30.01	25.27	0.5	3	97
13	30.00	24.75	0.5	2	98
14	30.00	21.44	0.5	7	93
15	30.01	23.68	0.5	5	95
16	30.01	16.94	0.5	14	86
17	30.01	23.44	0.5	7	93
18	30.01	22.69	0.5	3	97
19	30.00	21.16	0.5	10	90
20	30.01	17.62	0.5	15	85
21	30.00	11.77	0.5	20	80
22	30.00	18.38	0.5	10	90
23	30.00	24.60	0.5	10	90
24	30.01	9.24	0.5	24	76
25	30.00	9.91	0.5	30	70
26	30.00	17.10	0.5	21	79
27	30.00	10.41	0.5	29	71.00
28	30.00	24.17	0.5	6	94.00
29	30.01	27.96	0.5	3	97
30	30.00	26.15	0.5	5	95.00
31	30.01	19.97	0.5	5	95.00
32	30.00	11.62	0.5	11	89.00
33	30.00	10.65	0.5	19	81.00
34	30.01	16.40	0.5	18	82.00
35	30.00	13.74	0.5	28	72.00
36	30.01	19.67	0.5	14	86.00
37	30.00	17.87	0.5	12	88.00
38	30.01	27.53	0.5	11	89.00

39	30.01	27.04	0.5	13	87.00
40	30.00	27.36	0.5	13	87.00
41	30.01	20.47	0.5	11	89.00
42	30.01	15.85	0.5	11	89.00
43	30.01	23.71	0.5	9	91.00
44	30.01	23.01	0.5	7	93.00
45	30.00	24.65	0.5	10	90.00
46	30.00	17.41	0.5	21	79.00
47	30.01	21.78	0.5	15	85.00
48	30.00	14.19	0.5	23	77.00
49	30.00	19.35	0.5	15	85.00
50	30.00	20.03	0.5	18	82.00
51	30.00	13.67	0.5	15	85.00
52	30.01	13.82	0.5	30	70.00
53	30.00	6.55	0.5	28	72.00
54	30.01	23.73	0.5	23	77.00
55	30.00	24.25	0.5	12	88.00
56	30.00	28.90	0.5	1	99.00
57	30.00	10.58	0.5	26	74.00
58	30.01	16.20	0.5	22	78.00
59	30.00	26.56	0.5	2	98.00
60	30.00	23.60	0.5	13	87.00
61	30.00	18.19	0.5	31	69.00
62	30.00	23.04	0.5	21	79.00
63	30.01	15.63	0.5	29	71.00
64	30.01	17.32	0.5	27	73.00
65	30.00	15.63	0.5	32	68.00
66	30.00	13.70	0.5	37	63.00
67	30.00	22.63	0.5	9	91.00
68	30.00	20.25	0.5	12	88.00
69	30.00	19.75	0.5	20	80.00
70	30.00	20.63	0.5	16	84.00

APPENDIX C: Orthophosphate Analysis Results

Table C1: Extractable orthophosphate concentrations for grabbed channel bed, floodplain and mat samples

Sample	Label	Sediment Mass (grams)	Sediment Mass (kg)	Volume of extract (L)	Orthophosphate/Reactive P Conc.(mg/L)	Extractable Orthophosphate Conc. (mg/kg)
1	WWxs1 inlet bed 1	0.501	0.000501	0.2	2.1	838.3233533
2	WWxs1 inlet bed 2	0.506	0.000506	0.2	3.1	1225.296443
3	WWxs2 bed 1	0.502	0.000502	0.2	9.9	3944.223108
4	WWxs2 bed 2	0.505	0.000505	0.2	11.1	4396.039604
5	WWxs3 midbed 1	0.504	0.000504	0.2	10.7	4246.031746
6	WWxs3 midbed 2	0.501	0.000501	0.2	16.4	6546.906188
7	WWxs4 bed 1	0.502	0.000502	0.2	3.4	1354.581673
8	WWxs4 bed 2	0.505	0.000505	0.2	3.4	1346.534653
9	WWxs5 outlet bed 1	0.502	0.000502	0.2	8.1	3227.091633
10	WWxs5 outlet bed 2	0.503	0.000503	0.2	7.4	2942.345924

11	WW 1	0.501	0.000501	0.2	23.7	9461.077844
12	WW 2	0.506	0.000506	0.2	12.1	4782.608696
13	WW 3	0.503	0.000503	0.2	17.2	6838.966203
14	WW 4	0.503	0.000503	0.2	33.7	13399.60239
15	WW 5	0.5	0.0005	0.2	19.8	7920
16	WW 6	0.507	0.000507	0.2	41.5	16370.80868
17	WW 7	0.508	0.000508	0.2	22.4	8818.897638
18	WW 8	0.502	0.000502	0.2	29.9	11912.3506
19	WW 9	0.508	0.000508	0.2	25.8	10157.48031
20	WW 10	0.507	0.000507	0.2	32.2	12702.16963
21	WW 11	0.501	0.000501	0.2	60.4	24111.77645
22	WW 12	0.507	0.000507	0.2	34.2	13491.12426
23	WW 13	0.507	0.000507	0.2	14.5	5719.921105
24	WW 14	0.508	0.000508	0.2	65.6	25826.77165
25	WW 15	0.508	0.000508	0.2	76	29921.25984
26	WW 16	0.505	0.000505	0.2	47.9	18970.29703
27	WW 17	0.506	0.000506	0.2	70.3	27786.56126

28	WW 18	0.502	0.000502	0.2	47.1	18764.94024
29	WW 19	0.502	0.000502	0.2	6.4	2549.800797
30	WW 20	0.503	0.000503	0.2	14.1	5606.361829
31	WW 21	0.504	0.000504	0.2	20.9	8293.650794
32	WW 22	0.504	0.000504	0.2	78.2	31031.74603
33	WW 23	0.503	0.000503	0.2	61.6	24493.04175
34	WW 24	0.504	0.000504	0.2	31.2	12380.95238
35	WW 25	0.505	0.000505	0.2	50.1	19841.58416
36	WW 26	0.508	0.000508	0.2	22	8661.417323
37	WW 27	0.508	0.000508	0.2	36.6	14409.44882
38	WW 28	0.502	0.000502	0.2	3.6	1434.262948
39	WW 29	0.503	0.000503	0.2	7.5	2982.107356
40	WW 30	0.507	0.000507	0.2	5.5	2169.625247
41	WW 31	0.503	0.000503	0.2	17.4	6918.489066
42	WW 32	0.502	0.000502	0.2	35.8	14262.94821
43	WW 33	0.506	0.000506	0.2	17.7	6996.047431
44	WW 34	0.504	0.000504	0.2	15.8	6269.84127

45	WW 35	0.501	0.000501	0.2	15	5988.023952
46	WW 36	0.503	0.000503	0.2	30.4	12087.47515
47	WW 37	0.502	0.000502	0.2	18.2	7250.996016
48	WW 38	0.507	0.000507	0.2	34.3	13530.57199
49	WW 39	0.507	0.000507	0.2	26.4	10414.20118
50	WW 40	0.504	0.000504	0.2	26.4	10476.19048
51	WW 41	0.506	0.000506	0.2	38.6	15256.917
52	WW 42	0.504	0.000504	0.2	51	20238.09524
53	WW 43	0.5	0.0005	0.2	78.3	31320
54	WW 44	0.505	0.000505	0.2	14.5	5742.574257
55	WW 45	0.508	0.000508	0.2	12	4724.409449
56	WW 46	0.5	0.0005	0.2	5.6	2240
57	WW 47	0.5	0.0005	0.2	68.6	27440
58	WW 48	0.505	0.000505	0.2	45.6	18059.40594
59	WW 49	0.508	0.000508	0.2	14.3	5629.92126
60	WW 50	0.506	0.000506	0.2	16.2	6403.162055
61	WW 51	0.506	0.000506	0.2	27.8	10988.14229
62	WW 52	0.501	0.000501	0.2	13.8	5508.982036

63	WW 53	0.506	0.000506	0.2	42.3	16719.36759
64	WW 54	0.503	0.000503	0.2	30.1	11968.19085
65	WW 55	0.506	0.000506	0.2	40.2	15889.32806
66	WW 56	0.502	0.000502	0.2	48.6	19362.5498
67	WW 57	0.506	0.000506	0.2	16.3	6442.687747
68	WW 58	0.507	0.000507	0.2	24.1	9506.903353
69	WW 59	0.501	0.000501	0.2	21.9	8742.51497
70	WW 60	0.501	0.000501	0.2	15.3	6107.784431
71	Mat 1	0.502	0.000502	0.2	17.1	6812.749004
72	Mat 2	0.501	0.000501	0.2	5.4	2155.688623
73	Mat 3	0.5	0.0005	0.2	5.6	2240
74	Mat 4	0.502	0.000502	0.2	3.9	1553.784861
75	Mat 5	0.502	0.000502	0.2	6.1	2430.278884
76	Mat 6	0	0	0.2	0	N/A
77	Mat 7	0	0	0.2	0	N/A
78	Mat 8	0	0	0.2	0	N/A
79	Mat 9	0	0	0.2	0	N/A
80	Mat 10	0.502	0.000502	0.2	12.4	4940.239044
81	Mat 11	0.503	0.000503	0.2	48.6	19324.05567
82	Mat 12	0	0	0.2	0	N/A

83	Mat 13	0.502	0.000502	0.2	10.8	4302.788845
84	Mat 14	0.5	0.0005	0.2	67.8	27120
85	Mat 15	0.501	0.000501	0.2	75.3	30059.88024
86	Mat 16	0.503	0.000503	0.2	67.9	26998.01193
87	Mat 17	0	0	0.2	0	N/A
88	Mat 20	0.502	0.000502	0.2	8.9	3545.816733
89	Mat 21	0.502	0.000502	0.2	28.1	11195.21912
90	Mat 22	0	0	0.2	0	N/A
91	Mat 23	0	0	0.2	0	N/A
92	Mat 24	0.502	0.000502	0.2	33.1	13187.251
93	Mat 26	0.503	0.000503	0.2	28.1	11172.96223
94	Mat 27	0.505	0.000505	0.2	51.7	20475.24752
95	Mat 29	0.501	0.000501	0.2	6	2395.209581
96	Mat 30	0.5	0.0005	0.2	5.8	2320
97	Mat 32	0.501	0.000501	0.2	26.7	10658.68263
98	Mat 33	0.501	0.000501	0.2	15.8	6307.38523
99	Mat 34	0.503	0.000503	0.2	14	5566.600398
100	Mat 36	0.502	0.000502	0.2	20.3	8087.649402
101	Mat 37	0.503	0.000503	0.2	34.9	13876.73956
102	Mat 38	0	0	0.2	0	N/A

103	Mat 40	0.506	0.000506	0.2	32.6	12885.37549
104	Mat 42	0.501	0.000501	0.2	27	10778.44311
105	Mat 43	0.502	0.000502	0.2	72	28685.25896
106	Mat 44	0.508	0.000508	0.2	6.4	2519.685039
107	Mat 46	0.501	0.000501	0.2	16.4	6546.906188
108	Mat 50	0.505	0.000505	0.2	15.2	6019.80198
109	Mat 51	0.501	0.000501	0.2	32.9	13133.73253
110	Mat 52	0.504	0.000504	0.2	18.8	7460.31746
111	Mat 59	0.503	0.000503	0.2	11.1	4413.518887
112	Mat 60	0.501	0.000501	0.2	15	5988.023952