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A GEOMORPHOLOGICAL INVESTIGATION OF THE KLIP RIVER WETLAND, SOUTH OF JOHANNESBURG

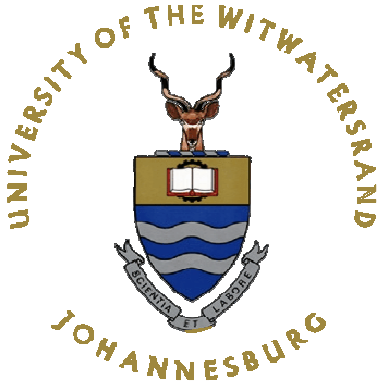
by

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A dissertation submitted in partial fulfilment of the requirements for the degree of

M.Sc. in Environmental Sciences

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2009

Supervisor: Prof. Terence McCarthy

Declaration

I declare that the dissertation which is being submitted for the Degree of Master of Science at the University of the Witwatersrand is my own, unaided work and has not been previously submitted by me at another University for any degree.

_____

Vanessa Mary Vermaak
December 2009

A Geomorphological Investigation of the Klip River Wetland, South of Johannesburg

Abstract

The Klip River Wetland is located south of Johannesburg. The city is a major conurbation which developed as a result of mining activity. The wetland has, and always had, economic importance to the region, firstly as a water source and later as a purifier of polluted water reporting from the urban-mining-industrial complex. A previous investigation determined that this wetland is in an advanced state of collapse. A network of irrigation canals dug in the early part of the 20th century to support agriculture in the area, provided a preferred discharge conduit for the sewage pumped into the Klip River. These irrigation canals have cut back and avulsed forming an almost continuous channel, with little water flowing through the wetland. The wetland's capability to remove contaminants from the water is therefore compromised.

The geomorphological study presented here aims at the quantification and the better understanding of:

- The extent of the degradation
- The rate of change to the wetland and
- To offer potential remedial solutions.

Desktop analysis was conducted on the following data:

- Aerial photography (1938, 1952, 1961, 1984, 2003, 2006)
- Historical maps from 1917
- High resolution topography data (LIDAR),
- Water quality
- Water discharge

In order to quantify the degradation of the wetland and associated rates, the following factors were considered:

- Wetland area and shape
- Channel formation, propagation and widening

- Knick point migration.

The major findings of this study are:

- The analysis of wetland area did not prove as effective a method as the study of the channels and knick points.
- Two major knick points are distinguished. The first is located at the outlet of the Olifantsvlei Sewage Works and the second represents a major rapid near Kromvlei. The latter has incised 5 m into the wetland.
- Knick point migration was not detected between 2003 and 2006, except for the rapid near Komvlei where the knick point migrated a significant 118 m in two years.
- Between Kibler Park and Kromvlei the wetland experienced the greatest head cut advance of all the sections, most significantly in the periods 1952 to 1961 and 2006 to 2008.
- The period of the most significant change for all channel width monitoring points was between 2001 and 2003.

Results of this investigation confirm that the current state of the Klip River Wetland is dire. Large tracts of wetland have disappeared over the last 100 years. The wetlands that remain are not functioning optimally. The importance of the wetland to purify the sewage, industrial and mining effluent is paramount. The window of opportunity to save or restore at least parts of the wetland, and therefore maintain the purification potential of the wetland, is closing. Peat burns will lead to erosion of the soils and therefore the reworking of the pollutants into the river system. It is anticipated that if the Klip River Wetland collapses completely, the water quality will worsen along the Vaal River and in the Vaal Barrage, which will impact negatively on the downstream users.

The proposed solution to protect the wetland from further erosion and head-cut advance is to force the water out of the channels and into the wetland. By building a number of weirs in the channels, it is possible to dam the water upstream of the weir, thereby forcing the water to flood the wetland again.

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1. Introduction

The Klip River Wetland is situated south of the Witwatersrand conurbation in the most densely populated province of South Africa, Gauteng (Figure 1.1). It lies between latitudes 26°10' and 26°25' south and longitudes 27°45' and 28°05' east, at an altitude of about 1750 m above mean sea level.

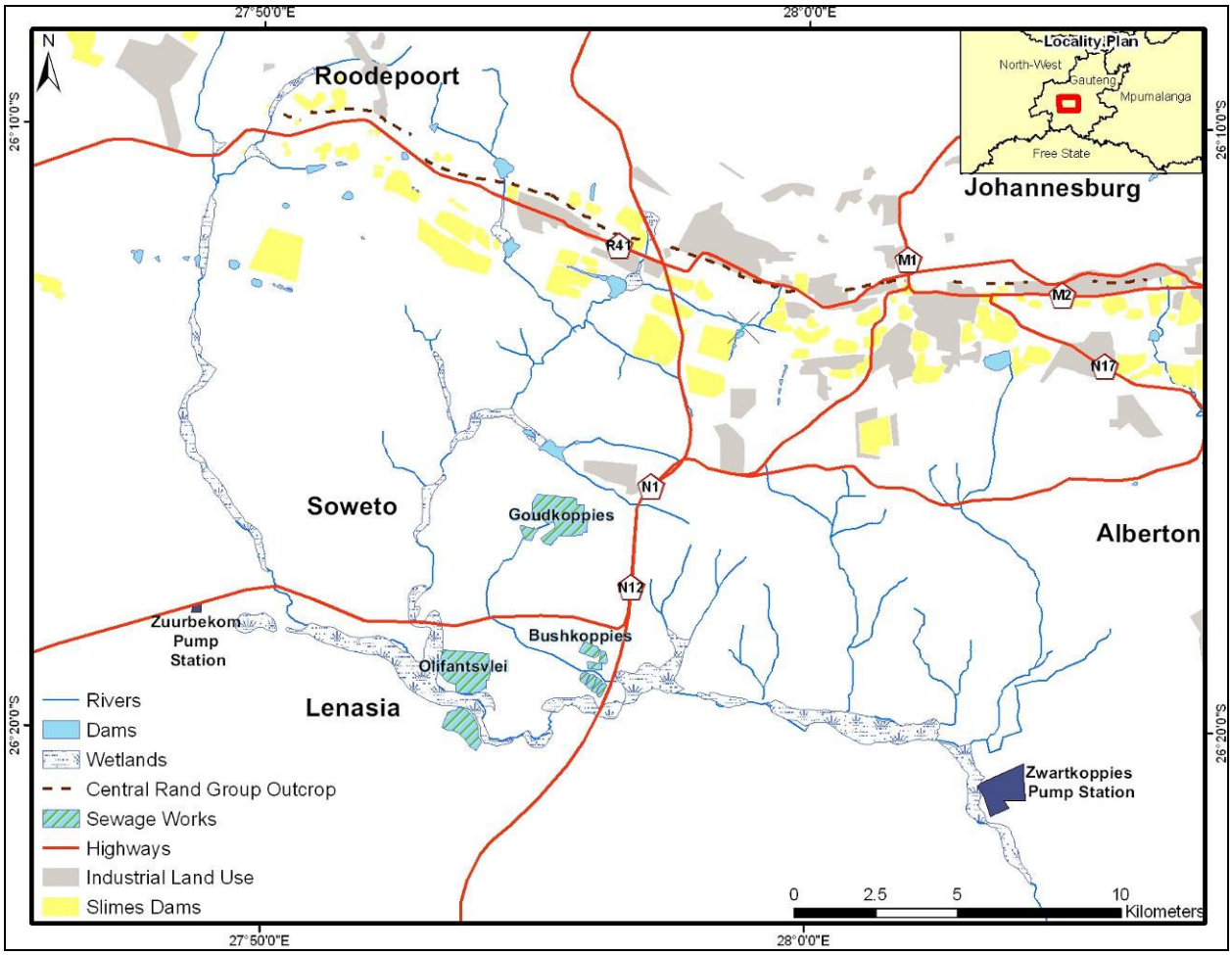


Figure 1.1: Location of the Klip River Wetland in relation to industrial, urban and mining development in the Johannesburg area.

The Witwatersrand is one of the few great conurbations (population of about 11 million people) of the world that is not located on a major river, lake or seashore (Turton et al., 2006). The existence of this city is solely due to the discovery of gold-bearing reefs of the Central Rand Group, which outcrop at surface as part of the greater Witwatersrand Goldfield (Figure 1.1). Gold mining began on the Witwatersrand in 1886 and it soon became evident that the gold occurrence was of considerable significance. Prospectors and miners flocked to the area and townships were established along the length of the outcrop. As the mining industry grew, secondary industries were established on the Witwatersrand, creating a vast mining–industrial complex. Most of this mining and industrial development took place along the southern flank of the Witwatersrand Ridge, which forms a major watershed that separates the Vaal River Basin (part of the Orange River) to the south from the Limpopo River Basin to the north. The Witwatersrand mining-industrial complex is therefore located at the headwaters of two major international river basins, the Orange River and Limpopo River. Most of the industrial development is located in one sub-basin of the Vaal River system, namely the Klip River Basin, and it is this sub-basin that receives the bulk of the run-off from the Witwatersrand mining–industrial complex (Figure 1.1). Run-off consists of surface water from rain, treated and untreated sewage, treated and untreated discharges from industrial sources, and water pumped from mines.

2. Aims and Objectives

The Klip River Wetland has always been economically important to this region, initially as a source of water and of late as a purifier for the mentioned contaminants. A geomorphological investigation has already determined that these wetlands are in fact in an advanced state of collapse. The study by McCarthy et al. (2007) identified that the network of irrigation canals dug in the early part of the 20th century to support the agriculture in the area, have provided a preferred discharge conduit for the sewage pumped into the Klip River. The network of irrigation canals have cut back and avulsed forming an almost continuous channel and therefore, little water is flowing through the wetland. The wetland's capability to remove contaminants from the water is compromised and McCarthy et al. (2007) predict that eutrophication problems can be expected down stream in the Vaal River Barrage as is experienced in the Hartebeestpoort Dam. This study aims to elaborate on the

above research, especially with some newly acquired data, to better understand the extent of degradation of the wetland.

The objectives of this research are to:

- Establish the current status of the Klip River Wetland.
- Calculate the progression of the degradation.
- Determine the mechanisms/causes for the degradation.
- Determine the broader implications to downstream users.
- Offer potential remedial solutions.

3. Literature Review

3.1 Klip River Catchment Description

3.1.1 Regional Setting

The Klip River Wetland is situated south of Johannesburg, beginning in Lenasia and continuing south of Alberton and the Zwartkoppies Pump Station. The wetland lies between latitudes 26°10' and 26°25' south and longitudes 27°45' and 28°05' east (Figure 1.1). Thus, this wetland falls within the south-central portion of the major urban, industrial economic region of South Africa, the Southern Gauteng Metropolitan area, where rapid urbanization is taking place. The land use impacting on the wetland varies from urban to rural, industrial as well as informal settlements and agriculture. Partridge (1968) commented that this region has witnessed the greatest physical development of any area in Africa south of the Sahara.
The Klip River headwaters are located south of Roodepoort with two main branches (Mindalore and Princess Dam) beginning on the continental drainage divide, the Witwatersrand ridge, at an altitude of about 1750 meters (Partridge, 1968). From there the Klip River gradually descends to the Vaal River, less than 1440 meters above sea level, near Vereeniging. The Klip River is therefore classified as part of the Orange/Vaal system draining into the Atlantic Ocean (Partridge, 1968).

3.1.2 River Systems and Water Resources

Impoundments or dams are confined mainly to the upper reaches of the catchment and are mostly man-made structures associated with mining activities (Davidson, 2003; Figure 3.1.1). Other water bodies along the Klip River are sewage works maturation ponds, vlei

areas and man-made recreational and farm dams. The tributaries of the Klip River include the Klipspruit, Harringtonspruit, Bloubosspruit, Glenvistaspruit, Rietspruit and Natalspruit, with the Foriespruit and Varkensfonteinspruit coming in at the lower Klip sub-catchment (Davidson, 2003; Figure 3.1.1).

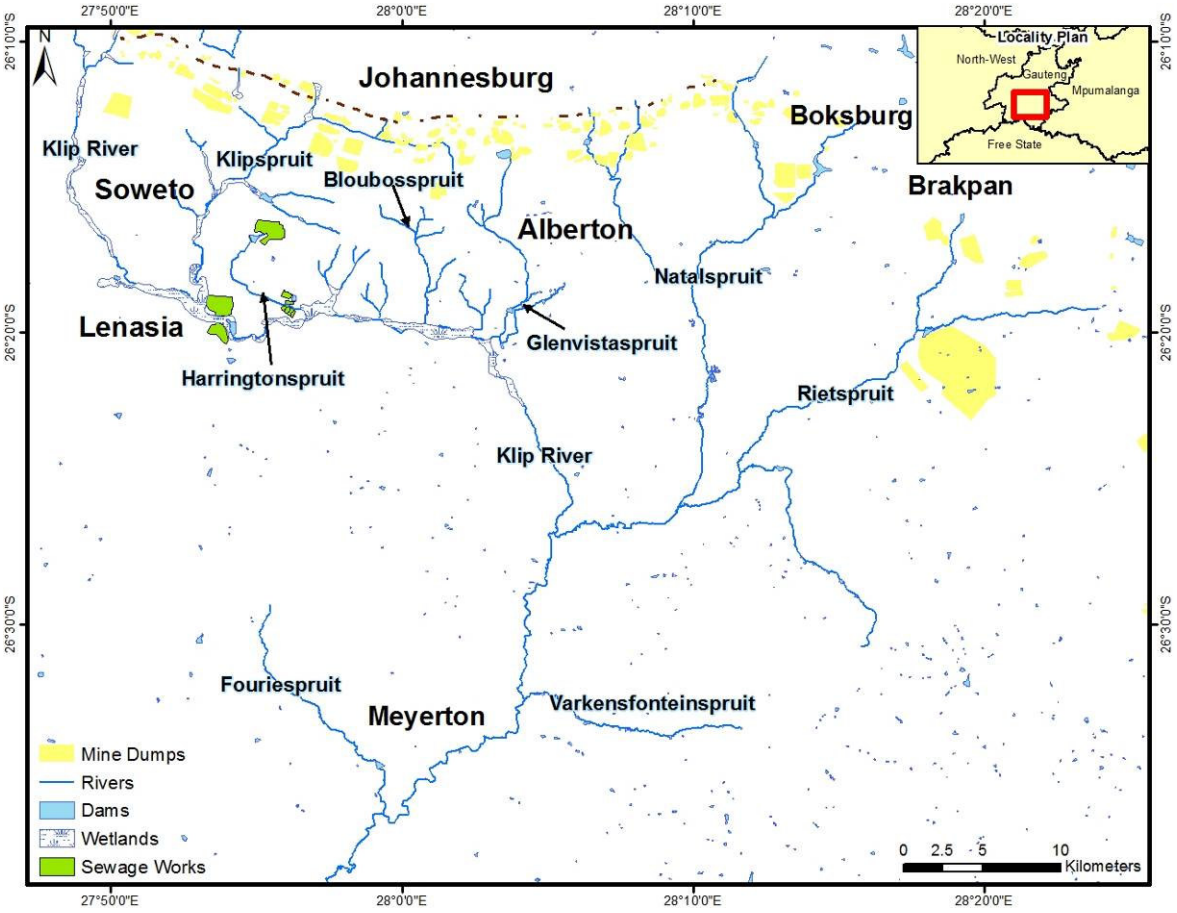


Figure 3.1.1: Location of the river system and water resources around the Klip River Wetland.

3.1.3 Climate, Hydrology and Geohydrology

The climate of the area is sub-humid with a tendency towards semi-aridity (Partridge, 1968). The entire Klip River catchment has a typical Highveld climate with warm to hot summers (October – March) and cool but generally cloudless winter days with cold nights, when frost is common (Davidson, 2003). Mean maximum temperatures average 26°C in January dropping to an average maximum of around 16°C in June. Precipitation is confined to the summer season mostly in the form of convectional downpours of high intensity, which favours rapid runoff (Partridge, 1968). The average summer rainfall is

between 600-750 mm per annum (Grundling and Marneweck, 1999). Partridge (1968) concluded that the highest rainfall occurs in the vicinity of the Witwatersrand ridges and high-lying country to the east, where the greatest degree of atmospheric convergence is induced by the topography, i.e. at the Klip River headwaters. The average evaporation in the area is 1600 –1700 mm a year with the highest evaporation taking place during the summer month of December (176 mm) and lowest rates during the winter month of June (70 mm) (Davidson, 2003). The evaporation rate is much greater than the rainfall and thus drought and water shortages may occur (Davidson, 2003). Water is transferred into the catchment for potable purposes through Inter Basin Transfer schemes (see Section 4.2; Davidson, 2003).

According to Partridge (1968) the Klip River Basin, along with other south draining rivers, does not contain any major tributaries other than its axial streams when compared to north flowing rivers. From the continental divide, the southern flowing rivers generally show a lower density than the north flowing rivers (Partridge, 1968). The south flowing rivers carry mainly fine sediment, whilst the north flowing rivers carry sand and gravel. Hence, the latter lack wetlands.

The Klip River Wetland is located on a plain and is underlain predominantly by dolomite of the Malmani Subgroup (Figure 3.1.2). These dolomite rocks form part of the Transvaal Supergroup and were deposited approximately 2, 500 m.y. ago in a shallow-marine, epeiric sea (Clay, 1981). In the past, natural dolomitic springs of pure water decanted into the Klip River Wetland (White, 1957). White (1957) describes natural springs of pure, dolomitic water in the Klip River beyond Olifantsvlei, which increases the pH, calcium and magnesium content and at the same time lowers the Total Dissolved Solids (TDS), sulphate (SO_4) and iron (Fe) content. However, probably due to excessive pumping of the dolomitic aquifer, the springs no longer flow and contaminants are discharging from the Klip River into the aquifer (Kafri and Foster, 1989).

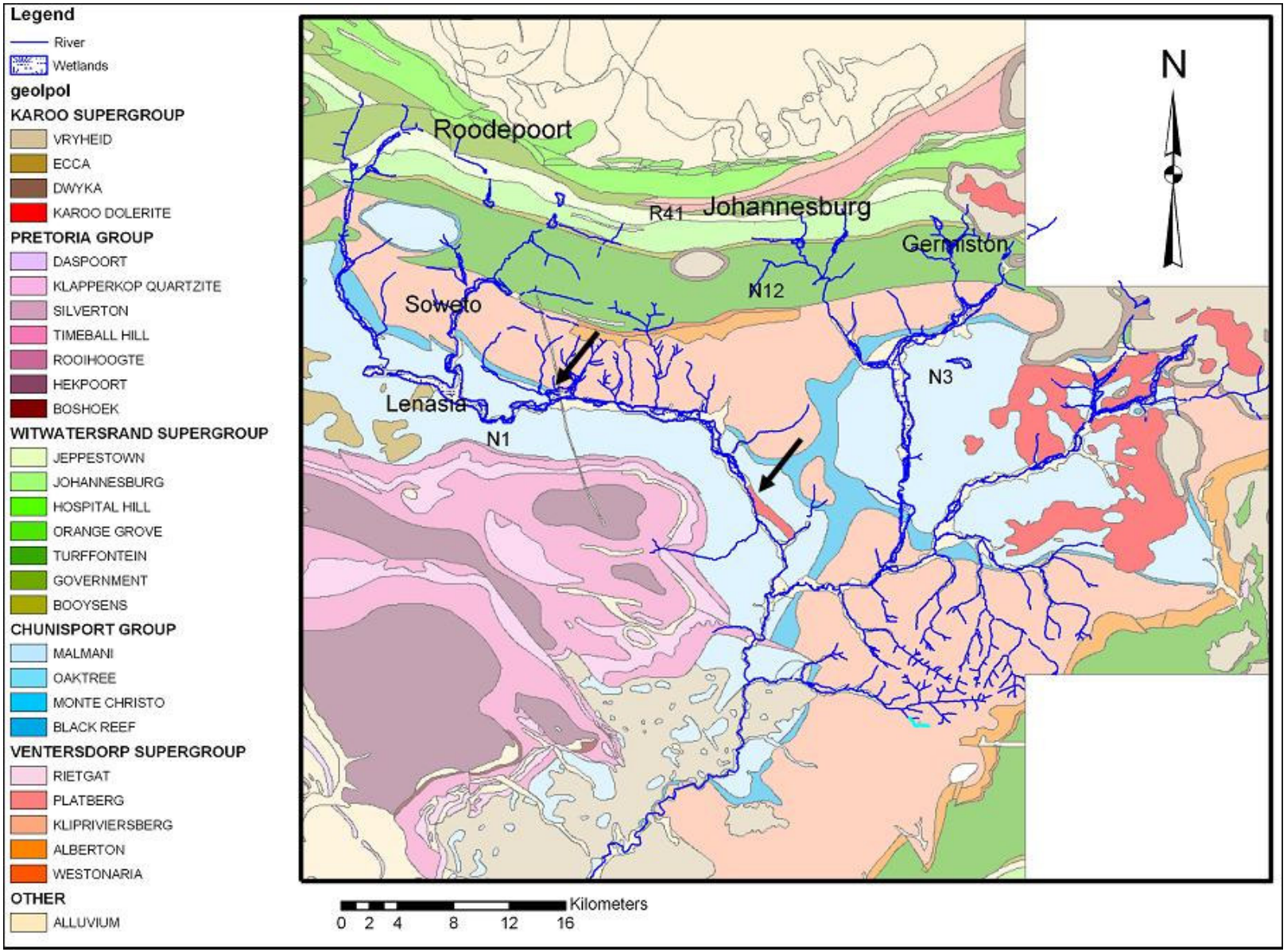


Figure 3.1.2: Surface geology of the Klip River Catchment (black arrows highlight dykes; after Arnold, 2004).

The annual recharge of the local aquifer varies between 75-110 mm per annum and a base flow of between 10-25 mm per annum (Grundling and Marneweck, 1999). The dolomitic aquifer is divided into sub aquifers on the basis of lithostratigraphy (Figure 3.1.3). Kafri and Foster (1989) found that the chert-poor units are poor aquifers compared to the chert-rich units. Groundwater barriers formed by dykes divide the aquifer into compartments, which are linked by flow across the groundwater barriers along the Klip River. Two barriers are highlighted (by black arrows) on the surface geology in Figure 3.1.2. Arnold (2004) and Schweitzer et al., (2004) interpreted dyke positions from aeromagnetic data (Figures 3.1.4 and 3.1.5) across the Klip River Wetland, which can be used to infer groundwater barriers. Kafri and Foster (1989) found that where the Klip River breaches the groundwater barriers the stream transcends in a series of small rapids until the groundwater level of the downstream compartment is reached.

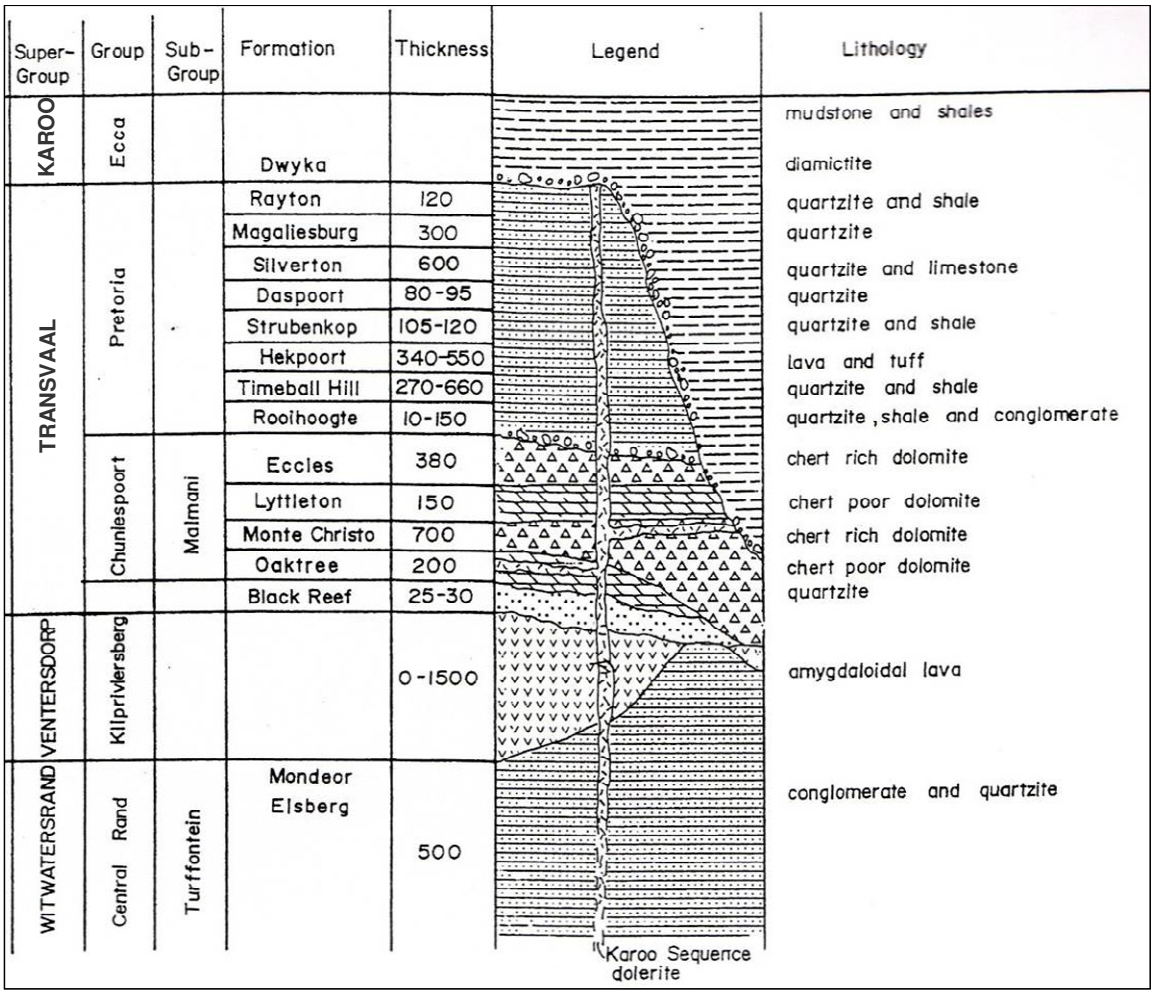


Figure 3.1.3: Lithostratigraphy of the Malmani Subgroup (Kafri and Foster, 1989).

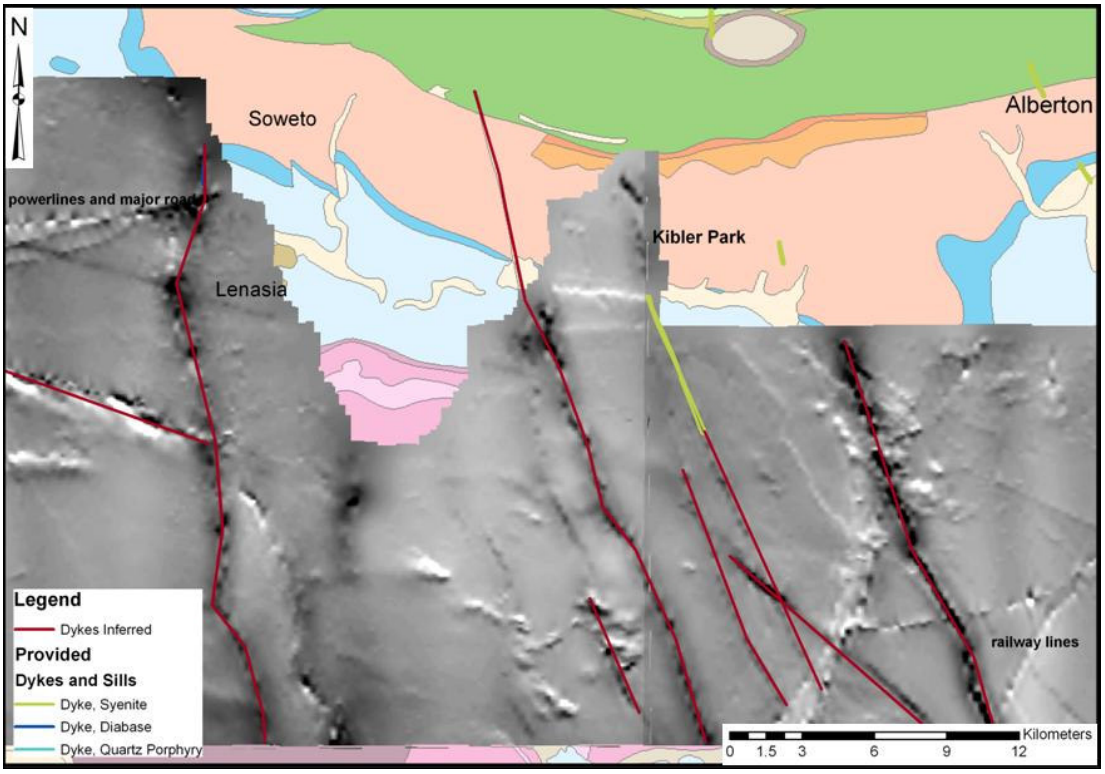


Figure 3.1.4: Aeromagnetic anomaly map with dykes inferred (Arnold, 2004).

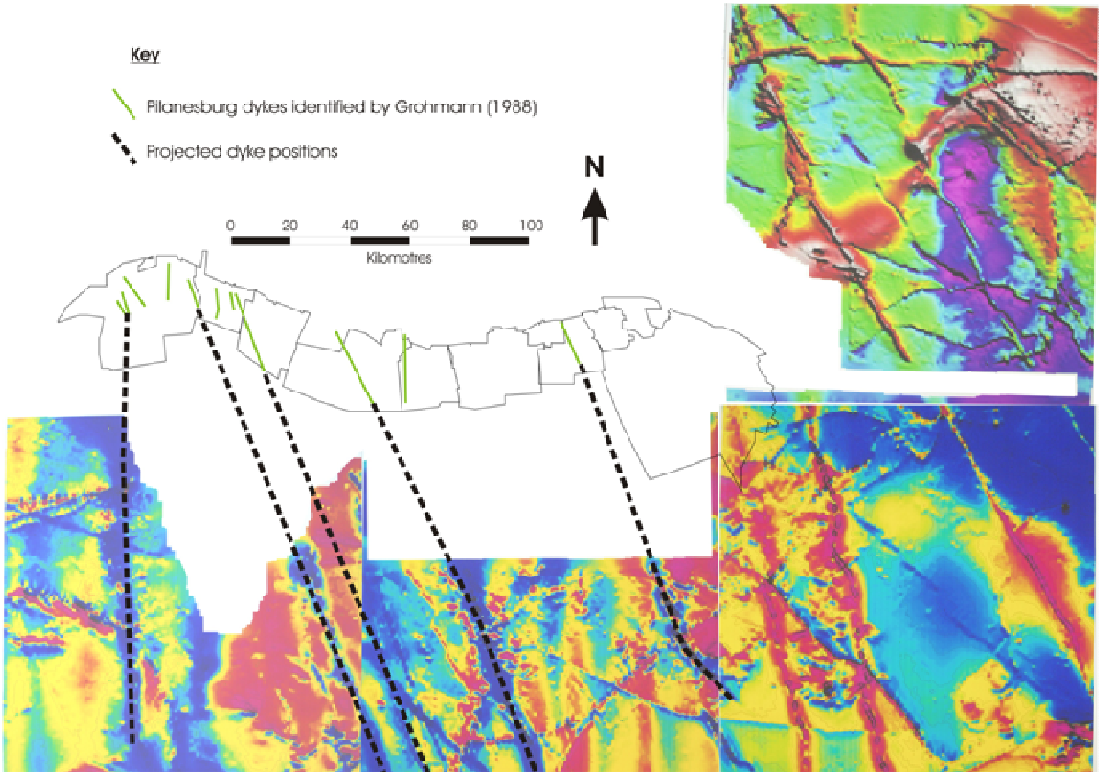


Figure 3.1.5: Aeromagnetic map with dykes projected onto Central Rand Goldfield (Schweitzer et al., 2004).

3.1.4 Vegetation

The vegetation within the Klip River catchment falls into three Bioregions, namely Mesic Highveld Grassland (the dominant Bioregion), Dry Highveld Grassland and Central Bushveld (Mucina and Rutherford, 2006). The Mesic Highveld Grassland is the largest grassland region in South Africa with the highest number of vegetation types. These grasslands are found mainly in the higher precipitation parts of the Highveld and extend northwards along the eastern escarpment (Mucina and Rutherford, 2006). The dominant vegetation type of the Klip River catchment is the Rand Highveld Grassland, which is a species-rich, wiry, sour grassland alternating with low, sour shrub land on rocky outcrops and steeper slopes (Mucina and Rutherford, 2006). This Highveld Grassland is a typical grassland of the high inland plateau found along the ridges of the Witwatersrand and the dolomite plains of Gauteng mainly between 1 300 to 1 635 m in altitude (Davidson, 2003).

Rogers and Herrera (1986) investigated three vegetation types in the Rietspruit Wetland, namely *Typha capensis* (Bulrush), sedentary and floating *Phragmites australis* (common reed) and *Scirpus lucustris*. The Klip River Wetland vegetation consists primarily of *Phragmites australis* with lesser *Typha capensis* and sedges.

3.1.5 Wetland Characteristics and Status

Wetlands are transitional areas between land and water and are distinguished by wet soils, plants that are adapted to wet soils, and a water table depth that maintains these characteristics. Since land and water can merge in many ways, there is no single correct definition for all purposes. According to Grundling and Marneweck (1999), the Klip River Wetland consists of four basins, all of which are classified as valley-bottom fens. The term fen is used mainly for minerotrophic peatlands (groundwater fed; Hájek, et al., 2006) and is a form of classification. Different from bogs (Ombrotrophic; rain fed), fens are identified on the basis of circum-neutral waters rich in dissolved minerals, notably calcium (Ca), and an abundance of brown mosses and vascular plant species (Warner, 1996). Wetland systems reduce or remove contaminants including organic matter, inorganic matter, trace organics and pathogens from the water. Reduction is said to be accomplished by diverse treatment mechanisms including sedimentation, filtration, chemical precipitation and adsorption, microbial interactions and uptake by vegetation (Watson et al., 1989).

Peatlands ranging in size from 1 740 000 m³ to 41 400 000 m³ in the main basin, and with depths of between 2 m and 3.5 m, were identified in the Klip River Wetland by Grundling and Marneweck (1999). A transect across the wetland south of Kibler Park revealed the maximum peat thickness at 4 m (McCarthy and Venter, 2006). All basins of this peatland in the catchment of the Klip River can be described as tall emergent (reed–sedge) fens, made up of reed-sedge peat with a fibrous to fine-grained texture (Grundling and Marneweck, 1999).

Peat mining, mainly for the horticulture industry, took place in the wetlands east and west of the Klipspruit Valley Road, before operations ceased due to high pollution levels (Grundling and Marneweck, 1999). Open water bodies and scars are now left from this peat mining as seen in Figures 3.1.6 and 3.1.7.



Figure 3.1.6: Open water bodies left from peat mining east of Klipspruit Valley Road (McCarthy et al., 2007).

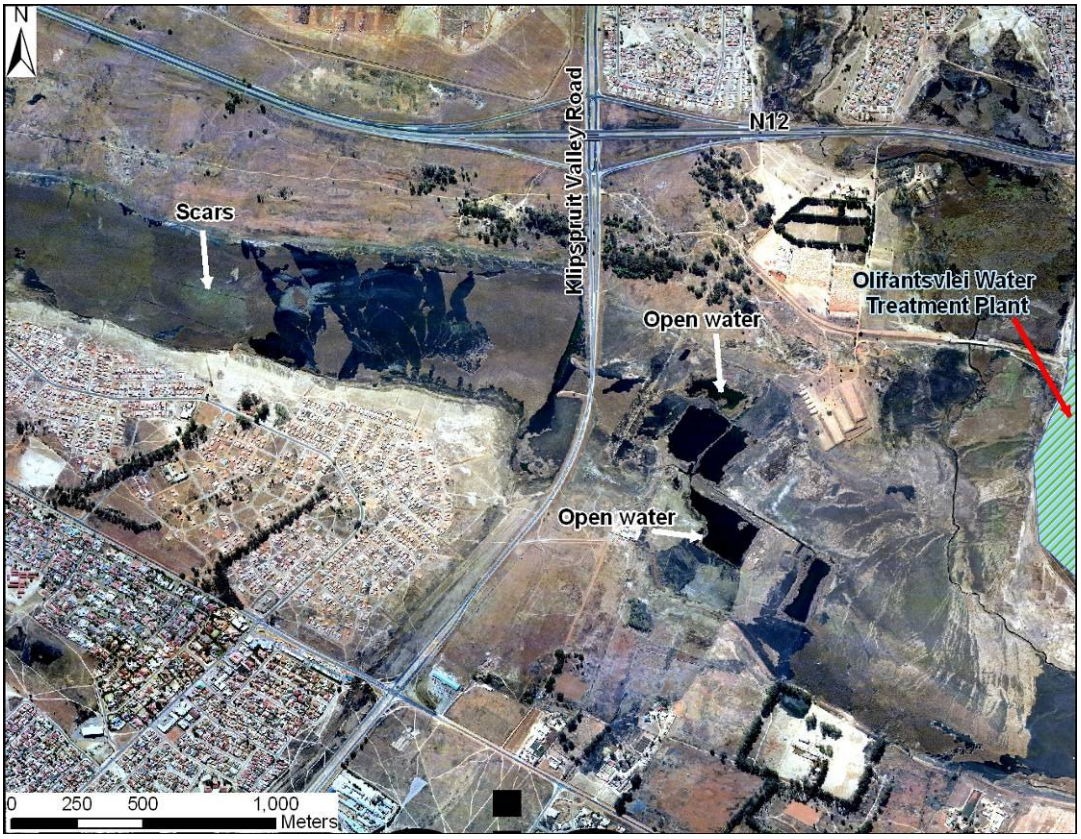


Figure 3.1.7: Open water bodies and scars left from peat mining.

3.1.6 Land Uses

The Klip River Wetland is located downstream and around the Witwatersrand mining–industrial complex. Land uses include:

- Urban
    - Sewage Works
- Mining
- Industrial
- Agriculture

3.2 The History of the Klip River Catchment

The name 'Witwatersrand' is literally translated as 'ridge of white waters'. This name arose because of the numerous small springs that were present along the ridge. The mining camps that sprung up along the Witwatersrand Ridge during the gold rush were generally sited according to this availability of water (Turton et al., 2006). George Harrison discovered gold on the ridge early in February 1886 and by October 1886 the city of Johannesburg was

officially founded. The first water for the mining town was drawn from two springs called Fordsburgspruit and Natalspruit (Turton et al., 2006). Prior to 1896 another source of supply was developed north of the mining operations in Roodepoort, on the farm Weltevreden (Turton et al., 2006). When this water supply failed to meet the demands, development turned to the dolomitic aquifers that underlie the Klip River Wetland, firstly on the farm Zuurbekom. The Zuurbekom pump station was erected in 1899 and is still in operation today (Turton et al., 2006; Figure 1.1). The water demand grew dramatically as more mines were founded. The water requirements for processing gold ore were approximately 2 000 litres of water per ton of ore. Between 1886 and 2002, 937 375 000 tons of ore was milled and 7 697 666 kg gold was extracted from the Central Rand Goldfield (Handley, 2004).

By 1902 there were three companies responsible for water supply in the Witwatersrand – Johannesburg area namely: the Johannesburg Waterworks Estate and Exploration Company, the Braamfontein Company and the Vierfontein Syndicate (Turton et al., 2006). The sources of water were from:

- The dolomites around Zuurbekom.
- Springs at Doornfontein, Natalspruit, Berea and Parktown.
- The Klip River Valley pumping station, i.e Zwartkoppies (Turton et al., 2006).

Turton et al. (2006) documents the first incidence of the Klip River being polluted in 1894, which resulted in the death of livestock. An enquiry established that the water in the Doornfontein Valley was also polluted by mine effluent (Turton et al., 2006). This was the beginning of a substantial water resource management problem that persists today. In 1903 the Rand Water Board (RWB) was established and given the responsibility of developing a secure water supply system. In 1914 the RWB adopted the Vaal River Development Scheme. The first phase of the Scheme was the construction of the Vaal Barrage (Figure 3.2.1) with purification works, pumping stations in Vereeniging and a main pipeline to the Witwatersrand being completed in 1923 (Turton et al., 2006). It is noted that the Klip River enters the Vaal River upstream of the Barrage, but downstream of the Vaal Dam (Figure 3.2.1). At this point in time the Witwatersrand was effectively recycling its waste water. The Vaal Dam being the second phase of the Scheme was built during the great depression. The yield of the Vaal Dam was increased in 1955/6 to result in the capacity of 2 330 million m^3. This was still insufficient with Pretoria and Vereeniging being incorporated into the Rand

Water Board supply area (PWV Triangle), the huge demand was reaching the limits of the Vaal's capacity. This gave rise ultimately to the Lesotho Highlands Project with the first water flowing into the Vaal Dam via the Ash River outfall on 8 January 1998 (Turton et al., 2006). The fact that the water is pumped to the Witwatersrand from the Inter Basin Transfer schemes, which is then transferred to the Klip River through the water treatment plants, means that this system is highly altered. The RWB eventually stopped pumping water from the Barrage due to water quality concerns. The Vaal River upstream of the Barrage is however still used as a major recreational area for the Gauteng region and water quality remains a concern.

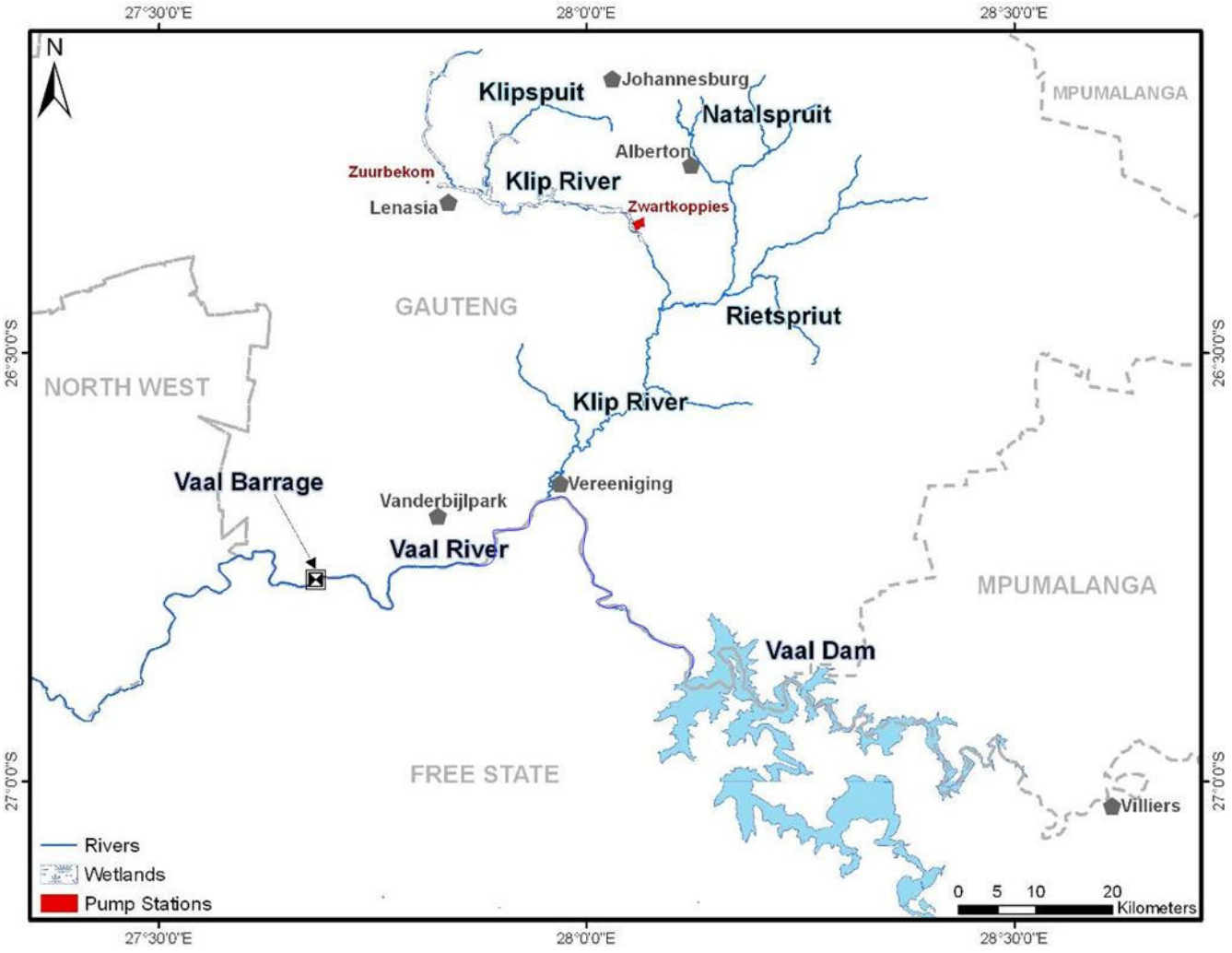


Figure 3.2.1: The Klip River in relation to the Vaal Barrage and the Vaal Dam.

3.3 Water Pollution Sources: Mining

The first incidence of the Klip River being polluted was documented in 1894 (Turton et al., 2006). Figure 3.3.1 illustrates the impact of mining on the wetland in aerial photographs of 1938. The glowing white substance washed from the river into the wetland is mine dump sediment entering this ecosystem from the Roodepoort mines. The effect of this effluent on the wetland can be seen by the absence of reeds and vegetation in the polluted areas. Today, however, the vegetation is fully recovered and no fluorescing white polluted water is evident (Arnold, 2004).

An evaluation of the hydrogeology of the Klip River Basin was carried out in 1989 in order to assess the aquifer's potential for public water supply. It was determined that effluents from sewage purification works and gold treatment plants have caused extensive deterioration of the quality of surface and groundwater (Kafri and Foster, 1989). High TDS and sulphate values were encountered along the Klip River Valley with contamination increasing towards the wetland (Figure 3.3.2). This indicates that there is a reversal of flow; while previously the wetland was fed by springs (Humphrey, 1910; White, 1957) now water flows out into the dolomitic aquifer, probably due to over pumping of the aquifer. Water sampled from a spring south of Olifantsvlei in the 1950's was found to have a low saline content, chlorides and sulfates were also low (4 ppm) and nitrogenous compounds were absent (White, 1957). Prior to 1957 the TDS were 138 mg/L, and in 1989 Kafri and Foster record this area to fall into the > 500 mg/L zone. White (1957) described natural springs of pure, dolomitic water in the Klip River beyond the Olifantsvlei, which used to increase the pH, calcium and magnesium (Mg) content and at the same time lower the TDS and sulfate and iron (Fe) content.

Figure 3.3.3 illustrates that Acid Mine Drainage (AMD) from the Klip River catchment is also reporting[1] to the Vaal River (DWAF, 2007). TDS values are low up until the Vaal Dam and thereafter increase significantly.

[1] Synonymous with "draining" or "entering"

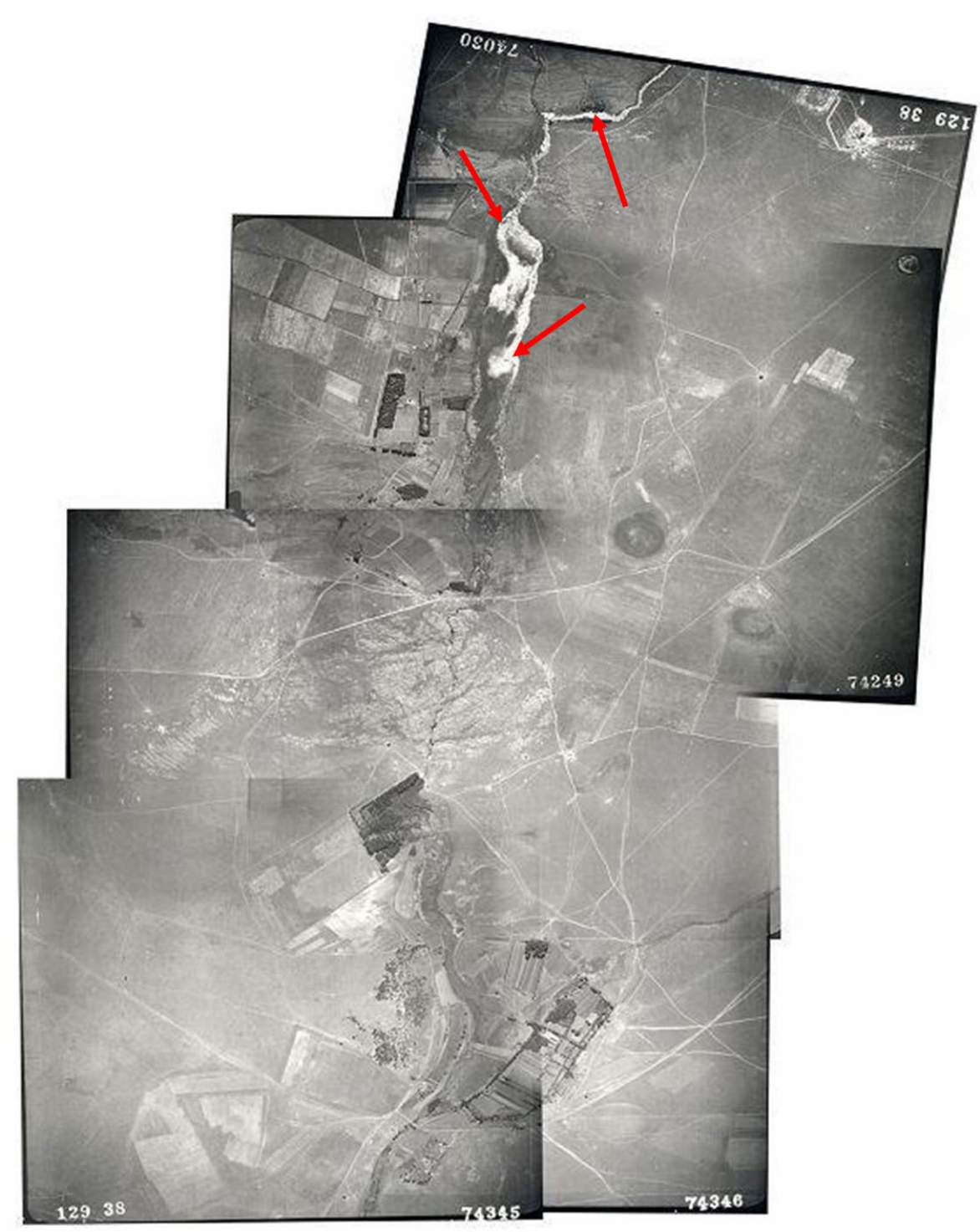


Figure 3.3.1: Acid Mine Drainage during 1938 impacting the Klip River Wetland. Areas impacted indicated by red arrows (Arnold, 2004).

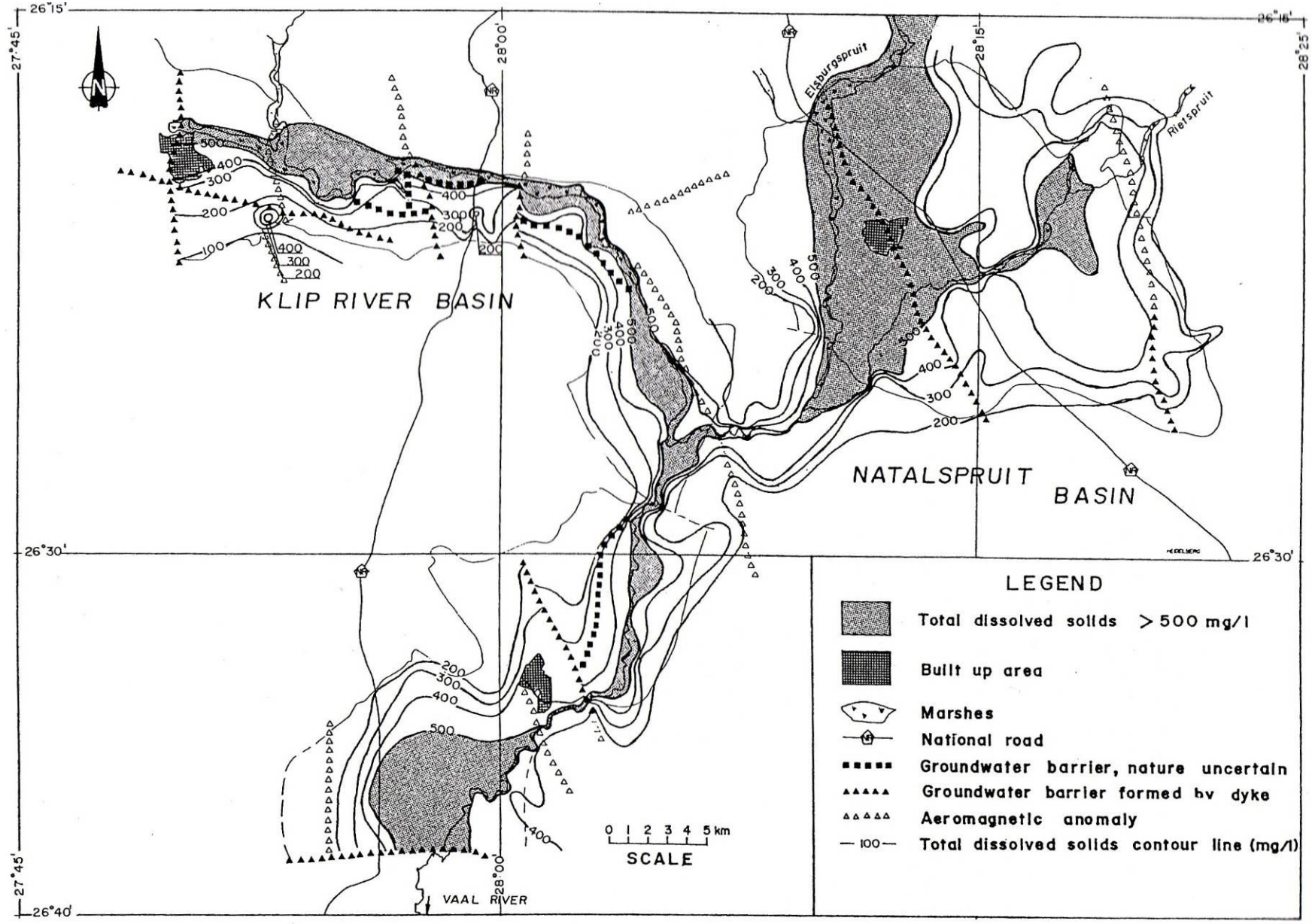


Figure 3.3.2: Total Dissolved Solids concentration map of the Klip River Basin (Kafri and Foster, 1989).

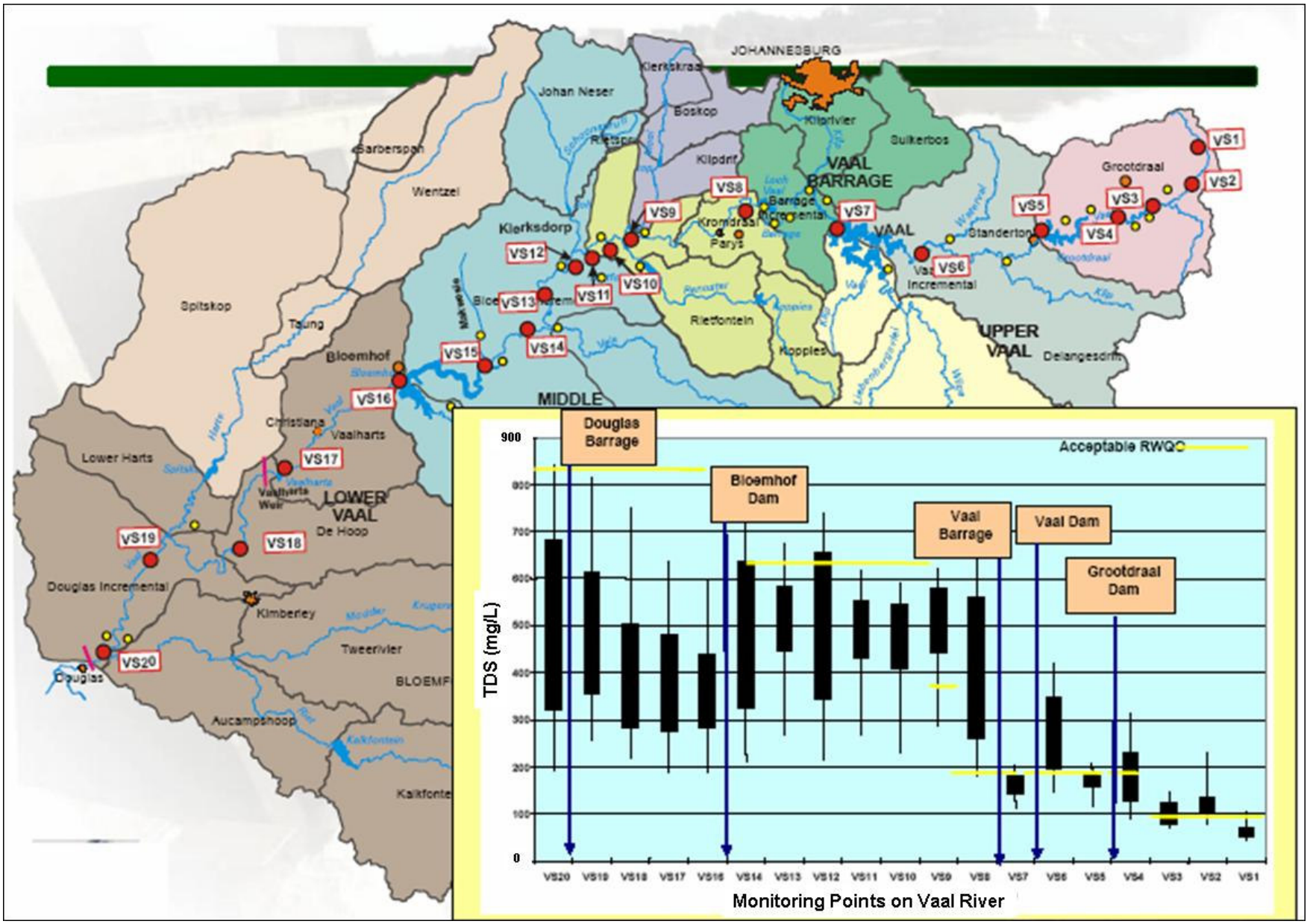


Figure 3.3.3: Total Dissolved Solids concentration map of the Vaal River Basin (DWAF, 2007).

Mine, sewage and industrial effluent has been flowing into the Klip River and the associated wetland for over a hundred years. AMD is the water flowing from or caused by surface mining, deep mining or refuse piles and is typically highly acidic with elevated levels of dissolved metals. The formation of AMD is primarily a function of the geology, hydrology and mining technology employed for the mine site. AMD is formed by a series of complex chemical and microbial reactions that occur when water comes in contact with pyrite (FeS_2), as contained in the auriferous conglomerates of the Witwatersrand, refuse or the overburden of a mine operation. The resulting water is usually highly acidic and has high TDS. The metals stay dissolved in solution until the pH raises to a level where precipitation occurs. AMD results when the mineral pyrite is exposed to air and water, resulting in the formation of sulfuric acid (H_2SO_4) and iron hydroxide ($Fe(OH)_3$):

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \Leftrightarrow Fe(OH)_3 + 2\ H_2SO_4$$

The products of AMD formation, acidity and iron, can devastate water resources by lowering the pH and coating stream bottoms with iron hydroxide, forming the familiar orange coloured Ferric Hydroxide or "yellow boy" common in areas with abandoned mine drainage.

3.3.1 Source of Acid Mine Drainage

On the Central Rand Goldfield, gold was initially extracted using a mercury amalgam method, but later as mining operations went deeper and unoxidized ore containing pyrite was encountered, the MacAuthur-Forrest process, using cyanide was implemented (Naicker et al., 2003). The cyanide process required fine milling of the ore, after which it was treated with a cyanide containing solution, which dissolved the gold. The solution was then separated for further processing, while the tailings were pumped to large dumps (slimes dams). Both the mercury amalgam and the cyanidation processes are highly selective for gold, and other ore minerals, such as pyrite, were unaffected and hence reported to the tailings dumps.

A principal environmental concern associated with mine waste results from the oxidation of sulfide minerals within the waste materials and mine workings, and the transport and release of these. The principal sulfide minerals in mine wastes are pyrite and pyrrhotite (FeS), which release elements such as aluminium (Al), arsenic (As), cadmium (Cd), cobalt

(Co), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn) to the water flowing through the mine waste and into the groundwater below. The Witwatersrand Supergroup sediments contain varying proportions of sulphide minerals, the predominant sulphide being pyrite. In many of the gold bearing reefs, this mineral may form up to three per cent (by mass) of the rock. Other sulphides such as pyrrhotite, arsenopyrite (FeAsS), chalcopyrite ($CuFeS_2$), galena (PbS), cobaltite ((Fe,Co)AsS) and gersdorffite NiAsS), occur as traces (Schweitzer et al., 2004). Average uranium (U) grades of Witwatersrand orebodies are about 250 ppm with uranium predominantly contained in uraninite (UO_2) and brannerite (UCaCeTiFeO), (Handley, 2004).

Mining of the Witwatersrand Supergroup sediments has produced rock piles, sand and slimes dams on surface, and underground backfilled rockpiles and reef remnants in stopes and developments[2]. These all contain pyrite that is constantly exposed to air and water. Due to oxidation and subsequent precipitation of secondary iron oxide minerals and mineraloids, the rocks and precipitates exhibit red and yellow staining and discoloration. Water that has passed through these precipitates exhibits low pH and high concentrations of metals in solution.

3.3.2 Transport of Acid Mine Drainage

Acidic environments, particularly at pH values less than 3, are very conducive to the mobility of contaminants at very high concentrations. The major contaminant that can move beyond the neutralization zone is sulfate. Its concentration in solution is not directly pH dependent; therefore neutralization will not inhibit its mobility as it does with metals (Deutsch, 1997). The dissolved concentration of sulfate is usually limited by the solubility of gypsum ($CaSO_4.H_2O$). However, the solubility of this mineral can vary depending on the other constituents in solution. In the neutralization zone, the solubility of gypsum will decrease as the cations are removed from solution (Deutsch, 1997). Because of the mobility of sulfate compared with the other constituents in this type of acid plume, sulfate is the best indicator of the first arrival of contaminants from a sulfide source. A study by Naicker et al. (2003) found ground water within the Central Rand mining district to be heavily contaminated and acidified. Naicker, et al (2003) commented that although erosion of dump material into water

[2] Refers to underground excavations, especially haulages and cross-cuts.

courses contributed to pollution, the major contribution came from rain water which had percolated through the dumps, creating polluted groundwater plumes beneath the dumps, which were emerging at surface in streams.

Formation of AMD on the Central Rand is dominated by the hundreds of mine tailings dumps which are scattered all along the Witwatersrand Ridge and form large footprint plumes contaminating the natural water table and associated surface water bodies, i.e. the Klip River Catchment. Some of these mine tailings have in the past been reprocessed, or are currently being reprocessed due to their relatively high gold values and more efficient processing methods. In some cases it takes up to 15 years to reprocess a large dump and during reclamation, vegetation cover is removed and exposed faces are subject to wind and water erosion and more importantly to oxidation (Mphephu, 2004).

Another major AMD source is the underground workings, which are now flooding and being pumped from East Rand Proprietary Mine (ERPM) in the eastern limit of the Central Rand Goldfield. This water is then treated with lime and sent through a High Density Sludge Plant where precipitated iron hydroxide is removed. The water is then pumped into the Elsburgspruit, which flows into the Natalspruit and Rietspruit through wetlands and the Malamani Dolomites to the south of Johannesburg before joining with the Klip River and then the Vaal Dam (Figure 3.1.1).

3.3.3 Bioaccumulation and the Toxicity of Oxidation Products

Metals released from mines and mine sites can harm aquatic biota in adjacent water bodies. Metals are present in aqueous environments in a variety of species with various toxicities and potential for bioaccumulation. Transformations among these species depend on the physical and chemical characteristics of the water body. Metal toxicity can be acute or chronic. For example, aluminium can precipitate to form species that result in sudden killing of fish in water bodies near mine sites. Other metals, such as mercury, can bioaccumulate, leading to chronic toxicity (Blowes et al., 2003). The extent of bioaccumulation and the toxicity of metals within natural environments are controlled by a number of factors, among which are pH, oxidation–reduction potential, organic carbon content, concentrations and compositions of other dissolved species, and the composition of the sediment (Blowes et al., 2003).

The acidification of wetlands can elevate the concentrations of metals and increase the potential bioavailability in aquatic plants and freshwater biota and influences the uptake of metals in both submerged and rooted plants. Metals such as iron, copper, cadmium, chromium (Cr), lead, mercury, selenium (Se), and nickel can produce reactive oxygen species, resulting in lipid peroxidation, DNA damage, depletion of sulfhydryls, and calcium homeostasis (Blowes et al., 2003).

Iron is an essential element for metabolic systems, but in iron-rich solutions toxicity can develop in both fish and biota. In mine-waste discharge, Fe(III)-sulfate and (oxy)hydroxide precipitates can accumulate on the gill epithelium, resulting in clogging and damage, and decreasing the available surface area and increasing the diffusion distance for respiratory exchange (Blowes et al., 2003).

Several studies considered the bioaccumulation of heavy metals in various components of the food chain in the Elsburg/Natalspruit wetland ecosystem which is fed by the water pumped out of the Central Rand Gold Mines at ERPM. In one study, the concentration of zinc, manganese and nickel in *Arundo donax* and *Typha capensis* increased significantly under more alkaline water conditions, while the uptake of iron was found to be less effected by the pH (Rall and Rall, 1996). The metals did not appear to be detrimental to these plant species, as the plants thrived under both acidic and alkaline conditions. One suggestion was that the reeds be cropped regularly during the summer growing season, so that a substantial portion of the heavy metals present in the plant, and thus in the ecosystem, could be effectively removed. At present the reeds are burned occasionally in the winter months, with most of the ash and therefore metals, being returned directly into the stream ecosystem.

The biological significance of heavy metals in aquatic and semi-aquatic bird eggs is still unknown, although potentially toxic metals in the egg shells could induce various teratogenic effects and may even be lethal to the developing embryo. High lead concentrations detected in adult coots may have a serious impact on the long term health status (Rall and Rall, 1996). Heavy metal levels detected in the muscular tissue of fish sampled in the Natalspruit were found not be unduly high and would therefore not pose any health threat to human life should these fish be consumed.

A study by Haywood (2004) investigated the use of *Xenopus laevis* embryos and tadpoles as biological indicators for the measurement of biologically available metals and acidity found in water associated with AMD within water bodies on the Witwatersrand. Exposure to pH 3 and pH 4 showed clear toxicological effects on the growth and development of the embryos and tadpoles. Upon exposure to individual bioavailable metals, the relationship between metal concentrations and the various physiological responses of the tadpoles was different for each of the metals tested. Copper and cadmium affected the hatching of the tadpoles whereas zinc and lead affected tadpole survival after hatching. For the field research, the physiological responses of *X. laevis* embryos and tadpoles exposed to water collected along the length of the Natalspruit provided a spatial and temporal indication of the impact of AMD within the river. The baseline physiological responses of the *X. laevis* embryos and tadpoles exposed to known pH levels and metal concentrations within the laboratory were used to correlate the responses of the embryos and tadpoles exposed to the water from the Natalspruit River. It was evident that the pH of the water influenced the toxicity of the lethal and sub-lethal pollutants within the river.

3.4 Water Pollution Sources: Waste Water

Another category of water quality problems in the Klip River Catchment relates to the effluent drainage from the Rand Water supply and runoff from the informal settlements. A number of informal settlements flank the banks of the Klipsruit and the Klip River. Ineffective maintenance and infrastructures of water and sewage systems results in raw sewage and polluted water entering the river system. Discharge from three sewage treatment plants enters the Klip River Wetland (Figure 1.1) namely:

- Olifantsvlei – 182 Ml/day
- Bushkoppies – 186 Ml/day
- Goudkoppies – 126 Ml/day

Consequently, approximately 500 Ml/day flows into the Klip River Wetland from these three plants. Figures 3.4.1 and 3.4.2 illustrate the velocity and volumes of water entering the Klip River Wetland from the Olifantsvlei and Bushkoppies sewage treatment plants in the dry winter month of August (2008) and a wetter November (2007).



Figure 3.4.1: Discharge point of the Olifantsvlei sewage treatment plant ponds into the Klip River Wetland (August 2008).



Figure 3.4.2: Discharge point of the Bushkoppies sewage treatment plant ponds into the Klip River Wetland (courtesy of T.S. McCarthy, November 2007).

Bushkoppies Wastewater Treatment Works collects and treats sewage from the southern suburbs of Johannesburg, Soweto East and from the industries to the south of Johannesburg. The works were commissioned between 1984 and 1985. It consists of a head of works with screening, degritting, primary sedimentation, thickeners for raw sludge, thickeners for waste activated sludge, bioreactors, final clarification and maturation ponds. No sludge is treated at this works. Gravity thickened raw sludge is pumped to Goudkoppies Wastewater Treatment Works for digestion, dewatering, solar drying and disposal. Gravity thickened waste activated sludge is pumped to Olifantsvlei's RSHF (Regional Sludge Handling Facility) for dewatering and composting (Johannesburg Water, 2004).

Goudkoppies Wastewater Treatment Works collects and treats sewage from the City Centre and the south-eastern areas of Johannesburg. The works was commissioned in

1978 and consists of a new head of works with screening, degritting, primary sedimentation, raw sludge thickening / acid fermentation, flow balancing, activated sludge incorporating the five stage Phoredox process, final clarification, chlorination, waste sludge thickening, digestion, dewatering and solar drying of sludge. Waste activated sludge is thickened in dissolved air flotation units and mixed with raw, thickened sludge and thickened sludge produced at Bushkoppies Works. The mixture is anaerobically digested and thereafter dewatered on linear screen/belt press units and solar dried on drying beds. The dried sludge is ultimately disposed of on privately owned farmland (Johannesburg Water, 2004).

Olifantsvlei Wastewater Treatment Works collects and treats sewage from 3 outfalls. The south-western outfall collects sewage from the western sewer areas of Soweto via the inlet screw pump station. The south-eastern outfall obtains sewage from the southern and south-eastern areas of Johannesburg. The third outfall collects sewage from Lenasia via the Van Wyksrust Pump Station (Johannesburg Water, 2004). The works consists of 3 units:

- **Unit 1**: Was commissioned in 1956, but was decommissioned and abandoned in the early 1990's.
- **Unit 2**: Was commissioned in 1973 and was originally an extended aeration plant (without primary sedimentation). The unit consists of four activated sludge bioreactors and final clarification. Each module was designed to treat 30 Ml/d. Two reactors were decommissioned in the mid 1990's.
- **Unit 3**: Was commissioned in 1996 and consists of a new head of works with screening and de-gritting, primary sedimentation, acid fermentation, flow balancing, four stage bioreactors incorporating the four stage Johannesburg process and final clarification. The capacity of each module is 50 Ml/d.

Effluent from Units 2 and 3 are combined and flow through a series of five maturation ponds before being discharged into the Klip River. Sludge treatment is carried out at the Olifantsvlei Regional Sludge Handling Facility (RSHF), commissioned in 1997. The facility has capacity to compost biological sludge produced at Olifantsvlei, Goudkoppies and Bushkoppies Works and primary sludge from Olifantsvlei. The facility consists of a sludge

dewatering facility (belt presses and linear screens) with liquor treatment, a sludge cake and bulking agent blender, a composting area, screens to recover bulking agent, and a bulking agent preparation plant. All primary sludge is thickened in acid fermenters / thickeners and anaerobically digested before being dewatered on belt presses. Waste activated sludge is gravity thickened and could either be digested with the primary sludge, or directly dewatered on belt presses. All dewatered sludge is composted or disposed of on private farms. Filtrates from the dewatering unit are lime treated to reduce phosphates (PO_4). After treatment, the lime treated liquors could either be pumped back to the head of works or to Bushkoppies Works for treatment and disposal (Johannesburg Water, 2004).

Associated with sewage treatment is nitrogen (N) and phosphates. Nitrogen is the most common element in the earth's atmosphere, where it is present as the gas N_2. Nitrogen is also an important nutrient required for all living things. The amount of nitrate (NO_3) present in a water body will determine how much algae and plant material will be able to grow. An excess of nitrogen will allow aggressive plant and algae growth and contributes to eutrophication of a water body. Nitrate is soluble in water, and thus naturally enters bodies of water via rain, surface runoff and groundwater. Yet anthropogenic sources can increase the amount of nitrate entering a water body. Sewage effluent and fertilizer runoff are the most significant sources of anthropogenic nitrate

Phosphorus (P), like nitrogen, is a nutrient required by all life forms. However, phosphorus is generally present in very small amounts, thus it is often the limiting nutrient in an aquatic system. This means that plants have all of the ingredients necessary to grow, except for phosphorus. When phosphorus is added, even in minor amounts, plant growth is possible and algae growth results. Because of its role as a limiting nutrient, phosphorus should be carefully monitored in areas where eutrophication is a threat. Phosphate can also be added to water bodies due to the addition of sewage effluent, fertilizer runoff, and urban runoff. For example, sewage that has been through primary and secondary treatment contains 5 to 8 ppm phosphate, most of which is a result of household soaps and detergents in the wastewater. Because of its role as a limiting nutrient, this additional phosphate can allow a tremendous amount of algae growth that would otherwise not occur.

It is possible to determine the trophic state of a lake by measuring the amount of nutrients in the water. The following classification terms are used by the Department of Water Affairs: National Eutrophication Monitoring Programme (NEMP, 2003):

- **Oligotrophic** – low in nutrients and not productive in terms of aquatic animal and plant life.
- **Mesotrophic** – intermediate levels of nutrients, fairly productive in terms of aquatic animal and plant life and showing emerging signs of water quality problems.
- **Eutrophic** – rich in nutrients, very productive in terms of aquatic animal and plant life and showing increasing signs of water quality problems.
- **Hypertrophic** – very high nutrient concentrations where plant growth is determined by physical factors. Water quality problems are serious and can be continuous.

Table 3.4.1 illustrates the method to determine trophic status statistics and Table 3.4.2 provides the trophic status classification of the Vaal Dam and the Vaal Barrage as determined for the period October 2002 to September 2003. Both the Vaal Dam and the Barrage were showing algal productivity in 2002 to 2003.

Table 3.4.1: Method to determine trophic status statistics (NEMP, 2003).

Statistic	**Unit**	**Current trophic status:**			
Mean annual chlorophyll *a*	µg/ℓ	0<x≤10	10<x≤20	20<x≤30	>30
		Oligotrophic (low)	**Mesotrophic (moderate)**	**Eutrophic (significant)**	**Hypertrophic (serious)**
		Current nuisance value of algal bloom productivity:			
% of time chlorophyll *a* > 30µg/ℓ	%	0	0<x≤8	8<x≤50	>50
		negligible	**moderate**	**significant**	**serious**
		Potential for algal and plant productivity:			
Mean annual Total phosphorus	mg/ ℓ	x≤0.015	0.015<x≤0.047	0.047<x≤0.130	>0.130
		negligible	**moderate**	**significant**	**serious**

Table 3.4.2: The Trophic Status classification of the Vaal Dam and the Vaal Barrage (NEMP, 2003).

Dam Name	Mean TP mg/L	n TP	Mean Annual Chlorophyll a (µg/l)	n Chl	Percent of Time Chl a > 30 µg/l	Trophic Status
Vaal Barrage	0.069	10	8.4	6	10	Oligotrophic, significant potential and current algal productivity
Vaal Dam	0.077	46	14.78	16	17	Mesotrophic, significant potential and current algal productivity

The rivers flowing north of the Witwatersrand Ridge (Crocodile River), where little to no wetlands are present, also have treated sewage water discharged into them. In contrast to the Vaal Barrage, the Hartebeespoort Dam is impacted chronically with eutrophication. The Trophic Status classification of South African impoundments determined, for the period October 2002 to September 2003, that the Hartebeespoort Dam was hypertrophic with significant current algal productivity. According to the North West Environmental Management Plan for the Hartebeespoort Dam Remediation (2005) roughly 90% of the yearly inflow is derived from the Crocodile River. During the dry season the water of the dam is more than 50% treated wastewater from urbanised areas upstream. Every year over 170 metric tonnes of phosphorus is discharged into the dam. The immediate cause of the unpleasant and often hazardous quality of the water is blue-green algae i.e. cyanobacteria. Green, smelling and often toxic algae blooms frequently cover large areas of the water surface (Figure 3.4.3).



Figure 3.4.3: Algal blooms seen at the Hartebeespoort Dam wall (North West Environmental Management Plan, 2005).

The excessive algae and cyanobacteria blooms considerably reduce the recreational values and usability of water as well as disturb the natural biological mechanisms in the water body. Often, people swimming and water-skiing end up in rashes or even more serious health problems. Domestic animals and pets die after consuming a sufficient quantity of this toxic water (North West Environmental Management Plan, 2005). The algae toxin (microcystin) levels of the water in the Hartebeespoort Dam are regularly so high, that according to the international guidelines of World Health Organisation, all uses of the water, including swimming and water-skiing, should be banned seasonally (North West Environmental Management Plan, 2005). These problems have prevailed in the Hartbeespoort Dam ever since the early 1970s. Studies (North West Environmental Management Plan, 2005) clearly established that the Hartbeespoort Dam can be saved. However, there are no cheap, quick or easy ways to do this. The North West Environmental Management Plan for the Hartebeespoort Dam Remediation (2005), predicts a start up cost of R2 million and annual running costs of R1.8 million to comply with this management programme.

3.5 Wetlands and their Importance

The value and importance of wetlands has been drawing increasingly more interest over the past few decades. Wetlands produce and sustain many diverse life forms, especially wetland dependant species as well as rare and endangered species (Begg, 1990). Their most important function is the fulfillment of hydrological and hydrochemical functions – intercepting storm runoff and storing storm water, recharging groundwater, removal of organic and inorganic nutrients as well as toxic materials (Hammer, 1997).

In 1975 South Africa became the first African signatory to the Ramsar Convention, which obligates government of this country to protect designated wetlands (Whyte and Shepherd, 1990). The strain on future resources of this country (such as freshwater) means that in the face of exponential population growth, man's dependence upon wetlands is steadily increasing (Begg, 1990).

As with the proximity to the metropolitan area of Johannesburg, the Klip River Wetland is impacted by infrastructure, transport systems, urbanisation and sewage as well as peat mining and gold mining activities (Grundling and Marneweck, 1999). Figure 1.1 highlights

industrial and mining areas as well as sewage and water works along the catchment. Cultivation, especially vegetable farming, on the perimeters of the wetland requires water to be abstracted and channelled for irrigation, while sewage works discharge effluent into the wetland impacting negatively on the quality of the water and peat (Grundling and Marneweck, 1999).

The wetlands of the Klip River have played a vitally important role to ensure the natural treatment of polluted mine water on the Central Rand. It has been observed that as water moves south of the catchment towards the Vaal River, element concentrations and attributes, such as iron, sulphate, conductivity and pH improve to acceptable and ideal levels, versus unacceptable levels near the mines and mine dumps (Figure 3.5.1). This dramatic improvement of water quality is attributed to the presence of the large tracts of Malmani Dolomites as well as the extensive wetlands in the area (Davidson, 2003). The alkaline dolomites lead to an increase in the pH of water, which enhances the precipitation of iron and other elements, which become insoluble in water of neutral pH (Davidson, 2003). The wetlands serve as a sink for pollution where polluting metals and other inorganic and organic constituents are trapped in sediments (Arnold, 2004). Dilution from runoff and treated sewage water probably is important in neutralizing the water chemistry.

Water analysis completed by Grundling and Marneweck (1999) in the northwest basin of the Klip River Wetland indicated slightly acidic to slightly alkaline (pH: 6.3 - 7.23) levels with the water rich in carbonates, because of it's dolomitic origin, and high sulphate and mercury levels, confirming the pollution by the gold mines. Analysis of the main basin further downstream indicated that, although sterilised, this wetland is still acting as a natural filter, since lower sulphate, mercury and cadmium levels were found (Grundling and Marneweck, 1999).

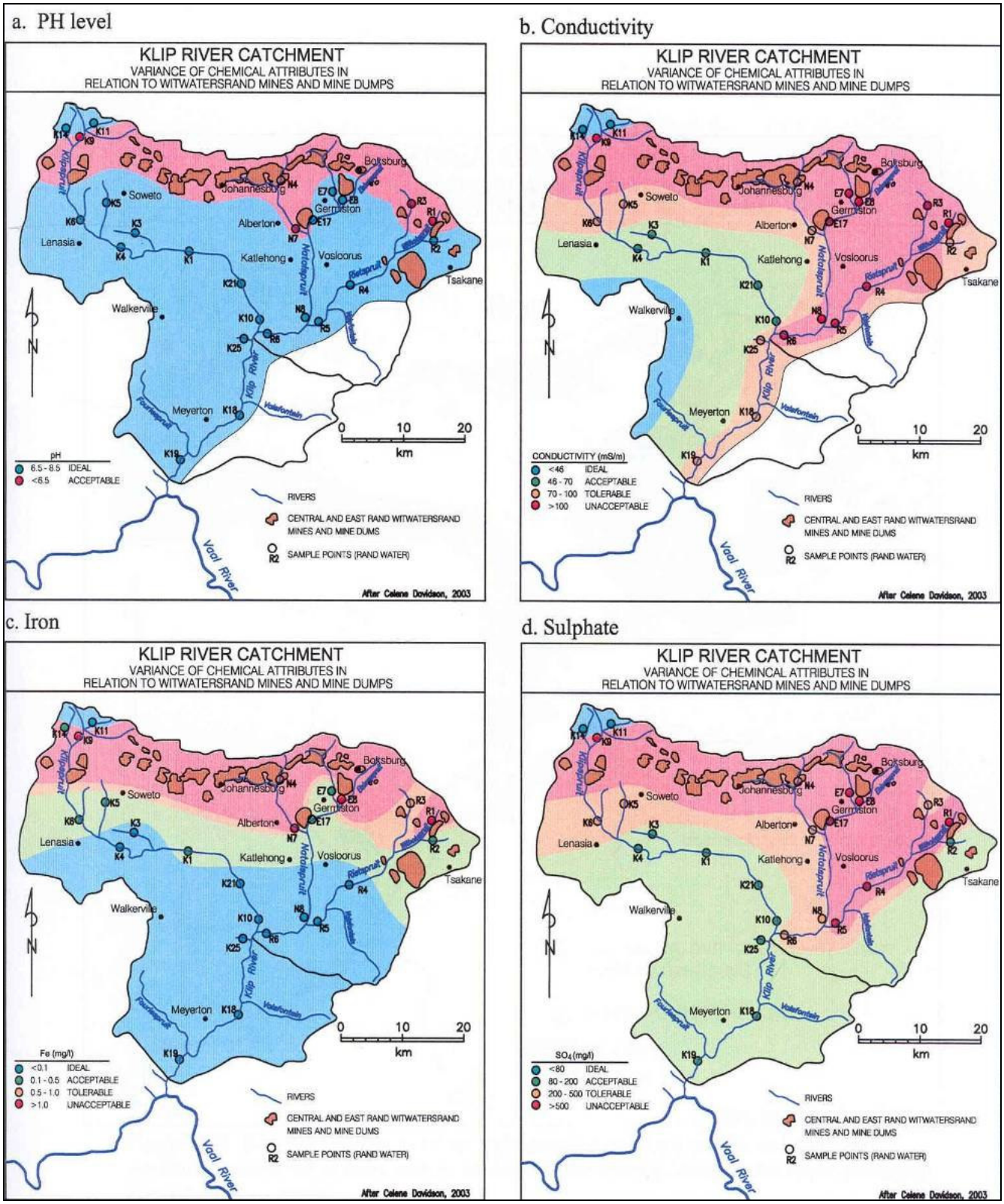


Figure 3.5.1: Klip River catchment showing distribution of a) pH b) conductivity, c) iron and d) sulphate (Davidson, 2003).

Peat sampling in the Klip River Wetland has also recorded these pollution levels. Concentrations of heavy metals and phosphorus in the inorganic content of the peat are higher in the uppermost reaches of the wetland (closer to the source) than downstream and further from the source (McCarthy et al.,2007). McCarthy and Venter (2006) concluded that were it not for the Klip River Wetland trapping the pollutants, they would have reported directly to the Vaal River system, which would have created a much more widespread pollution problem. It was further noted by these authors that this wetland fulfills such an important function to the region that it should be rigorously protected.

Hancock (1966) realized the importance of these reed swamps for water purification prior to 1966 when completing her thesis on the algal ecology of the Klip River in the gold mining area of Johannesburg. Proximal to the mine dumps, which is at the source of the Klip River, she described the water quality as “Lethal” (Hancock, 1966, page 49).

> *In the Klip River all populations (of algae), from whatever source, are completely destroyed in the lethal stretches.*

Her conclusion on what conditions brought about the recovery of the stream from degradation, caused by the gold-mining industry, were three fold:

1. The nature of the stream bed (dolomitic limestone)
2. Dilution (from the natural springs and sewage water)
3. Reed swamps

The open swamps of Phragmites, she highlights, improve conditions physically by causing the slowing down of water, which permits greater sedimentation of suspended materials, while the vegetation acts as a mesh to “flotsam and jetsam”. The chemical improvement was attributed to the fact that there is greater degree of neutralization, as the water has a longer contact time with the dolomite beds. The rise of pH then causes the precipitation of iron-hydroxide. Biological effects were seen in the increase of bacteria, nitrification, and algal populations. This in turn, during photosynthetic activity, further raised the pH, oxygenated the water, and together with the increase in heterotrophs, added further organic material to the stream.

4. Methodology

Johannesburg has an extensive aerial photography collection and the Klip River Wetland was analysed using photographs going as far back as 1938. By studying the changes seen in successive photographs, including 1938 (job 129), 1952 (job 314), 1961 (job 438), 1984 (job 881) 2003 and 2006, the aim was to determine the changes to the wetland over time and associated rates of change. The photos were georeferenced in GIS (Geographic Information Systems; ArcMAP Version 9.2) to allow convenient comparisons.

Historical maps of the area were also anlaysed. The Klip River Wetland was included in the area geologically mapped between 1910 and 1915 by Mellor, E.T. Although Arnold (2004) analysed the wetland as recorded by Mellor, these maps will be analysed again, now with a better insight of the system, especially in relation to channel formation. Goldman maps of the 1890's (Goldmann, 1895-6) were also considered for analysis but unfortunately this section of the Witwatersrand was not mapped in detail. Historical reports and descriptions of the study area were analysed in conjunction with the aerial photographs.

In 2006 a LIDAR survey was undertaken from April to May 2006 by Airborne Laser Solutions (ALS) to produce digital orthophotos with 20 cm pixels, and 25 cm contours for the City of Johannesburg. Light Detection and Ranging (LIDAR) is a remote sensing system used to collect topographic data. This survey was carried out using an aircraft mounted LIDAR system that "scanned" the ground below with a 33kHz laser resulting in a dense DTM of the ground surface and objects above the ground. The flying height of the aircraft was 1 100 m above the ground level with a swathe width of approximately 700 m. The project survey report is provided in Appendix 1. This topographic data was analysed to document topographic changes along the wetlands length, i.e. a long river profile. A test was conducted along the N1 Highway to determine the noise (error) in the dataset (Appendix 2).

The Department of Water Affairs and Forestry (DWAF) and Rand Water Board have monitoring points along the length of the Klip River (Figure 4.1). Water chemistry and discharge data from these points were evaluated to determine secular changes in water

quality. Where water chemistry and discharge data is sparse, technical reports by the hydrological research units and results of Ph.D. and M.Sc. theses were used.

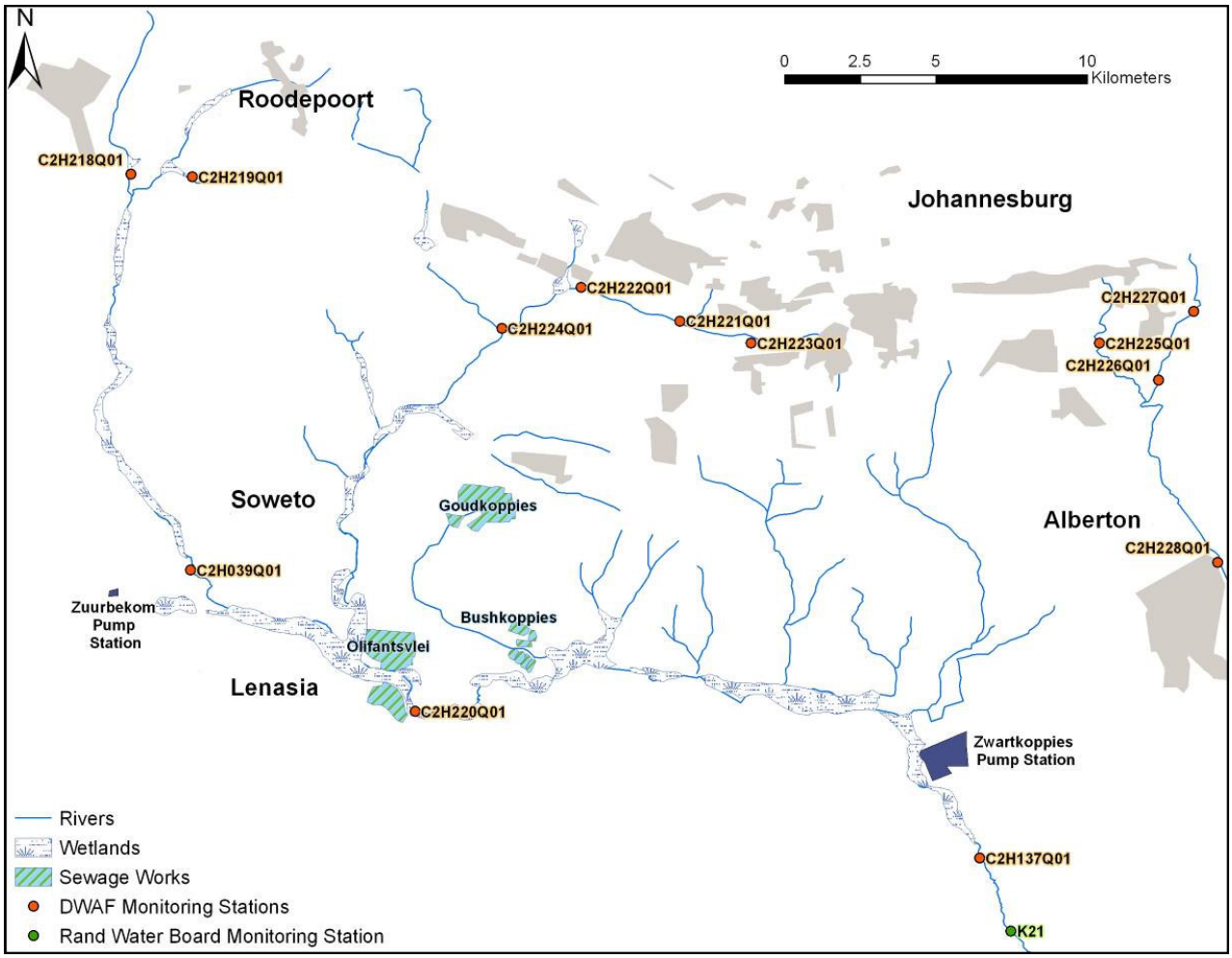


Figure 4.1: Location of monitoring stations along the Klip River (grey areas indicate industrial land use).

5. Results

The extent of the Klip River Wetland is vast and the impacts along it variable, thus the wetland has been divided into five sections (Figure 5.1.1):

- Section 1: Lenasia to Olifantsvlei Water Treatment (Golden Highway)
- Section 2: Golden Highway to the N1
- Section 3: N1 to Kibler Park
- Section 4: Kibler Park to Kromvlei
- Section 5: Zwartkoppies Section

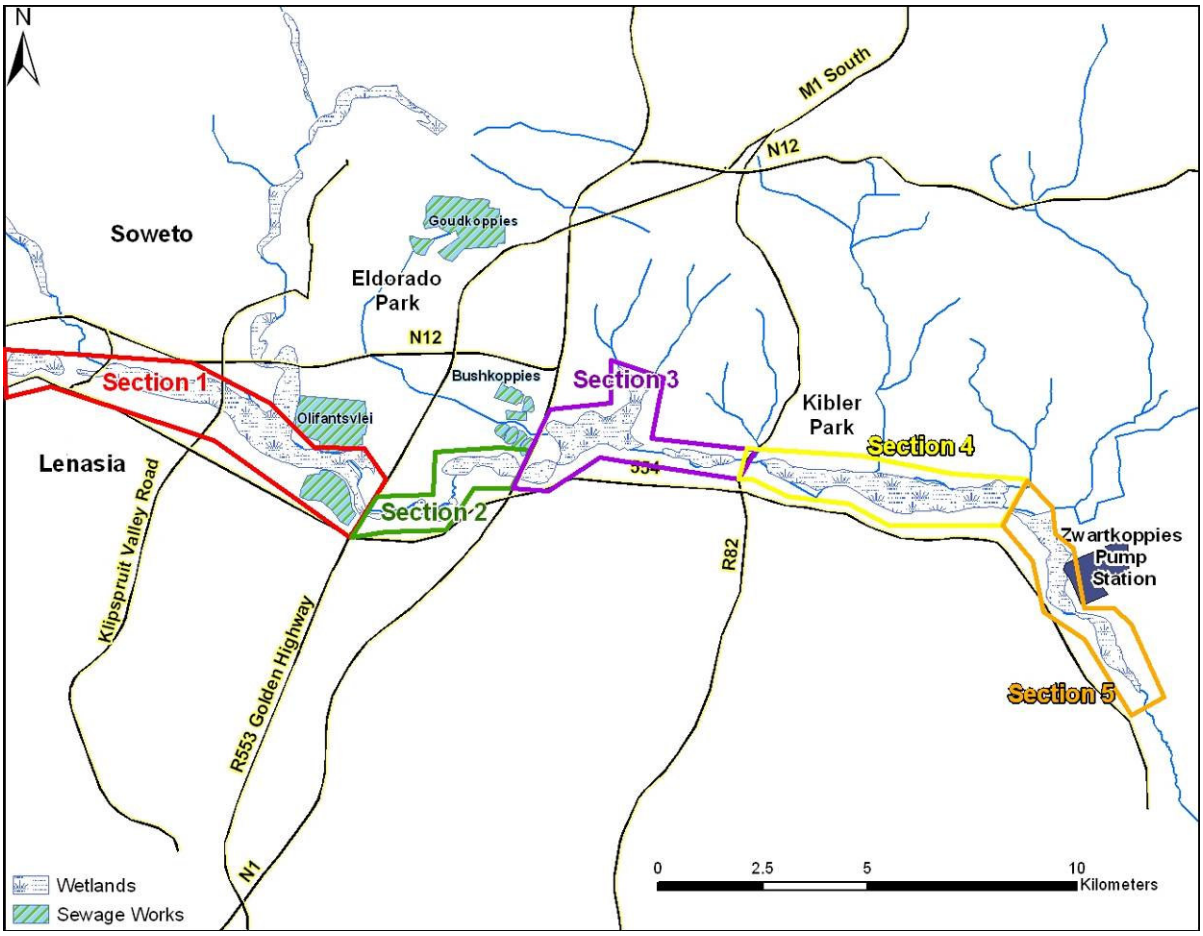


Figure 5.1.1: The wetland divided into five sections.

5.1 Aerial Photography

Attempts were made to quantify the extent of the wetland over time to determine the rate of wetland deterioration. This proved to be subjective using aerial photography only. Wetlands have historically been one of the most difficult ecosystems to quantify. A Landsat image of the wetland was sourced to determine if satellite multi-spectral imagery could be used to quantify the extent of the wetland. The Landsat image (Figure 5.1.2) identifies water as black. Using this methodology the wetlands (or peat) only contain moisture in the western, very proximal section totalling 57.45 ha. Without further analysis it is uncertain whether this represents peat moisture or flow of water across the wetland. The 2003 photography shows burns from the winter fires downstream of this moist zone (Figure 5.1.3), potentially confirming this moisture.

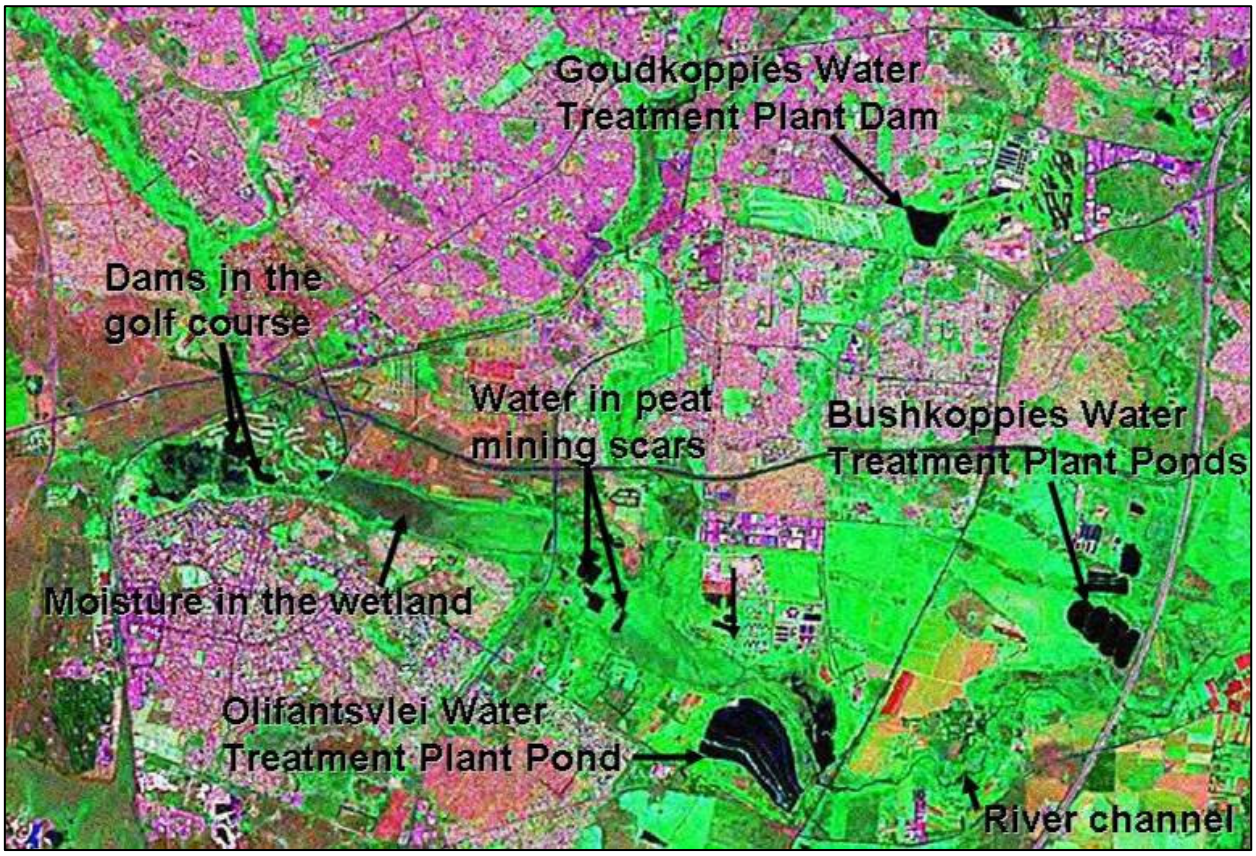


Figure 5.1.2: Landsat image showing the water and moisture content of the wetland.



Figure 5.1.3: Burns in the wetland (2003) downstream of the moist section of wetland.

It would be expected that with the diversion of water from the wetland into channels, as was discovered by McCarthy et al. (2007), the wetland area would reduce in size over time. A portion of the geological map of the Witwatersrand mapped between 1910 and 1915 by E.T. Mellor covers the Klip River Wetland. Using the georeferenced aerial photography and augmenting it with Mellor's mapping (Mellor, 1917) it was possible with GIS to quantify the wetland area at particular periods of time (Table 5.1.1).

Table 5.1.1: Change in wetland area over time.

Section	Wetland Area (ha)			
	1917	1938	2006	
1	456	569	546	
2	105	47	56	
3	199	39	78	
4	>634	465	221	415
5			194	

In Section 1 the wetland area increased in size between 1917 and 1938 (Table 5.1.1). This is confirmed by the increased rate of peat accumulation since the establishment of Johannesburg, as described by McCarthy and Venter (2006). Subsequently, there was a slight decrease in wetland size between 1938 and 2006 which can, in part, be attributed to peat mining.

The wetland in Section 2 decreased in size by 58 ha over 20 years (1917 to 1938). The wetland area then increased marginally (9ha) over the period 1938 to 2006. In Section 3 the wetland decreased in size by 179 ha in 20 years and then doubled in size between 1938 and 2006. A combined area measurement was taken for Sections 4 and 5. Unfortunately Mellor's mapping only extends through to a part of Section 5 and so the minimum area was calculated for 1917 at 634 ha. The wetland area decreased by more than 170 ha between 1917 and 1938 (a similar reduction as Section 3 over the same time period) and a further 50 ha by 2006.

To summarise, with the exception of Section 1, the wetland decreased in size by 41% between 1917 and 2006. Sections 2 and 3 increased in extent by 9 and 39 ha, respectively between 1938 and 2006. It is evident from this summation that the measurement of wetland area is not an effective way to quantify the extent of the wetland degradation from canalisation. This might be due to the wetland receiving sufficient water from rainfall and local runoff to remain functioning, albeit not optimally.

Channel formation, propagation and widening along with knick point migration are potentially better indicators of wetland deterioration. At six points (A to F) along the wetland's length the channel width was measured off aerial photography and with the use of GIS between 1938 and 2006 (Figure 5.1.4 and Table 5.1.2).

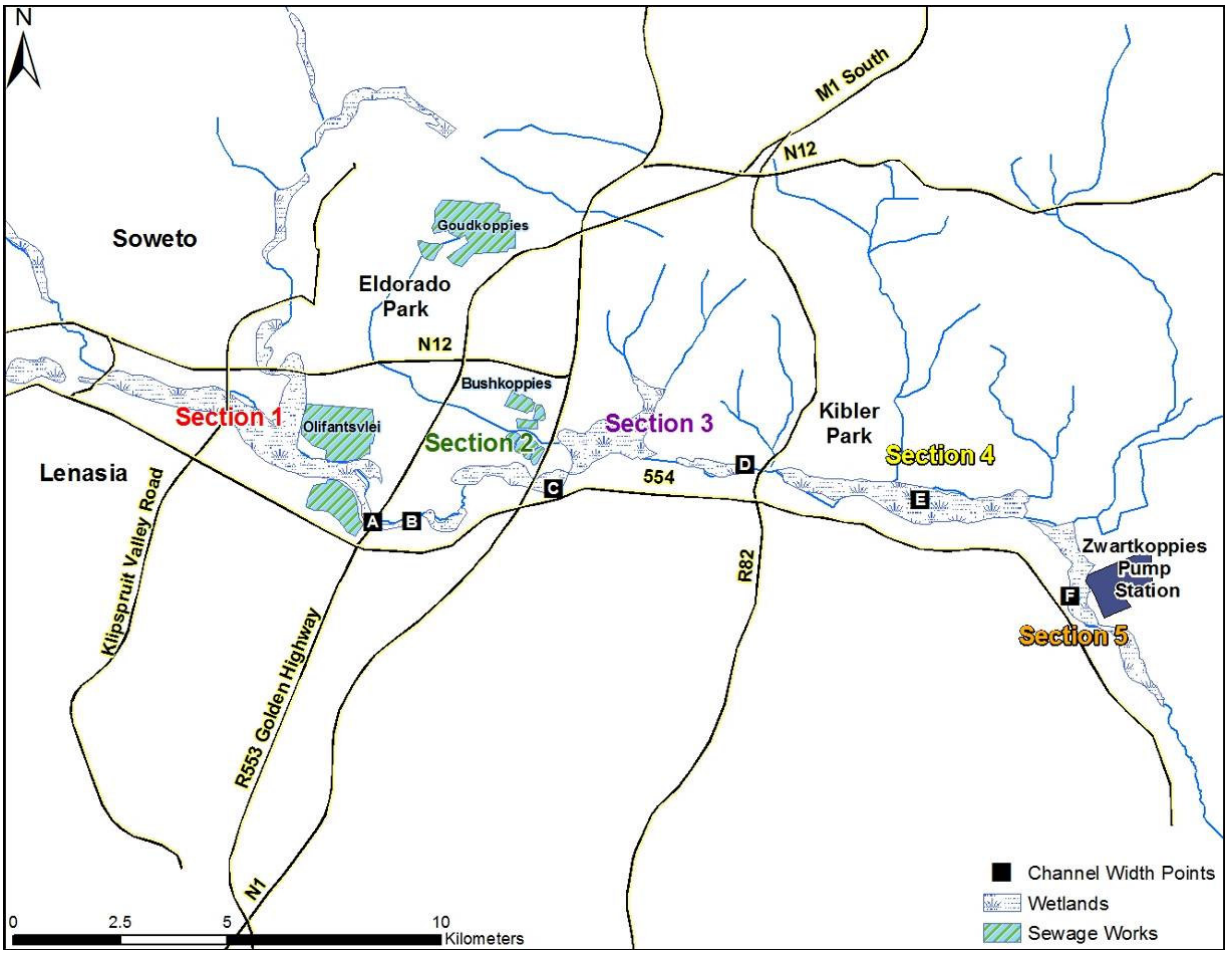


Figure 5.1.4: Locality of channel width measurements.

Table 5.1.2: Channel widths over time along the length of the Klip River Wetland.

Point	Channel Width (m)				
	1938	1961	Approx. 2001	2003	2006
A	6	19	24	25	27
B	2.5	3	6	8	8
C	2	2.5	8	10	10
D	5	5	13	15	15
E	0	1	11	13	13
F	0	3	5	9	9

A - Downstream of Olifantsvlei Water Treatment Plant
B - Downstream of Golden Highway
C - Downstream of N1
D - Downstream of Bushkoppies Water Treatment Plant
E - Downstream of R82
F - At Zwartkopjes Pump Station

The first channel to be considered is at Point A (Figure 5.1.4), which today flows under the Golden Highway. This channel was mapped initially by Mellor in 1917 as a major crossing of the wetland. At Point A only a channel was developed and no marsh or reed beds were recorded (A in Figure 5.1.4). This channel increased in breadth by 21 m between 1938 (6 m) and 2006 (27 m) (Table 5.1.2). The channel width at Point B increased only 5 m over the same time period (Table 5.1.2), even though Points A and B are in close proximity. Channel widths were measured at two locations (C and D in Figure 5.1.4) in Section 3 and were calculated to have increased by about 8 to 10 m between 1938 and 2006 (Table 5.1.2). Both, Sections 4 and 5 had no channels present in 1938 but measurements at E and F show channels about 9 to 13 m wide in 2006 (Table 5.1.2). The most noticeable change in Section 4 (Point E) is recorded between 1961 and 2003 where the channel width increased from 1 m to 11 m (Table 5.1.2).

The channel at Point A, downstream of the Olifantsvlei Sewage Works, had the greatest growth with a 21 m widening over 68 years. Point E in Section 4 exhibits the second-largest increase of width, and Point A the largest at 13 m over the same time period. The intervals between the channel width measurements are not consistent. Consequently, the rates of change where calculated (Table 5.1.3) to provide a better indication of which channels are the worst impacted and over which periods of time. The channel at Point A widens at the greatest rate over periods 1938 to1961 and 2003 to 2006 (Table 5.1.3 and Figure 5.1.5). For the period 1961 to 2001 the channel at Point E enlarges at the greatest rate (Table 5.1.3 and Figure 5.1.5). Point F however, changes at the greatest rate with a widening of 2m/year between 2001 and 2003 (Table 5.1.3 and Figure 5.1.5). When calculating the average rate of change for the entire period, 1938 to 2006 and 1938 to 2003, Point F experiences the greatest rate of change (Table 5.1.3 and Figure 5.1.5).

Table 5.1.3: Rates of change for channel widths for Points A to F.

Point	Rate of Channel Width Change (m/year)					
	1938 to 1961	1961 to 2001	2001 to 2003	2003 to 2006	Average 1938 to 2006	Average 1938 to 2003
A	0.57	0.13	0.50	0.67	0.46	0.40
B	0.02	0.08	1.00	0.00	0.27	0.37
C	0.02	0.14	1.00	0.00	0.29	0.39
D	0.00	0.20	1.00	0.00	0.30	0.40
E	0.04	0.25	1.00	0.00	0.32	0.43
F	0.13	0.05	2.00	0.00	0.55	0.73

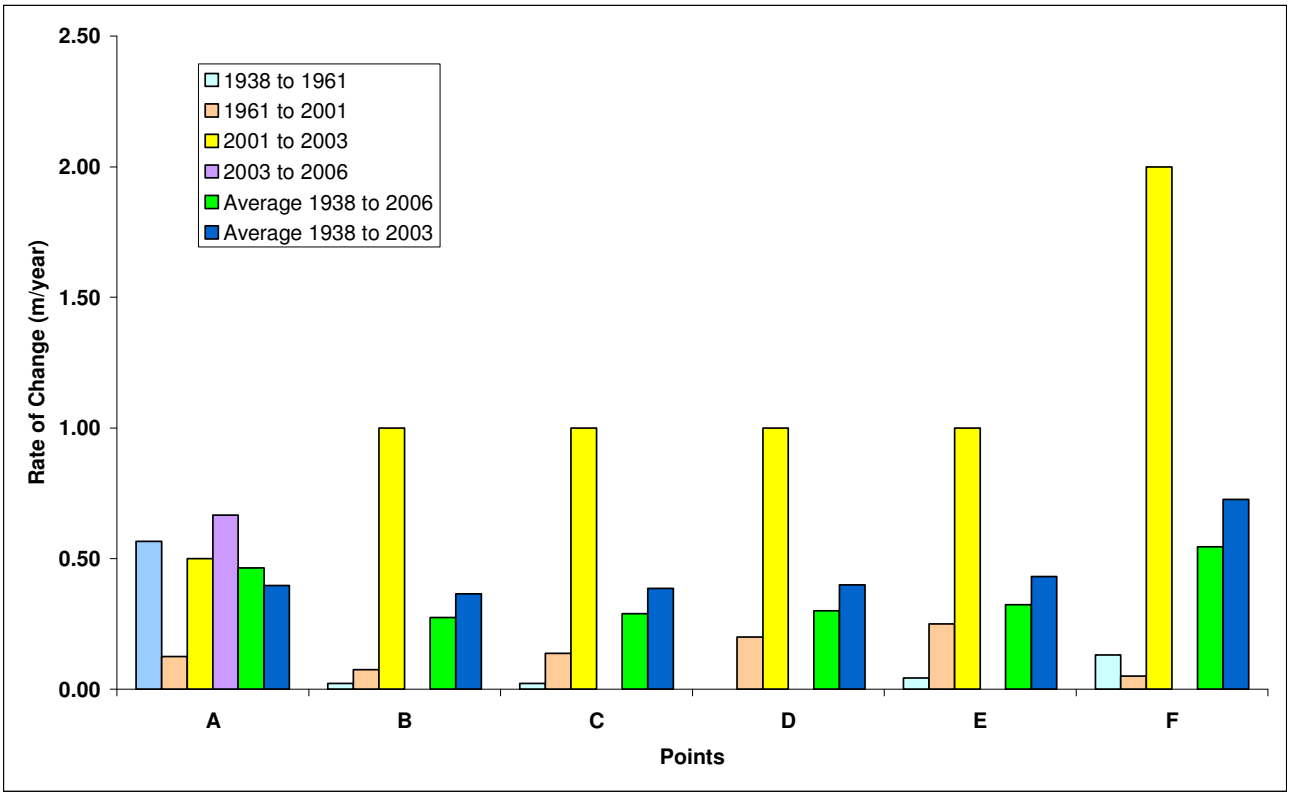


Figure 5.1.5: Rate and average rate (m/year) of change of channel width over time.

It is important to consider the above changes in the wetland area and channel formation and widening in conjunction with the analysis of the aerial photographs, which is outlined in the following.

5.1.1 Section 1: Lenasia to Olifantsvlei Water Treatment

The Klip River Wetland first occurs in the Lenasia area of Johannesburg (Figure 5.1.1). The wetland in this reach is between 450 and 500 m in width and is a reed-covered swamp dominated by *Phragmites australis* (Figure 5.1.6). McCarthy et al. (2007) recorded flow velocities in Section 1 between 0 and 0.03 m/s, with flow depth rarely exceeding 20 cm. Peat in this area is about 4 m thick with an upper rhizome layer of 30 to 50 cm (McCarthy et al., 2007). McCarthy et al. (2007) also commented that although heavy metal concentrations in the peat are high, the vegetation does not appear to be adversely impacted. This section of the wetland is described as the best approximation of the appearance and hydrological functioning of the Klip River Wetland prior to the development of the Witwatersrand mining and industrial complex (McCarthy et al., 2007).



Figure 5.1.6: The reed-covered swamp in the Lenasia area (450 m width) dominated by *Phragmites australis* (courtesy of T.S. McCarthy, November 2007).

Anthropogenic impacts in this section appear to be minor, apart from the golf course development in the far west (excluded from analysis). Peat mining has also occurred in this section of the wetland east of Klipspruit Valley Road and has left large open water bodies (Figures 3.1.3 and 3.1.4). Olifantsvlei Sewage Works have been established in the lowest reaches of Section 1. McCarthy (op. cited) describes a contact dam from the treatment works, which has been constructed in the wetland itself.

Prior to the summer rains in 2008, a white crust was seen on the banks of the Lenasia section of wetland (Figure 5.1.7). This occurrence is described in Naicker et al. (2003) as being attributable to the effect of capillarity and surface evaporation. Metal-rich ground water, which is drawn up by capillarity evaporates on the soil surface and produces a gypsum crust, which is enriched in metal sulfates. This effect is most noticeable in winter when evaporation exceeds rainfall.

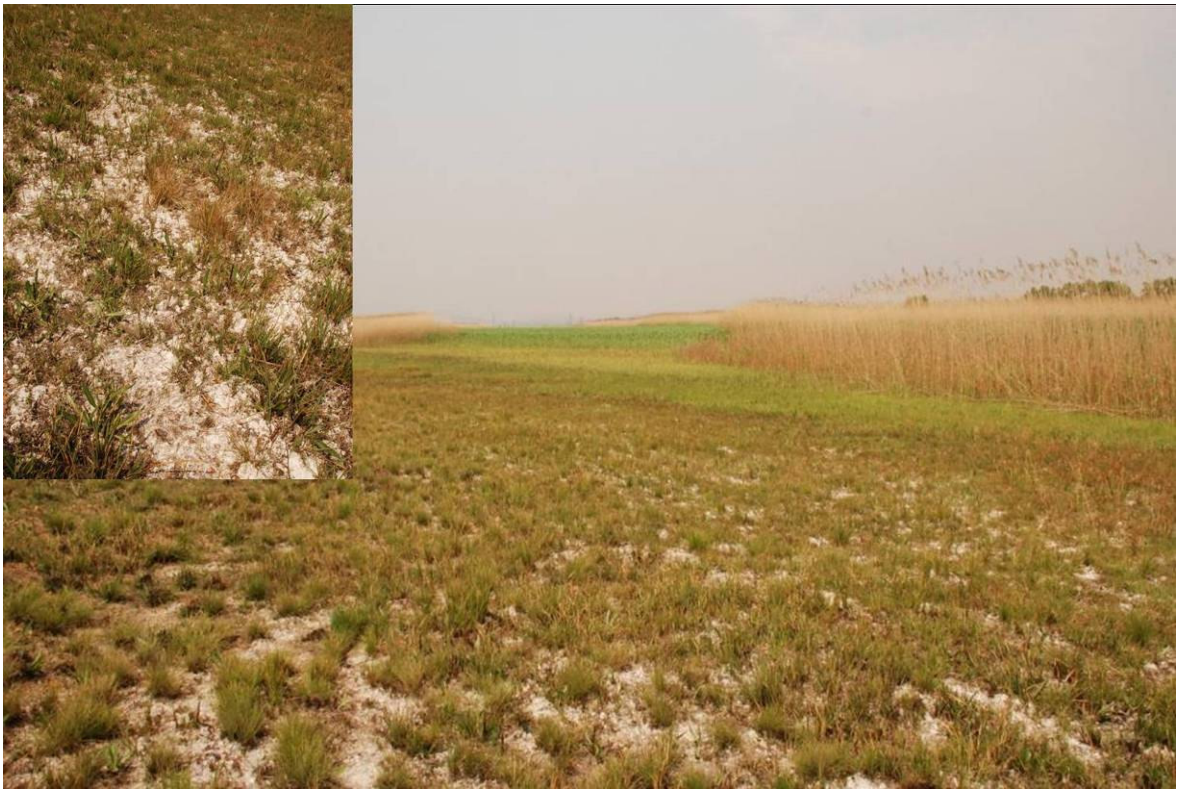


Figure 5.1.7: Gypsum crust accumulated on the banks of the Klip River Wetland at Lenasia.

White (1957, page 13) also described this section of wetland:

> *Soon after crossing the Johannesburg – Potchefstroom Road the Klip River widens out considerably and flows through four or five miles, firstly of marshy land, and then of reed beds, until it is joined by the Klipspruit tributary. Small, good springs of clear water enter the Klip River in the marshy area. These springs are from dolomitic areas and, while their general tendency is to dilute the mine dump contributions, they increase the calcium content and raise the pH, with consequent fall in the iron content.*

A study in 1980 used the Klip River Wetland upstream and downstream of the Golden Highway to formulate an optimisation model for sewage treatment plants (Arnold, 1980). Arnold (1980) highlighted the presence of a large vlei at the confluence with the Klipspruit and upstream of the Golden Highway. A portion of the Klipspruit had been diverted into an open pond area which discharged via a sluice gate back into the main river immediately upstream of the bridge. This ponded area is the contact dam described by McCarthy et al. (2007).

The geological mapping by Mellor (1917) does not illustrate any channels in the wetland in Section 1, except near the road crossing where Olifantsvlei is now built (B in Figure 5.1.8a). Examination of aerial photographs further support that in 1938 and 1961 channels were still absent in Section 1. However, as mentioned previously the channel at the road crossing increased in width by 21 m between 1938 and 2006 (Table 5.1.2 and Figure 5.1.9). The 1938 and 1961 aerial photography shows the wetland to consist of an extensive reed bed with irrigation canals cut along the northern and southern banks (C and D in Figures 5.1.8b and c). These canals are still apparent in the 2006 photography (D in Figure 5.1.8d) but they have been heavily encroached by *Phragmites* reeds (McCarthy et al., 2007). At C (Figure 5.1.8d) discharge into the Klipspruit tributary from the Goudkoppies Sewage Works appears to have led to the widening of an old irrigation furrow. This furrow was present prior to 1938 but channelizing of the water only occurred after 1961 (Figures 5.1.8a to d).

The building of the Olifantsvlei Treatment Works and the construction of the contact dam in the wetland occurred prior to 1961 (E in Figures 5.1.8c and d) but after 1957 (White, 1957). The maturation ponds built to the south of the wetlands were constructed after 1961 (F in Figure 5.1.8a to d). A portion of these ponds were evident by 1984, which is illustrated in Figure 5.1.10 (Arnold, 1980).

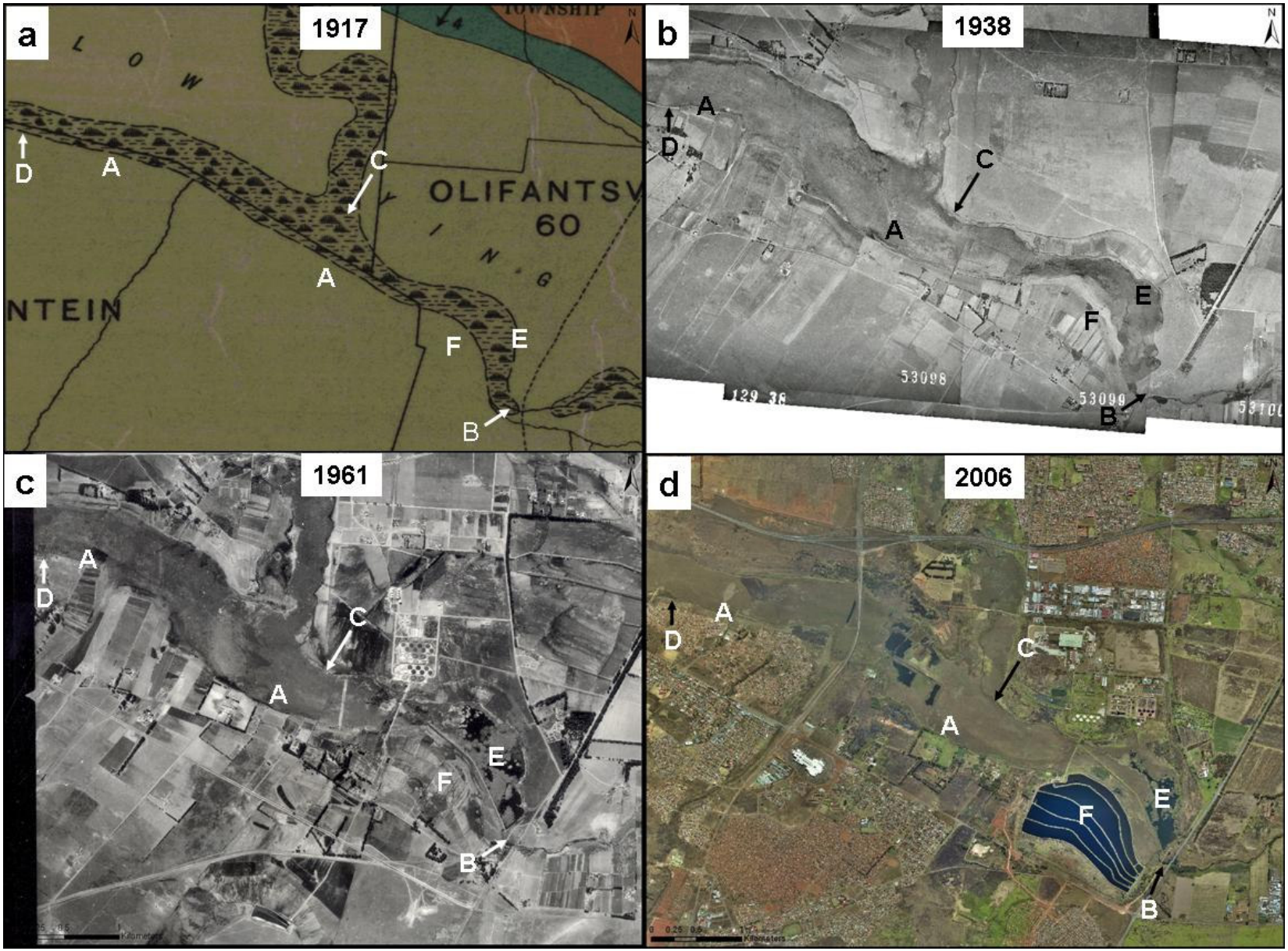


Figure 5.1.8: The wetland in the Lenasia area in (a) 1917, (b) 1938, (c) 1961 and (d) 2006.



Figure 5.1.9: Point A: Channel cut after the Olifantvlei discharge point (Golden Highway in background; August 2008).

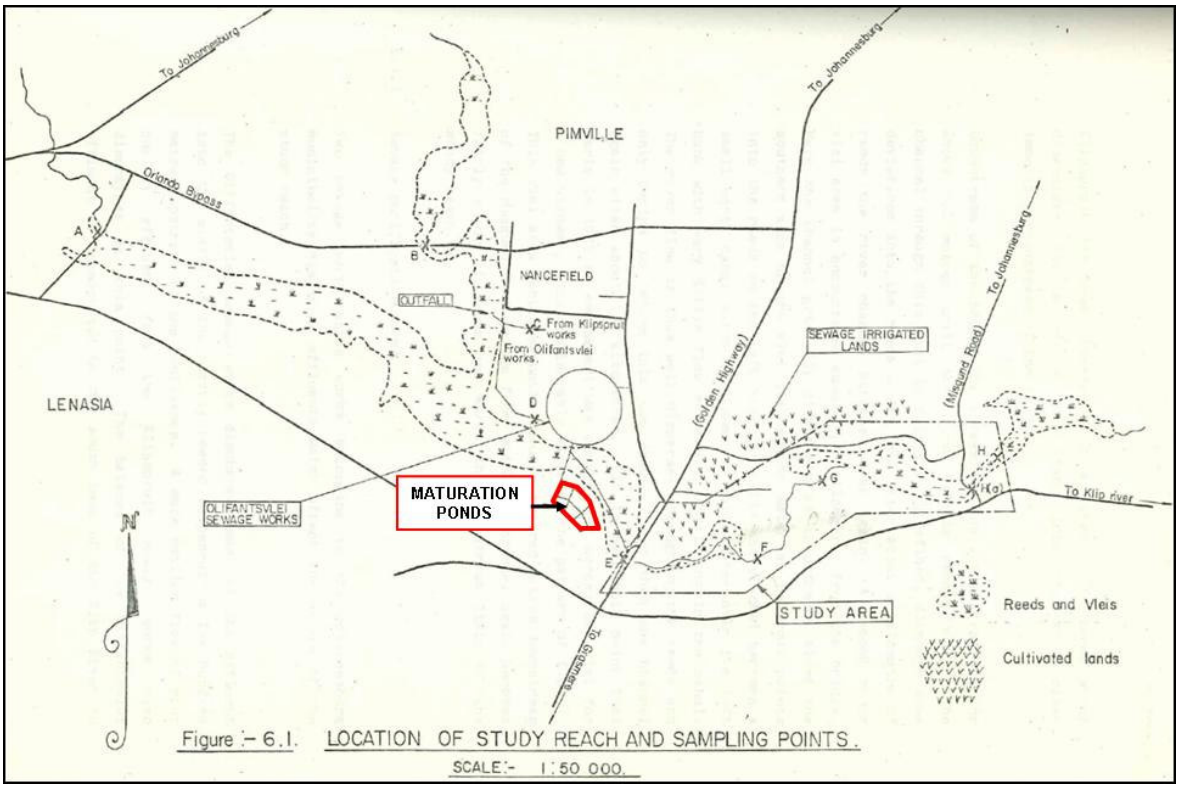


Figure 5.1.10: Study site of Arnold (1980), showing the extent of the wetlands at this time, the maturation ponds and his sampling points (after Arnold, 1980).

5.1.2 Section 2: Golden Highway to the N1

Section 2 of the Klip River Wetland has been highly impacted by farming. In 1917, Mellor's mapping depicts a continuous wetland after a short section of channel (Figure 5.1.11a). By 1938 large tracts of the wetland were drained by furrows for development of agricultural land (A and B in Figures 5.1.11a to c). This is confirmed by the extent that the wetland decreased, 58 ha over 20 years (1917 to 1938; Table 5.1.1). White (1957) does not depict wetlands in this section either. Arnold (1980, page 59), however, does illustrate and describe wetlands in 1980 (Figure 5.1.10).

> *Downstream of the Golden Highway bridge the stream follows a clear channel for about 700 meters until the first heavily reeded vlei. The channel through this vlei is fairly well defined, although some deviations into the reeds occur, and after about a kilometer of reeds the river channel becomes clear again. A second major vlei is encountered about 3.75 kilometers from the bridge. Here the channel gradually disappears as it proceeds along the southern side of the vlei discharging water at numerous points into the reeds on the left bank. Finally the channel becomes a small earth canal which continues to spill water over its left bank with very little flow eventually continuing in the canal. The river flow is thus well dispersed throughout the reeds.*

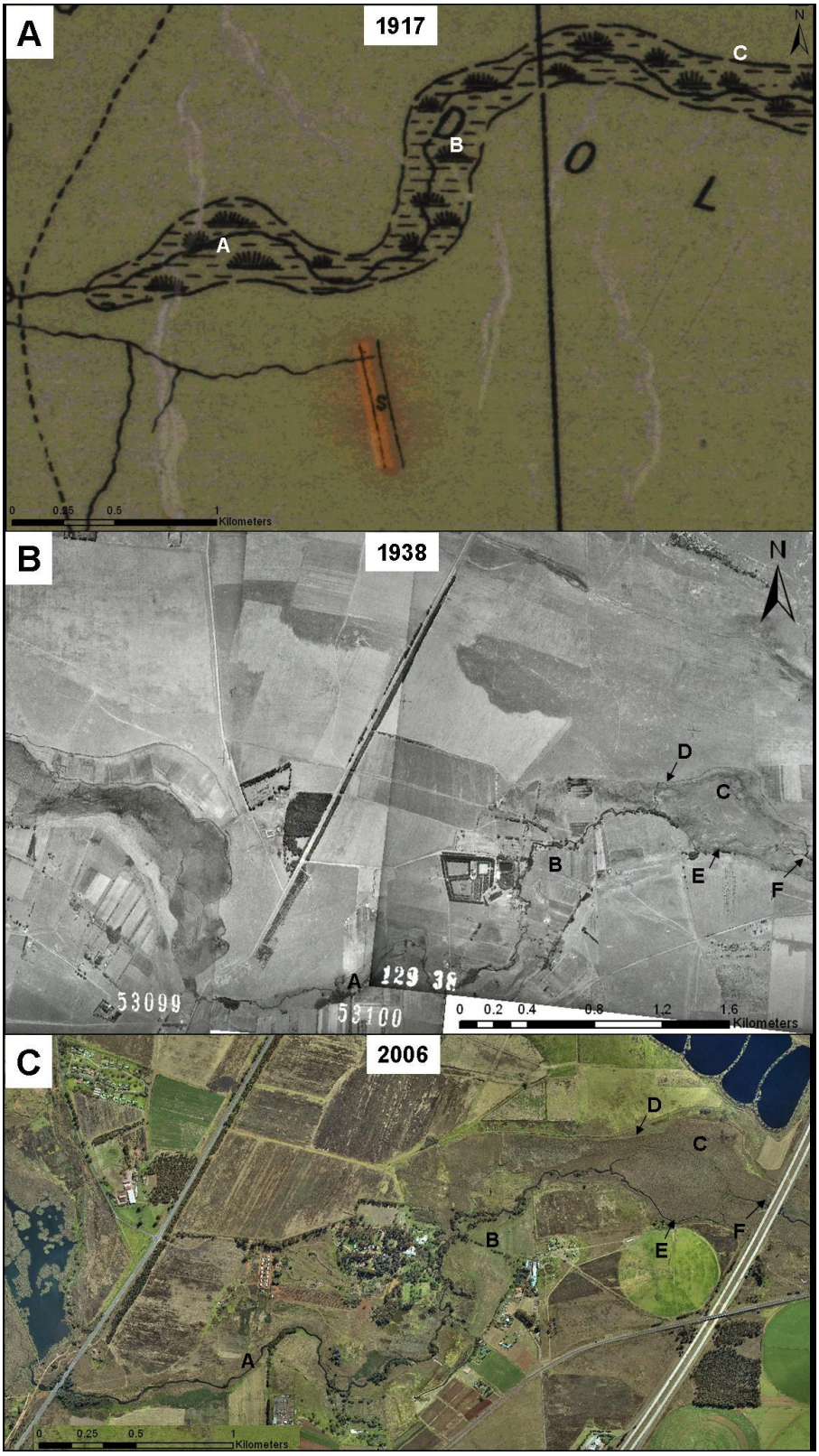


Figure 5.1.11: The wetland between the Golden Highway and the N1 in (a) 1917, (b) 1938 and (c) 2006.

Floodplain wetlands reappear further downstream in 1938. Point C in Figure 5.1.11 illustrates that this area has increased in size between 1917 and 1938 and continues to grow into 2006. This is likely due to pooling of water behind a road in 1938 and the N1 after 1961 (Figure 5.1.12).

According to the geological map (Mellor, 1917) Section 1 of the wetland had a single channel in 1917 (Figure 5.1.11a). Potentially farming was occurring in these parts by 1917 and this channel actually represents a furrow cut by the farmers. The channel of 1917 however, does not match any of the 1938 furrows. Furrows were cut by 1938 on the north and south banks of the wetland (D and E in Figures 5.1.11b and c). The furrow to the south becomes the preferred channel by 1984. The central channel present in 1938 (Figure 5.1.12a) propagates through the wetland and connects with the south bank furrow after 1961 (Figure 5.1.12b). The bridge for the N1 Highway was built to accommodate this central channel in 1979 (Arnold, 1980). The southern branch of this channel propagates into the wetland by about 200 m between 1938 and 1961 (Figure 5.1.12b). This branch extends a further 770 m by 2003 to connect with the furrow on the southern bank (Figure 5.1.12c). The northern branch of the channel in 1938 grows over by 1961 (Figure 5.1.12b).

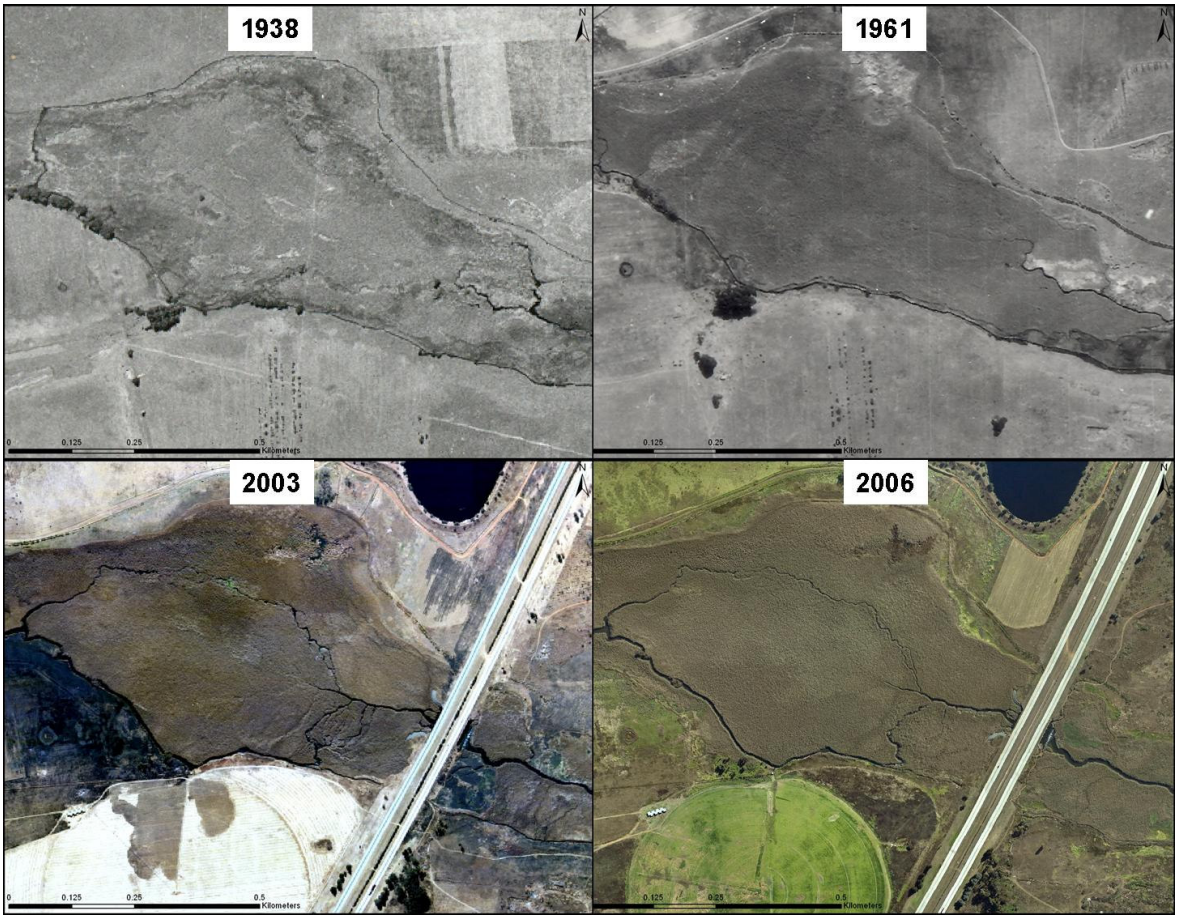


Figure 5.1.12: Detail of the wetland at the N1 Highway in (a) 1938, (b) 1961, (c) 2003 and (d) 2006.

5.1.3 Section 3: N1 to Kibler Park

Similar to Section 2, Section 3 is highly impacted by farming prior to 1938. The wetlands were completely drained with the use of furrows (A to D in Figure 5.1.13) to convert the wetland into agricultural land (E to H in Figure 5.1.13). In 1917 this was a continuous section of wetland almost 200 ha in extent and by 1938 only 39 ha remained. The wetland decreased in size by 179 ha in 20 years (Table 5.1.1). White does not depict wetlands in this section in 1957 either. The central channel in Figure 5.1.12 and I in Figure 5.1.13 (discussed in the previous section) is found to be derived from a furrow cut on the northern bank of the wetland prior to 1938 (A in Figures 5.1.13b to d). The furrows have therefore become connected between sections and the water has been channelised away from the wetland. The channel depicted in 1917 is the preferred channel today (I in Figure 5.1.13).



Figure 5.1.13: The wetland between the N1 Highway and Kibler Park in (a) 1917, (b) 1938, (c) 1961 and (d) 2006.

As a result of Mellor's attention to detail, a pond was illustrated in 1917at Point J, Section 3 (Figure 5.1.13a). This ponding is not evident at all by 1938. A fork in a channel mapped by Mellor (1917) is evident in 1938, 1961 and 2006 (C in Figure 5.1.13). Channels mapped by Mellor in 1917 match furrows in 1938, for example Point K in Figure 5.1.13.

Flow has become confined to the irrigation canal along the northern bank at Point D (Figures 5.1.13b to d). This irrigation canal propagated upstream and southwards by 500 m between 1938 and 1961 to connect with another irrigation furrow on the south bank (L in Figure 5.1.13). Toward Kibler Park, agriculture has declined over time. Between 1961 and 1984 the irrigation canals became dysfunctional and reeds have over grown some of these furrows as they still hold water (Figures 5.1.14a and b). A gypsum crust (discussed in Section 5.1.1) is also evident between the N1 and Kibler Park (Figure 5.1.14c), which gives an indication of the mine pollutants in the groundwater and soils. The Bushkoppies Sewage Works, built after 1961, decants east of the N1 into the wetland. Unlike the Olifantsvlei Sewage Works outlet, no single channel has formed. The former sewage works discharge diffuses through the wetland in multiple small channels (Figure 5.1.14d).

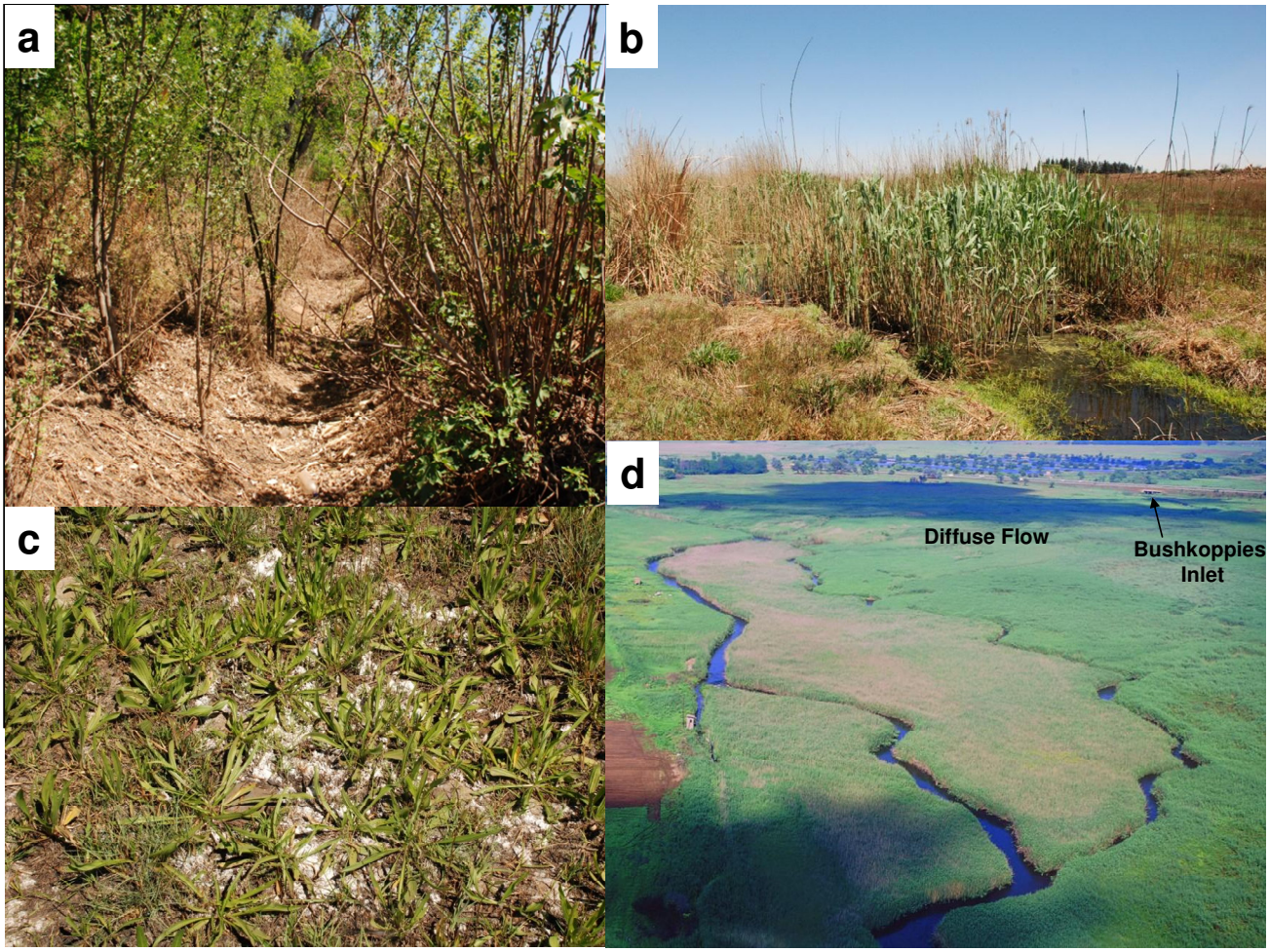


Figure 5.1.14: Field and aerial reconnaissance photos between the N1 Highway and Lenasia (d is courtesy of T.S. McCarthy, November 2007).

5.1.4 Section 4: Kibler Park to Kromvlei

Section 4 represents the largest portion of the Klip River Wetland and has been negatively affected tremendously since 1917. For ease of discussion Section 4 has been split into three parts as seen in Figure 5.1.15.



Figure 5.1.15: The breakdown of Section 4 as to be discussed from Jackson's Drift (Kibler Park) to Kromvlei.

Near Jackson's Drift, Mellor (1917) mapped the channel in Section 3 to continue under the bridge for a short distance downstream until the flow dispersed into the wetlands of Section 4 (A in Figure 5.1.16a). This channel on the northern bank in 1917 evolves into the main channel in 1938 and this remains the case today (A in Figure 5.1.16e). The wetland south of Jackson's Drift was completely drained by 1938 for agriculture (B in Figure 5.1.16b) using furrows cut to the south (C and D in Figure 5.1.16b to d). Furrows cut into the north and south bank prior to 1938 represent the main water conduits today (D and E in Figure 5.1.16).



Figure 5.1.16: The wetland at Jackson's Drift Bridge in (a) 1917, (b) 1938, (c) 1961, (d) 2003 and (e) 2006.

East (downstream) of the Jackson's Drift Bridge the 1917 mapping illustrates a channel free wetland (Figure 5.1.17a). By 1938 several irrigation canals were cut on the north and south banks (A to C in Figure 5.1.17b). Similar to Sections 2 and 3, this was done to drain the wetland for agriculture (D in Figures 5.1.17b and c). By 2003 most of these irrigation canals are derelict and farming is not very prevalent. Another means of draining the wetland was to cut a diagonal drain across the wetland, which then collected water that flowed through the wetland and diverted it into a canal on the bank. The drain at E (Figure 5.1.17) was cut prior to 1938 and was overgrown in 1961 and 1984. The 2003 and 2006 photographs show a number of diffuse channels which eroded head-ward into the wetland, upstream of the drain (F in Figures 5.1.17d and e, Figure 5.1.18) and by 2003 the drain had connected to the north bank irrigation canal (Figure 5.1.17). In 2006 this was the main water conduit canalizing water from Jackson's Drift through the irrigation canals across the wetland (in the drain) and into a south bank furrow.

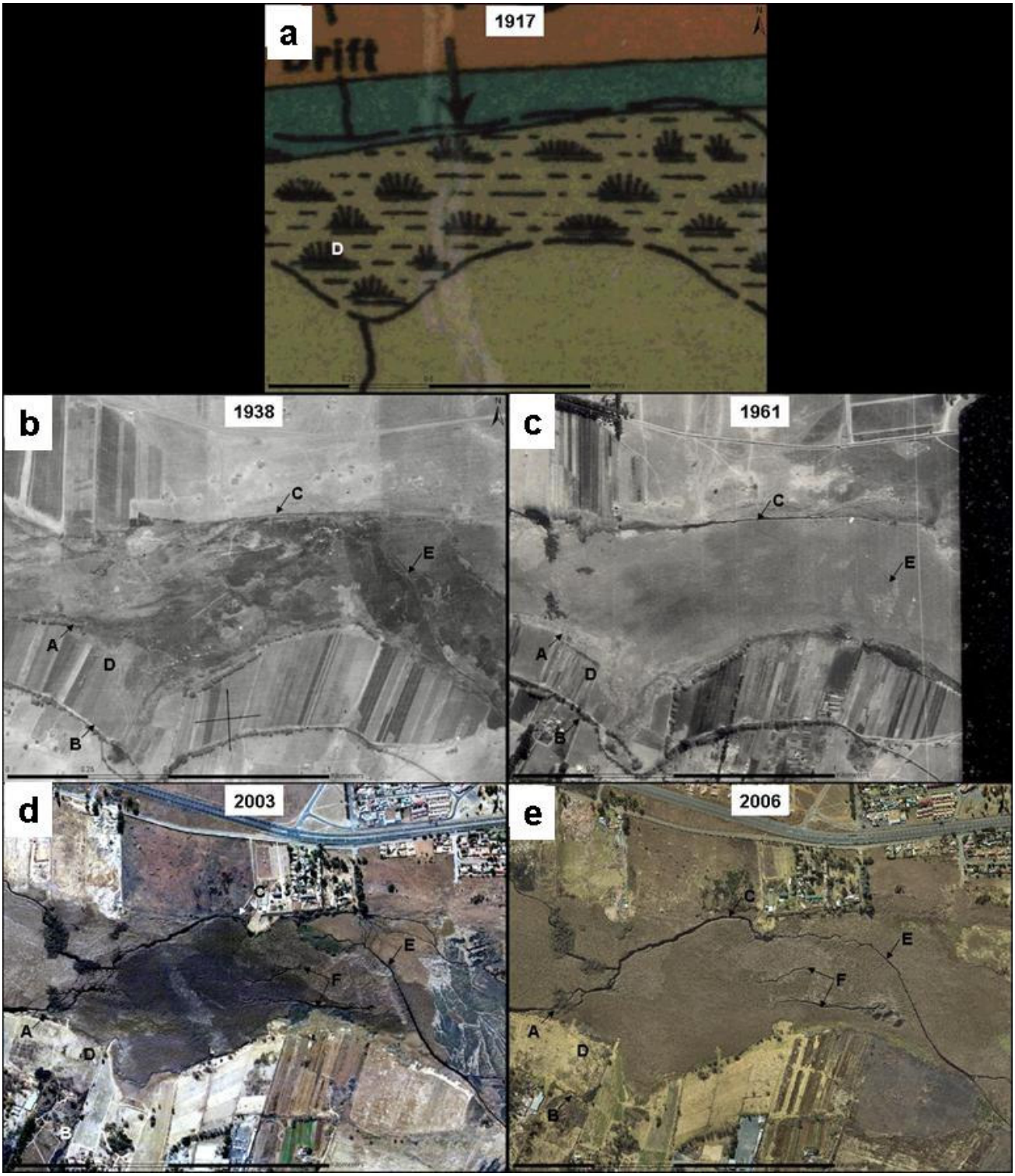


Figure 5.1.17: The wetland south of Kibler Park in (a) 1917, (b) 1938, (c) 1961, (d) 2003 and (e) 2006.

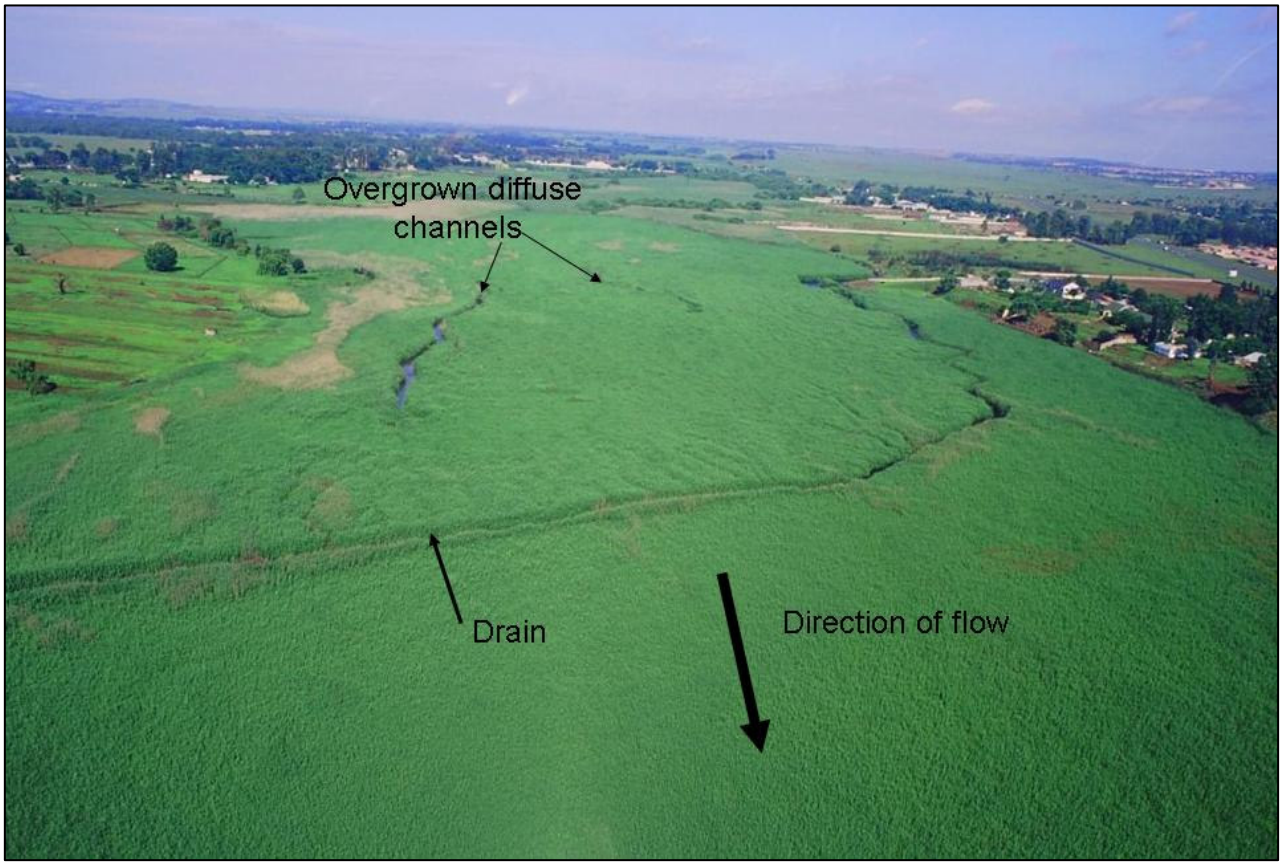


Figure 5.1.18: Diffuse channels as seen in an aerial survey eroding upstream of the drain (courtesy of T.S. McCarthy, November 2007).

The eastern section of the wetland, toward Kromvlei, was an expansive wetland in 1917 covered by *Phragmites* and with no channels evident (Figure 5.1.19a). In 1917 the wetland was in places more than 900 m in width. It appears that flow was distributed across the 350 to 900 m width up until 1961 (Figure 5.1.19d), much like the wetlands in Lenasia (Section 5.1.1). As seen in Sections 2 and 3, entire portions of the wetland were drained completely between 1917 and 1938 (A and B in Figure 5.1.19) by irrigation canals on the north and south banks (C to G in Figure 5.1.19b). Many of these canals were supplied water by drains cut across the wetland (H to J in Figure 5.1.19). The drain at H was cut prior to 1938 and, although it was overgrown in the 1952 photographs, it propagated head-ward by 400 m in 1961. This feeder channel eroded head-ward from the drain to almost connect to the northern bank irrigation canal by 1984 (Figure 5.1.19e). The feeder channel, however, continued to erode head-ward and bypassed the northern irrigation canal to connect to another drain at Point I prior to 2003 (Figure 5.1.19f). Between 1938 and 1952 another large diagonal drain was cut across the wetland to divert the water and drain the wetland for

irrigation in the east as seen at K (Figure 5.1.19). A south bank furrow cut prior to 1938 to divert all the flow for irrigation to the south of Kromvlei develops into major conduit for the entire Section 4 wetland (L in Figures 5.1.19b to g). This furrow was cut in order to drain the wetland for agriculture downstream of Kromvlei in the south. Through the connection of all these drains and irrigation furrows a continuous channel has formed throughout Section 4. A definite impact on this section of wetland is observed where soil is exposed and no reeds are growing (M in Figures 5.1.19f and g). Another illustration of the impact is the decrease in wetland area by more than 219 ha (Table 5.1.1).



Figure 5.1.19: The wetland downstream of Kibler Park in (a) 1917, (b) 1938, (c) 1952, (d) 1961, (e) 1984, (f) 2003 and (g) 2006.

5.1.5 Section 5: Zwartkoppies Section

The geological map from 1917 (Mellor) does not cover the full extent of the Zwartkoppies Section. In 1917 a channel had developed near the Zwartkoppies Pump Station and continued beyond the mapped extent (A in Figure 5.1.20). By 1938 the wetland had already shrunk in extent and was drained in sections for agriculture (B in Figure 5.1.20) by irrigation canals (C and D in Figure 5.1.20). Other anthropogenic impacts included an elevated road (bridge; E in Figure 5.1.20) across the wetland to the pump station and an underground pipeline across the wetland (F in Figure 5.1.20). Both of these were constructed prior to 1938. A number of openings were incorporated under the road in order to allow through flow of water. McCarthy et al. (2007) identified that one of the culverts under the roadway is today deeply incised and is carrying all of the discharge, with the remaining culverts no longer functioning. It is also evident that the reed bed in the south of this section of wetland is receding upstream (G in Figure 5.1.20). The wetland was described by Humphrey (1910) as a series of extensive marshes that extended to within 1.6 km of the Klip River Railway Station (south of Zwartkoppies Pump Station). Today the wetland terminates more than 6.5 km from this railway station, which means that the wetland has retreated 5 km upstream (Figure 5.1.21). The 1938 photography does not extend to the railway station. However, it is suggested that this retreat had occurred by 1938. By 1961 the southern extent of the wetland was completely canalized and there was very little evidence of the wetlands (Figure 5.1.22). In the field, peat burns are evident. As a result of the burns, the soil becomes a clayey ash, which is then washed into the river system. Remaining are donga-like gullies in which bedrock is often exposed (McCarthy et al., 2007).

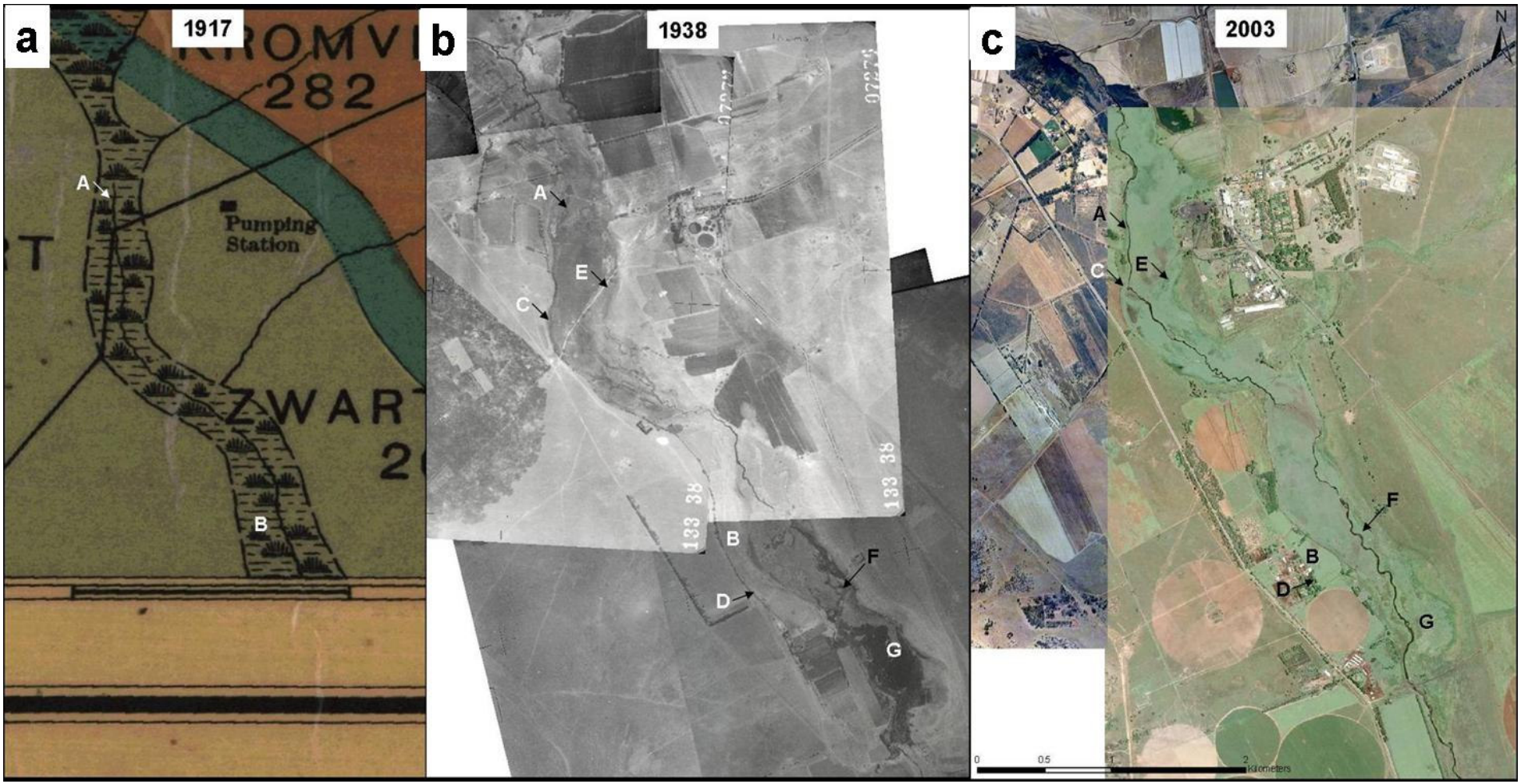


Figure 5.1.20: The wetland of Section 5 in (a) 1917, (b) 1938 and (c) 2003 (a and b have the same scale as c).

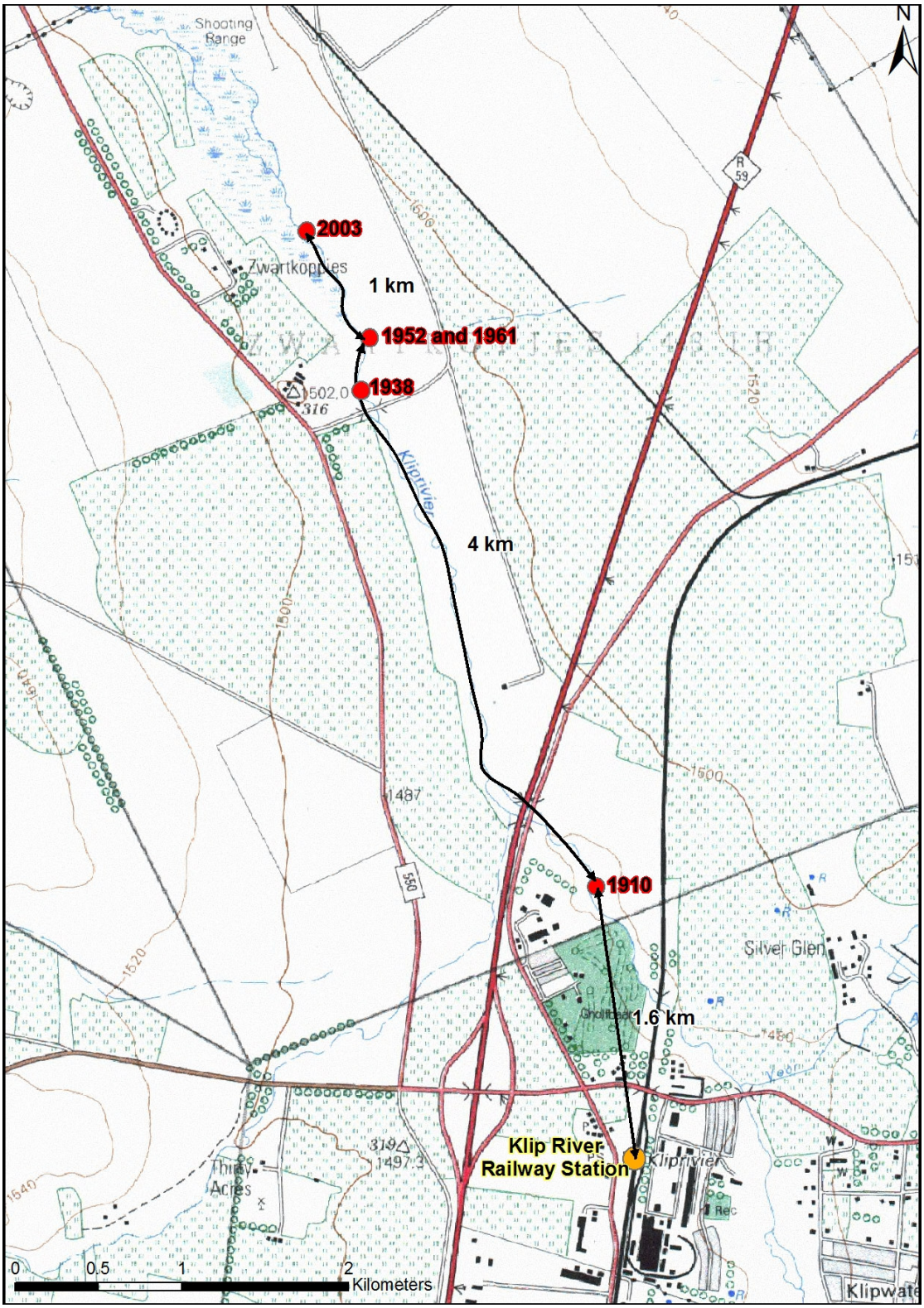


Figure 5.1.21: Wetland retreat from the Klip River Railway Station between 1910 and 2003.

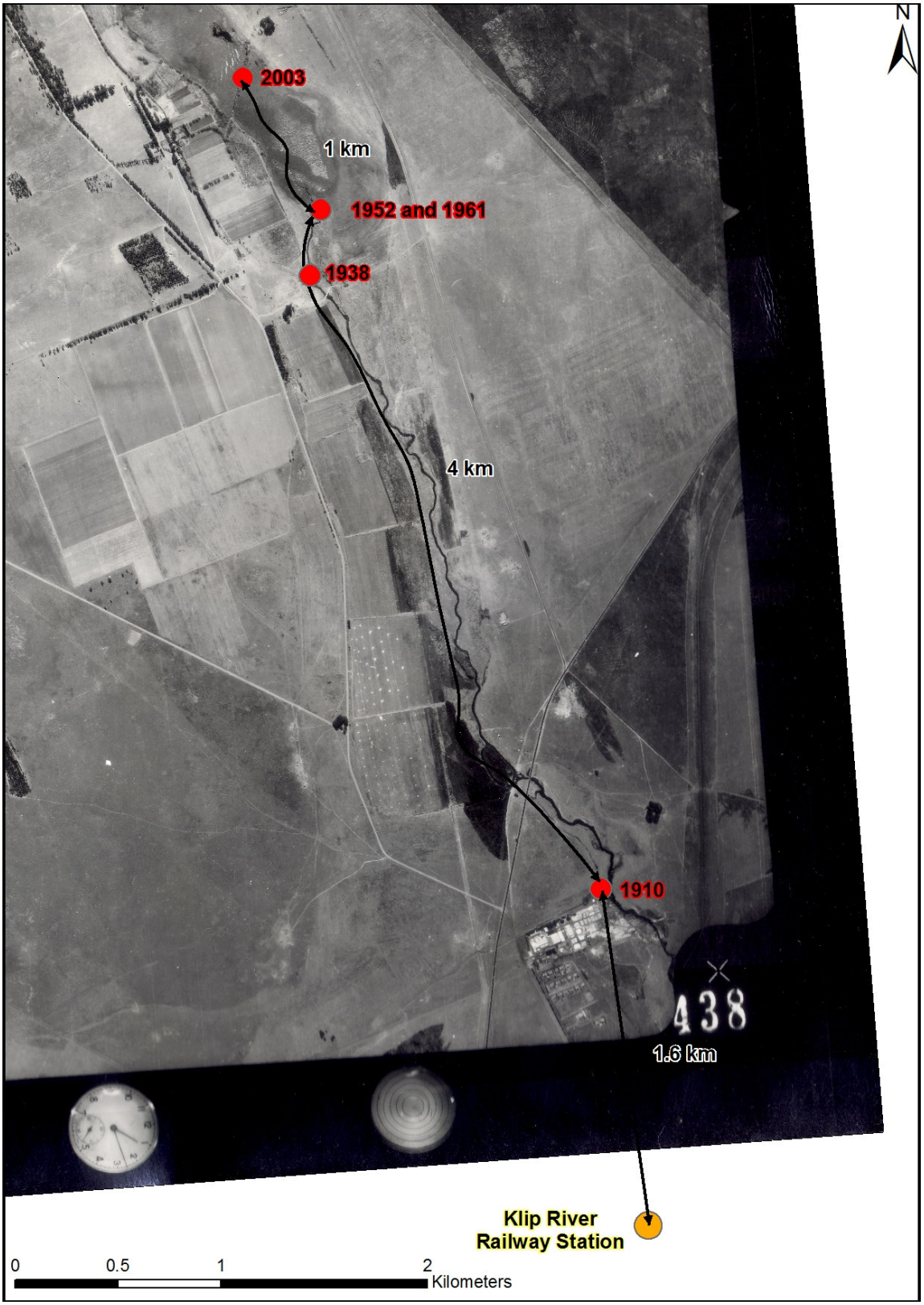


Figure 5.1.22: Wetland retreat from the Klip River Railway Station between 1910 and 1961.

After Kromvlei the wetland is channelized at the south bank as it enters the Zwartkoppies Section (A in Figure 5.1.23). From 1938 to 1952 the channel cuts down and extends downstream 200 m in 14 years. The channel propogates a further 20 m/year between 1952 and 1961, and advances downstream a swift 1 200 m between 1961 and 1984, a rate of 57 m/year. The channel pirates an irrigation canal on the western bank by 1984 (B in Figure 5.1.23). At the same time a channel to the south (C in Figure 5.1.23) was propagating upstream. It is unclear whether the two streams connect by 1984 but by 2003 the channels had broken though the road (D in Figure 5.1.23) to connect. Today there is one continuous channel throughout this section of wetland. The channels are still flanked by reed beds, but these appear to experience only limited inundation.

South of the Zwartkoppies Pump Station another channel was advancing upstream toward the pipeline and the channels to the north (A in Figure 5.1.24). Table 5.1.4 provides the rate of head-cutting of this southern channel.

Table 5.1.4: Advance rate of the channel south of the Zwartkoppies Pump Station.

Years	Advance of head-cutting	Rate of head-cutting
1938 - 1952	127m	9m/year
1952 - 1961	124m	14m/year
1961 - 1984	912m	43m/year
1984 - 2003	784m	37m/year

The incising channel intersected a bedrock barrier in around 1984, resulting in a 2 m high waterfall (C in Figure 5.1.24). The last remaining unchannelised portion of the Zwartkoppies section (B in Figure 5.1.24) will soon converge to one channel as seen in Figure 5.1.25.



Figure 5.1.23: The wetland at Zwartkoppies Pump Station in (a) 1938, (b) 1952, (c) 1961, (d) 1984 and (e) 2003.



Figure 5.1.24: The wetland south of the Zwartkoppies Pump Station in (a) 1938, (b) 1952, (c) 1961, (d) 1984 and (e) 2003.



Figure 5.1.26: A 2 m high waterfall on bedrock (courtesy of T.S. McCarthy, November 2007).



Figure 5.1.25: Aerial photograph of the final stages of the formation of a single channel in the Zwartkoppies section of the wetland.

5.2 Long River Profiles

Arnold (2004) used 1: 10 000 orthophoto contours to determine the long river profile for the Klip River Wetland (Figure 5.2.1). The knick points observed in the field and documented by McCarthy et al. (2007) however, were not evident in the profile. A higher resolution topography dataset was required. The LIDAR data flown in 2006 produced 25 cm contours and this was used to document topographic changes along the wetlands length, i.e. a long river profile was constructed. A profile was delineated through the channel as well as the wetland (Sections 4 and 5) to determine the gradients of each. This is crucial in determining the reference gradient for the Klip River Wetland, which in turn will determine the gradient that must be attained in any remediation efforts.

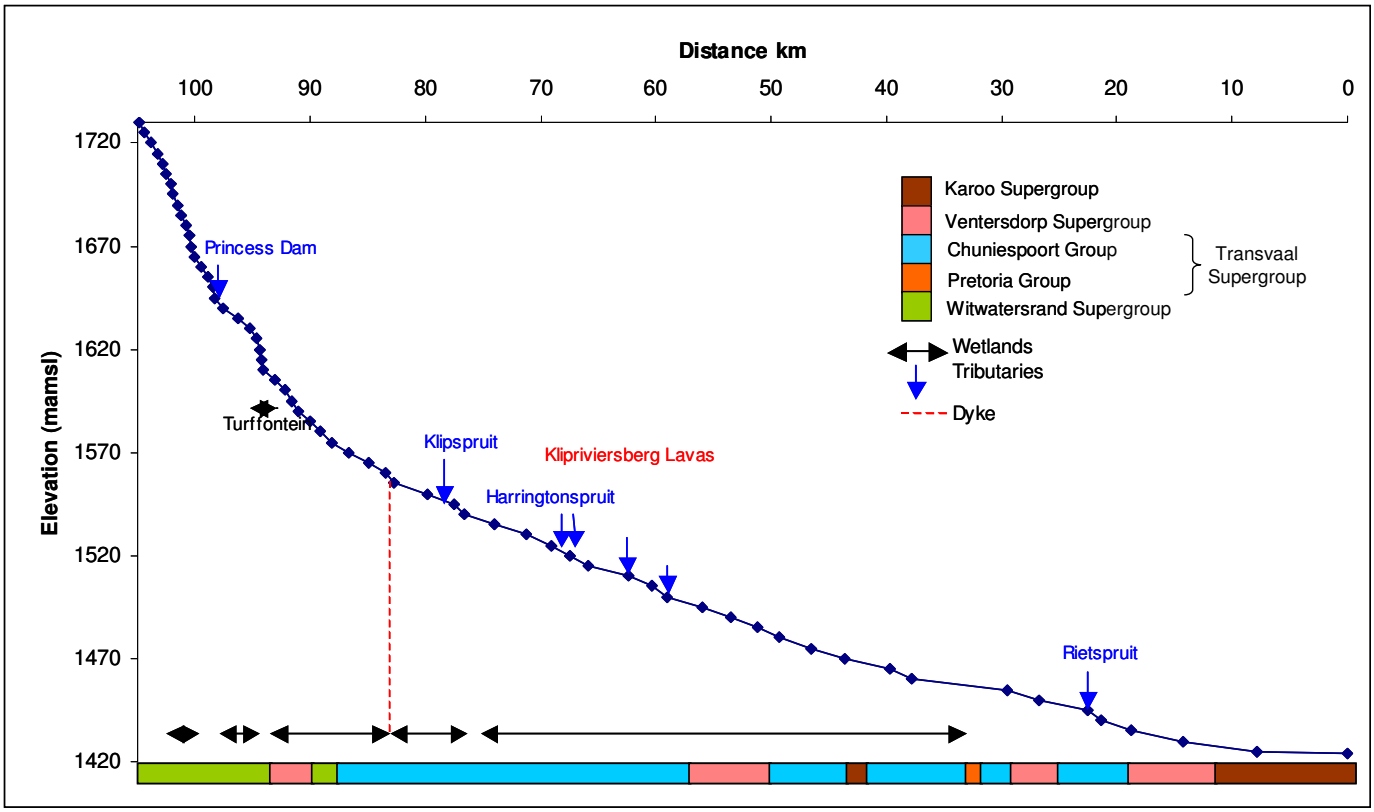


Figure 5.2.1: Long river profile as recorded from 1 : 10 000 orthophotos (after Arnold, 2004).

5.2.1 Section 1: Lenasia to Olifantsvlei Water Treatment

The profile of Section 1 deduced from the LIDAR data reveals that the gradient increases downstream of the entry of the Klipspruit tributary (Figure 5.2.2). A cutting down of 3 m is recorded in the profile at the outflow of the Olifantsvlei Sewage Works (Figure 5.2.2) as large quantities of treated sewage water with little sediment load is discharged into the wetland (Figure 3.4.1). The peat mining and contact dam can also be identified in the profile (Figure 5.2.2). Less clear is the groundwater barrier (dyke) depicted by Kafri and Foster (1989). The gradient of the wetland west of the Klipspruit Valley Road (unchannelised section of the wetland), i.e. a reference gradient for the Klip River Wetland, is 1 : 0.001. West of the Klipspruit Valley Road the gradient increases to 1 : 0.004.

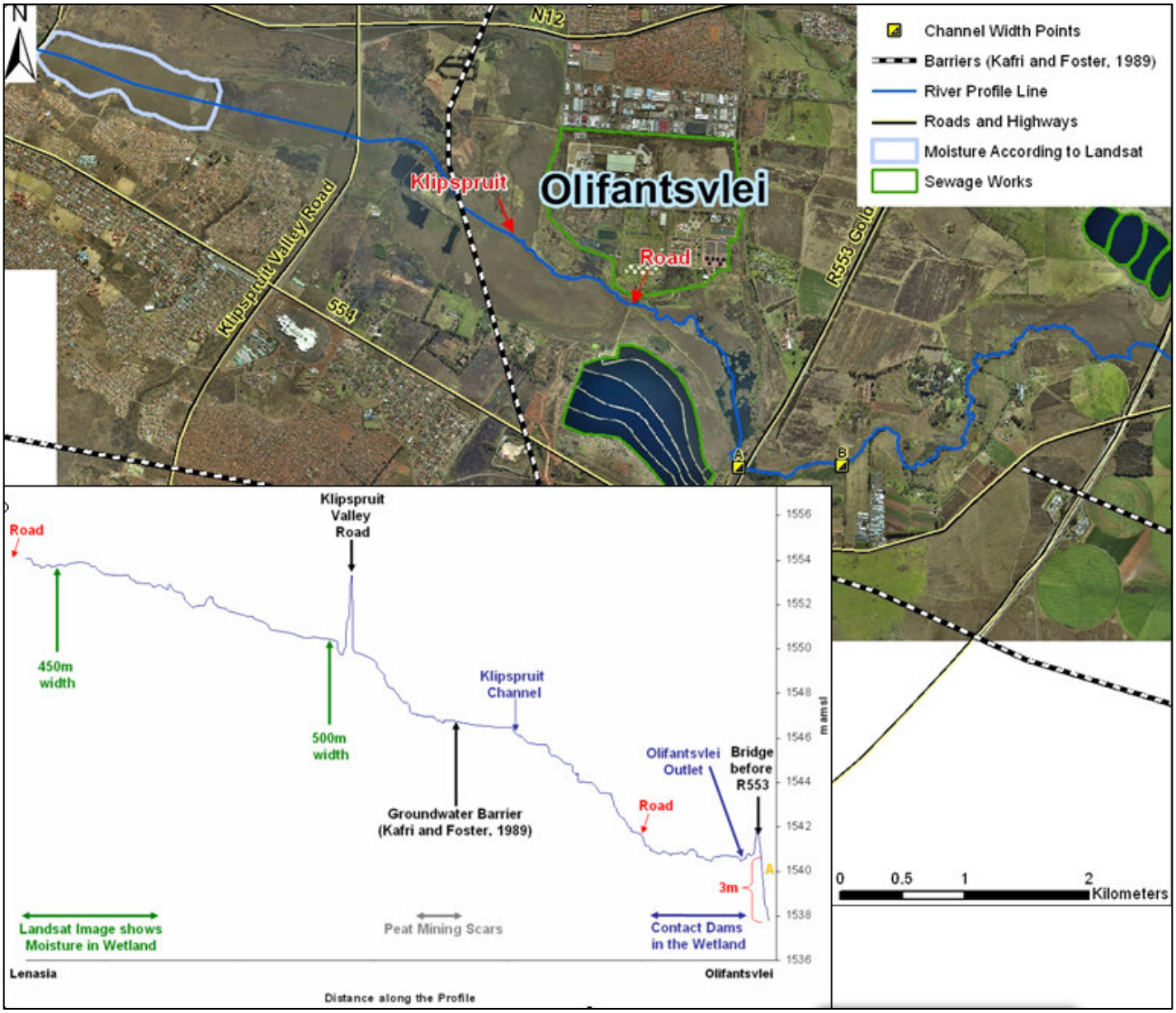


Figure 5.2.2: Long river profile from the road east of the golf course to the Golden Highway in relation to 2006 photography.

5.2.2 Sections 2 and 3: Golden Highway to Kibler Park

Three rapids are evident in Section 2 (Points 1 to 3 in Figure 5.2.3). The gradient of the long river profile increases to 1 : 0.0015 in this section and cutting down is evident at Rapid 2 (1.5 m) and 3 (1 m), (Figure 5.2.3).

The largest down cutting in the profile of Section 3 can be seen at Rapid 4 (Figure 5.2.4). After being piped under an old road, the river cuts down by 1.8 m (Figures 5.2.4 and 5.2.5a). Rapids 4, 5, 6 and 8 can be related to groundwater barriers (dykes) as defined by Kafri and Foster (1989) and Schweitzer et al; (2004, Figure 5.2.4). Three rapids (5, 7 and 8) were evident in 2003 and in 2006 and no movement was recorded in the three years. The other rapids evident in 2006 could not been seen on the 2003 photography due to the low resolution. After 1984 a bridge was built at Rapid 9 for access to a home. This bridge has caused a dam to form south of the main channel (Figures 5.2.5b and c). A cut in the profile of 1 m has formed at this bridge (9 in Figure 5.2.4 and Figure 5.2.5d). Between Sections 2 and 3 an increase in gradient to 1 : 0.002 is observed.

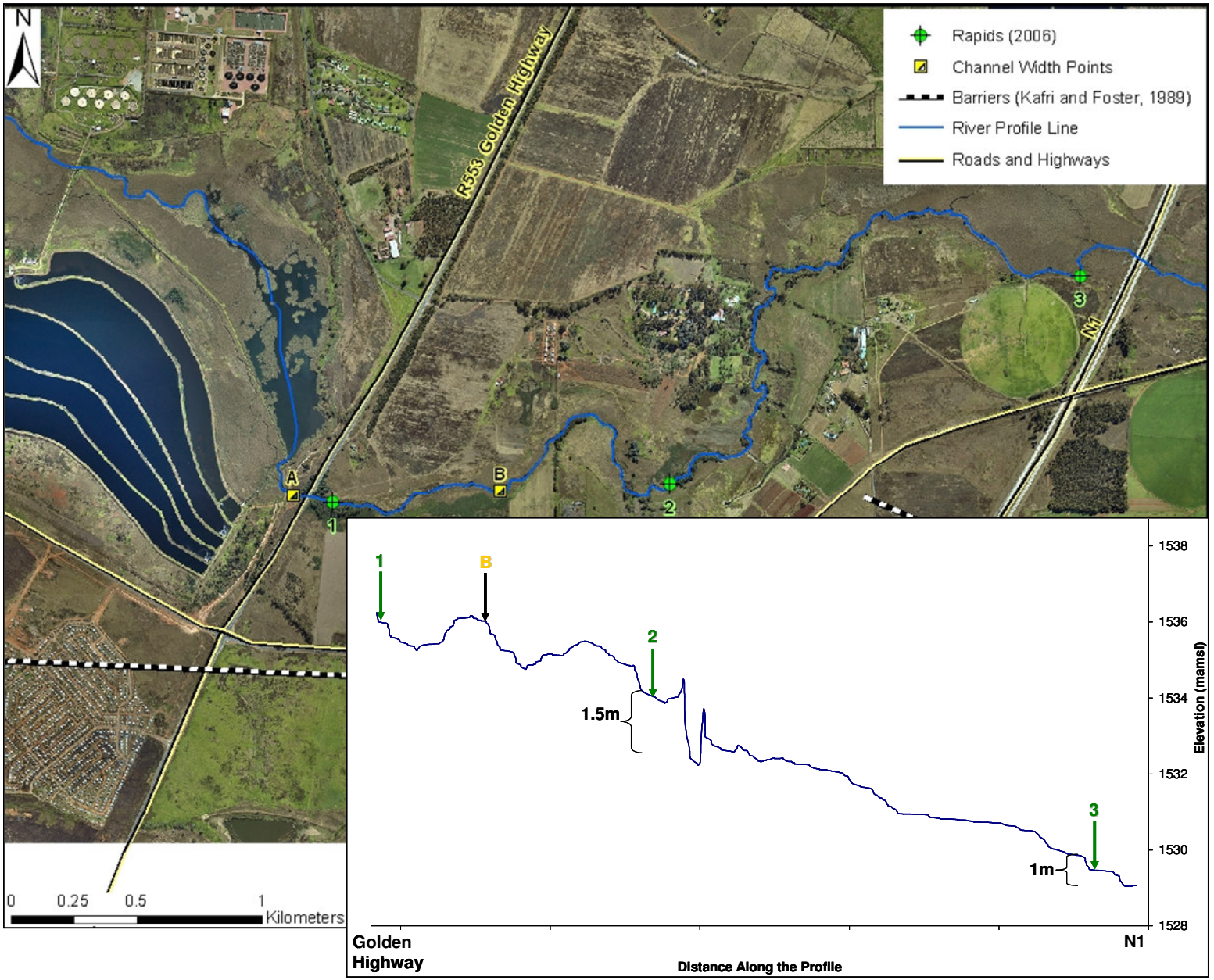


Figure 5.2.3: Long river profile from the Golden Highway to the N1 in relation to 2006 photography.

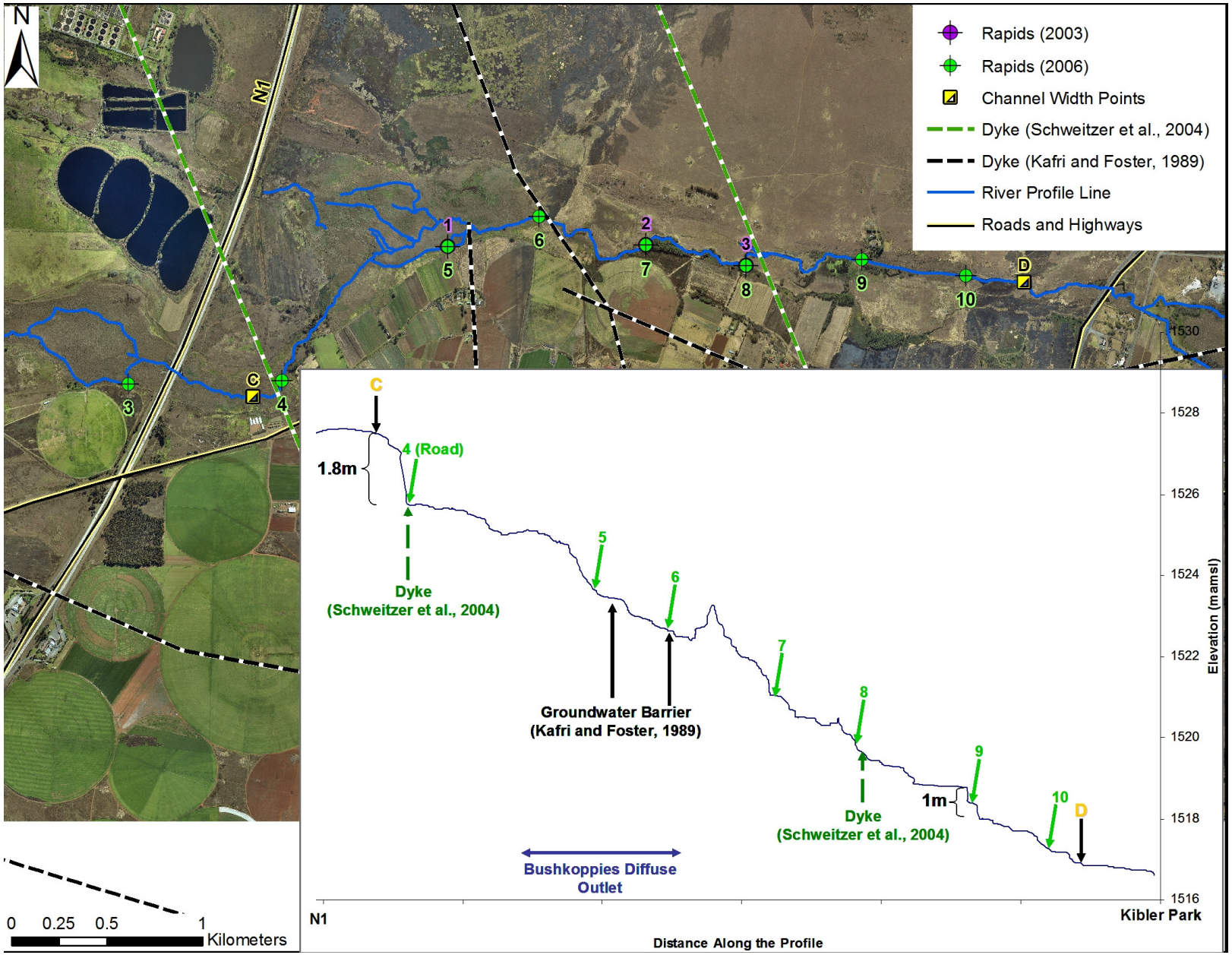


Figure 5.2.4: Long river profile from the N1 Highway to Kibler Park in relation to 2006 photography.

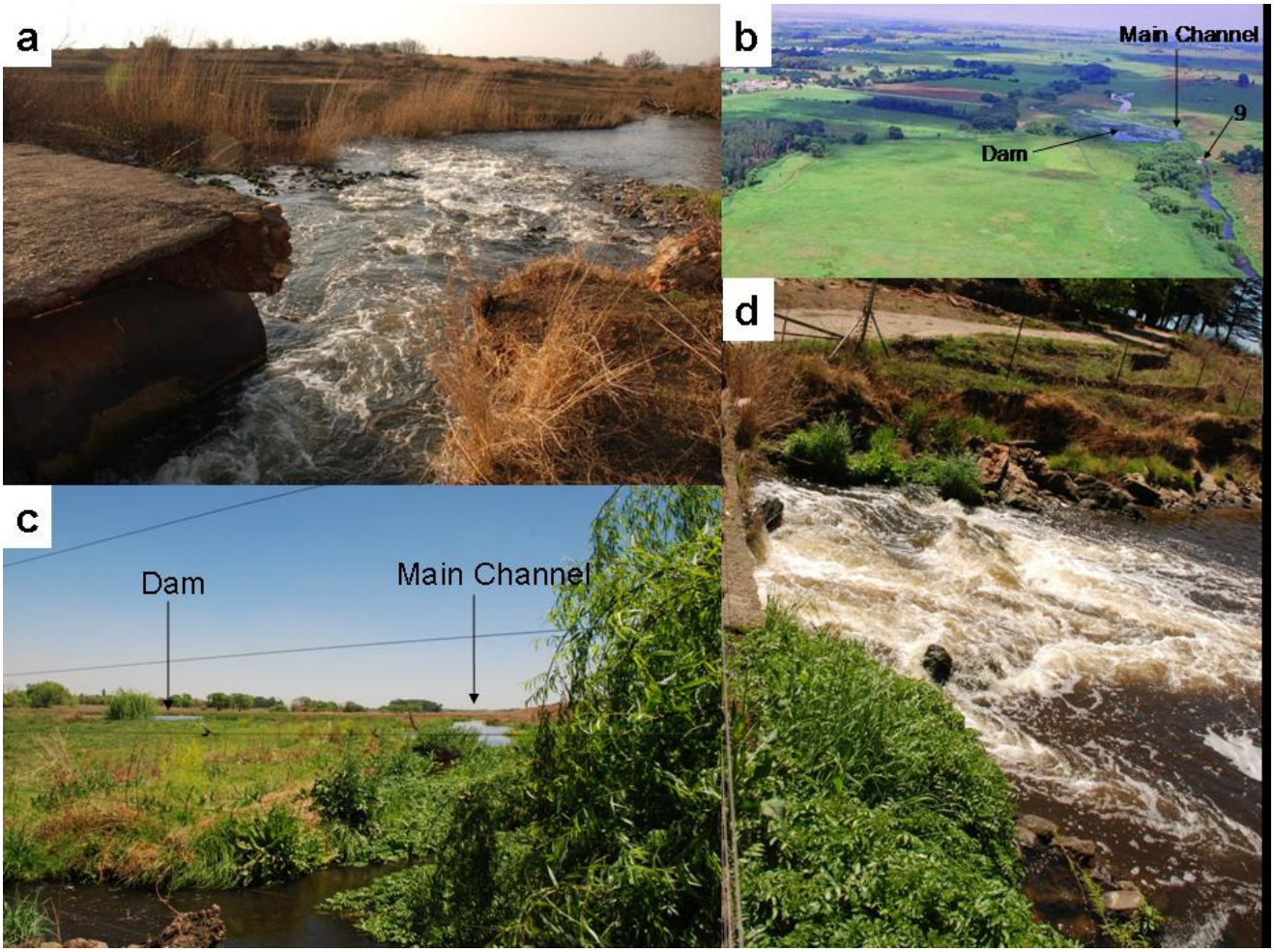


Figure 5.2.5: Field and aerial reconnaissance photos of the rapids between the N1 Highway and Lenasia (c courtesy of T.S. McCarthy, November 2007).

5.2.3 Sections 4 and 5: Kibler Park to Zwartkoppies

The long river profile was drawn for Sections 4 and 5 combined (Figure 5.2.6). A profile was also constructed through the wetland to determine the difference in gradient between the wetland and the channel. In the west, where the wetland and channel are at the same elevation, the gradient is approximately 1 : 0.0026. In the east, where the channel cuts through the wetland by more than 5 m, the gradient increases to more than 1 : 0.0036. The rapids at Point 14 correlate with a groundwater barrier (dyke) as described by Kafri and Foster (1989). Rapid's 13, 14, 16 and 17 were evident in 2003 and 2006. After the rapids at 15 (Figure 5.2.6) the channel incises through the wetland and the difference in elevation between the bed of the channel and the wetland surface increases from 2 m to 5 m over about a kilometer distance. A major knick point

is highlighted at Point 16 by a cut of over 4 m. According to the aerial photography this knick point eroded back 85 m in three years between 2003 and 2006 (Figure 5.2.7). Field reconnaissance has shown that this rapid has migrated a further 118 m between 2006 and 2008 (Figure 5.2.7), which means that the rate of knick point migration is increasing. Across the entire wetland this is the only knick point which is migrating at a significant rate. This is likely due to the fact that the knick point is eroding through soil and not bedrock (Figure 5.2.8).The Rapids at 17 are also significant as they have incised into the wetland about 2 m. Communications with Terrance McCarthy (2007) indicated that peat burns are occurring around this knick point as well. McCarthy et al., (2007) calculated that the water surface near Rapid 17 has lowered by 2.5 m since 1983. Rapid's 8 and 9 from the 2003 photographs could be related to the dykes interpreted by Schweitzer et al., (2004).

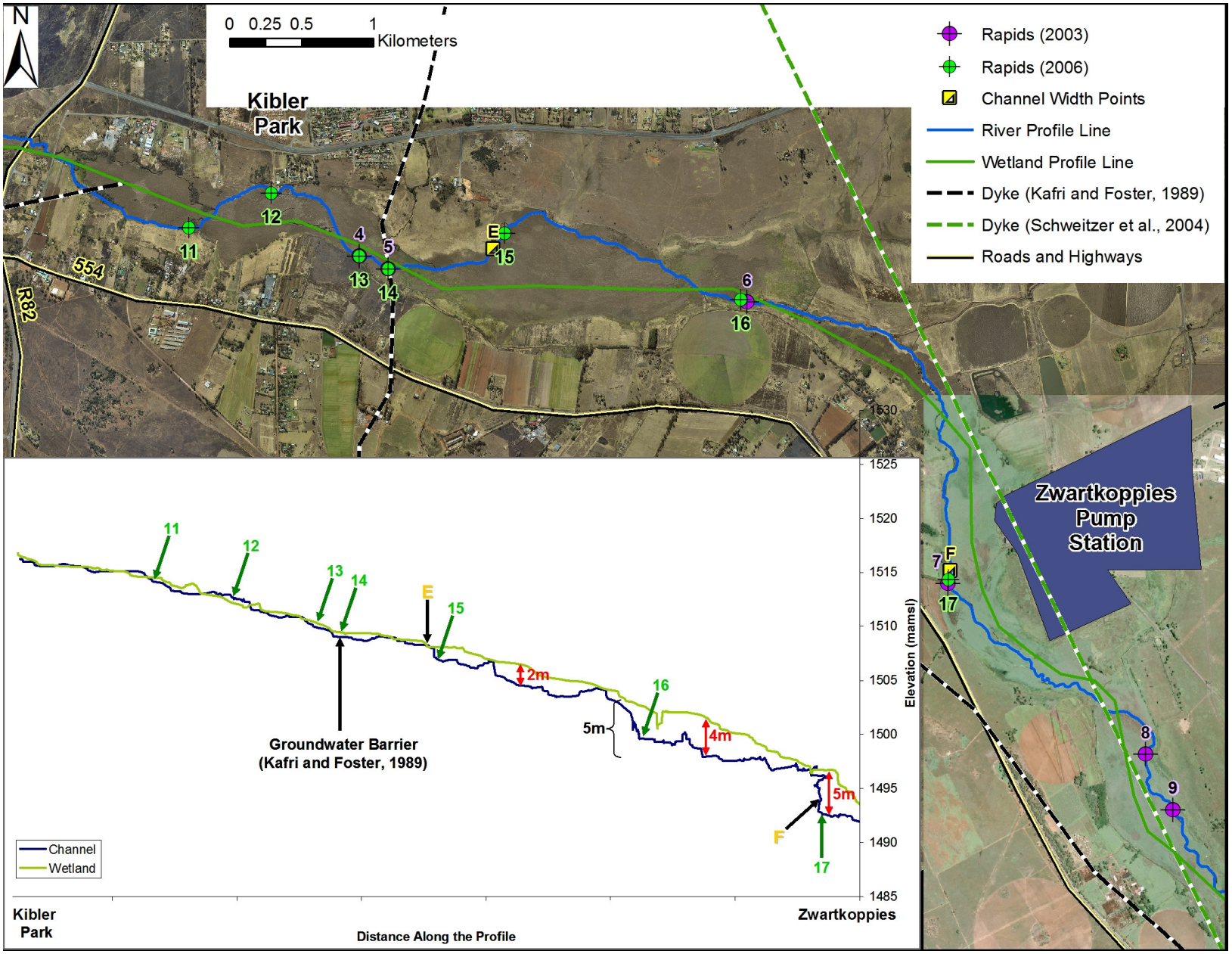


Figure 5.2.6: Long river profile from the Kibler Park to Zwartkoppies Pump Station in relation to 2006 photography.

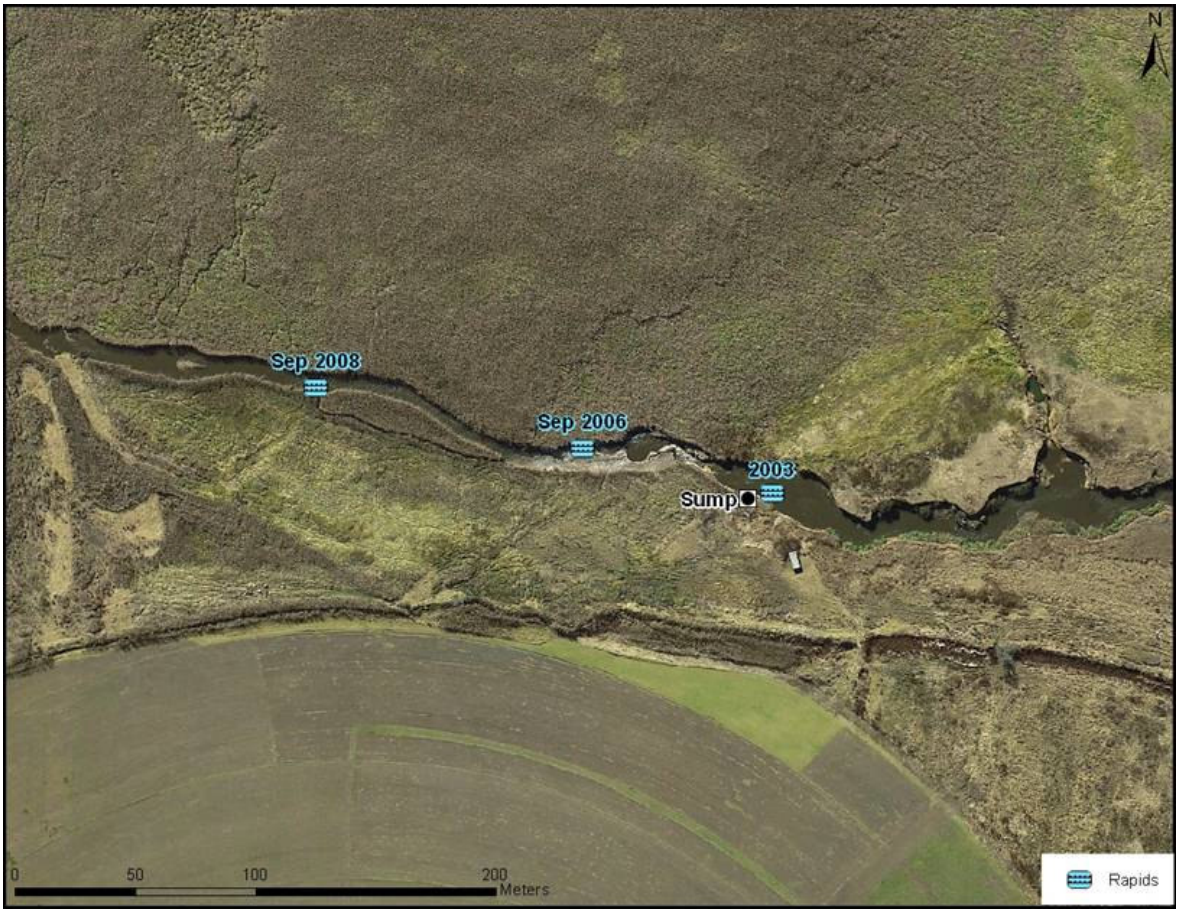


Figure 5.2.7: Knick point migration between 2003 and 2008 at Point 16.



Figure 5.2.8: Field photos of the knick point eroding through soil at Point 16 (Figure 5.2.6).

5.3 Digital Terrain Model

A Digital Terrain Model (DTM) was created from the LIDAR contour data and from the original point data. The point data were obtained because the resolution of the contour data was insufficient (Figure 5.3.1) and gaps in the dataset became evident in the DTM. The gaps became more prominent as the cell size was reduced and the resolution increased.

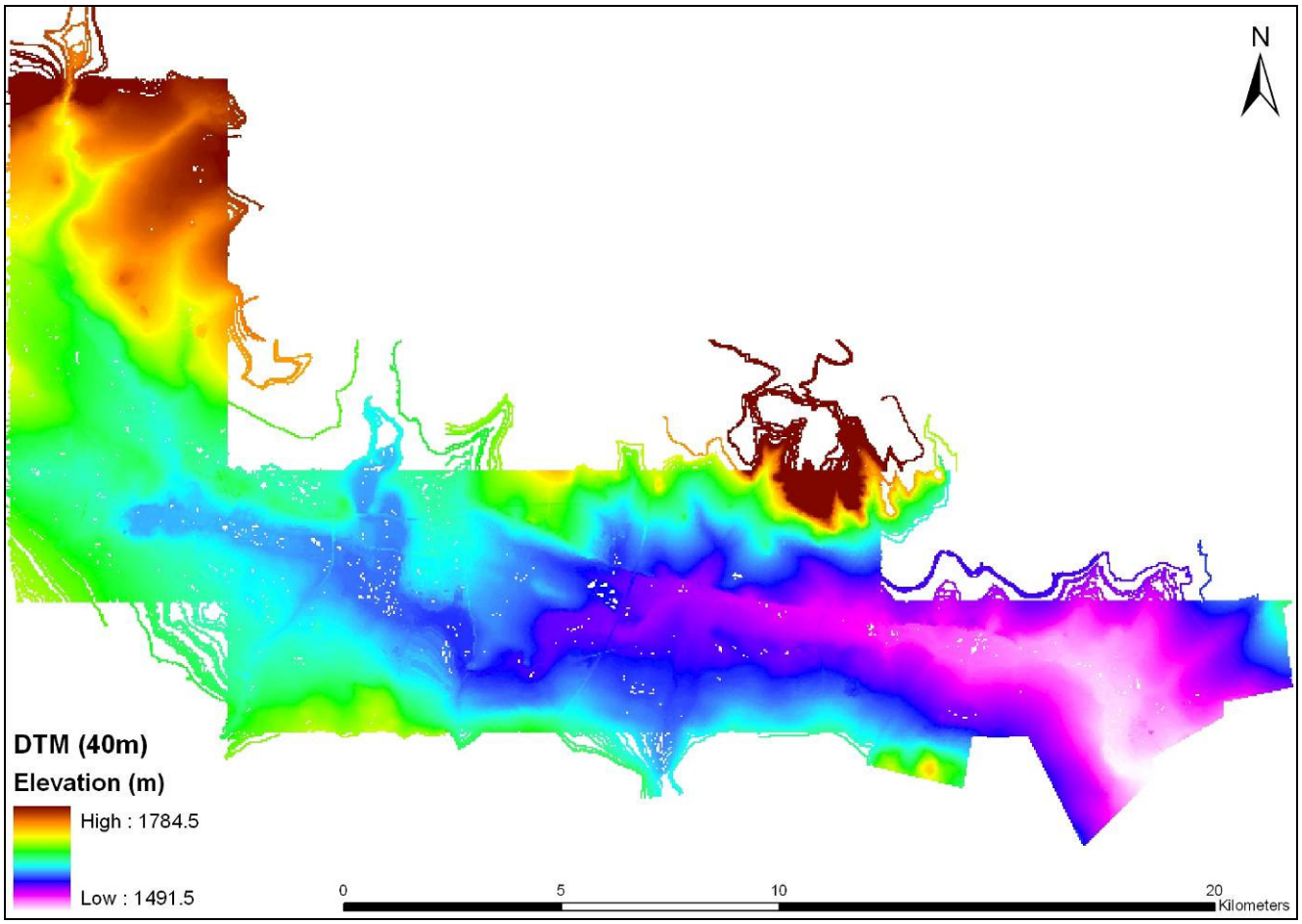


Figure 5.3.1: DTM derived from the contour LIDAR data at 40 m resolution.

The LIDAR point data were previously separated into “ground” and “non-ground” data using algorithms tailored to suit the project as a whole (Appendix 1). The majority of the wetland data were within the “non-ground data”. The two datasets were merged in order to produce a complete high resolution DTM with a 10 m pixel size (Figure 5.3.2). Open water bodies such as dams or ponds appear to have been blanked out of the dataset. This is possibly due to the back scatter or absorption of the laser strikes.

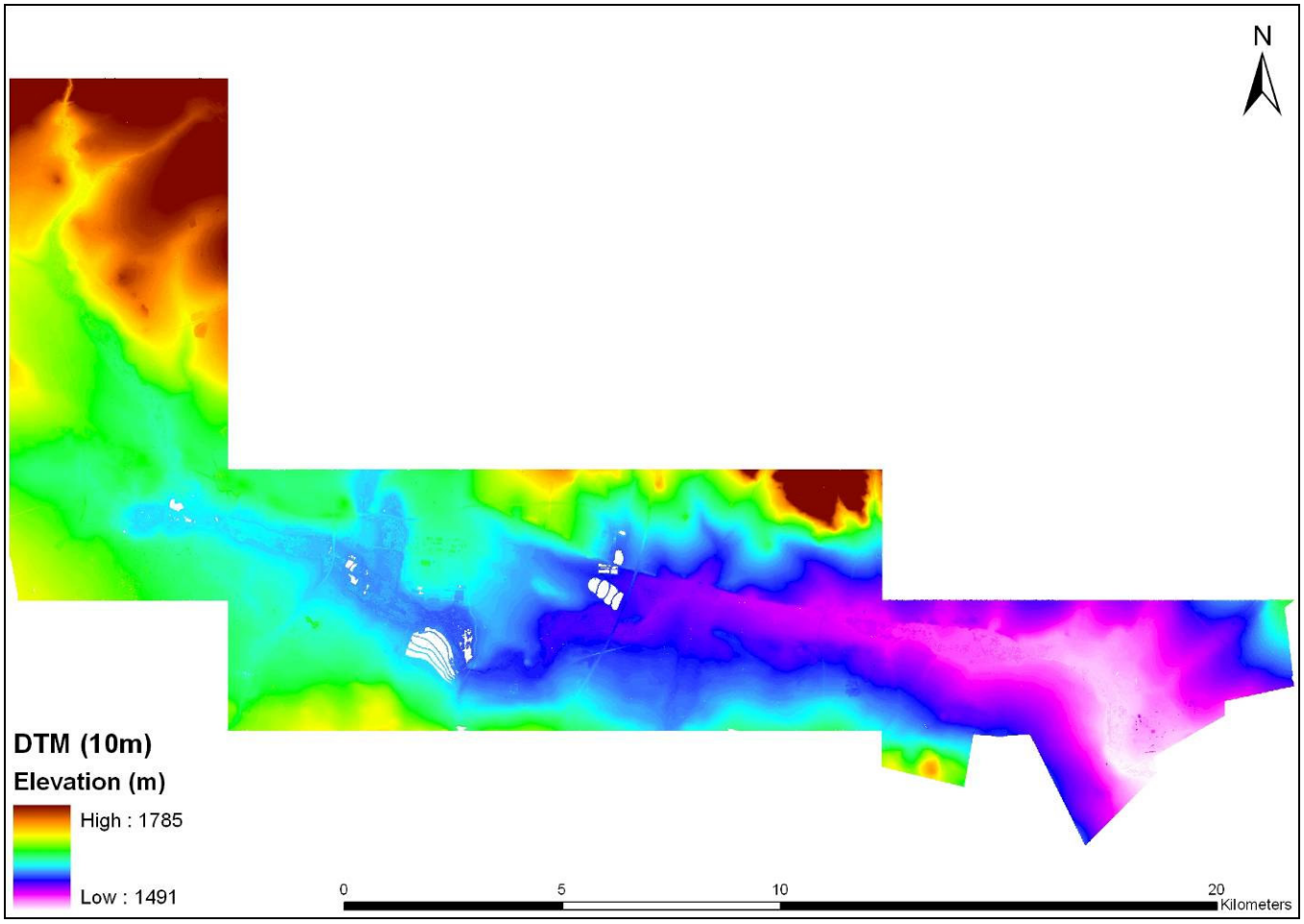


Figure 5.3.2: DTM derived from the original LIDAR point data at 10 m resolution.

Hillshading was applied to the DTM raster dataset, which predicts where shadows exist in the DTM, depending on the origin (direction) of the light source and the elevations that exist. A very low sun angle was chosen (5°) in order to identify slight variances in this floodplain terrain (Figure 5.3.3). The hillshade of the 10 m DTM was able to provide some insight into the topographical constraints on the wetland. The Black Reef to the north of the wetland, which is extremely clear in the hillshade, is acting as a physical constraint on the northern limit of the wetland. Another topographical constriction, possibly a dyke, is evident running under the Golden Highway. This could explain why even in Mellor's time there was no wetland in this segment. Groundwater barriers as described by Kafri and Foster (1989) are not manifested in the DTM or the hillshade.

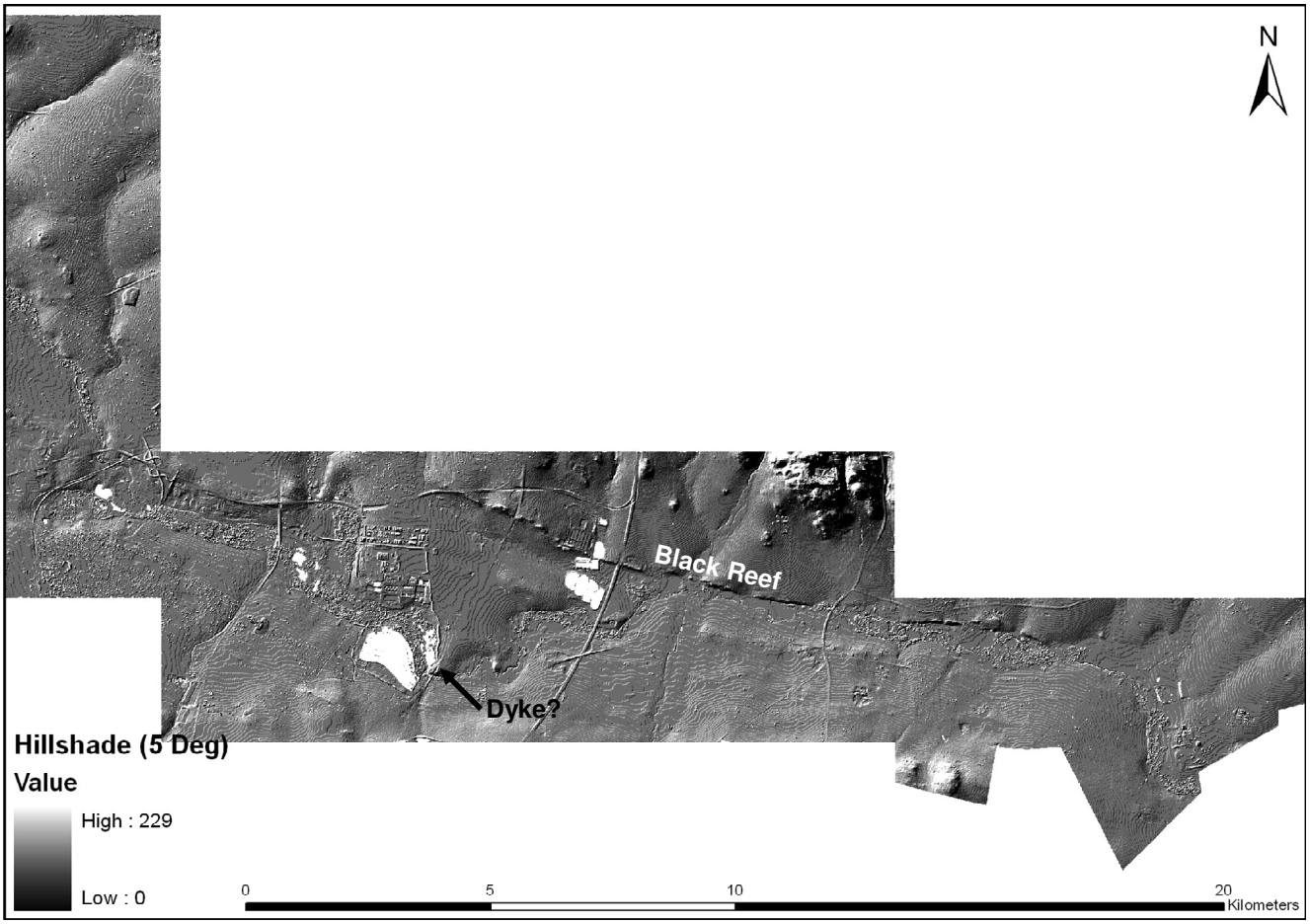


Figure 5.3.3: Hillshade at 5° sun angle derived from the DTM at 10 m resolution.

5.4 Water Chemistry

Often referred to as the "kidneys" of the environment, wetlands filter the waters of rivers and streams, therefore reducing pollution. The vegetation in wetlands removes phosphates and other plant nutrients washed in, thereby slowing the growth of algae and aquatic weeds wetlands. With the degradation and diminishing extent of the Klip River Wetland, it would be expected that the water quality downstream should also deteriorate.

As mentioned before the major pollutants entering the Klip River are sewage and acid mine drainage. The chemical signatures of these two pollution sources are phosphates, nitrates and sulfates. These chemical components are monitored by both Rand Water and DWAF on a regular basis. The Rand Water Monitoring Station (K21; Figure 4.1) data covers the period 1992 to 2006. Phosphates (Figure 5.4.1) and sulfates (Figure 5.4.2) were found to decrease marginally over this time period while nitrate levels increased (Figure 5.4.3). The sulfate levels are likely to decrease

due to the dilution effect of the sewage effluent. Dissolved oxygen was also considered, and is seen to be decreasing over time (Figure 5.4.3). Low dissolved oxygen levels indicate an excessive demand on the oxygen of the system. The build up of organic material from human activities is one source of oxygen depletion. Micro-organisms in the stream consume oxygen as they decompose sewage, urban and agricultural runoff. Acid mine drainage is also known to produce direct chemical demands on oxygen in the water. The only indication that water quality is deteriorating over time is through the increased nitrate levels and decreasing oxygen levels.

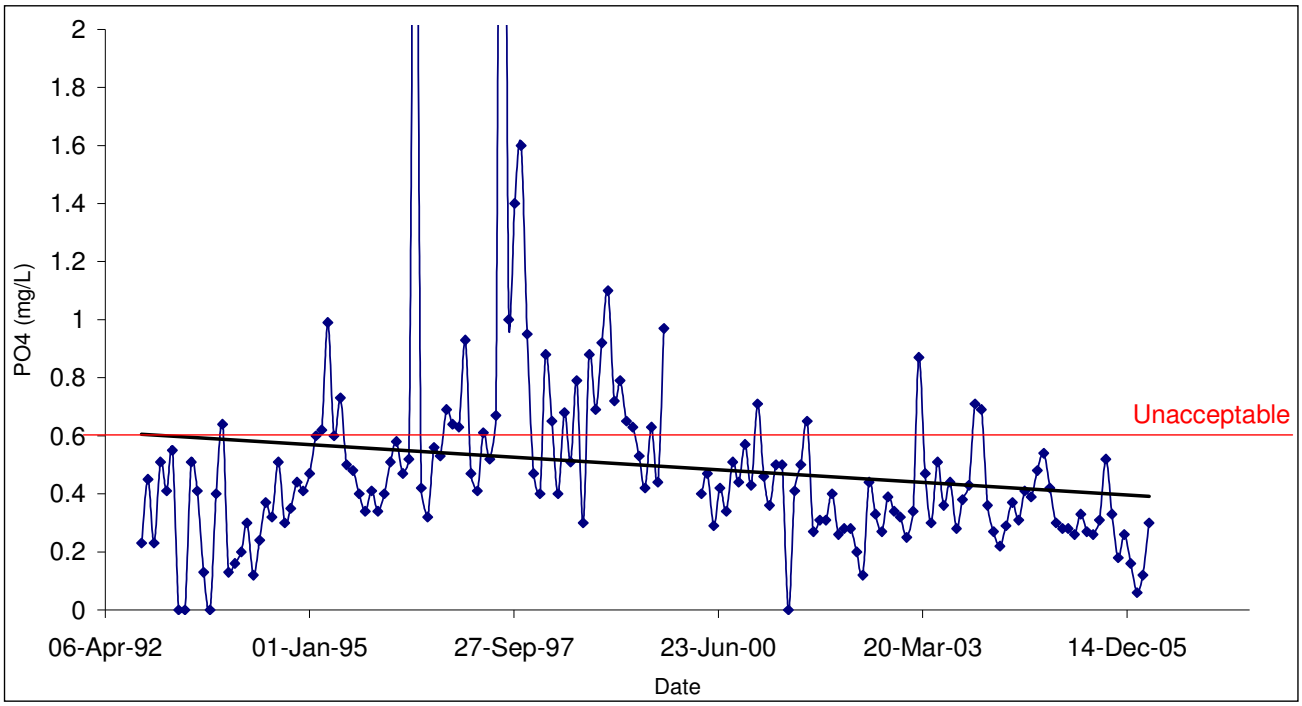


Figure 5.4.1: K21 phosphate levels from 1992 to 2006 (acceptability according to DWAF domestic water quality standards).

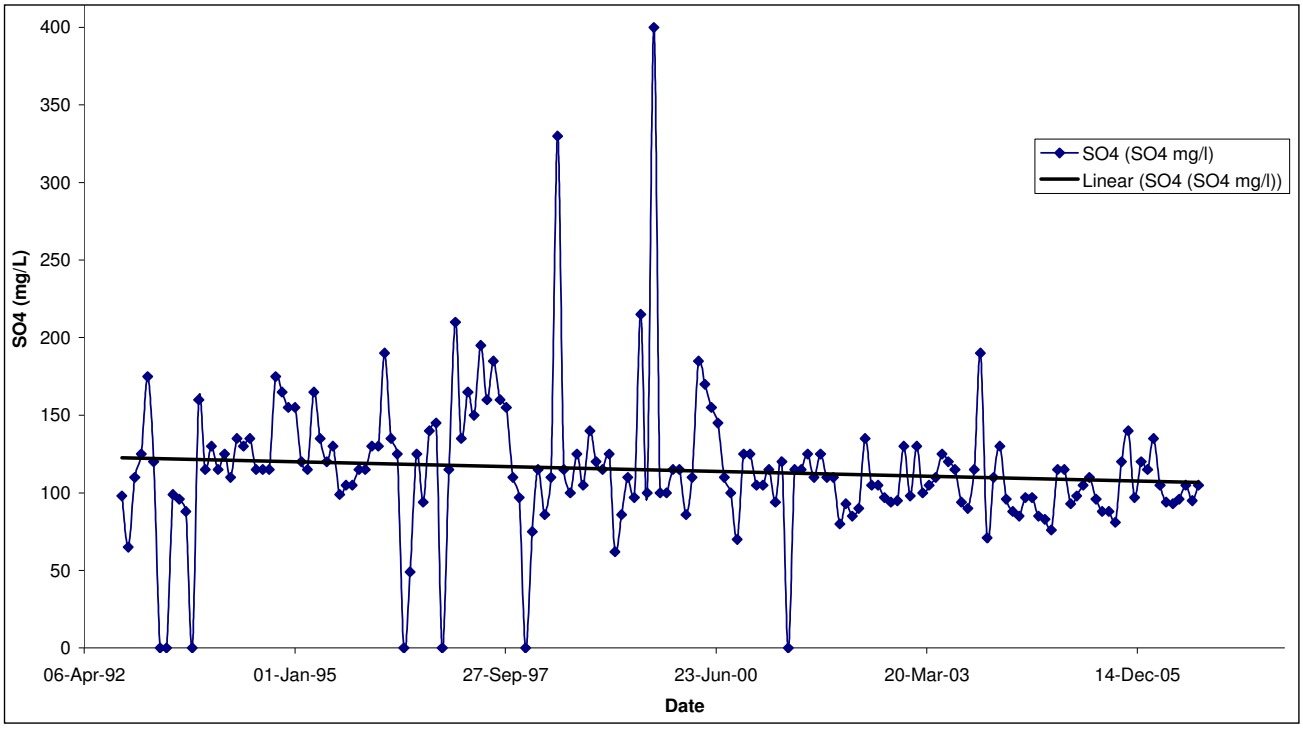


Figure 5.4.2: K21 sulfate levels from 1992 to 2006.

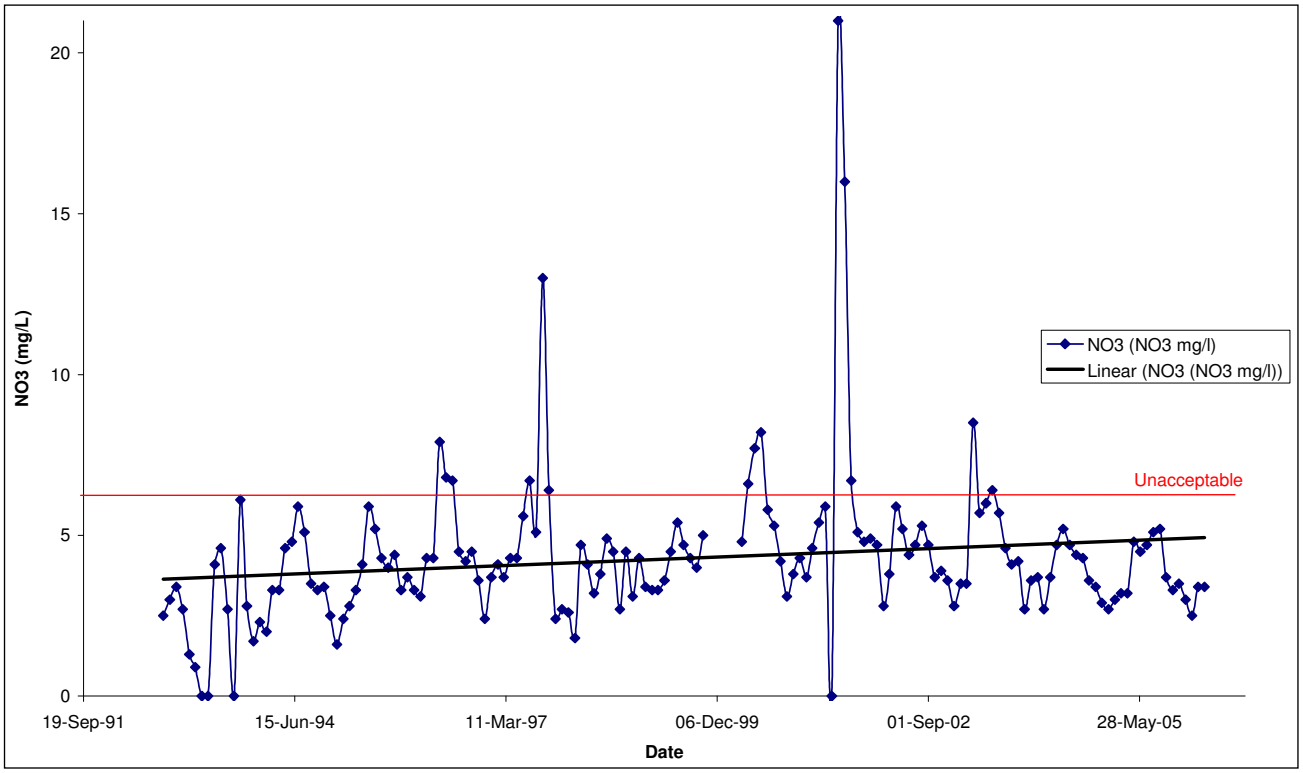


Figure 5.4.3: K21 nitrate levels from 1992 to 2006 (acceptability according to DWAF domestic water quality standards).

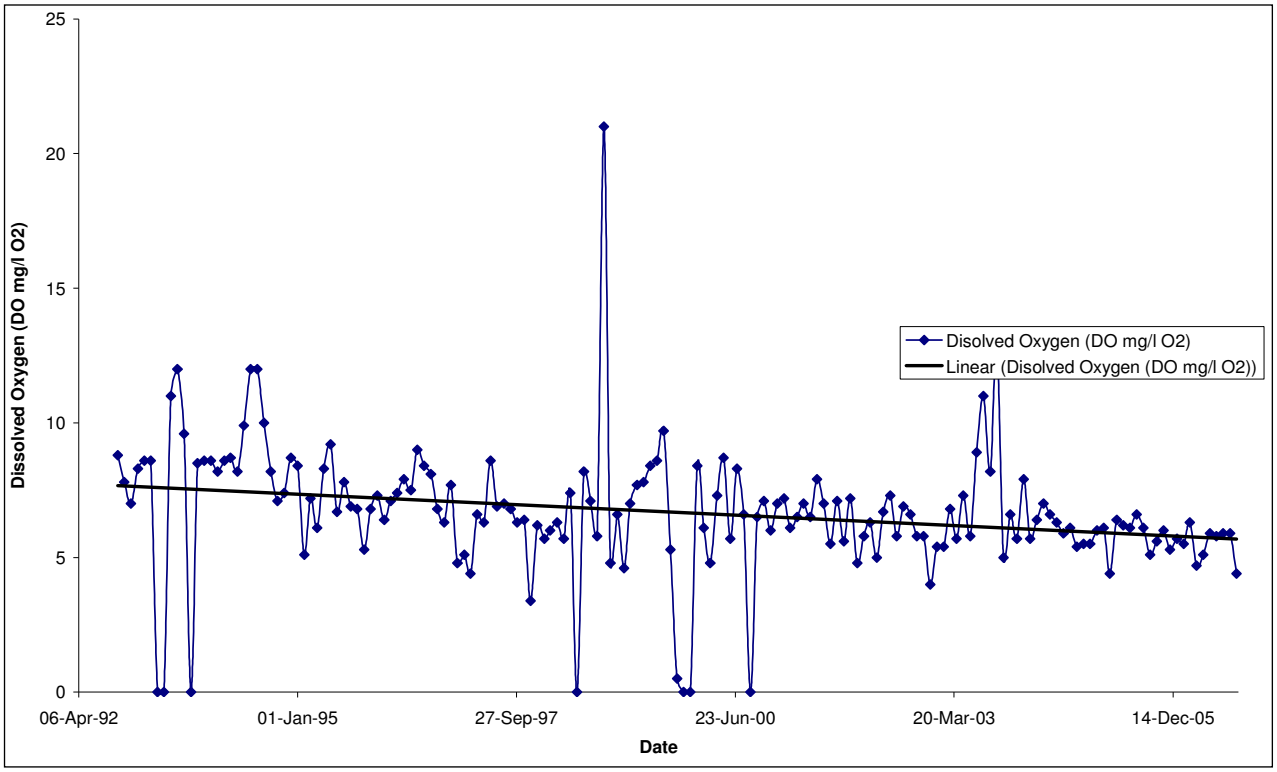


Figure 5.4.4: K21 dissolved oxygen levels from 1992 to 2006.

From the aerial photography analysis it is evident that the Klip River Wetland experienced the majority of its degradation prior to 1992 and thus these results are inconclusive. Attempts were made to obtain data prior to 1992. White (1957) provides some water quality analysis of the Klip River above the confluence of the Natalspruit (comparable to Station K21) during the dry season. The range of sulphate levels for example where recorded at 80 to 800 ppm in 1957. White (1957) did, however, comment that the Klip and Suikerbosrand Rivers were in 1957 contaminating the Vaal River though heavy minerals from mining activities at their headwaters.

5.5 Water Discharge

With the deterioration of the wetlands, it would be expected that the water discharge in the Klip River would increase (similar to the argument for the water chemistry discussion). This is due to the fact that wetlands act as a flood attenuation mechanism and slow the release of the water into the system. Water that previously was forced to flow through the wetland is evidently (from Section 5.1) being directed straight into the interconnected furrows and transported quickly out of the system.

Water discharge data were supplied by DWAF for the Witkop Station downstream of where the Rietspruit enters the Klip River. The dataset spans from 1977 to 2006. However, the data was sparse from 2004 onwards. From Figures 5.5.1 to 5.5.3 it is evident that an increase in discharge over time occurred at this station. It is difficult to attribute this increase in discharge to the decreasing impact of the wetlands only. With the rapid growth of the city of Johannesburg it is also logical that the sewage input increases over time. Urban expansion has also caused decreased infiltration and faster runoff due to low infiltration surfaces (i.e. roads, gutters, etc). It is however, noted that the flood peaks in February and March (rainy season) have increased over time and this can possibly be attributed to the decreased residence time in the wetlands and reduced capacity of the wetlands for flood attenuation. Another consideration

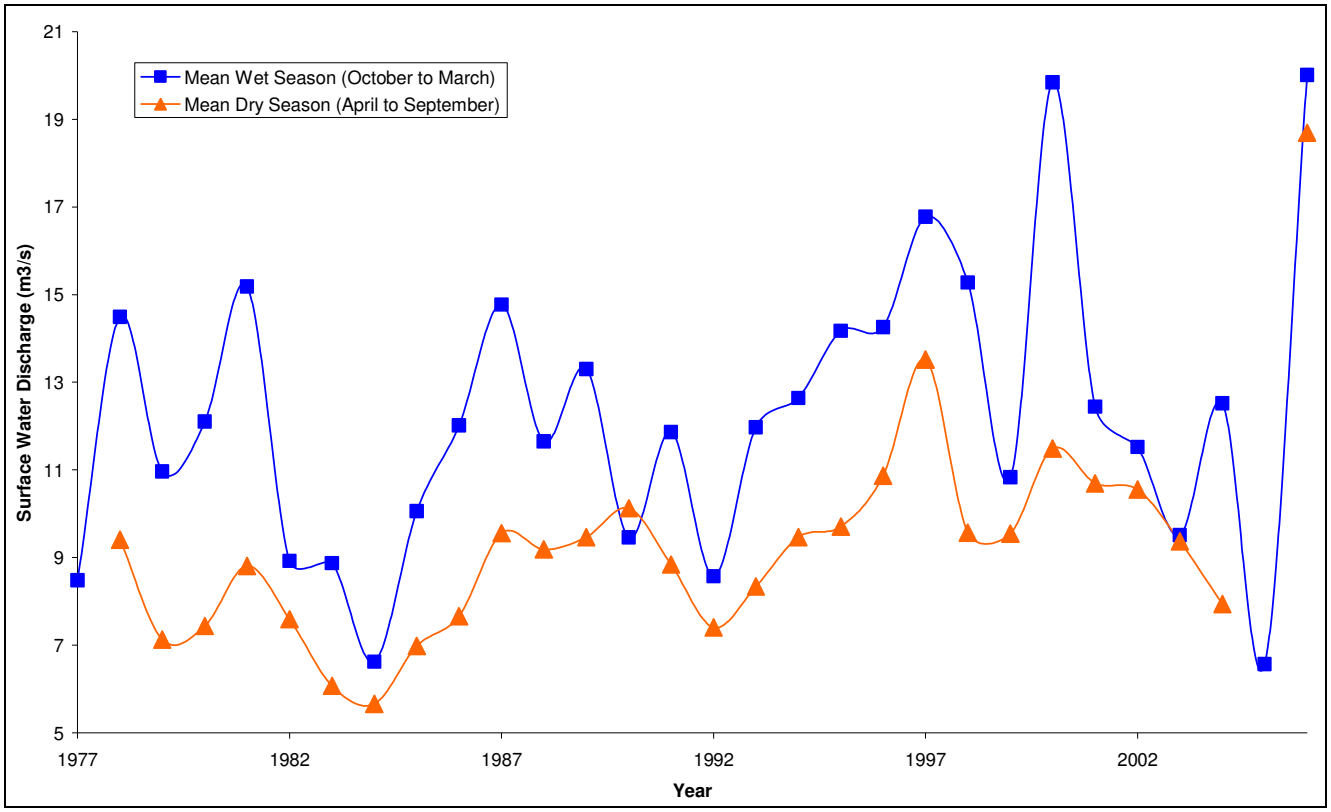


Figure 5.5.1: Mean wet and dry season trends for water discharge data at Witkop Station (C2H141) between 1977 and 2006.

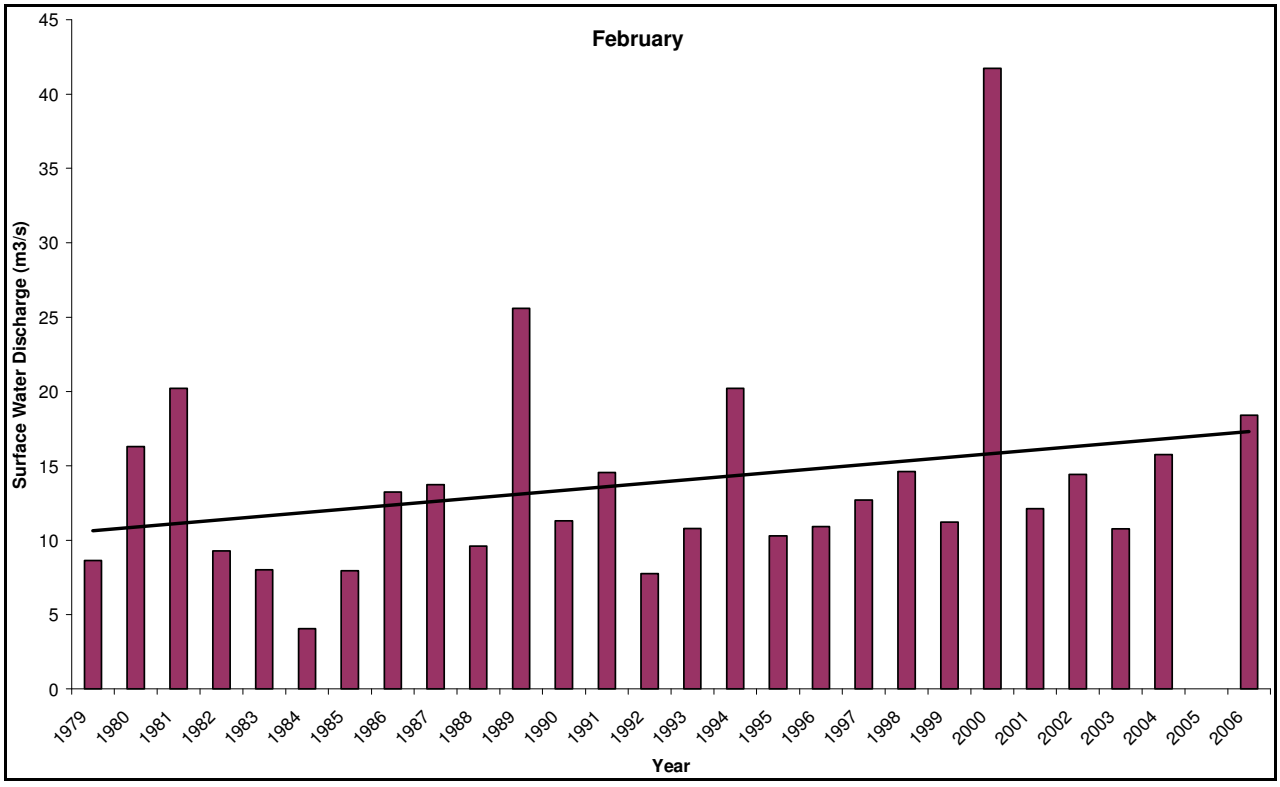


Figure 5.5.2: Water discharge in February at Witkop Station (C2H141) between 1979 and 2006.

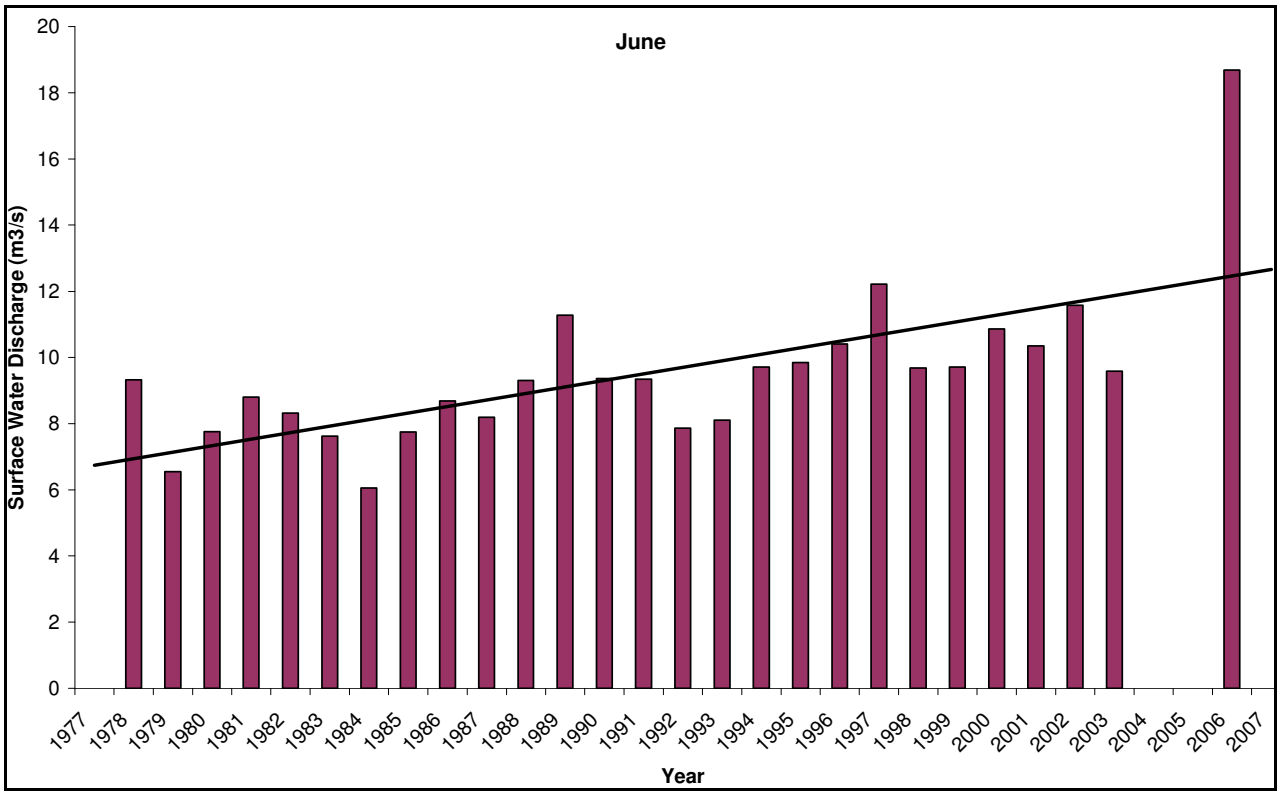


Figure 5.5.3: Water discharge in June at Witkop Station (C2H141) between 1977 and 2006.

The Witkop discharge data were also compared to rainfall data recorded at OR Tambo Airport (Figure 5.5.4). Although the rainfall data is from a separate catchment the two data sets follow similar trends. Around 2006 the discharge increases significantly, with no relationship to the rainfall data being evident.

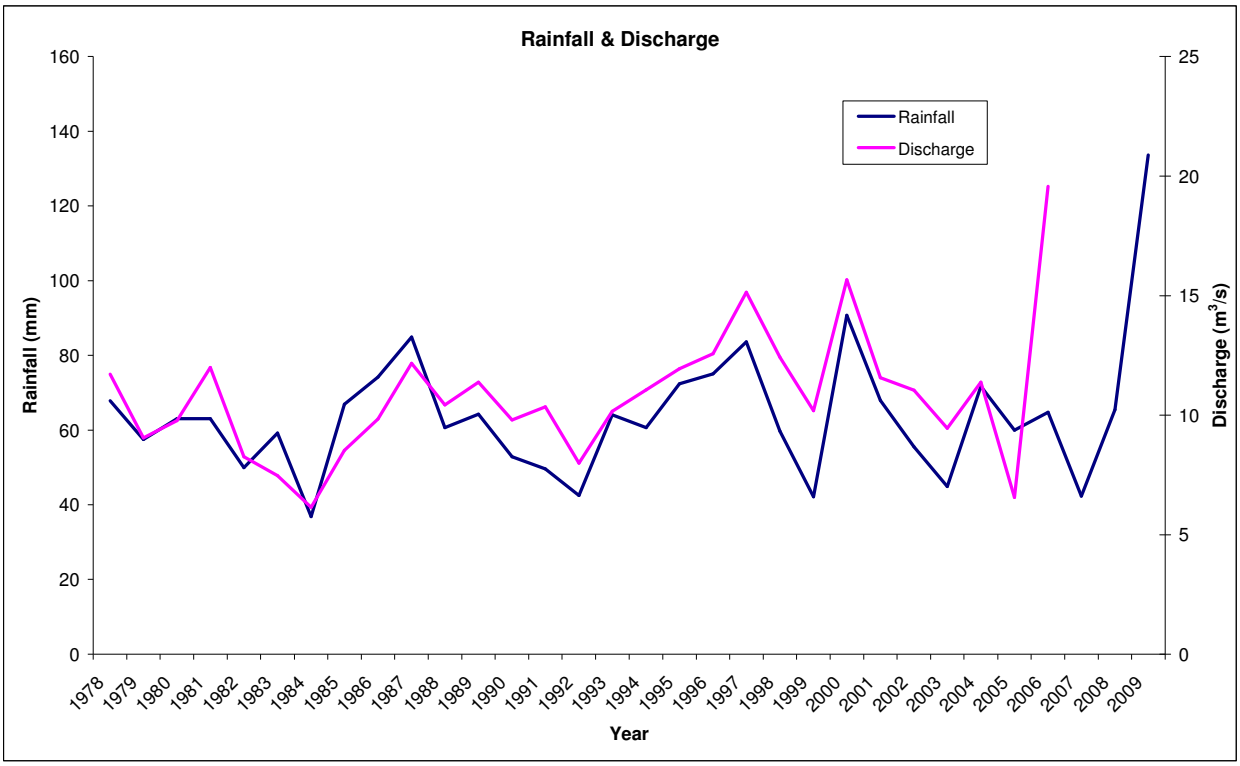


Figure 5.5.4: Water discharge at Witkop Station (C2H141) between 1977 and 2006 compared to rainfall data (OR Tambo Airport).

Figure 5.5.5 considers the change in rainfall and discharge data per month during the periods 1978 to 1987, 1988 to 1997 and 1998 to 2006. The rainfall trends remain consistent over all three of these time periods. The discharge data however, indicate that discharge is increasing over time, most noticeably in the dry winter months.

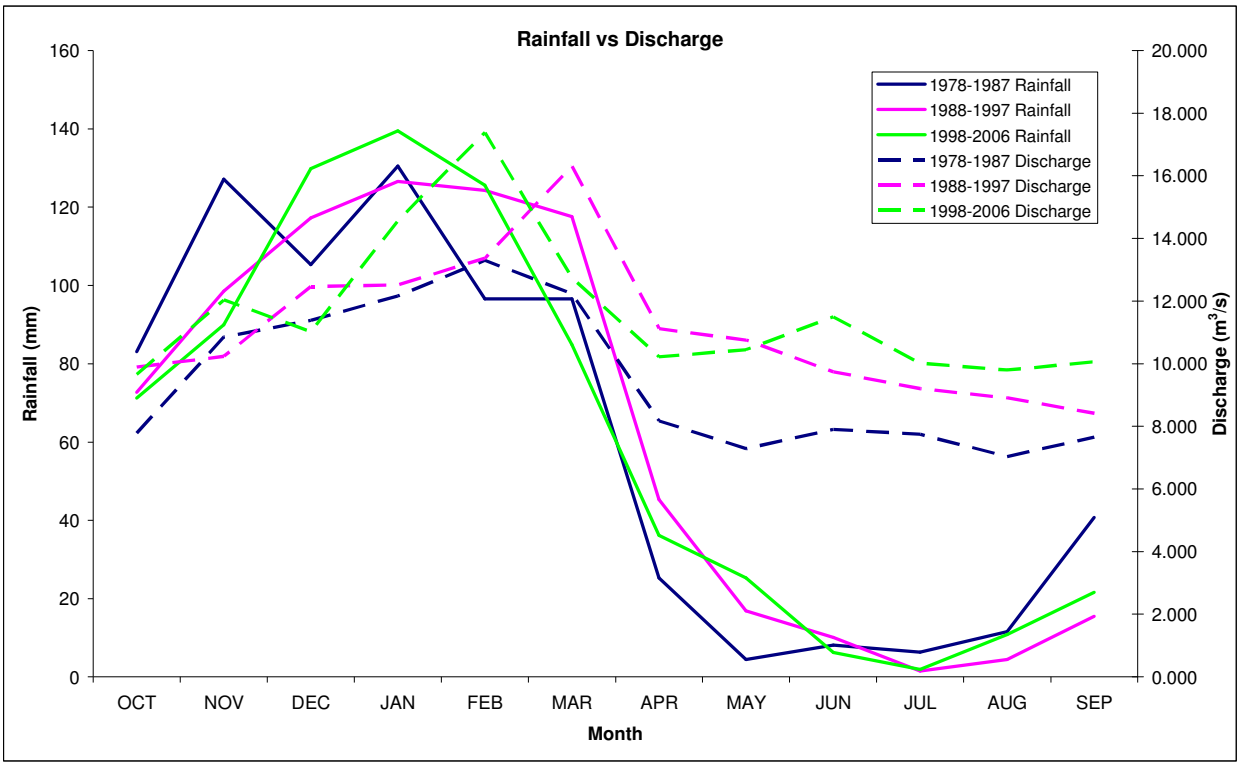


Figure 5.5.5: Water discharge at Witkop Station (C2H141) per month compared to rainfall data (OR Tambo Airport).

6. Discussion and Conclusions

6.1 Wetland Degradation

Prior to 1938, water from the Klip River Wetland was used extensively for agriculture. The agricultural practise was to drain the wetland by means of canals and furrows to then develop the land. Furrows, canals and drains were also used to irrigate farm lands. The majority of the irrigation canals incising along the banks of the wetland and the drains that cut across the wetland have now connected to form a single main channel diverting water away from the wetland. Analysis of aerial photographs reveals that only one small section (500 m long) of the wetland near Zwartkoppies Pump Station has not formed a single channel yet. The furrows and drains cut in the early part of the century have provided the perfect conduit for the large quantities of sewage and runoff funnelled into the wetland. The growing city of Johannesburg has caused the sewage influx in the river to increase resulting in the pirating of the otherwise harmless channels.

The only section of wetland which has not become channalised is in the Lenasia section west of the Klipspruit Valley Road. This section of wetland, however, is not pristine. The salt crust on the wetland banks indicates that the water quality is poor and metal rich, due to mine discharge. Up until 1961 the flow was across the entire width of the wetland at Kromvlei, similar to Lenasia. This is no longer the case as a channel on the south bank cuts through the wetland, incised by more than 5 m. Peat burns have been documented in Sections 4 and 5 of the wetland. Subsequently, soils containing heavy metals are being washed into the system and transported to the Vaal River.

With the degradation of the wetland, it was expected that the downstream water quality would deteriorate and that water discharge would increase. The only indications that water quality is deteriorating over time are increased nitrate and decreased oxygen levels. Since the wetland experienced the majority of its decline prior to 1992, the extent of the water quality data is insufficient to determine when the water quality was affected by the lack of water purification. An increase in discharge over time has occurred at the Witkop Station. It is difficult to attribute this increase in discharge to the decreasing impact of the wetlands only. With the rapid growth of the city of Johannesburg it is also logical that sewage input increased over time and ideally sewage discharge data needs to be acquired to better understand this relationship.

When considering the long river profile from Lenasia to the Zwartkoppies Pump Station, two major knick points are identified. The first is located at the outlet of the Olifantsvlei Sewage Works and the second represents a major rapid near Kromvlei. The latter has incised by 5 m into the wetland (Figure 5.2.8). Channel incision at the Olifantsvlei outlet is also significant (3 m). This channel has widened over time but the knick point has not migrated because it currently rests on bedrock (a resistant dyke as determined from the LIDAR). If it were to migrate upstream it would intersect the weir and then the man-made pond, which means the unchannelised wetlands at Lenasia will be protected from this knick point.

The knick point of concern is therefore in Kromvlei and the dashed line in Figure 6.1 illustrates the expected incision potential, assuming that this knick point does not intersect a resistant bedrock barrier.

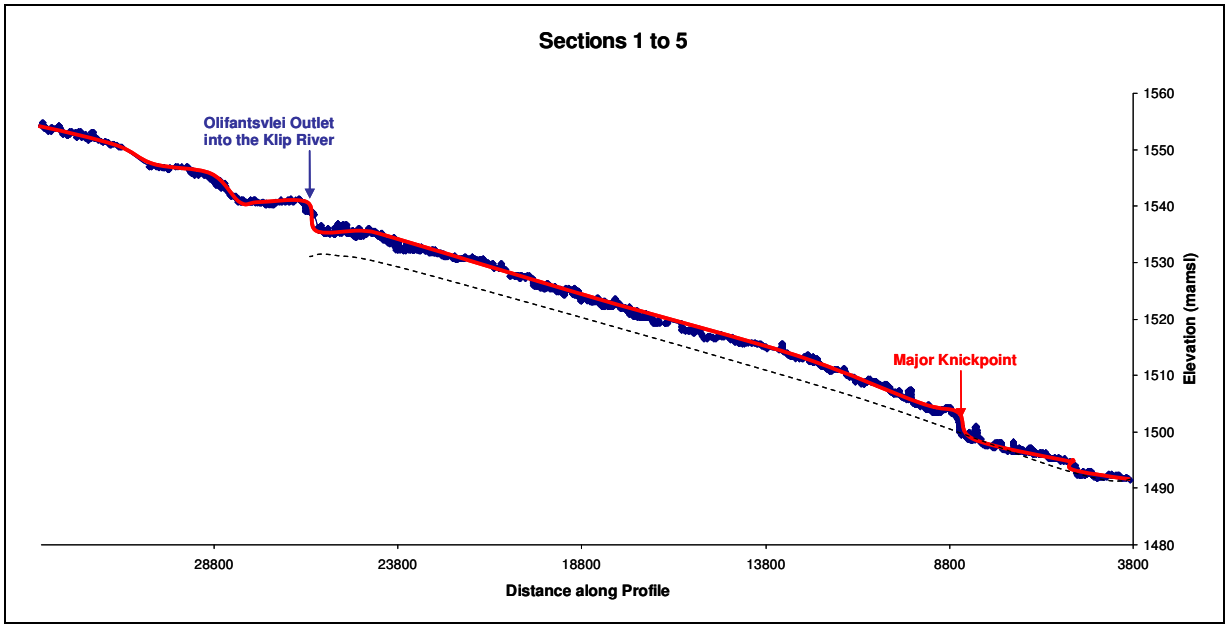


Figure 6.1: Long river profile from Lenasia to the Zwartkoppies Pump Station.

6.2 Rate of Wetland Degradation

Measuring the change in wetland area over time is not an effective method of quantifying the extent of wetland degradation and associated rates of change. Although, wetland area does decrease dramatically between 1917 and 1938 (Sections 2 to 5 in Figure 6.2), some wetland areas increase between 1938 and 2006 (Sections 2 and 3 in Figure 6.2). The wetland is therefore receiving sufficient moisture from rain, surface runoff and groundwater for the majority of the reed beds to remain intact. Channel formation, propagation and widening along with knick point migration prove to be the best methods of quantifying the collapse of the wetland (Figures 6.3 and 6.4). Furrows active in 1938 and 1961 are today derelict (Figures 6.3 and 6.4). No knick point migration is recorded between 2003 and 2006 except near Kromvlei at Point 16 (Figures 6.3 and 6.4). This knick point migrated 118 m in two years. This is likely due to the fact that this knick point is eroding through soil and not bedrock. It was also determined that groundwater barriers (dykes), as identified by Kafri and Foster (1989) and Schweitzer et al. (2004), could be correlated to rapids.

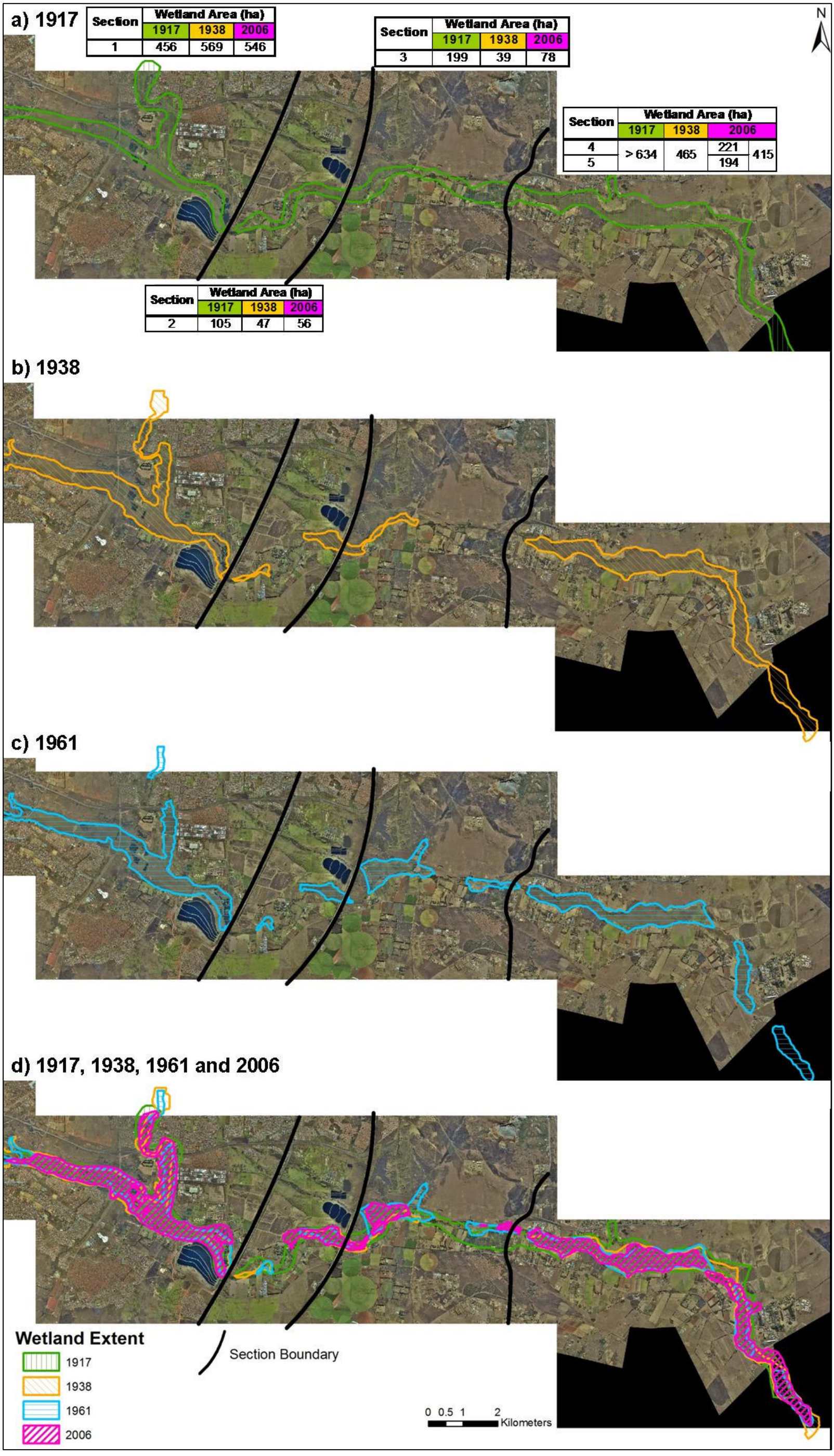


Figure 6.2: Wetland area in (a) 1917, (b) 1938, (c) 1961, and (d) 2006.

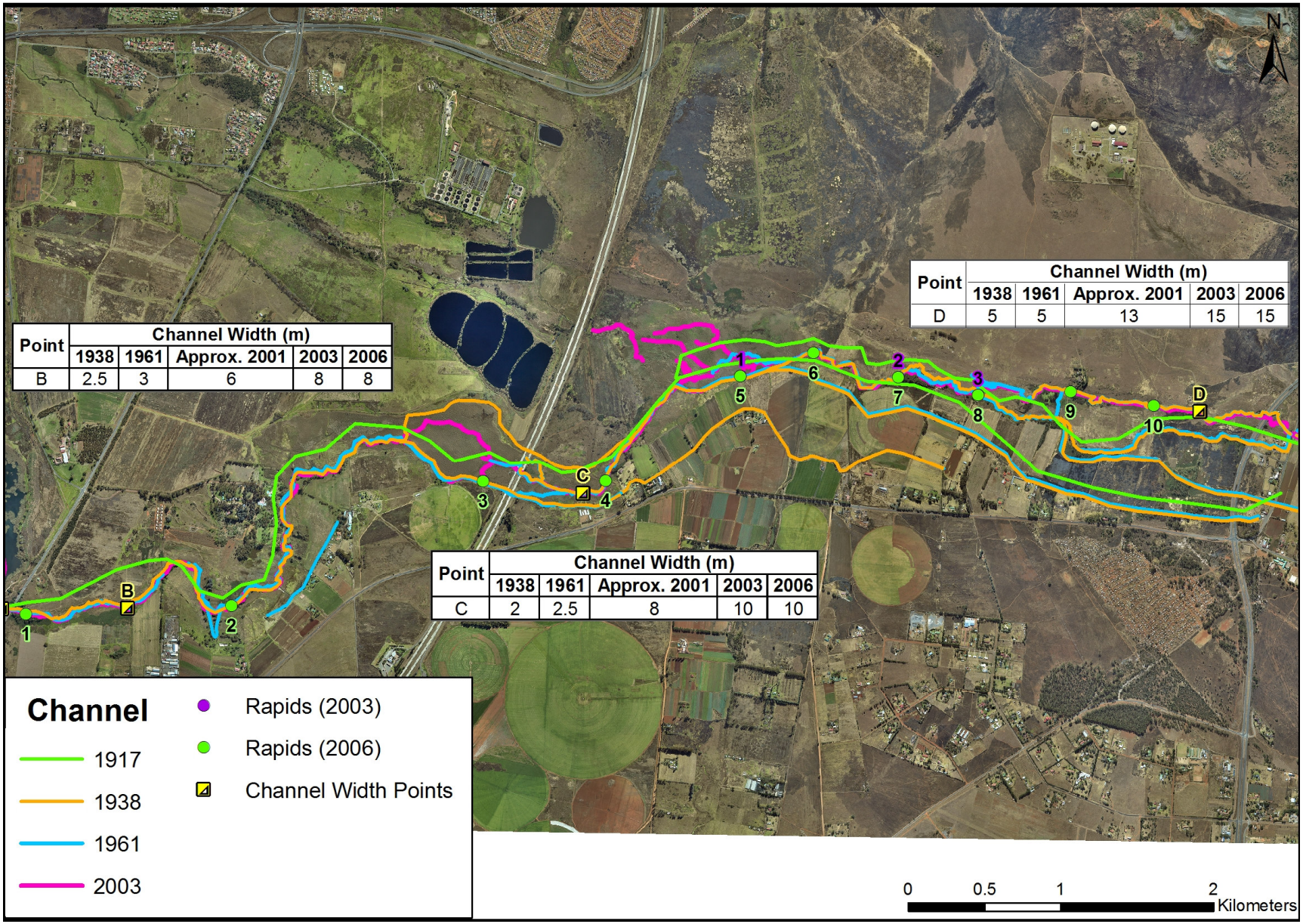


Figure 6.3: Channel formation, propagation and widening from the Golden Highway to Kibler Park between 1917 and 2003.

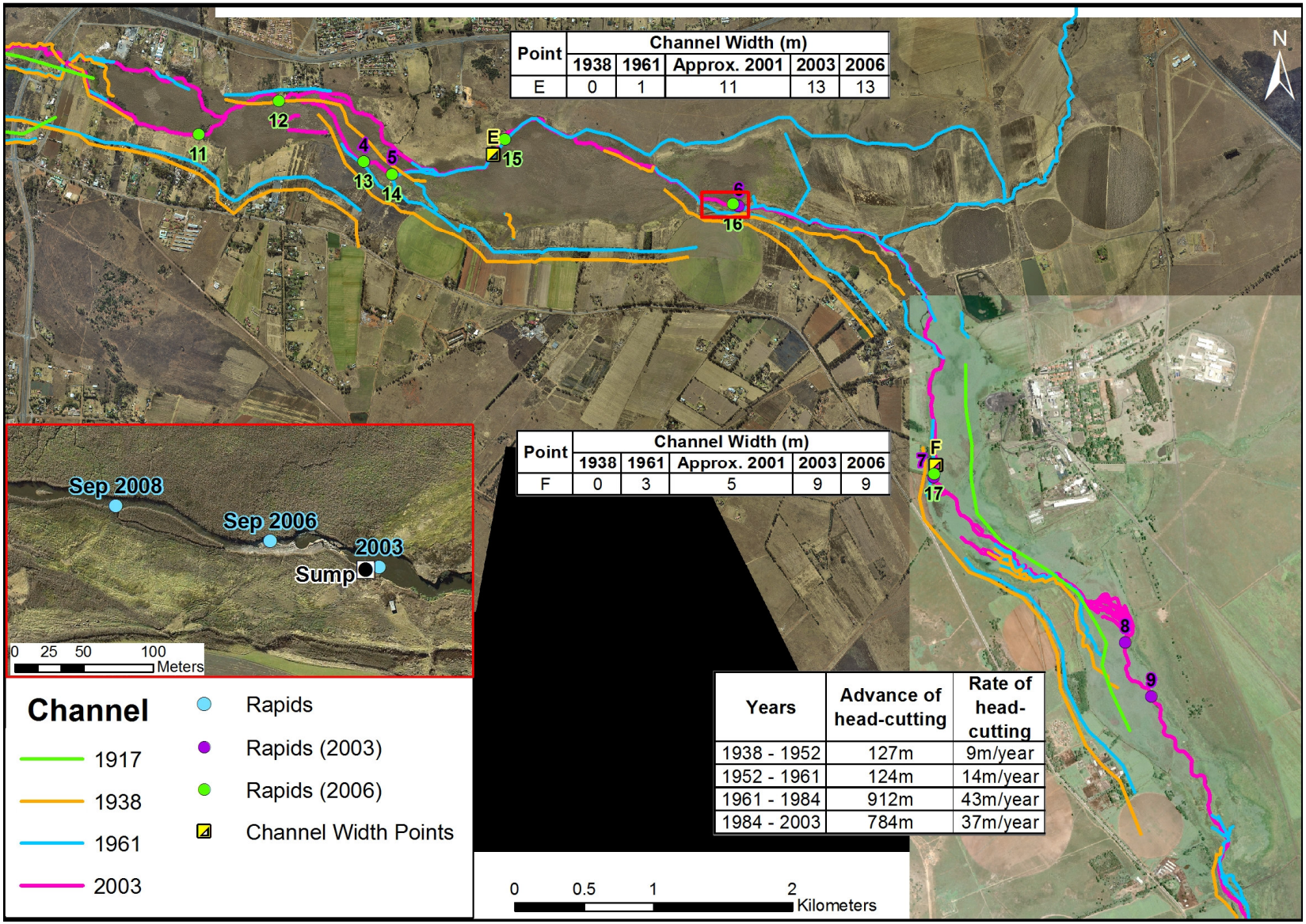


Figure 6.4: Channel formation, propagation, widening and knick point migration from Kibler Park to the Zwartkoppies Pump Station between 1917 and 2006.

The channel downstream of the Olifantsvlei Sewage Works widened most significantly (21 m), when compared to the remaining five channel width measuring stations, due to large amounts of sewage inflow. Point F near the Zwartkoppies Pump Station widened at the greatest rate between 1938 and 2006 (0.73 m/year, Figure 6.4). The period of most significant change for all monitoring points was between 2001 and 2003 (Tables 5.1.2 and 5.1.3, Figures 6.3 and 6.4).

The rate of head cut advance over time was also variable (Table 6.1). Between Kibler Park and Kromvlei the wetland has experienced the greatest head cut advance of all the sections, most significantly in the periods 1952 to 1961 (56 m/year) and 2006 to 2008 (59 m/year). The wetlands at the Zwartkoppies Pump Station exhibit significant head cut advance, after 1961 (52 m/year).

Table 6.1: Rates of head cut advance for Sections 2 to 5 (See Figure 6.3 and 6.4 for locality).

Section	Rate of Head Cut Advance (m/year)					
	1938 to 1952	1952 to 1961	1961 to 1984	1984 to 2003	2003 to 2006	2006 to 2008
2	9		18			
3	22					
4		56			14	59
5	14	20	52			
5	9	14	40	41		

The wetland described by Humphrey (1910) that extended to within 1.6 km of the Klip River Railway Station (south of Zwartkoppies Pump Station) retreated 5 km upstream by 1938. This equates to a retreat of 180 m/year.

7. Recommendations

Results of this investigation confirm that the current state of the Klip River Wetland is dire. Large tracts of wetland have disappeared over the last 100 years. The wetlands that remain are not functioning optimally. The importance of the wetland to purify sewage, industrial and mining effluent is paramount. The window of opportunity to save or restore at least parts of the wetland, and therefore maintain the purification potential of the wetland, is closing. Peat burns will lead to erosion of the soils and therefore the reworking of the pollutants into the river system. It is anticipated that if the Klip River Wetland collapses completely, the water quality will worsen along the Vaal River and in the Vaal Barrage, which will impact negatively on downstream users.

The proposed solution to protect the wetland from further erosion and head-cut advance is to force the water out of the channels and into the wetland. By building a number of weirs in the channels, it is possible to dam the water upstream of the weir, thereby forcing the water to flood the wetland again. The choice of weir location and design is key to the success of this kind of intervention. It is essential that the weirs are constructed on resistant strata, as water will follow a path of least resistance and will undermine the weir built on any rock which is easily eroded, for example dolomite. The weirs should ideally be located on resistant dykes which cut across the wetland and penetrate through the entire dolomite sequence. From the long river profile analysis it is determined that the gradient attained by the current functioning and unchannelised wetland (Lenasia area, Section 1 in Figure 5.1.8) is between 1 : 0.001 and 1 : 0.002. It is recommended that the installation of the weirs aims at attaining an equivalent gradient. Four weirs are proposed at dykes projected from regional aeromagnetic data (Figure 7.1). It is recommended that a detailed magnetic survey is carried out to confirm the location of these dykes before weir construction is considered.

In order to better understand the correlation of the deterioration of the wetland and changes in the water discharge from the wetland, discharge data from the sewage works should be acquired and analysed. The use of satellite multi-spectral imagery to quantify and investigate the Klip River Wetland and the true extent of its moisture content should also be investigated further. This analysis might be useful in better determining the rate of change, since the Landsat program is the longest running enterprise for acquisition of imagery of Earth from space, with the first Landsat satellite having been launched in 1972.

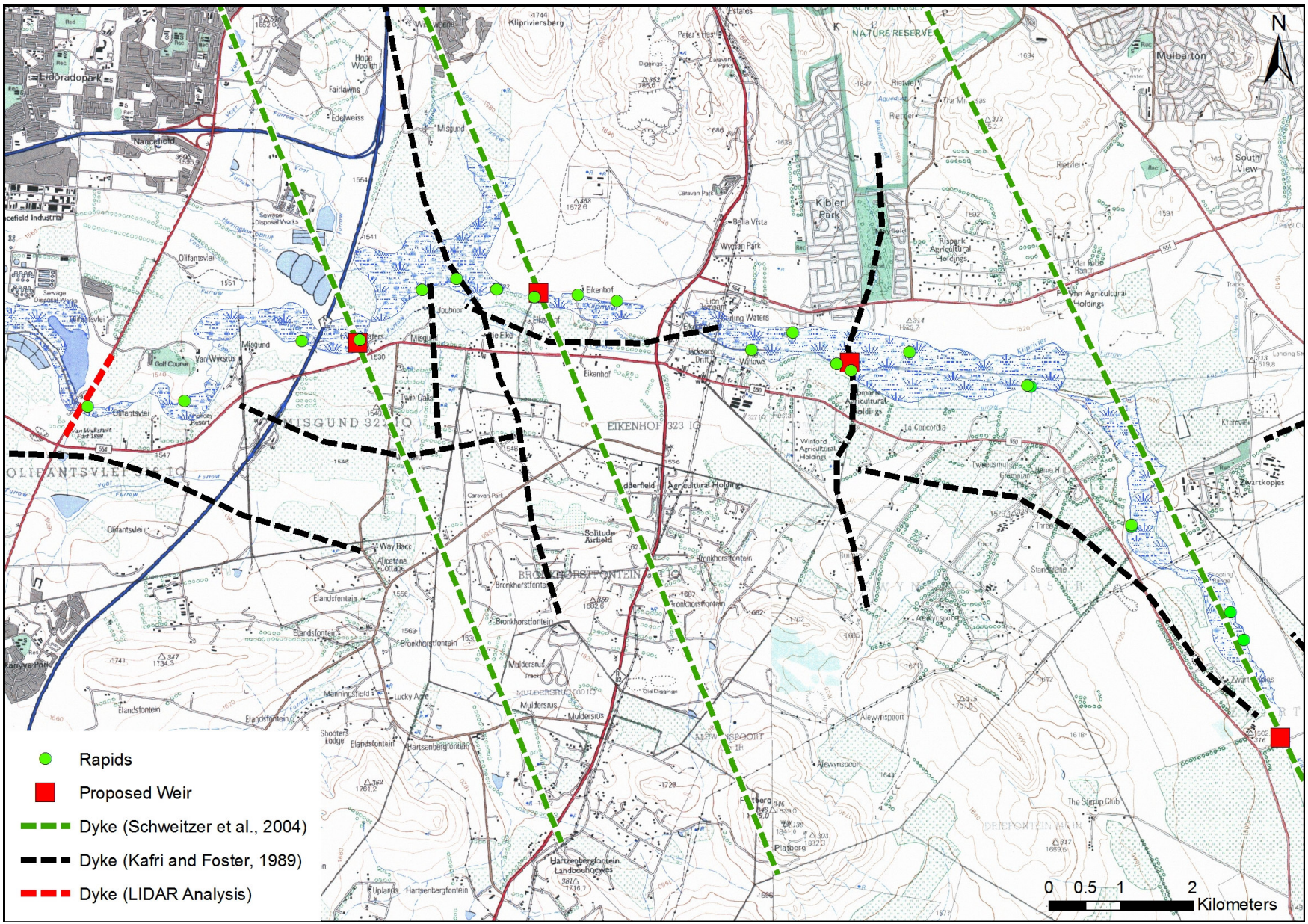


Figure 7.1: Proposed weir locations according to dyke positions.

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