The collapse of Johannesburg's Klip River wetland

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The Klip River wetland south of Johannesburg has long been economically important to the region, initially as a source of water, and latterly as a purifier of polluted water arising from the western section of the Witwatersrand urban-industrial-mining complex. A geomorphological investigation into the current state of the wetland has revealed that the upper reaches, which receive polluted water from old gold mines, are in reasonable condition, apart from a few sections that have been severely degraded by peat mining. The lower reaches, however, are in an advanced stage of collapse. A network of irrigation canals, dug to support intensive agriculture during the early part of the last century, provided nuclei for the development of major channels as discharge of treated sewage water increased in the latter portion of the century. The channels have become interconnected, and an almost continuous, single channel has formed downstream of the sewage works. The problem is likely to have been exacerbated by a falling water table in the area due to excessive groundwater extraction. The wetland's ability to remove phosphates and nitrates from the water has been seriously compromised, and eutrophication problems can consequently be expected to arise in the Vaal River above the Barrage. In addition, it is anticipated that the reed beds flanking the single channel will degrade over the coming years, releasing sequestered heavy metals, organic load and phosphates into the Vaal River system.

Introduction

The Klip River wetland (Fig. 1) is possibly one of the most economically important wetlands in Africa. It was important historically because it provided the first reliable water supply to the growing towns of the Witwatersrand gold field.[1] Large quantities of ground water were located in the dolomitic rocks that underlie the wetland,[2,3] and extraction of this water began at Zuurbekom in 1899 and at Zwartkoppies in 1905 (Fig. 1). These became the primary water sources for the Witwatersrand. Rapid growth in demand for water soon rendered these sources inadequate, and the Vaal Barrage was built to augment supply. This was completed in 1923[1] and the dolomitic aquifers became increasingly less important as a source of water. Although no longer used as a water source for the human population, the wetland became progressively more important in other respects, namely as a significant agricultural area and as a site where the natural treatment of polluted water from the central and western Witwatersrand occurred. What makes this aspect of the wetland especially important is the fact that the Klip River enters the Vaal a short distance upstream of the Barrage. This meant that the Witwatersrand effectively recycled its waste water, albeit in diluted form. Moreover, the reach of the Vaal River upstream of the Barrage is a major recreational area for the Gauteng region and good water quality is highly desirable.

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The reason the Klip River receives much of the industrial pollution from the Witwatersrand is that the northern watershed of the basin passes across the outcrops of the West Rand Group that form the Witwatersrand escarpment. Much of the early economic development of the region took place south of the watershed within the Klip River catchment, where the gold-bearing conglomerates outcrop. Most of the polluted water arising from the region therefore reports to the Klip River via tributaries that enter the wetland on its northern bank (Fig. 1). Pollution from this source continues to this day, and consists of water that has been contaminated by acid mine drainage and industrial sources, as well as by run-off from urban areas. In addition, sewage treatment plants have long been a feature of the Klip River valley, and they discharge water that, although treated, nevertheless contains elevated concentrations of residual phosphates and nitrates.

Polluted water arising from these sources has left clear symptoms in the chemistry of the wetland peat. Concentrations of heavy metals in the inorganic content of the peat are higher in the uppermost reaches of the wetland: for example, in the Lenasia area Ni contents in peat ash reach 4500 ppm and Cu 1200 ppm, whilst in the Kibler Park area further downstream Ni attains a maximum of 1500 ppm and Cu about 170 ppm (Fig. 1; refs 4, 5). The efficacy of this wetland for reducing pollution from industrial and mining sources has long been known (e.g. ref. 6 and references cited therein), although in spite of this, a steady rise in metal concentrations in the Vaal River at the Barrage was noted by the 1980s.[7] The wetland's ability to remove phosphates and nitrates from treated sewage water has been well documented.[8] Phosphate sequestration by the wetland biota is recorded in the elevated phosphorus content of peat in the wetland.[4] Recent regional studies using historic data have shown conclusively that the wetland has a beneficial effect on the quality of water entering the Vaal River.[9,10] By contrast, treated sewage water discharged into the Crocodile River to the north of the Witwatersrand watershed, which has no associated wetlands, has led to chronic eutrophication in Hartebeespoort Dam.

Wetlands remove pollutants in a variety of ways: phosphates and nitrates are sequestered directly by wetland vegetation, as their presence in the water promotes plant growth. Possibly for this reason, the rate of peat accumulation in the Klip River wetland has greatly accelerated since the establishment of Johannesburg.[4] In situations where polluted water contains elevated sulphate and heavy metal concentrations from mining wastes, such as in the Klip River wetland, the principal mechanism of water purification is by reduction of sulphate to sulphide and the concomitant precipitation of most heavy metals as sulphides. Excess sulphide is released as hydrogen sulphide gas. In instances where elevated concentrations of calcium sulphate are present in the water, the reduction of sulphate to sulphide leads to the formation of calcium bicarbonate. Uranium, which is also derived from the mining wastes, is precipitated directly by reduction to the insoluble U(IV) oxidation state.[4]

The Klip River wetland has been accumulating heavy metal and other pollutants since the founding of Johannesburg, and this has led to the elevated concentrations in the peat referred to above. The efficacy of a wetland for removing pollutants is

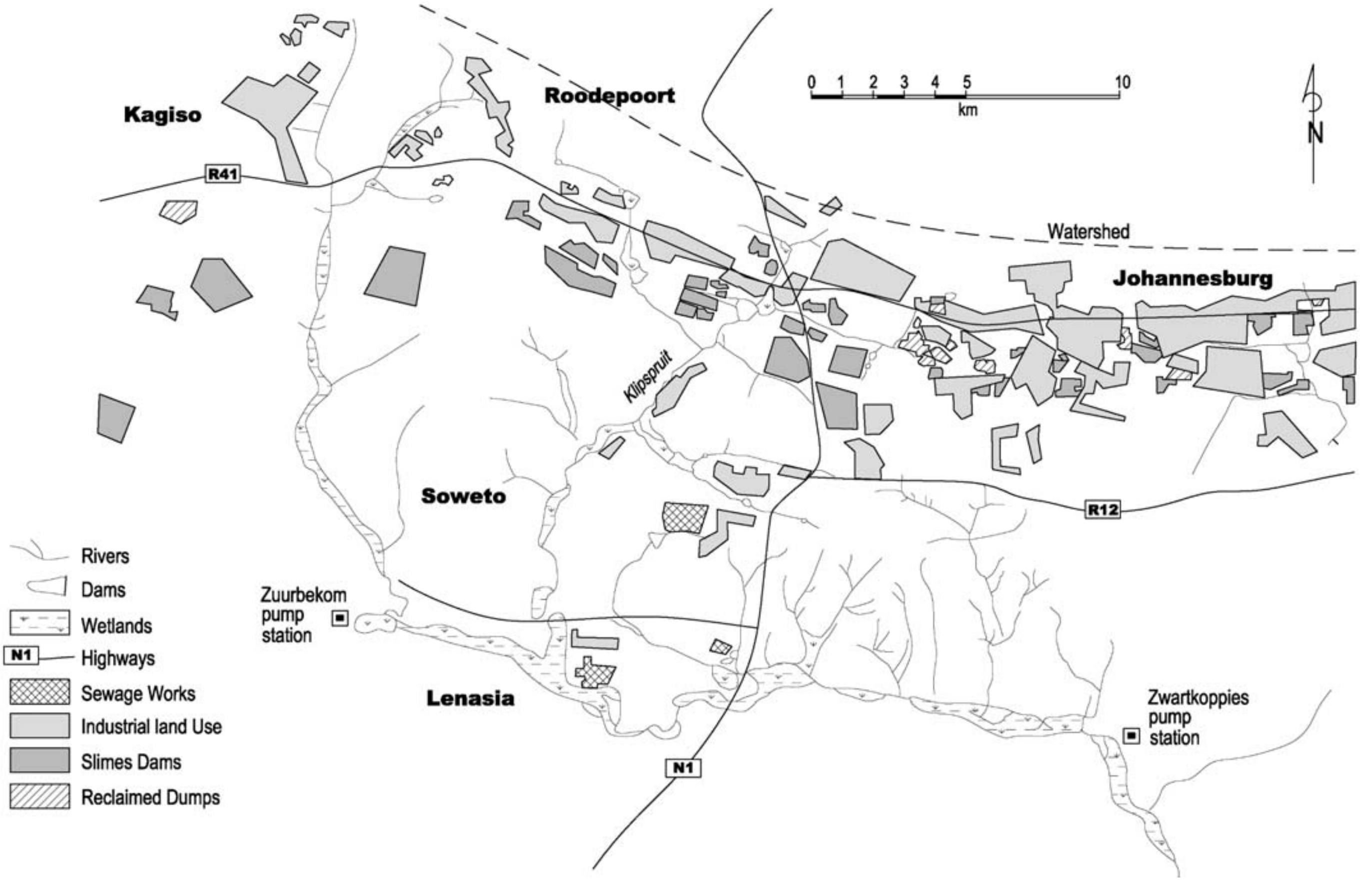

Fig. 1. Location of the Klip River wetland in relation to industrial and mining development in the Johannesburg area.

critically dependent on residence time of the water in the wetland, and on pollutant load. The ideal situation is where flow is shallow and slow, and the width of flow is maximized.

The Klip River wetland has been exposed to intensive anthropogenic impact for 120 years, and we analyse in this paper the nature of these impacts, the manner in which the wetland has responded to them, and its likely future prospects.

Temporal changes in morphology of the Klip River wetland

Early records

Sources of quantitative information on the wetland from the early years of development of the Witwatersrand gold field are few. The wetland was described by Humphrey in 1910[3] as a series of extensive marshes that extended to within 1.6 km of Klip River railway station. The marshes acted as large, natural reservoirs:

> After a series of dry years, they dry up, beginning from below and gradually drying upstream. When in this condition, they act as huge, dry sponges and the tributary streams may be in flood, while the dry vleis in the river bed receive and conserve the water which filtering gradually through only reaches the lower portions of the river course after a considerable time. In the rainy season the vleis become saturated and then all surplus water takes its course along their surface to the lower reaches of the river. (ref. 3, p. 92)

Sources of water in the Klip River were tributaries on the north bank, notably the Klipspruit, and several strong springs in the underlying dolomite along the length of the wetland, the most westerly being developed east of the Zuurbekom pump station (Fig. 1). Humphrey identified several dykes striking perpendicular to the course of the river, and suggested that these may divide the dolomitic aquifer into several watertight compartments, connected only via springs and overland flow. This has subsequently been confirmed by a detailed hydrogeological study of the dolomitic terrain that hosts the wetland.[11]

While descriptions such as those of Humphrey are useful, they provide little of the detail needed to assess changes experienced by the wetland. Nevertheless, there is some useful information in that, as far as the authors are aware, there are no longer any active springs along the course of the river. Water in the underlying dolomites along the river course shows significant levels of pollution, indicating that, rather than receiving water from the dolomitic aquifers, the river now discharges into them.[11] Moreover, the wetland now ends about 6 km from the Klip River railway station, indicating a slight decrease in wetland area.

Most of the wetland was included on the geological map of the Witwatersrand published in 1917,[12] based on mapping carried out between 1910 and 1915. A detailed comparison of the area currently occupied by the wetland with that in the 1917 map suggests little change,[13] with small increases in some areas and decreases in others. The study suggests that the wetland is essentially in pristine condition today in terms of its spatial extent (the lowermost reach was not covered in the geological map).

The aerial photographic record

More detailed spatial information can be obtained only by analysis of aerial photographs. The oldest aerial photographs available were taken in 1938. These cover only the upper reaches of the wetland, and are used to provide the base-line condition for that portion of the wetland. It will be shown, however, that important consequences had already arisen locally for the

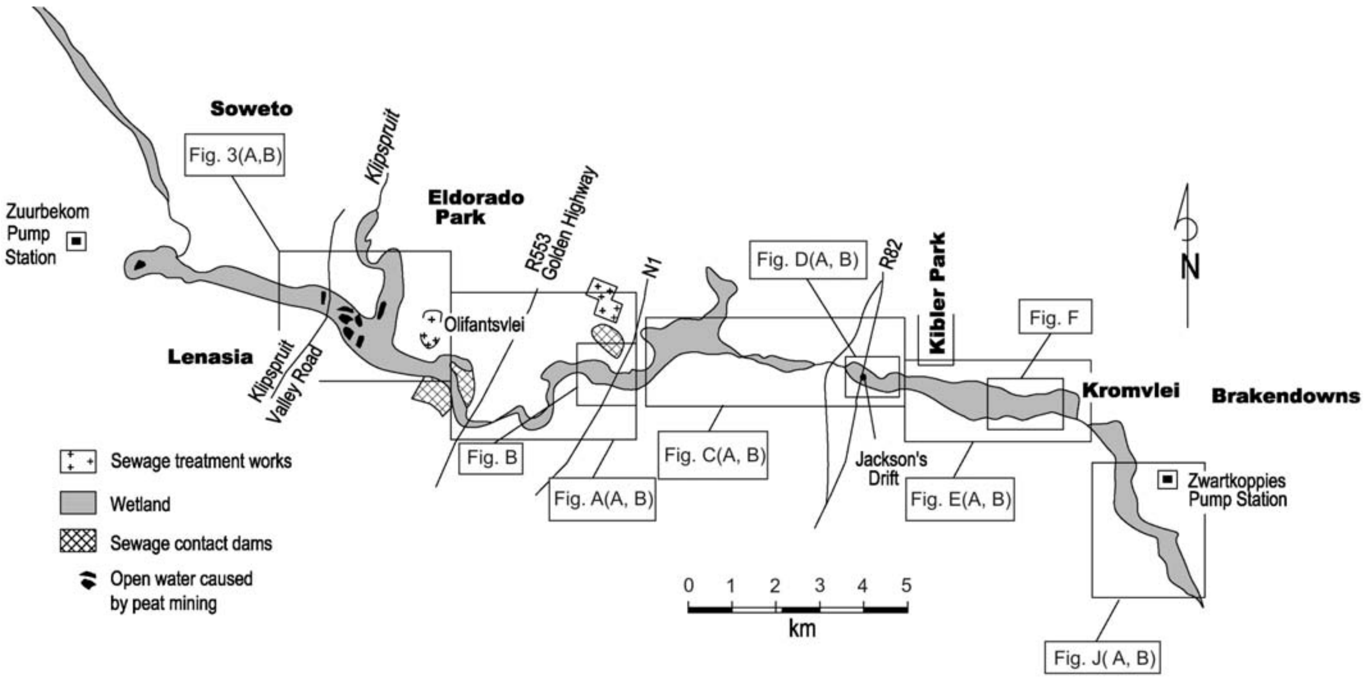

Fig. 2. Map of the wetland, showing the geographical features referred to in the text and the locations of the aerial photographs used in the analysis.

wetland by that time. For the lower reaches, we have had to use aerial photographs taken in 1952 and 1961. The earlier photography is compared with that taken in 2003. This analysis of aerial photographs was augmented by field investigations and aerial reconnaissance. The extent of the impacts is widely variable along the wetland, and for convenience, we have therefore divided it into several sections, each of which will be discussed separately (Fig. 2).

(i) *Lenasia to Olifantsvlei*

In its western, most proximal section (Lenasia area), the wetland consists of a *c.* 500-m-wide, reed-covered swamp dominated by *Phragmites australis.* There are no channels in the wetland. On 29 September 2006, prior to any significant summer rain, water was flowing through this section over a width of 400 m. Flow velocities (measured using fluorescence dye) varied from zero to about 0.03 m/s, and flow depth rarely exceeded 20 cm. It is estimated that discharge at this time was 1.6 m^3/s. Cores taken in the wetland revealed an upper rhizome layer about 30 to 50 cm thick, underlain by up to 4 m of peat. The peat is very fibrous and relatively low in inorganic components (about 30% by dry mass on average[5]), but at depth becomes clay-rich and grades down over about 1 m through clayey sand to bedrock.

The 1938 photography shows the wetland to consist of an extensive reed bed (Fig. 3A). Irrigation canals had been dug along the fringes of the reed bed. The wetland in the 2003 aerial photographs is very similar in

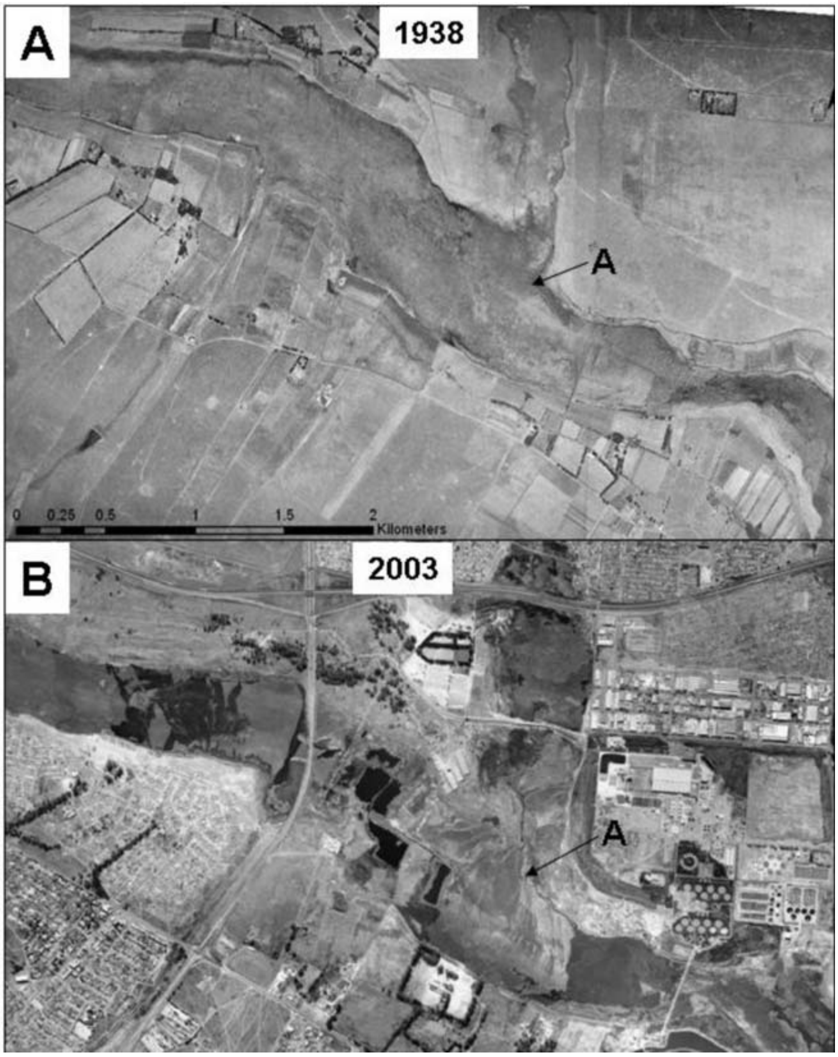

Fig. 3. The wetland in the Lenasia area in (**A**) 1938 and (**B**) 2003. See Fig. 2 for location.

Fig. 4. Aerial view of the open water bodies left from peat mining in the area east of Klipspruit Valley Road, Lenasia.

appearance (Fig. 3B) apart from an apparent slight increase in width, suggesting minimal macroscale anthropogenic influence. The irrigation canals are no longer evident, but were seen during aerial reconnaissance. They are heavily encroached by *Phragmites* reeds. Anthropogenic impact in this section of the wetland appears to be minor. Although heavy metal concentrations in the peat are high, as mentioned above, the vegetation does not appear to be adversely affected. As seen today, this section probably provides the best approximation of the appearance and hydrological functioning of the wetland, prior to the onset of gold mining on the Witwatersrand. Unfortunately, the area has not escaped completely unscathed, as some mining of peat has taken place in the very far western extremity of the wetland and especially in the area east of the Klipspruit Valley road crossing, which has left extensive bodies of open water in the wetland (Figs 3B, 4).

Sewage treatment works have been established at Olifantsvlei, and one of the contact dams appears to have been constructed in the wetland itself. Discharge of water into the Klipspruit tributary from the sewage works appears to have led to widening of an old irrigation furrow (A in Figs 3A, B).

(ii) *Golden Highway (R553) to the N1 motorway*

There appears to have been little wetland development in the upper portions of this reach in 1938, and the river formed a single channel. Some of the wetland may have been converted to agricultural land prior to 1938 (A in Fig. A in supplementary material online). Floodplain wetlands reappeared further downstream, but some of the river discharge had been diverted into canals on the north and south banks (B and C, respectively, in Fig. A(A)). In the 2003 photographs the river is similar to 1939, although the channel has widened substantially. Most of the changes that are evident have taken place in the lowermost reach. The bridge for the N1 motorway was built to accommodate the central channel in the wetland (D in Figs A(A) and (B)). The central channel has developed a series of headcuts that are propagating upstream to link with the remnants of the south bank canal (Fig. B in online supplement).

(iii) *N1 to Jackson's Drift/Kibler Park*

This reach of the floodplain was intensely farmed by 1938 (Fig. C(A) online) and the course of the river was largely manipulated. Irrigation canals carried much of the water through the reach. It may formerly have consisted of a *Phragmites* reed bed. Downstream of the bridge at Jackson's Drift, the water can be seen to have dispersed in a wide reed bed, although irrigation canals are evident on the margins of the wetland.

By 2003, agriculture had declined along this reach of the river (Fig. C(B)) and the irrigation canals were largely dysfunctional. Flow had become confined to the irrigation canal along the northern bank of the wetland (A in Fig. C(B)), which had widened considerably. Downstream of the bridge at Jackson's Drift, flow continued to disperse into the extensive wetland as in 1938, but discrete channels now extended further into the wetland on the north and south banks (Figs D(A) and (B) online).

(iv) *Jackson's Drift/Kibler Park to Kromvlei*

This reach was not covered by the 1938 photography, and the 1952 photographs were of a poor quality. Consequently, we have used 1961 photographs as the basis for assessing changes in this reach. This is not ideal, but for most of the reach the main changes post-date 1961.

The reach was almost entirely covered by *Phragmites* wetland in 1961, and flow was apparently distributed across the wetland, as still occurs in the Lenasia section discussed above. Several irrigation canals had been cut on the south (A to C in Fig. E(A) online) and north banks (D, E in Fig. E(A)). Many of these canals were supplied with water by drains cut diagonally into the wetland at their heads (e.g. I in Fig. E(A)).

Flow had been fully diverted into a single channel on the south bank in the eastern section on Kromvlei (F in Fig. E(A)), using drains dug across the wetland (H in Fig. E(A)). These collected water that flowed through the upstream reed bed and diverted it to the canal on the south bank. This was evidently done to facilitate draining of the wetland to the downstream for agriculture (area G in Fig. E(A)). These diversions were carried out prior to 1952.

The wetland in the western extremity of this reach was still largely intact in 2003, with minor channel development. Opposite Kilber Park, however, a wide channel had formed across the wetland along a former diagonal drain. This had linked through to a greatly widened former diagonal drain and irrigation canal on the northern bank (J in Fig. E(B)). Downstream, the canal on the south bank (F in Fig. E(B)) had widened substantially, and had extended upstream across the wetland along a diagonal drain (I in Figs E(A) and (B); Fig. F online). A number of diffuse channels were eroding headward into the wetland upstream of the canal (Fig. F). Aerial reconnaissance has shown that one of these feeder channels has since linked through to the widened canal on the north bank, and the channel is now continuous from Kibler Park to Kromvlei.

The channel on the south bank (F in Fig. E(B)) is undergoing rapid incision (Fig. G online). The extent of incision is difficult to gauge from aerial photographs, but field measurements indicate that the water surface at the pump station seen in the centre of Fig. G has been lowered by 2.5 m since the pump was erected in 1983 (Fig. 5). This incised reach has a nick point at its head with a 2 m waterfall (Fig. H online). Incision of this channel has also led to incision of the drain across the wetland (H in Fig. E(B)), resulting in a deep gully entering the main channel on the north bank (Fig. G).

The extent of incision is further illustrated by a surveyed topographic profile extending from the pump to the northern bank of the wetland (Fig. I online). The water level at the time the pump station was constructed was determined from rust marks on the pipes in the sump, and this provides an indication of water level in the wetland at the time the pump was in use (late 1980s and possibly early 1990s). The banks of the incised channel

Fig. 5. Photograph showing the extent of channel incision at the inlet (concrete structure next to figure) to the irrigation pump shown in Fig. G. Figure G provides an aerial view of this location.

Fig. 6. Aerial photograph showing the final stages of the formation of a single channel in the Zwartkoppies reach of the wetland (reach E in Fig. I(B)).

lie at a higher elevation than the former water level in the wetland, a consequence of the fact that the channel has incised along a former irrigation canal located outside the wetland.

(v) *The Zwartkoppies section*

The lowermost reach of the wetland, in the vicinity of the Zwartkoppies pump station, was also not covered by the 1938 photography, and the earliest photographic record we have was acquired in 1952. Anthropogenic impacts evident at that time were an elevated road across the wetland to the pump station (A in Fig. J(A)) and an underground pipeline across the wetland (B in Fig. J(A)). A number of openings had been built under the road to allow through-flow of water. Canalization had begun in the central portion of the wetland with pronounced head-cuts migrating upstream towards the elevated roadway (C in Fig. J(A)). Elsewhere, the wetland appears to have been functional. The wetland converged to a single channel at its termination, with some evidence of head-cutting (D in Fig. J(A)).

The channel in the central reach had extended upstream by 2003 and had linked with the channel on the south bank at Kromvlei, although the lower portion of this reach had closed. Field investigation revealed that one of the culverts under the roadway was deeply incised and carried all of the discharge, and the rest were no longer functioning. Water level behind the roadway had been lowered by about 2 m. Head-cutting had also proceeded upstream from the distal extremity of the wetland and flow in this lower reach in 2003 was completely canalized except for one section of diffuse channel development (E in Fig. J(B)). Canalization had occurred on the north bank, possibly along a former irrigation ditch, and the channel is incised. The incising channel has intersected a bedrock barrier along this reach, resulting in a 2-m-high waterfall (Fig. K online). Aerial examination indicates that the last remaining unchannelized portion of this reach (E in Fig. J(B)) will soon converge to a single channel (Fig. 6). The channels are still flanked by reed beds, but these appear to experience only limited inundation, and may be mostly supplied by groundwater and occasional overbank flooding. It is also evident that the reed bed in the southernmost section of the wetland is retreating upstream. There is evidence that burning of the peaty, rhizome layer has taken place, which is followed by erosion of the resulting clayey ash. This often produces shallow, donga-like gullies in which bedrock is exposed (Fig. 7).

A discharge of 3.8 m^3/s was measured on 29 September 2006 in the Klip River at a weir located just downstream of the termination of the wetland. Mean flow velocity was estimated to be 0.53 m/s in the single channel below the weir.

Fig. 7. Bedrock exposed in a donga formed by erosion of the burnt-out wetland in the Zwartkoppies reach.

Discussion

It is evident from this comparison of old and recent aerial photographs that the Klip River wetland has experienced substantial degradation in the past 65 years. What is also evident is that there was already significant anthropogenic impact prior to 1938, in which certain reaches of the wetland had been converted to agricultural use. Most of the wetland appeared to be functioning normally, however, with only localized impacts in the form of irrigation canals. The practice at that time was to cut a diagonal drain into the wetland at the head of each canal, to feed water into the canal. The canal would follow the edge of the wetland for a short distance and then diverge along a contour, allowing irrigation of downslope fields by gravity flow. Some canals seem to have been confined exclusively to the edge of the wetland. Agriculture along the Klip River has declined substantially in recent times, and the main use of the fields now appears to be for the cultivation of instant lawn. Irrigation is done by the use of pivots. The irrigation canals have deteriorated and most are dysfunctional.

In themselves, the irrigation canals appear to have constituted a relatively benign intervention, as can be seen in the Lenasia area today, where they have become largely overgrown or are otherwise non-functional. There seem to be no lasting adverse effects arising from these canals, and the reed bed is intact, with discharge being dispersed over a very wide zone.

This is not the case in the lower reaches of the wetland downstream of Olifantsvlei, however. Here, the canals have undergone major widening and incision. Many of these canals lay on the periphery and even beyond the limits of the wetland and were thus elevated relative to the adjacent bed of the Klip River, and consequently have become deeply incised (e.g. Figs G and I). In places, bedrock barriers have been encountered during incision, resulting in several waterfalls and rapids along the modern river (e.g. Fig. K). The incising channels have also exploited some of the diagonal head drains and thus the new, widened channels migrate from one side of the wetland to the other (Figs E and F). These diversions across the wetland have had the effect of capturing progressively more of the dispersed flow and focusing it into a widening, single channel, thus further promoting incision and channel-widening. As these diagonal drains widen, headcuts extend upstream into the wetland, draining water into the widening channel (e.g. Fig. F). The parallel and linear nature of these headcuts (e.g. Fig. F) suggest that they may be nucleating on pre-existing lines of weakness—possibly pathways made by water mongoose (*Atilax paludinosus*), which are common in the wetland.

The slope on the water surface may also have contributed to the deep channel incision seen in some reaches. Although quantitative data are not available, it is likely that the original diffuse flow through the wetland would have supported a relatively steeper water surface slope than is possible in an open channel. Thus, as more of the discharge diverted into a single channel, the channel would tend to become increasingly incised in order to reduce its water surface slope. The base level for the Klip River is set by the gauging weir at the lower end of the wetland, but numerous secondary base levels have fortunately been created by rock barriers that became exposed as the channel became increasing confined and incised. These have restricted incision to some extent, although it is still severe along many reaches (Fig. G). It is possible that lowering of the water table beneath the wetland has exacerbated incision. Although the current status of the water table is unknown, the spread of polluted water into the underlying aquifer suggests that lowering has taken place. Moreover, in the surveyed cross section (Fig. I), the water table has clearly dropped relative to its position when the wetland was still functional. However, it is difficult to establish whether lowering of the water table in this instance was a cause or a consequence of the incision.

Discharge in the wetland downstream of Olifantsvlei has become increasing canalized over the last 65 years, and currently it appears that almost the entire base flow is accommodated in a single channel. Extensive reed beds still flank the channel, but the reeds appear to be sustained either by occasional overbank flow during the summer rains, or by groundwater. Flow velocity in a functioning reed bed such as at Lenasia is in the region of 0.03 m/s and the contact area between aquatic vegetation and water is very large. Residence time of the water in the reed bed is relatively long and removal of pollutants is therefore effective. In contrast, flow velocity in the canalized section is in the region of 0.5 m/s, reducing residence time by a factor of about 20, and contact with the vegetation is now minimal. It is therefore likely that the reed bed downstream of Olifantsvlei has virtually ceased to sequester pollutants.

Canalization of the wetland seems to be confined to the reach downstream of Olifantsvlei, and the upstream reach is unaffected. This suggests that canalization has been induced by the increasing volume of water discharged from the sewage treatment plants located at Olifantsvlei. It seems that irrigation canals provided a more rapid route for the water and were widened and deepened, and ultimately began to link together to form what will in the near future become a single channel extending from Olifantsvlei to the end of the wetland. Lowering of the water table in the vicinity of the wetland by excessive pumping may have also contributed to incision.

Sewage water discharged at Olifantsvlei will no longer undergo bioremediation once canalization is complete. Eutrophication problems, similar to those occurring at Hartebeespoort Dam, are likely to develop in the lower Klip River and in the Vaal downstream of its junction with the Klip at Vereniging, and especially behind the Barrage.

Some indications of the long-term consequences for the wetland arising from canalization are provided by changes that have taken place at the downstream end since 1952. As the incision became deeper, inundation of the reed bed became less frequent and the peaty, rhizomatous layer dried out and burnt off, possibly in peat fires. The ash thus produced formed a soil that became vegetated by various pioneer species, but is very susceptible to erosion, and has become extensively gullied (Fig. 7). In the long term, therefore, it seems likely that this final destruction of the wetland will progress upstream as far as Olifantsvlei, and the wetland will be completely lost and replaced by a single channel, gravel-bed river, such as currently exists immediately downstream of the wetland, where the process is complete.

The destruction of the wetland in this way will release heavy metals and phosphates, currently bound in the peat, into the Vaal River. The total metal content in the peat is unknown, but a study is in progress to establish this. Significantly, pollution arising from acid mine drainage will continue to be trapped in the still-functioning upper reaches of the wetland. Here, too, the wetland has been severely compromised, in this case by peat mining, and its capacity to trap heavy metals, particularly arising via the Klipspruit, is substantially reduced. The areas affected by peat mining show no trend towards recovery.

Conclusions

The Klip River wetland south of Johannesburg has been an important asset to the city, initially as a source of water, and later as a purifier of polluted water, especially from mining sources and sewage treatment. In essence, the Klip River wetland protected the region's water supply. This wetland has, however, suffered severe adverse anthropogenic effects. Initially, these arose from intense cultivation in the Klip River valley, and sections of the wetland were drained and converted to farmland. A network of irrigation canals was created along the entire wetland. Apart from the loss of some sections of the wetland, these impacts were localized in extent, and compromised the wetland's beneficial functions. These canals became the Achilles heel of the wetland, however, as the volume of treated sewage water steadily increased. The canals increasingly became the preferential route for the discharge, and erosional widening and deepening has occurred on a large scale. Head cutting into the wetlands, initiated along diagonal drains, has proceeded apace, linking separate sections of ditches to the point where there is now a single channel extending almost the entire length of the wetland downstream of the Olifantsvlei sewage treatment works. This channel accommodates almost the entire base flow of the river, and the flanking wetlands appear to be dry for much of the year. The residence time of water in the wetland has been reduced from days to hours, and contact between water and aquatic vegetation is now minimal.

This degradation affects the lower reaches of the wetland, where sewage water would have experienced bioremediation. The pollution arising from acid mine drainage along the western Witwatersrand enters the wetland via tributaries upstream of Olifantsvlei, and this section of the wetland is still functional, except for a reach which has been severely impacted by peat mining. Polluted water emanating from mine sources that enters the wetland via the Klipspruit is likely to be only partially remediated, and it is probable that some of the residual unsequestered metals will enter the canalized section of the Klip River below Olifantsvlei. However, dilution of this water by treated sewage water should reduce the potential threat from this source.

In the longer term, it seems likely that the reed beds flanking the canalized Klip River will desiccate and burn off, and that the Klip downstream of Olifantsvlei will become a gravel-bed river. Heavy metals and phosphates trapped in the peat will be released into the Vaal River system, and nitrate- and phosphate-enriched water will flow directly into the lower Klip and Vaal rivers. It is likely that eutrophication problems, similar to those experienced at Hartebeespoort Dam, will begin to plague the lower Klip and especially the Vaal River between Vereniging and the Barrage in the near future, and more so during drought periods when dilution of Klip River water is reduced. The resulting increased pollution load in the Vaal River is likely to severely affect downstream users.

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This article is accompanied by supplementary material online at www.sajs.co.za.

Supplementary material to:

McCarthy T.S., Arnold V., Venter J. and Ellery W.N. (2007). The collapse of Johannesburg's Klip River wetland. *S. Afr. J. Sci.* **103**, 391–397

Fig. A. The wetland in the area between the Golden Highway (R553) and the N1 motorway in (**A**) 1938 and (**B**) 2003. See Fig. 2 for location.

Fig. B. Detail of the wetland at the N1 motorway crossing. See Fig. 2 for location.

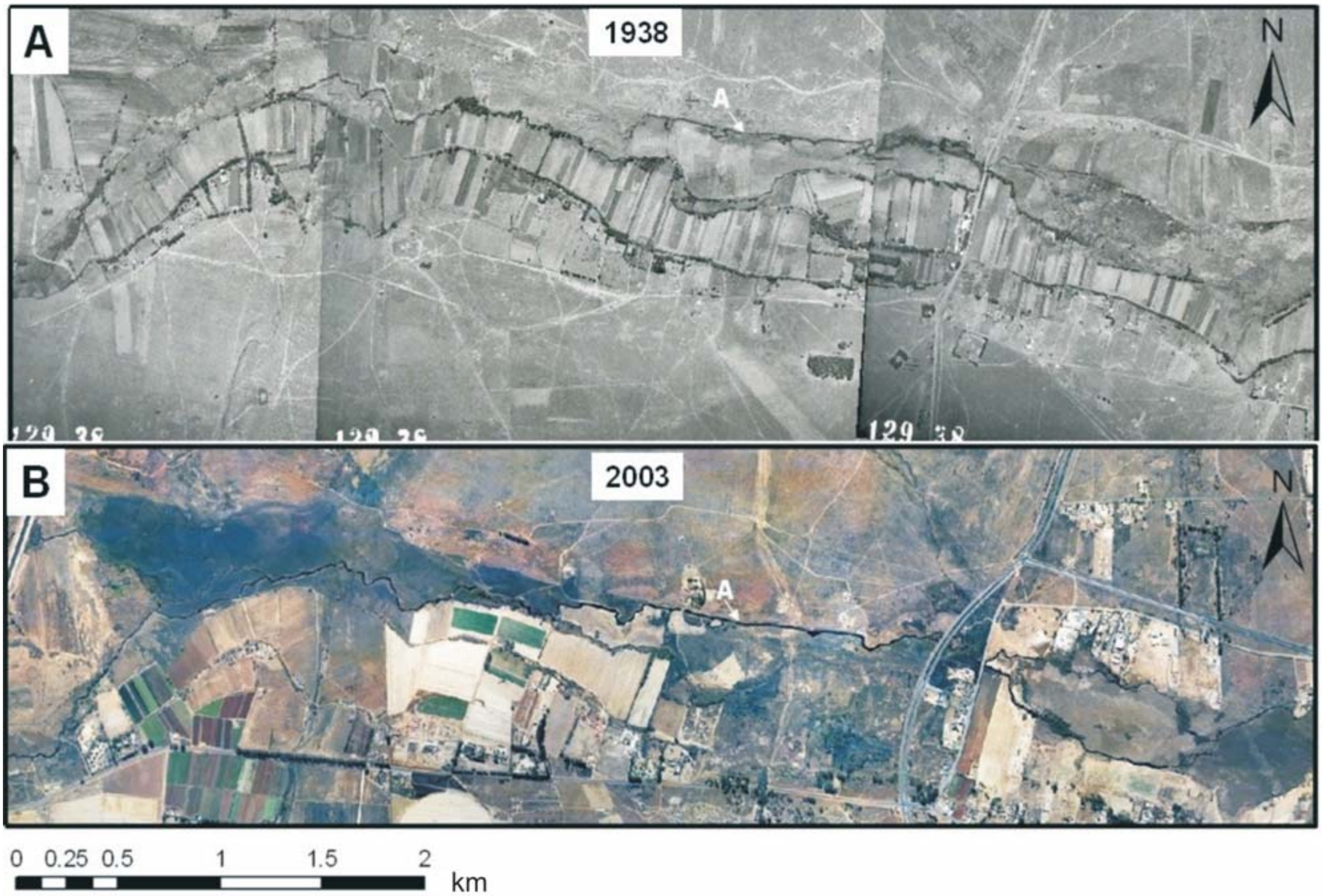

Fig. C. The wetland between the N1 and Kibler Park in (**A**) 1938 and (**B**) 2003. See Fig. 2 for location.

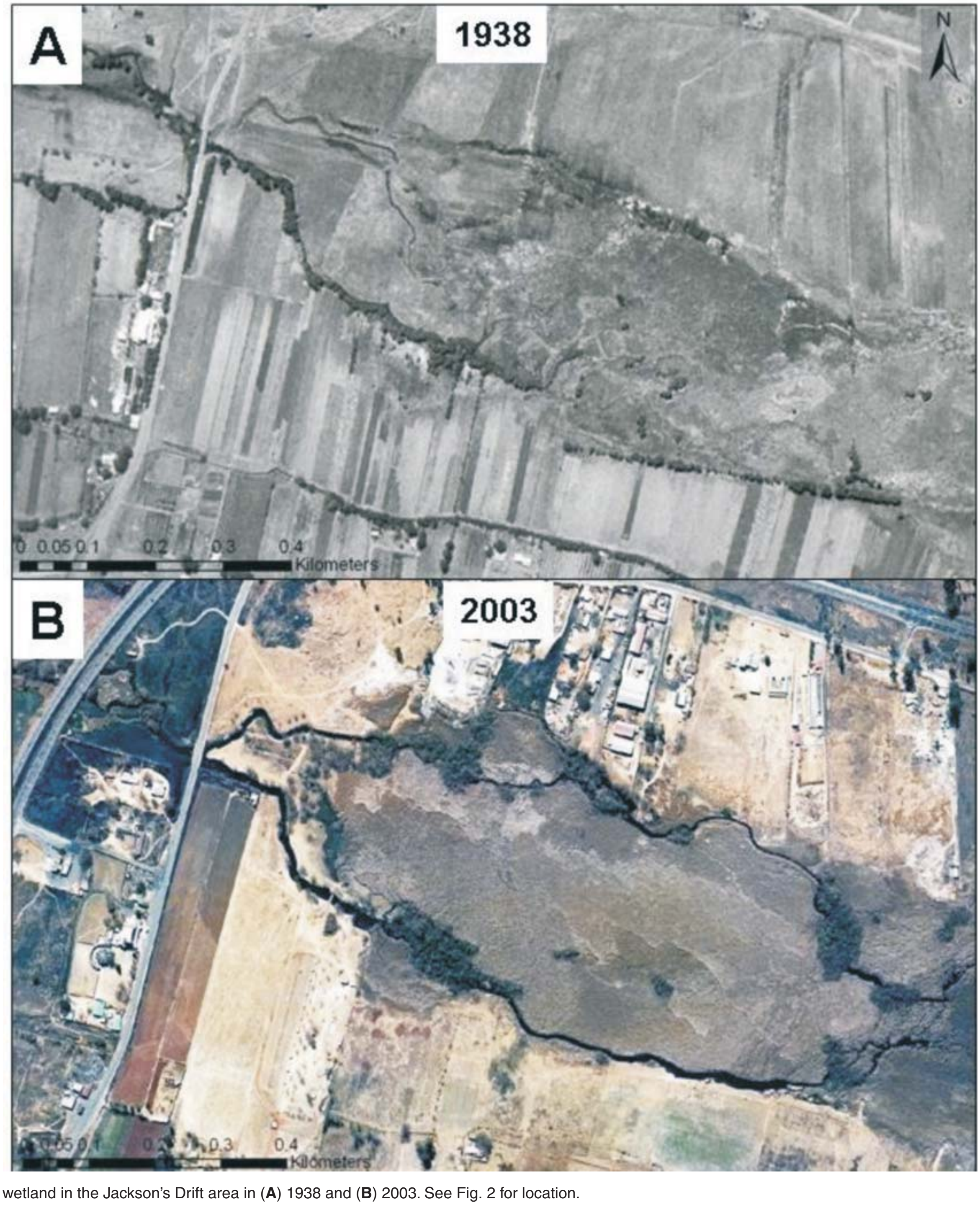

Fig. D. The wetland in the Jackson's Drift area in (**A**) 1938 and (**B**) 2003. See Fig. 2 for location.

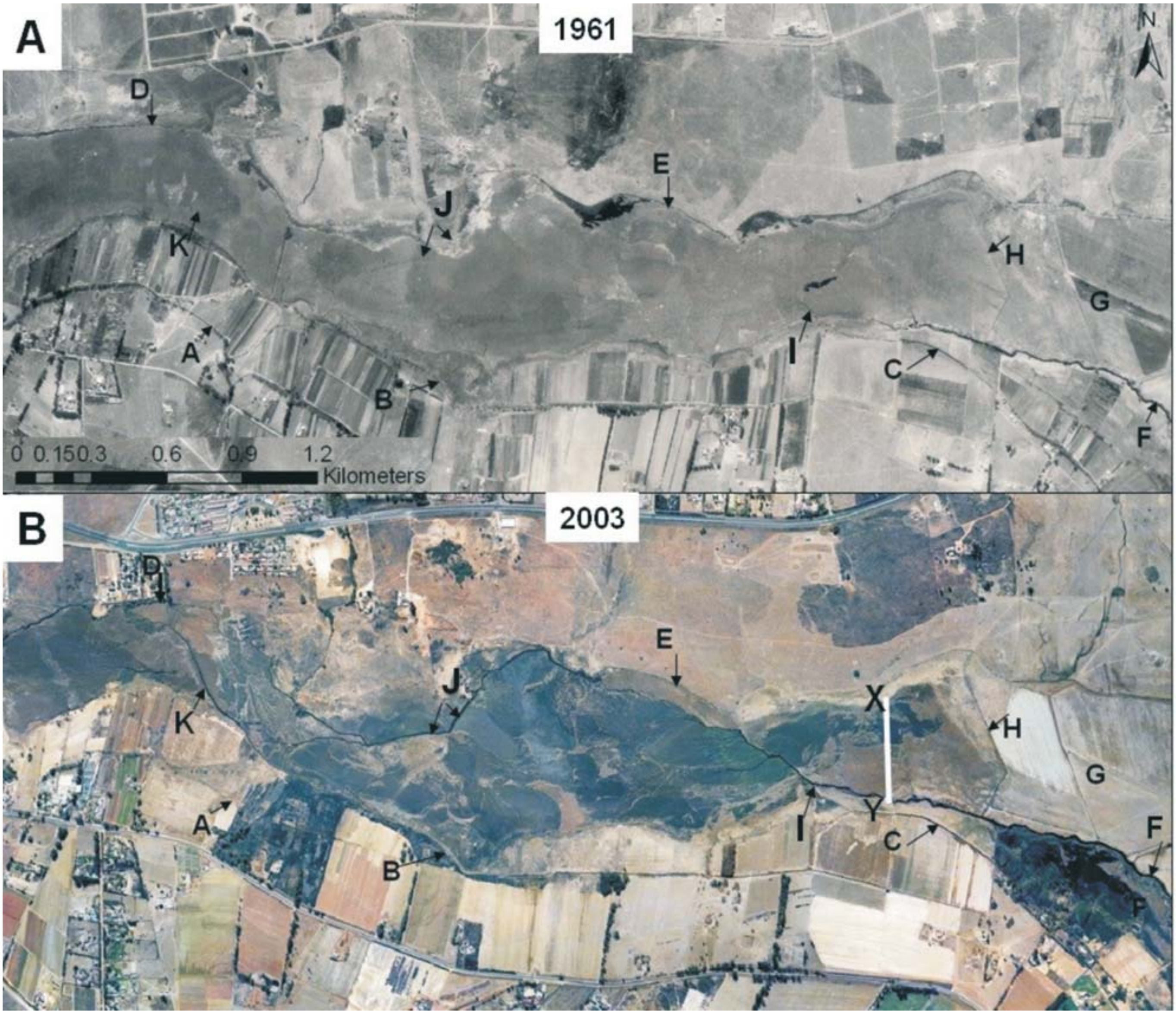

Fig. E. The wetland between Kibler Park and Kromvlei in (**A**) 1961 and (**B**) 2003. See Fig. 2 for location.

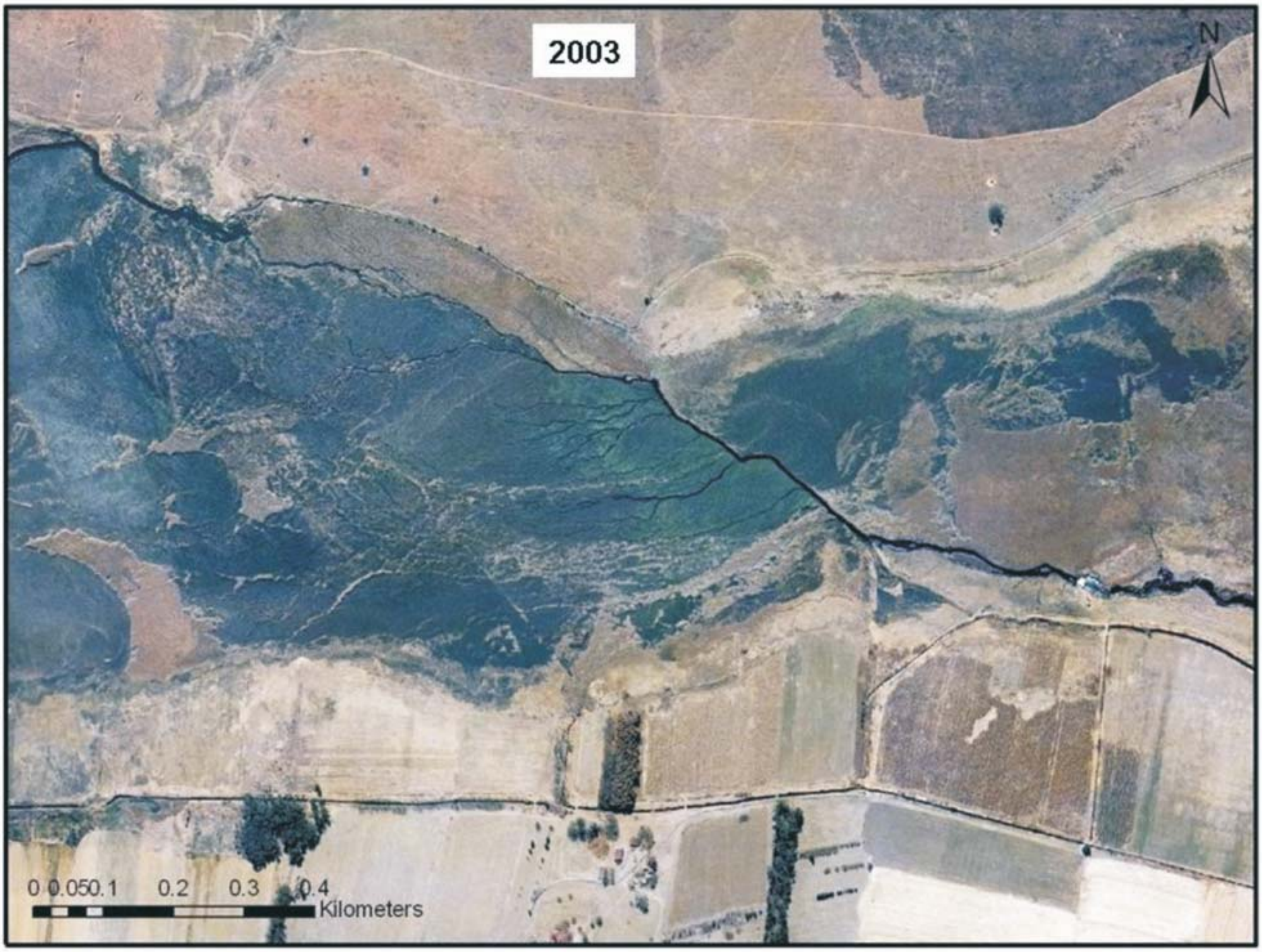

Fig. F. The wetland in the Kibler Park area in 2003. See Fig. 2 for location.

Fig. G. Aerial view of an incised channel on the south bank of the wetland. The direction of view is upstream and the field of view encompasses the channel on the extreme right of Fig. F. The building in the centre of the photograph is an abandoned pump house. The sump is located in the small structure to the right of the building. A nick point (waterfall) is visible in the channel a short distance upstream of the pump station.

Fig. H. A ground view of the nick point visible in Fig. G.

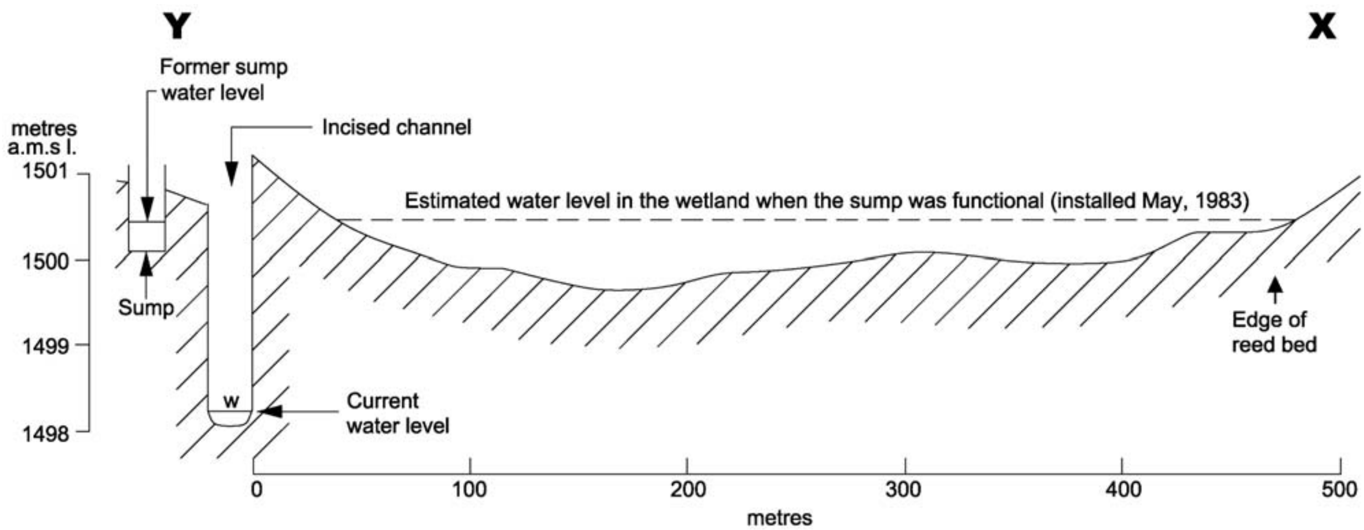

Fig. I. A topographic profile extending from the sump of the pump station in Fig. G to the northern margin of the wetland (line XY in Fig. E(B)).

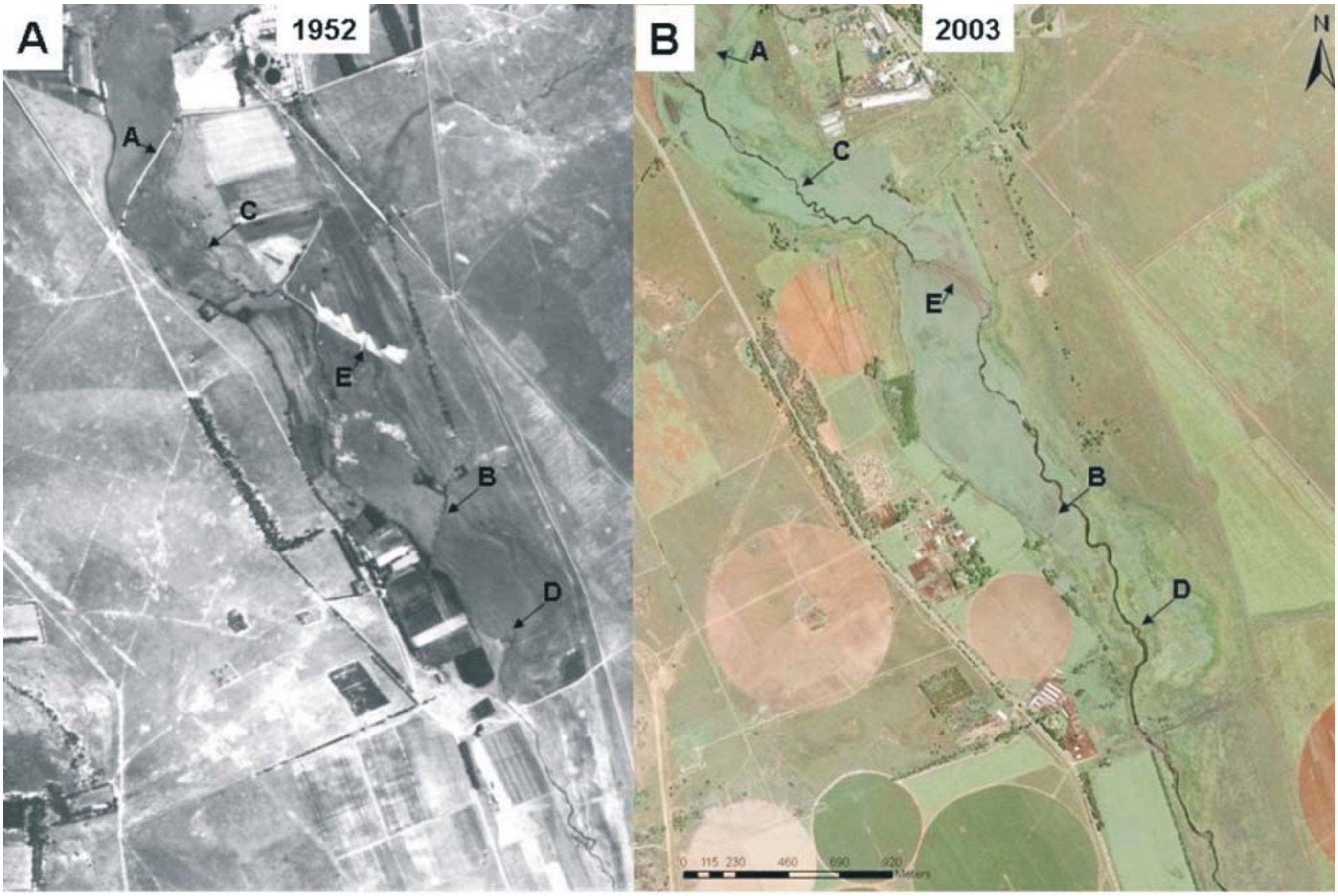

Fig. J. The wetland in the Zwartkoppies area in (**A**) 1952 and (**B**) 2003. See Fig. 2 for location.

Fig. K. Channel incision in the Zwartkoppies reach of the wetland has exposed a rock barrier, resulting in a waterfall.