Changing land use/land cover around an urban estuary: Implications for ecosystem functioning

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Abstract

The changing spatial and temporal patterns in land use/land cover surrounding Zandvlei estuary were investigated over the period 1944 to 2005. Changes in the extent of four terrestrial and two aquatic land use/land cover categories were mapped from high quality aerial photographs using Arcview GIS. Basic spatial analyses were performed to quantify changes in area, 'edge-effects' and relative dominance through time. Semi-natural and seasonally inundated classes accounted for over 70% of land cover in 1944, but declined steadily as urban land use and permanently inundated land cover expanded to a present day extent of 42% and 19% respectively. The following major drivers of change were identified: 1) the construction of the railway embankment bisecting Westlake wetland and Zandvlei estuary, which led to sedimentation and a change in plant species composition of the wetland, but decreased nutrient inflows into the vlei; 2) agricultural practices within the catchment at the start of the 20th century which increased sediment and nutrient inflows; 3) elevated water levels due to dredging operations between 1947 and 1961, which resulted in a significant loss of seasonally inundated land cover with concomitant changes in species composition and nutrient dynamics; and 4) urban development surrounding the vlei (with particular reference to Marina da Gama), which has expanded at the expense of semi-natural areas and significantly increased effluent and litter inputs into the vlei. A socially and ecologically balanced management policy governing the entire catchment is required to mitigate future impacts.

Introduction

Anthropogenically driven land use/land cover change continues to be the most serious threat facing the global biosphere (Meyer & Turner, 1992; Gustafson, 1998; Matsushita, 2005). Impacts are especially severe in and around urban centres, where natural landscapes have undergone profound and extensive modification to fulfill human needs (Forman & Godron, 1986; McDonnell & Pickett, 1990; Luck & Wu, 2002). Indeed, natural areas within the urban landscape are often completely obliterated in favour of alternative (and often more profitable) land use types, while those that remain are usually highly fragmented and ecologically compromised.

The situation is no different in southern African cities, where wide scale poverty and rapid urbanization as a result of the influx of rural people to urban centres compound the pressure placed on urban ecosystems. The Cape Flats, located north of False Bay in the Western Cape of South Africa, is a case in point. This area is comprised of sensitive estuarine, wetland and lowland fynbos elements, which are threatened by the continued expansion of large informal settlements (Rouget *et al*, 2003). Expansion has historically occurred without adequate provision for the conservation of rare and endemic species (e.g. Wood *et al*, 1994; Rouget *et al*, 2003). Significant challenges are faced in terms of infrastructural development which would mitigate some of the more obvious human impacts such as pit-latrines, indiscriminate rubbish dumping and firewood collection. Trends are hopefully changing with the establishment of environmental initiatives such as the Cape Town Urban Biosphere Group and community partnerships such as Cape Flats Nature (Jackson *et al*, 2005).

The fact remains that global and local trends of urbanization are unlikely to change, as burgeoning human populations both add to existing centres and create new ones. This highlights the need for urban conservation and a means to assess the ecological integrity of the natural systems that remain in urban areas. There has been a revival in urban ecological studies in recent times (Luck & Wu, 2002). From a previous view that urban systems were too degraded to warrant study and conservation, there is now a growing realization that we need to understand the ecological consequences of urbanization (McDonnell & Pickett, 1990; Luck & Wu, 2002) and develop ecological principles that apply to them (Forman & Godron, 1986). These principles can then be utilized to inform management decisions, educate the surrounding and affected communities, and mitigate anthropogenic impacts.

Landscape ecology has historically been a useful tool in linking environmental patterns with ecological processes (Turner, 1989). Large scale anthropogenic activities can fundamentally alter these patterns, disrupting ecological processes (e.g. animal and plant dispersal, energy flows, nutrient cycling) and threatening ecosystem health (Gardner *et al*, 1993). A number of quantitative methods have thus been developed to describe spatial patterning and heterogeneity in natural landscapes (Forman & Godron, 1986; McGarigal & Marks, 1995; Gustafson, 1998). These range from basic area, density and edge metrics to more complex measures of connectivity, isolation and contagion (McGarigal & Marks, 1995).

Gustafson (1998) has pointed out that indices describing spatial patterns are of little value in themselves and ultimately need to be linked to ecological processes to be useful. However, it is important to note that mapping and quantification of spatial patterns in a landscape is necessary before any relationships with ecosystem functions or processes can be elucidated or management decisions made (Turner, 1989; McGarigal & Marks, 1995; Matsushita, 2005).

In the past, studies in landscape ecology have been constrained by the difficulty of representing spatial and temporal patterns across broad spatial scales. Advances in computer technology and the development of Geographical Information Systems (GIS) software over the last two decades has been of tremendous benefit to the discipline (Forman & Godron, 1986; Johnson, 1990; Johnston, 1998; Matsushita, 2005). Nowadays sophisticated and user friendly GIS software, coupled with long term datasets and high resolution aerial and satellite photography, provide a powerful analytical tool to answer questions about heterogeneity in ecosystems at different spatial and temporal scales (Johnson, 1990; Johnston, 1998). Landscape ecology and GIS techniques have been used to quantify spatial patterns for rural areas (e.g. Zaizhi, 2000), rural-urban gradients (e.g. Luck & Wu, 2002), and natural areas within the urban environment (e.g. Foresman *et al*, 1997; Antrop, 2000).

This study draws on basic pattern quantification methods developed in landscape ecology and advanced GIS spatial mapping techniques to document spatial and temporal changes in a southern African estuarine and wetland ecosystem. The work is important and relevant for several reasons, notwithstanding its vulnerability due to being located within an urban environment.

Estuarine and wetland ecosystems are highly productive and generally occur in small discrete patches, which lead to rich, specialized biotas (Davies & Day, 1998; Gibbs, 2000; Turpie *et al*, 2002). Wetlands are especially important for the ecosystem services they provide to humans in terms of hydrological control and water purification (Davies & Day, 1998). However, the same factors that cause them to be so biodiverse also make them vulnerable to exploitation, degradation and species loss (Gibbs, 2000; Turpie *et al*, 2002). This is particularly true in the case of estuaries, which have historically been important nodes of urban development (Allanson & Baird, 1999) and more recently, the location many marina and resort developments (Turpie *et al*, 2002).

A brief history of Zandvlei

The first account of human presence in the vicinity of Zandvlei is from 1673, when the edge of the vlei started being used as a cattle outpost (Morant & Grindley, 1982; Azorin, 1988; Thornton *et al*, 1995). The Dutch East India Company established a fortified post west of the vlei in 1744 (Morant & Grindley, 1982), during which time human activities had changed from cattle rearing to market gardening (Thornton et al, 1995). The next significant mention of the vlei was in 1866, when lower water levels from a preceding drought prompted the idea to reclaim the vlei for additional agricultural land (Morant &

Grindley, 1982; Thornton *et al*, 1995). The mouth of the vlei was closed, but the project failed, as no contingency plan had been made to divert water entering the vlei via its rivers after winter rainfall (Morant & Grindley, 1982; Azorin, 1988; Thornton *et al*, 1995).

A radical alteration came in 1882, when the railway line was extended to Muizenberg, all but severing the link between the wetland to the north west and the estuary to the south. This heralded the start of more than a century of recreational use and catalysed further changes to the vlei. Dredging operations proceeded in 1947, after proposals that the vlei be used as a permanent venue for rowing and sailing (Morant & Grindley, 1982). A total of 760 000 m^3 of spoil had been removed by 1961, creating 60 ha of open water and destroying an estimated 32 ha of wetland (Morant & Grindley, 1982). At some stage between 1947 and 1961 a rubble weir was installed at the mouth of the vlei to maintain a constant water level of 0.7-0.9 above m.s.l. This was necessary to ensure that artificially stabilized banks did not collapse (Morant & Grindley, 1982).

By the early 1960's the agricultural industries surrounding the vlei had given way to burgeoning residential areas (Thornton *et al*, 1995). Between 1969 and 1973 the profile of the vlei again changed drastically when the waterside housing project of Marina da Gama was developed (Morant & Grindley, 1982; Thornton *et al*, 1995). This entailed the digging of a series of canals which, when connected to the main vlei basin, increased the surface area of water by 32,6 ha (Morant & Grindley, 1982).

Today the vlei serves as a popular recreational facility for all forms of non-motorised watersport, while the grass banks are frequented by between 2000 and 3000 people per day in peak summer season (Thornton *et al*, 1995).

It is with the preceding history of transformation in mind that the current study aims to:

a) quantify the major spatial and temporal changes in land use/land cover and link them with historical records, and

b) explore the implications of specific changes on the functioning of the terrestrial and aquatic ecosystem.

Methods

Study area

Zandvlei (34°05’S; 18°28’E), the central and dominant feature of the study area, is located on the far north-western shore of False Bay, on the Cape Peninsula. The full extent of the study area is bounded by Prince George Drive to the east, Military Road to the north, Main Road to the west and a diagonal line linking Main Road and Prince George Drive to the south (see Fig. 1). This line follows the approximate high tide mark and is approximately 237 m south of the old road bridge on Royal Road, which runs over the mouth of the estuary. The total area of the study site is approximately 570 ha.

The study area incorporates a number of landscape components peripheral to Zandvlei. Westlake wetland adjoins Zandvlei to the north west and connects to the estuary via a culvert in the earth embankment on which the railway line runs. Zandvlei Nature Reserve is situated immediately north of the vlei. Norfolk Park occupies the north-western corner of the study area, while Steenberg, the only residential area in the low to middle income bracket in the study site, occupies the north and north east corner. Marina da Gama residential development extends along the eastern edge of the vlei. Park Island lies west of the marina, separating it from the main body of the vlei. The mixed residential and commercial centre of Muizenberg lies to the south, while Lakeside residential area forms the western edge of the study area. Parklands and fields act as a buffer between Lakeside and the vlei.

Three watercourses enter at the northern edge of Westlake wetland and Zandvlei. Westlake River enters Westlake wetland from the north east and flows, via a man-made channel, to the south eastern edge of the wetland. Here it meets the Keysers River, flowing from the north. Both watercourses enter the north western end of Zandvlei via the culvert in the railway embankment. The Sand River, which is canalized within the boundaries of the study area, meets Langvlei Canal approximately 850 m before entering Zandvlei at its north east extremity.

The study area is subject to a Mediterranean climatic regime, characterized by winter rainfall and hot, dry summers. Mean annual precipitation in the area varies between 400 and 600 mm, but can be much higher due to orographic rainfall associated with the vlei's proximity to Muizenberg mountain (Thornton *et al*, 1995). The study area is exposed to south easterly winds in summer and north westerly, rain bearing winds in winter. The approximate north south axis of wind facilitates the mixing of vlei water.

<u>Land use/land cover classification</u>

Land use/land cover was placed in a simple two tiered hierarchy based on visual interpretation from aerial photographs digitally scanned at high resolution. Initially the total extent of the study area was defined as either terrestrial or aquatic. Area classed as terrestrial was then further classified into 4 different categories, namely urban, landscaped, agricultural and semi-natural. Area classed as aquatic was subdivided into seasonally inundated, and permanently inundated.

Urban denotes both isolated and grouped residential, commercial and industrial buildings and the road networks in which they occur. Landscaped is a fairly broad classification, referring to areas functioning as parkland, fields, recreational areas, open space, and areas within urban matrices which aren't built upon (e.g. vacant plots). Essentially, landscaped areas differ from semi-natural areas by either being so modified as to appear un-natural (e.g. parks and fields) or show some recent sign of anthropogenic disturbance.

Agricultural areas pertain to fields showing recent or current signs of cultivation, as well as associated homesteads and out-buildings.

Semi-natural areas are those terrestrial plant communities which *appear* undisturbed or have been undisturbed for a period of time long enough for vegetation to recover to a state similar to pre-disturbance. Indigenous species occurring in notable densities include *Metalasia muricata*, *Carpobrotus acinaciformis*, *Rhus* spp and *Tetragonia* spp (Morant & Grindley, 1982).

Newly created terrestrial areas (e.g. Park Island) are assessed in terms of how long they have remained undisturbed and how quickly cover has returned. It is noted that a patch which appears to be semi-natural may in fact contain alien vegetation. However, given the resolution of past aerial photographs; the fact that most are black and white; and the lack of differential growth form in alien versus indigenous vegetation, this distinction could not be made, and this needs to be taken into account when interpreting the results.

The seasonally inundated classification refers both to areas which are inundated for most of the year and to areas which often dry out during summer, leaving more saline conditions. An important aspect to the classification is the presence of specialist plant forms which can either tolerate almost permanent inundation or saline conditions or both. Vegetated areas which remain inundated for most of the year are typified by the presence of reed species such as *Phragmites australis*, bulrushes such as *Typha*, and sedges such as *Scirpus* and are defined by Azorin (1988) as the swamp communities sub-group. Areas which dry out more frequently and are associated with more saline conditions are referred to by Azorin (1988) as the flood plain-marsh vegetation communities sub-group. The main species in this grouping are *Paspalum*, *Juncus*, *Scirpus maritimus*, *Sporobolus* and *Arthrocnemum*. It is important to bear in mind that aerial photography presents only a snapshot in time, therefore seasonally inundated areas may expand or contract depending on the season.

Permanently inundated areas include the main body of the vlei, watercourses entering the vlei, the waters of the marina, and any other standing water devoid of emergent plant species.

Image processing

A historical series of black and white/colour aerial photographs of Zandvlei and the surrounding study area dating back to 1944 was obtained as contact prints from The Chief Directorate of Surveys and Mapping, Mowbray. A 2005 colour, digital, ortho-rectified and geo-referenced image of the study site was obtained from AOC Geomatics, Westlake. In preparation for warping, contact prints were scanned to digital format at high resolution (1200dpi), then cropped to the extent of the study area and resized to an average of 20 Mb each, while maintaining a fixed aspect ratio.

Table 1. Attributes of maps used for further warping and theme generation. Stitching refers to the merging of two overlapping maps. The 2005 image is obtainable from AOC Geomatics, Westlake.

Year	Job No._Strip No._Image No.	Scale	Stitched	Colour/B&W
1944	61_006_00105; 61_006_00106	1:10 000	Yes	B&W
1958	335_009_06125	1:30 000	No	B&W
1968	620_013_00576; 620_014_00594	1:10 000	Yes	B&W
1983	498_188_007_00624	1:30 000	No	B&W
1992	498_305_007_01635	1:30 000	No	B&W
2001	498_388_09_0471; 498_388_10_0511	1:30 000	Yes	Colour
2005	CMC_2005	1:30 000	No	Colour

ImageWarp ver. 2.0 (McVay, no date), an extension designed for use in Arcview GIS 3.2 (Environmental Systems Research Institute, 1992), was used to warp the unrectified digitized images to the ortho-rectified 2005, using a second order fit. Some of the digitized images did not cover the total extent of the study area, requiring that they be stitched to an adjacent aerial photograph. This process was performed using Adobe Photoshop CS (Adobe Systems Incorporated, 1990).

The specified land use/land cover classes were then mapped using Arcview GIS 3.2 (Environmental Systems Research Institute, 1992) software by tracing polygons around all the features of a certain class. The grain at which the mapping was done was governed by the smallest scale (i.e. resolution) in the aerial photography. The minimum patch size was set at $50m^2$.

Mapped land use/land cover classes were then transferred via 1^{st} order warping (i.e. simply spatial shift with no contortion or change in scale), using ShapeWarp ver. 2.1 (McVay, 1998) to a 2005 ortho-rectified and geo-referenced map, identical to the 2005 ortho-rectified map.

<u>Analyses</u>

Compositional analyses were performed on the data generated from land use/land cover classes using Microsoft Excel. These include relative changes in area and perimeter of classes with time, as well as simple perimeter/area 'edge effects' analysis. 'Edge effects' analysis was carried out by using the following formula (Forman & Godron, 1986; Cook, 2002):

$$D_i = \frac{P}{2\sqrt{A\pi}}$$

where D_i = is considered to be the ratio of the specified shape length P to the circumference of a circle which would have the same area as the area of the shape, A.

Simpson's Evenness Index (SIEI) was used to assess whether patches types were evenly distributed within the landscape or whether there was dominance by one or more patch types. A value of 0 indicates a landscape with only one patch type and no diversity, while a value of 1 suggests distribution of area among patch types is perfectly even. The formula is as follows (McGarigal & Marks, 1995):

$$SIEI = \frac{1-\sum_{i=1}^{m} P_i^2}{1-\left(\frac{1}{m}\right)}$$

where P_i is equal to the proportion of landscape occupied by patch type i, and m is equal to the number of patch types present in the landscape, excluding the landscape border.

Results

The temporal changes in composition and spatial configuration of the Zandvlei environment from 1944 to 2005 are show from Figures *2a* to *g*.

<u>1944</u>

In 1944 the dominant land cover was semi-natural vegetation, accounting for 38.1% of the total surface area and covering almost the entire eastern side of the vlei, as well as a large proportion of the north and west (Fig. *2a* & *3a*). At that time the total area of seasonally inundated vegetation was extensive (22.7% of the total area) (Fig. *3b*), bordering the entire circumference of the main body of the vlei and acting as a buffer between permanently inundated areas and other patch types. The buffering distance was as much as 435 m on the eastern side of the vlei and consistently between 150 m and 200 m on the western side. Several seasonally inundated islands existed, of which some were natural and some of anthropogenic origin (Fig. *2a*).

In 1944 water levels were extremely low, resulting in permanently inundated land cover registering its lowest surface area for the entire time series: 60 ha. Also, the incised channel linking Westlake River with the Keysers River was not apparent, though the latter must still have joined the Keysers and flowed through the culvert to join Zandvlei proper. The upper reaches of both the Sand and the Langvlei rivers were not canalized at this stage and follow a meandering path mainly through agricultural land, before meeting at their present day confluence. About 450 m further south the combined waters of these rivers make a 90° turn to the west and enter Zandvlei at its northern extremity.

An additional stream (or possibly dredging channel), not mentioned in any previous literature, entered the vlei from the east and was distinct for its journey through seasonally inundated land cover, but not before that. Two large, isolated bodies of water, between one and two hectares each, were found on the south western side of the vlei. The more southerly water body drained, via a narrow stream, into the southern section of a 1.4 km long linear dredged drainage channel, which ran from the main vlei to within 400m of the coast.

At this stage urban and landscaped area accounted for just 15.5% of the total area (10% and 5.5% respectively). The urban component was almost exclusively comprised of the settlement at Muizenberg in the south west, while landscaped areas were concentrated around the agricultural activities at the north of the study area.

Agriculture was at its maximum area in 1944, constituting 11.3% of the total area. It was concentrated mainly in the north, where it occupied 53 ha and bordered the watercourses and seasonally inundated land cover component. A large tract of land measuring almost 8 ha on the western side of Westlake was also dedicated to agriculture.

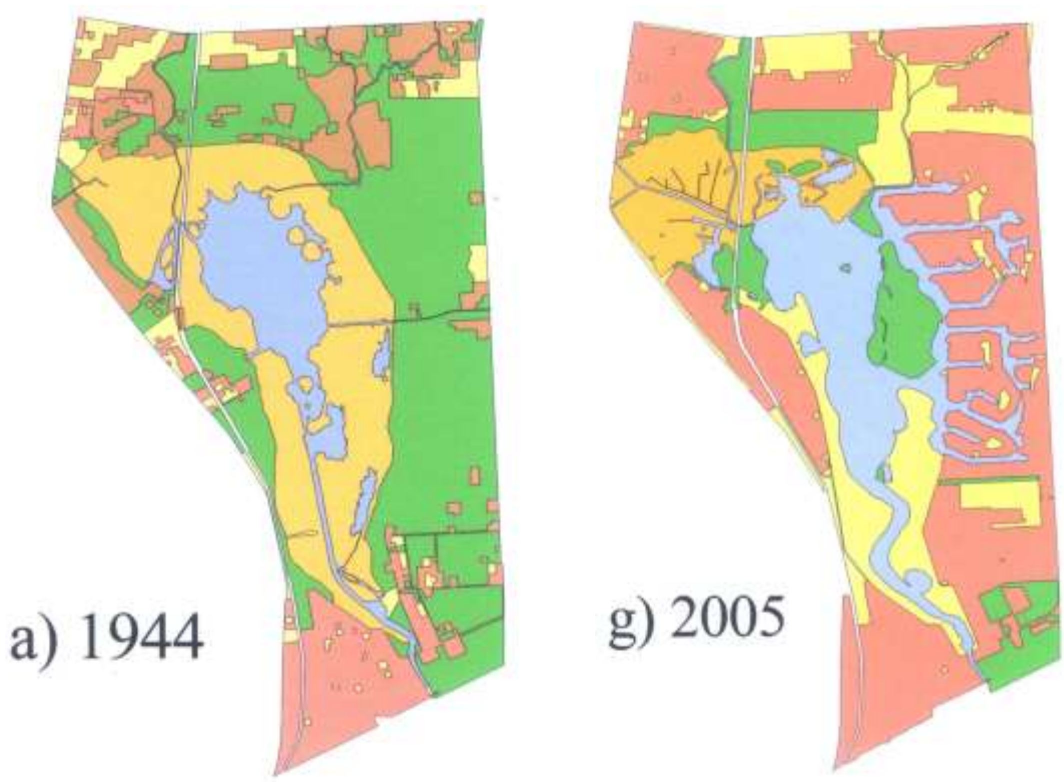

Figure 1. Changes in land cover classes of Zandvlei estuary as derived from aerial photography between 1944 and 2005. Pink = urban, light yellow = landscaped, green = semi-natural, blue = permanently inundated, orange = seasonally inundated, brown (1944 only) = agricultural land.

<u>1958</u>

Semi-natural and permanently inundated land use/land cover types remained relatively constant for the period 1944 to 1968. The semi-natural landscape component remained dominant in the east and north of the study area, ceding slightly to urban and landscaped in the west. The proportion that the urban component contributed to total area increased by 3.7% from 1944 to 1958 (Fig. *2b* & *3a*). This increase was due to an expansion in the settlement adjacent to Muizenberg in the south east increasing from 11 ha to 17 ha, while the area north of the vlei increased from 4 ha to 15 ha.

While the gross area of permanently inundated land cover increased by only 1.7% from 1944 to 1968 (Fig. *3b*), the change in shape was significant. A small area of land on the western side of the Zandvlei was dredged to form an inlet for the Imperial Yacht Club, while on the eastern side a series of kidney shaped inlets were created; one directly opposite the yacht club, a second 300 m south, and a third 650 m from the mouth. A sand embankment was constructed in an east-west orientation across the middle of the vlei, as well as along the north eastern shore. The channel leading from the main vlei basin was altered to form a widened 'S' shaped passage to the mouth, which is how it has remained to the present day.

By 1958 the channel connecting Westlake River and the Keysers River was visible and, besides this change, the general shape of Westlake wetland did not change a great deal until 1983. The Sand and Langvlei rivers now appeared to be canalized, but still entered the vlei at its far northern end. The river/dredging channel entering the vlei basin from the east now had a channel extending south, forming the eastern edge of an island create by dredging activities.

The largest reduction in seasonally inundated land use/land cover for the entire time series occurred between 1944 and 1958 when the entire western portion was lost. Much of the eastern side also disappeared, resulting in a total loss of 45 % when compared to the area it covered in 1944. Conversely landscaped area had nearly doubled since 1944, replacing large tract of seasonally inundated surface area on the western and eastern shores of Zandvlei. The western shoreline of the vlei basin retained its general shape until present day.

In 1958, agricultural land use had declined to 6.8% of the total study area; the largest concentration being found flanking the Sand River Canal and Langvlei Canal. This downward trend continued through to 1983 when the last patch of agricultural land, measuring 7 ha, was all that remained on the western border of the combined Sand River/Langvlei Canal

<u>1968</u>

Urban and permanently inundated land use/land cover remained relatively unchanged for the period 1958 to 1968 (Fig. *3a* & *3b*). The shores of the main vlei basin appeared smoother and the northern section had a more rounded profile, as well as the addition of two new islands, created in the period prior to 1968 (Fig. *2c*). A number of new channels were present in the seasonally inundated area north of the vlei basin and the entry of the Sand River/Langvlei Canal had been rerouted to enter Zandvlei about 160 m to the south east.

The semi-natural component achieved its highest representation in 1968, comprising 38.7% of the total surface area. It replaced seasonally inundated land cover as the north western border of the vlei, as well as some landscaped terrain on the vlei's north eastern border.

In 1968 the most dramatic change was, once more, the reduction in seasonally inundated land use/land cover, which fell to its lowest value (7.5% of the total area) for the complete time series. This landscape component completely disappeared along the north eastern shore of Zandvlei and was restricted to Westlake wetland and the area directly north of the main vlei basin for the remainder of the time series.

In 1968 landscaped land use/land cover expanded to 19.3% of the total study area, replacing a seasonally inundated and semi-natural area in the east and south east.

<u>1983</u>

The shape of the vlei had again changed significantly by 1983 (Fig. *2d*). Previously semi-natural land on the eastern shore of the vlei had been dredged into a 6.7 km long series of key-shaped channels forming the waterside housing development of Marina da Gama. This change effectively increased the permanently inundated surface area recorded in 1968 by 50%, and 18.4% of the total area in 1983 (Fig *3b*) - the approximate proportion it would maintain to the present day. Further changes to permanently inundated land use/land cover included the incision of several narrow channels in Westlake wetland and an increase in the permanently inundated component of what is nowadays the Zandvlei Nature Reserve (previously the Bird Sanctuary). Of the two islands which were present in 1968, only the eastern one was retained in the 1983 landscape.

The increase in area of the seasonally inundated landscape component by its extension to the western boundary on Main Road was mostly offset by the new channels in Westlake wetland and increased area of permanently inundated elements in Zandvlei Nature Reserve.

Between 1968 and 1983 landscaped area replaced almost all of semi-natural land use/land cover on the eastern side of Zandvlei, resulting in decrease of 50% in the latter and a concomitant increase of 50% in the former (Fig. *3a*). However, a large semi-natural area measuring 63 ha still remained in the far north of the study area as well as a medium sized patch south of Westlake wetland and a third patch in the extreme south eastern corner. A significant addition to the semi-natural landscape class was the creation of Park Island (16 ha), which is located due west of Marina da Gama.

In 1983 urban land use increased by approximately 36% compared to surface area in 1968. Urban land now accounted for 21.1% of the total study area. This increase in area was apportioned chiefly along Main Road on the western side of Zandvlei, while the residential development on the eastern side of Muizenberg became more consolidated. In addition, urban development on Eastlake Island (part of Marina da Gama) replaced some landscaped surface area.

<u>1992</u>

The proportion of urban land grew most between 1983 and 1992, when it expanded by 75% to occupy 36.9% of the study area (Fig. *2e* & *3a*). Extensive urban development of the marina replaced much of the landscaped area in the east, which was reflected in a 22% reduction of landscaped area since 1983.

Urban land use also grew in the north in the form of low cost housing which, in combination with some landscaped areas, replaced a large proportion of semi-natural land cover. Semi-natural area thus continued its downward trend to 11.4% of the total area; a reduction of 41% in its 1983 size.

The agricultural land use disappeared between 1983 and 1992. Seasonally inundated and permanently inundated land use/land cover classes remained constant in the preceding nine years and were only fractionally different at the end of the time series (Fig. *3b*).

<u>2001</u>

Semi-natural landscape component increased only fractionally from 1992 to 2001 and decreased by a similar fraction between 2001 and 2005 (Fig. *3a*).

The notable change in 2001 came in the form of the urban component increasing to cover 41.6% of the total study area; the largest proportion yet held by any single land use/land cover class (Fig *2f*). The increase came at the expense of the landscaped category, which decreased to 17.8% of the total area.

2005

The landscape in 2005 was essentially the same as in 2001 (Fig *2g*). Only minor changes in area were recorded. There was a slight decrease in the area of the landscape class and an increase in urban area, as isolated pockets of landscaped terrain within urban matrices were built upon. In the preceding four years permanently inundated area increased by 5 ha to 18.5% as a result of a slight expansion within the Westlake wetlands.

Change in land use/land cover classes: 1944 - 2005

Figures *3* summarises the trends in landscape classes between 1944 and 2005.

Semi-natural and seasonally inundated landscape components were dominant in 1944, while urban, agricultural, permanently inundated and landscaped classes made relatively minor contributions to the total area (507.1 ha) (Fig. *3a* & *3b*). Seasonally inundated area declined immediately and then stabilized after 1968, semi-natural experienced a lag time before declining after 1968, only leveling off again after 1992. Throughout the time series urban land use/land cover increased; at first gradually and then at an increasing rate, until showing some sign of plateauing after 2001. Starting from the lowest base level in 1944, landscaped area showed the fastest rate of expansion initially, reaching a peak in 1983 and gradually declined since then.

Permanently inundated land use/land cover increased from 1944 to 1983 and has since leveled off. Land devoted to agricultural activities declined steadily and linearly from an initial area of 64.4 ha until it had disappeared from the post-1983 landscape.

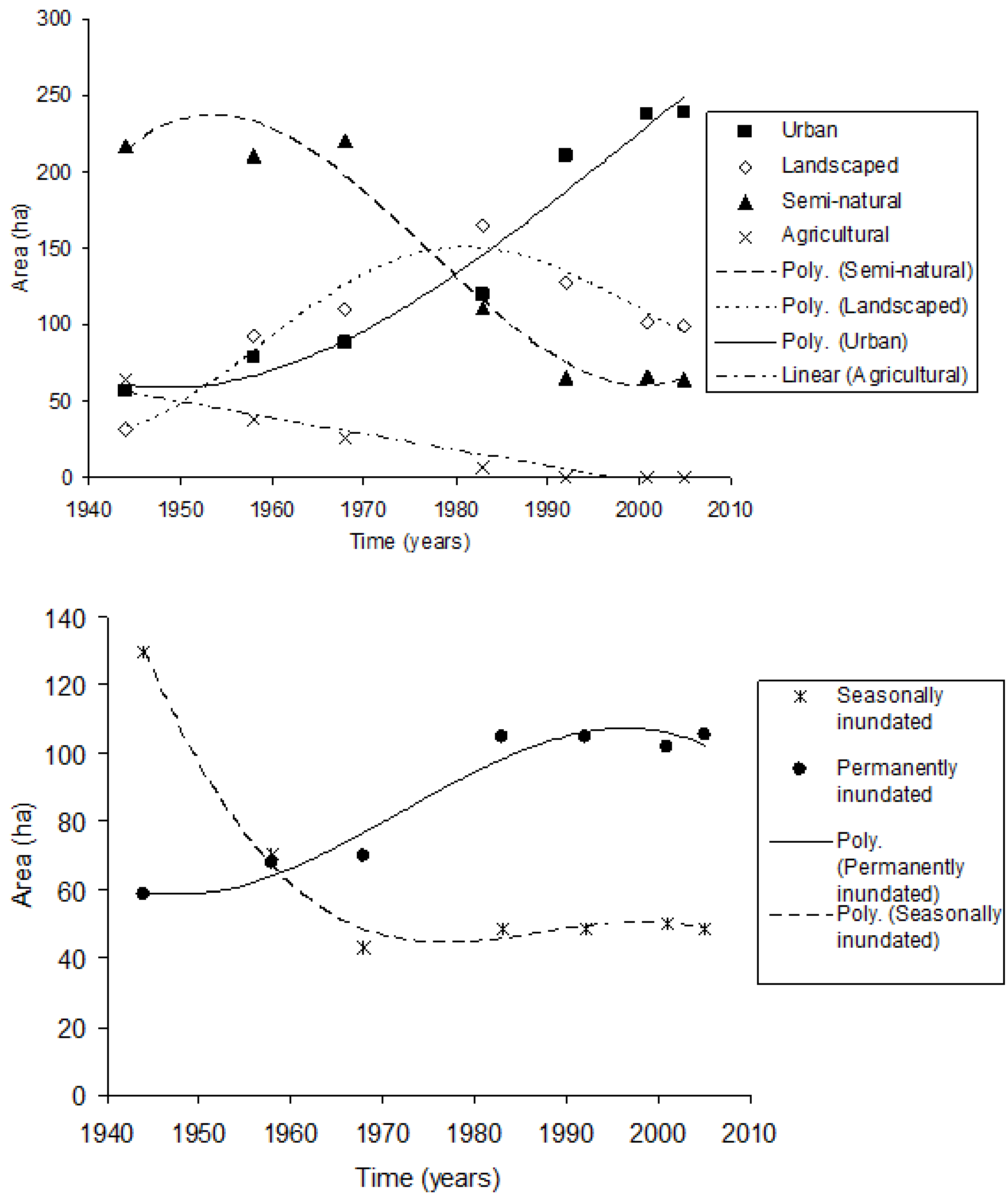

Fig. 3. Change in terrestrial (top) and aquatic (bottom) land use/land cover area with time (total area: 570 ha). Trend lines are used to describe trends and not as predictive tools.

Image analysis

The 'edge effects' index in Figure 4 illustrated that both semi-natural and seasonally inundated landscape components had highly complex shapes indicated by *D* values of between 2.5 and 5. Initially the perimeter/area ratio for seasonally inundated land cover followed a lower trajectory than that of the semi-natural class. However, the seasonally inundated class showed a rapid increase after 1968 to achieve the highest *D* value in 1983 (4.91), indicating that average shape perimeter was longest in relation to area for *any* of the classes in this year. The perimeter/area ratio for semi-natural land cover showed an initial gradual decrease from 3.28 to 2.86 – the lowest *D* value of the time series for any landscape element - and then a gradual increase until the present day.

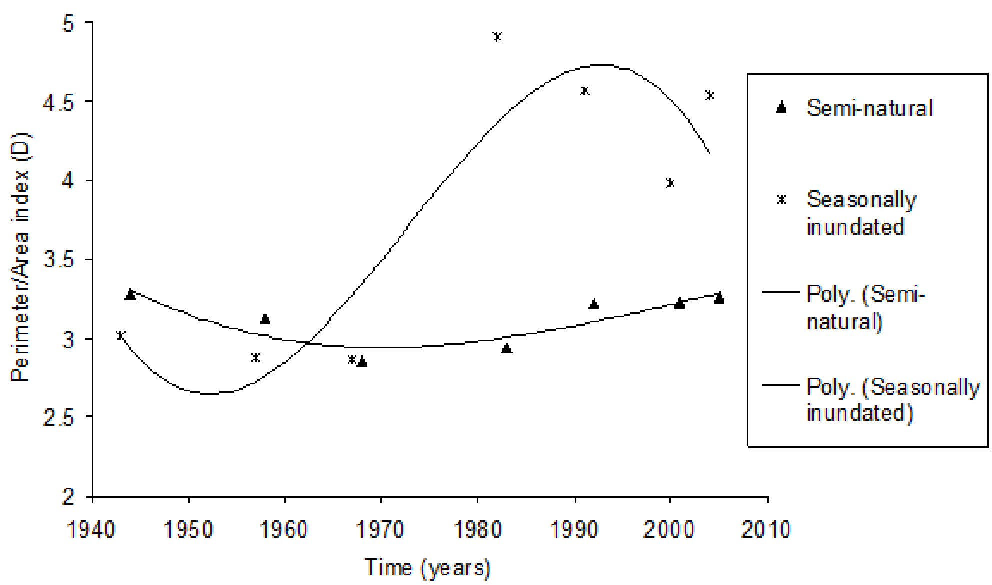

Figure 4. Relative 'edge effects' index illustrating the relationship between perimeter and area for the mean patch size in two land use/land cover components over time. The smallest possible perimeter for a given size would yield a value of 1 (i.e. a perfectly circular shape). The larger the value, the greater the perimeter-to-area ratio (i.e. the more convoluted the shape). Trend lines are used to describe trends and not as predictive tools.

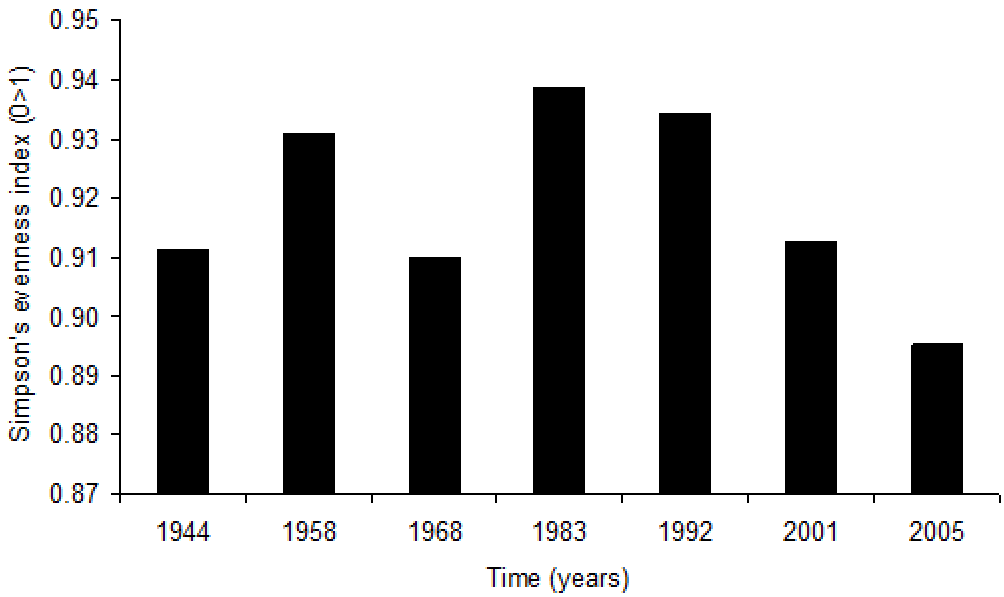

Figure 5. Simpson's Evenness Index illustrating the relative evenness of landscape elements over time. *0* indicates no diversity and complete dominance by one patch type; *1* indicates a perfectly even distribution among patch types.

In terms of the classification method used, the study area has a low degree of richness. Initially there are six land use/land cover classes, but this falls to five with the disappearance of agriculture in the post 1983 landscape. The number of patches per class is consistently highest for the landscaped component. If one excludes 1944, the number of landscaped patches tallied to more than double the next most abundant patch type in every year, reaching a maximum of 84 patches in 1968. The most unified theme (i.e. fewest patches) was permanently inundated, which had a maximum of three parts prior to 1983, when isolated water bodies in Westlake wetlands, Zandvlei Nature Reserve and Park Island increased its number to sixteen.

Mean patch size was investigated but was found to be a poor measure of the observed average size. This was due a large range in patch sizes and the presence of outlier in certain years. Nevertheless, it serves as a useful indicator for urban and semi-natural when interpreted with the aid of Figures *2a-g*. General trends indicate an exponential increase in urban patch size as isolated patches coalesce with time. Semi-natural land cover shows a slight increase initially, but after 1968 a decline starts that only stabilizes in 2001.

Simpson's Evenness Index (SIEI), which sums across all landscape classes, indicated that the total area in the landscape was dominated by certain landscape elements in 1944 and 1968 (Fig. 5). The study area was most evenly distributed amongst different land use/land cover components in 1983, and has since become progressively unevenly again. According to SIEI, the relative division of space is, at present, the most skewed it has been in over 60 years.

Discussion

Zandvlei and the surrounding environment have witnessed a long history of human modification, leading to a radical shift in land use/land cover over the past 62 years. In 1944 as much as 70% of the landscape had escaped significant anthropogenic impacts. At this stage semi-natural land cover was the dominant element in the landscape (see Fig *5*). Four major anthropogenic impacts have led to changes in the spatial configuration of the study area and a subsequent shift in dominance to urban land use, which occupies 41% of the present day landscape. Often changes in land use/land cover have profound implications for ecosystem functioning. These changes are discussed in more detail below.

<u>1. Effects of the railway embankment</u>

The first major anthropogenic impact on the Zandvlei ecosystem occurred in 1882, when the construction of the railway embankment to Muizenberg effectively separated what is today Westlake wetland from the Zandvlei estuary (Morant & Grindley, 1982). Prior to that event, there may not have been such a disparity in vegetative appearance and functioning of the two systems, as the slightly saline water from the north of the main vlei basin would have been able to mix freely with that of Westlake wetland.

After the railway embankment was put in place, the Westlake section of the vlei effectively became a sediment trap, as water was forced to exit via a narrow culvert leading to the Zandvlei basin. The persistence of freshwater conditions was also aided by the installation of a salinity barrier in the railway culvert in the 1930's, probably to allow for the water to be utilized for agricultural purposes (Thornton *et al*, 1995). Thus, a lowering of salinity levels, increases in sediment, and a constant supply of nutrients from agricultural fertilizers washed into the Westlake and Keysers rivers from farms within the catchment, might have contributed to an increase in the growth of *Typha*, *Scirpus* and especially *Phragmites*. Ironically, it appears that this engineering calamity might have benefited Zandvlei in the long term by providing it with a filtering system for sediment and nutrients entering the main basin from the Westlake and Keysers rivers.

Support for the above argument is found in a 1988 vegetation survey by Azorin, who determined that the plant communities in the two systems were distinctive (Azorin, 1988; Thornton *et al*, 1995). Westlake wetland supported plants associated with freshwater conditions, while Zandvlei Nature Reserve (previously known as the Bird Sanctuary) at the head of the main vlei basin, supported plants of a more saline nature (Azorin, 1988).

2. Effects of agricultural practices within the site and catchment

Agriculture has a long history in the study area and especially in the Zandvlei catchment. Although cattle rearing and market gardening were practiced in the vicinity of the vlei for almost two centuries (Thornton *et al*, 1995), the extent and effect of commercial agricultural activities were probably greatest at the turn of the 20^{th} century. By the 1940's agriculture was already giving way to changing land use around the vlei. This is illustrated by the linear decline in area devoted to agricultural in the study site after 1944 (see Fig *2a*). Smaller patches were the first to disappear. Some of the homesteads became incorporated into the residential matrix, while others were simply abandoned and fields left fallow - in many instances to be colonized by dune scrub and invasives such as *Acacia cyclops* and *Acacia saligna*. Present day agricultural activities within the Zandvlei watershed are chiefly in the form of viticulture, and restricted to the slopes of Constantiaberg (Thornton *et al*, 1995).

In 1944 all of the rivers entering the vlei had cultivated fields extending to the water's edge for some length along their course (see Figs. *2a-d*). This would have greatly increased the amount of sediment and nutrients such as fertilizers and pesticides washed or blown into the rivers (Day, 1981), probably contributing to the siltation of Westlake wetland and, to a lesser degree, the northern part of Zandvlei. Even so, all the rivers had some form of riverine vegetation in their southern reaches, prior to entering the main Zandvlei basin. The filtering effect of reeds such as *Phragmites* and *Typha* are well documented (e.g. Day, 1981; Azorin, 1988; Allanson & Baird, 1999), and would have decreased the sediment and nutrient load reaching the Zandvlei basin. However, an unknown amount of sediment and nutrients undoubtedly found its way into the vlei as is evidenced by a sediment plume from the joint Sand/Langvlei river in the 1944 aerial photograph and the extension of the Sand/Langvlei canal, as sediment settled on either side of the mouth (see Fig. *2b*).

Despite the mitigating effects of riverine vegetation, the accrual of sediment and nutrients over time as a result of the lack of seasonal flushing is thought to have contributed to an increased layer of nutrient rich organic mud on the bed of the vlei, as opposed to sand in a normally functioning tidal estuary. Siltation of this nature has wide reaching implications for benthic communities, often resulting in anoxic conditions if circulation in the water column is inhibited (Day, 1981), as well as a switch from organisms preferring a sandy substrate to those more suited to a muddy substrate and a shallower, warmer environment (Morant & Quinn, 1999).

Estuaries are natural sink for river catchments and are thus able to manage fairly high doses of nutrients, provided they are regularly flushed (Allanson & Winter, 1999). The problem in the case of Zandvlei is that the main basin has been dredged to a depth of 1.1m and its water level maintained by a rubble weir at a level of approximately 0.7-0.9 m.s.l. since the 1960's (Heydenrych, 1976; Morant & Grindley, 1982). Water circulation patterns have thus been altered (Badenhorst, 1986), resulting in nutrients from agriculture accumulating in the northern section of the vlei over time (Thornton *et al*, 1995). Once again Zandvlei seems to be blessed with natural mitigation measures. The presence of extensive beds of the pondweed, *Potamogeton pectinatus*, both oxygenates the water and locks away nutrients as plant biomass, and has been harvested and removed on a regular basis since 1976. The effects of prevailing south easterly and north westerly winds on the waters of the vlei also contribute to circulation and oxygenation of the water (Shelton, 1975; Heydenrych, 1976; Morant & Grindley, 1982).

Water abstraction from rivers in the catchments above estuaries and wetlands is a major concern, especially in a water deficient country such as South Africa (Morant & Quinn, 1999). The historical amount of water abstraction from the rivers feeding Zandvlei is unknown, but the drying of the vlei prior to 1866 (Morant & Grindley, 1982; Thornton *et al*, 1995) was almost certainly a combination of reduced rainfall and abstraction.

There is no mention of any of the rivers entering Zandvlei being dammed to any significant extent, although water abstraction for use in the Constantia winelands still happens today. Stands of alien pine trees in Tokai Forest, as well as Steenberg golf course almost certainly reduce water flow in the Keysers River.

The posited reduction in flow should intuitively translate to a decrease in the size of the main vlei basin, but this is not so. Water levels have remained relatively constant since the early 1970's (see Fig. *3b*) due to the installation of a Fehlman artesian well by the Marina da Gama Corporation, which replenishes water lost through evaporation and abstraction to maintain a minimum level of 0.7-0.9 m.s.l. (Heydenrych, 1976). However, the water pumped into the vlei is saline and if insufficient catchment water is available to dilute the seawater, the salinity levels may well rise above the threshold tolerated by certain estuarine organisms.

<u>3. Effects of dredging operations</u>

The aerial photograph in 1944 indicated that the vlei was a large shallow water body, with gently sloping shores, which extended to large adjacent areas of wetland vegetation (Morant & Grindley, 1982). Seasonal fluctuations in the water level thus resulted in an extensive area of about 130 ha being inundated (see Figs. *2a* & *3b*) (Morant & Grindley, 1982).

At this time the vlei functioned as a seasonally blind estuary, cut off from the sea by the presence of a sandbar, which formed at the mouth during the summer months (Bourgeois, 1948; Heydenrych, 1976; Morant & Grindley, 1982). If winter rains raised the water level in the vlei sufficiently, the sand bar would be breached artificially, and its waters would communicate with the sea (Bourgeois, 1948). This had important implications for juvenile fish species such as mullet (*Mugil cephalus*) and steenbras (*Lithognathus lithognathus*), which used the vlei as a nursery and spawning ground (Shelton, 1975) and supplemented commercially harvested fish stock in False Bay (Thornton *et al*, 1995). Despite severe transformation to the mouth it is believed that Zandvlei still performs this vital function today (Morant & Grindley, 1982; Thornton *et al*, 1995).

However, during years of low rainfall the vlei may have dried towards the end of summer (Morant & Grindley, 1982), converting what is represented as seasonally inundated land cover in Figure *2a* into a mudflat with an extent of approximately 50 ha. A mudflat of this magnitude would have supported a variety of wading birds (Day & Grindley, 1981), which would feed on numerous species of epifauna and infauna (Shelton, 1975; Day, 1981). Burrowing sand prawns and polychaetes, crabs and shrimps were just some of the benthic fauna recorded at Zandvlei mouth by Shelton (1975). It is therefore highly likely that these, and other species, occurred in greater densities and extent in the 1940's. Flamingos and Little Stint were just two of many wading bird species which used to frequent Zandvlei's mudflats in significant numbers in the 1950's (Morant & Grindley, 1982).

It is clear from various accounts (e.g. Bourgeois, 1948; Shelton, 1975; Heydenrych; 1976; Morant & Grindley, 1982) that, despite the likely presence of a sluice and weir at the mouth (Bourgeois, 1948), the pre-1947 vlei still had a relatively dynamic function, oscillating between periods when the vlei was a shallow expanse of water and times of drought, when it dried substantially. While the dredged channel leading from the southern end of the vlei basin to the mouth would probably have assisted drainage during winter and sand deposition at the mouth during summer (see Fig. *2a*), water levels were not strictly controlled. The salinity of the vlei thus varied with season according to changing patterns of inflow, outflow and evaporation (Day, 1981).

In the late 1940's it was proposed that Lakeside be converted to a pleasure resort (Shelton, 1975), initiating a period of change between 1947 and 1961 that would completely alter the function and appearance of the vlei and its adjacent seasonally inundated floodplains.

The two-dimensionality of Figure *2b* gives no indication of the significant modification to the vlei bed. Water was abstracted from the vlei and the lower half deepened (Shelton, 1975). Dredging operations on the upper half only commenced after an initial attempt to bulldoze away the sediments failed (Shelton, 1975). Conformational evidence of these activities can be seen in the general smoothing of the shoreline, the creation of a sand embankment across the middle of the vlei, as well as the sheltered bay of the Imperial Yacht Club, playwaters (adjacent to the present day caravan park) and an additional inlet to the south of this (see Fig. *2b*).

Dredged spoil was used to raise the level of the banks above the high water mark on both eastern and western shores (see Fig. *2b*). Fifty hectares of seasonally inundated area was covered by spoil, predominantly on the western bank where the nutrient rich sediments would no doubt provide a good substrate on which to plant grass for proposed parklands. Some of the eastern and north eastern sections remained, but eventually dried because they were cut off from the vlei by a sand embankment. Eventually these areas were recolonized by terrestrial vegetation; hence the reclassification to semi-natural (see Fig. *2c*).

Sediment sucked from the vlei basin and dumped on the shores of the vlei changed the profile from a gentle gradient to a steep bank, which required concrete reinforcement (Morant & Grindley, 1982). The deleterious effects of this process have subsequently been highlighted by Day (1981) who stated that dredging sediments from shallow mudflats of marshland and using this material to elevate the banks is "the most detrimental work as far as life in an estuary is concerned…" (Day, 1981).

In addition, it has been stated that changes in the physical nature of an estuary, including lowering of the bottom topography, increasing turbidity and disruption of the mechanical properties of sediments, have profound effects on the resident biota (Badenhorst, 1986), and possibly ecosystem functioning. The most serious impacts in terms of benthic organisms are, a) direct burial and habitat destruction, including decreased light levels due to suspended particulates, and b) altered water chemistry due to oxygen depletion and the release of contaminants previously locked within the sediments (Badenhorst, 1986). As with eutrophication in the vlei, the impacts of dredging were compounded by the fact that suspended particulate matter and potentially harmful contaminants were unable to be flush out to sea. Rooted plant material and algae usually recover well after dredging, but this is highly dependant on the extent of the area dredged (Badenhorst, 1986).

Zandvlei was a perfect realization of the above statements. The habitat of mudflats fauna was all but destroyed, save for a small area close to the mouth. Certain benthic species favouring a freshwater habitat may have been lost as a result of the decreasing salinity gradient that exists from the mouth to the head of the estuary. Virtual disappearance of mudflats fauna prompted a switch in dominant avifauna from waders to piscivorous (e.g. comorants, grebes, Darters and White Pelicans) and herbivorous (e.g. Red-knobbed Coot, Hartlaub's Gull) species (Morant & Grindley).

The waterways of the southern section of the Marina da Gama development were initially excavated 'dry' during the period of 1969 to 1973 (Thornton *et al*, 1995), possibly contributing to increased sediment deposition in the vlei during this period (see Fig. *2d*).

The waterways were later connected to the main Zandvlei basin, while dredging of the northern portion commenced in 1976 (Heydenrych, 1976).

Despite the waterways of Marina da Gama being lined with concrete retaining walls, a constant water level was henceforth required to prevent them from collapsing (Heydenrych, 1976). To this end an artesian well was installed, as has been mentioned previously. Impacts arising from the constant water level have undoubtedly changed the functioning of the estuary from a dynamic system of fluctuating water levels with a variety of habitats at different depth profiles, to one that is more homogenous and consequently less biodiverse.

The importance of wind induced mixing of the water to avoid the development of anoxic benthic conditions has been highlighted in the marina canals, despite Heydenrych (1976) commenting that this would not become a problem. Architectural features designed to deflect the prevailing winds, as well as the orientation of the canals, have decreased water turnover and sparked the development of haloclines, which when disturbed, release toxic sulfide gas (Morant & Grindley, 1982) which often results in the mortality of aquatic flora and fauna. This seems to be an ongoing problem (Thornton *et al,* 1995), but the presence of *Potamogeton* in the canals has acted as a partial remedy by removing nutrients (Morant & Grindley, 1982).

4. Effects of urban development

The Marina da Gama development was indicative of a larger trend of urbanization that had been gradually expanding and coalescing in areas surrounding the vlei since 1944 (see Fig. *3a*). However, the construction of the marina both accelerated urbanization, and contributed the single most radical change to the topography of the study site (see Figs. *2c-d*). It resulted in a significant reduction in semi-natural land cover east of the vlei, as well as the loss of the buffering capacity provided by the natural vegetation (see Figs. *2c-d* & *3a*).

Despite the employment of a full-time ecologist to advise on mitigation measures, the marina development had profound impacts on the vlei and surrounding ecosystem; hardly "…an outstanding contribution to the environment" as suggested by Mr. Revel Fox, at that time the President of the Cape Provincial Institute of Architects (Baker, 1976). On the eastern side of the study site, the marina development effectively severed an already tenuous connection between coastal dune vegetation and dune asteraceous fynbos found further inland. The *low* perimeter-area ratio at this stage belies the fact that a huge tract of semi-natural vegetation had been erased (see Fig *4*). The loss and fragmentation of sensitive dune vegetation continues to be a problem as development spreads to the east of the study site. A species inventory and management plan is urgently required to curtail further losses.

In some ways the impacts from urbanisation have replaced those from agriculture. Sediment load has probably decreased as agriculture has declined and the landscape surrounding the vlei has become more built up. However, new sources of pollution, in the form of household and industrial effluents, pose significant eutrophication and toxicity threats.

The development of the Retreat light industrial complex, to the north of Norfolk Park, and the expansion of low-income housing to the north and east of the study site, probably constitute the largest urban threats facing the present day vlei (Morant & Grindley).

If nutrient concentrations and toxicity are held at acceptable levels, the Keysers River will continue to act as a valuable buffer between industry and the vlei. The same buffering service cannot be expected from the Sand/Langvlei canal (Morant & Grindley, 1982), as its hard, square profile simply acts as a conduit for storm water, effluent and litter (see Figs. *2e-g*). A small scale attempt has been made to reroute the Sand River canal through some natural vegetation prior to its confluence with the Langvlei canal. However, the inherent risk of flooding residential areas bordering the canal prevents this scheme from being implemented along the entire watercourse. At present, the solution is a sediment and refuse trap at the mouth of the Sand/Langvlei canal, but this is not as effective as natural vegetation as it gets clogged during winter floods (Morant & Grindley, 1982) and does not filter out any nutrients.

Urbanisation around the vlei has also lead to increased use of the vlei for recreational purposes. This has resulted in a decline in sensitive bird species, while ‘urban’ species such as Hartlaub’s Gull, Egyptian geese, feral ducks and the European Starling have significantly increased in number.

Conclusion

There is no doubt Zandvlei is a highly modified system. According to a list of seven key management considerations drawn up by Heydorn (1988) detailing which anthropogenic activities would be especially harmful to an estuarine environment, Zandvlei has experienced all of them! The gradual switch in dominance from semi-natural and seasonally inundated land *cover* to agricultural and then urban land *use* has been the broadest significant change within the study area. The single most catastrophic human-induced impact on Zandvlei as a functioning estuary were the dredging activities which changed it from a shallow, seasonally dynamic system, to a more stable and homogenous environment.

Despite these changes Zandvlei continues to be a popular public amenity and provides valuable ecosystem services as a nutrient sink. In addition it may well still function as a nursery for juvenile fish, thus contributing to fish stocks in False Bay. It therefore seems logical that future management decisions take into account the role that it plays, both socially and ecologically.

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