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Research article

Towards a rapid assessment protocol for identifying pit lakes worthy of restoration

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ABSTRACT

Before the introduction of reclamation legislation in South Africa, final cut lakes in mining areas were left without any restoration while the final excavation was not back filled. Characteristics of these lacustrine water bodies vary considerably, but they are often linear in shape, large (1–30 ha), deep (2–30 m) and have poorly developed littoral zones. With water tables often near the surface; a variety of vascular hydrophytes can colonize these bodies, thus establishing emerging wetland type ecosystems. These, man-made aquatic structures that are (unintentionally) created potentially offers some realistic and inexpensive mitigation options for some of the negative impacts associated with mining, i.e. these water bodies can become useful by yielding potentially valuable services. However, no method currently exists to compare and rank these water bodies according ecological integrity and the expected monetary value to be derived from them in order to select sites for restoration. To answer this need, we applied an index to determine the ability of these water bodies to provide useful services in their current state. The index was then used to derive estimates of the monetary value of potential services in order to allow comparison with the cost of restoring the water body in question or to compare with other pit lakes. We present a South African case study to illustrate the method. As far as could be established, this is the first attempt towards creating a rapid assessment tool as standardised way of comparing pit lakes that allows for the ranking and identification of those pit lakes worthy of restoration.

1. Introduction

Although mining remains a major catalyst for economic development, it also has a legacy of perpetuating environmental impacts. Water pollution (salinization in particular) and the disruption of water ecosystems due to riverine tailings, tailing impoundment releases, and acid mine drainage from abandoned mines, are of particular concern.

Over 6000 abandoned or ownerless mines in South Africa require rehabilitation at an estimated cost of $3 billion and ongoing maintenance cost in excess of $1 billion per annum (Genthe et al., 2017). This mining legacy problem is not unique to South Africa and whilst the mining sector has become more socially and environmentally conscious, it remains a major problem for the country. Ample opportunity (bolstered mainly from new reclamation legislation) for innovative interventions that goes beyond mitigating risk and more towards socially and economically inclusive development solutions remains.

One of such is the restoration of pit lakes in order to derive some benefit to society from these otherwise unwanted water bodies. These water bodies are created when final cut lakes in mining areas are left without any restoration while the final excavation is not back filled. These new aquatic bodies are then formed by the natural filling of water during the post mining phase. Although the characteristics of these bodies vary significantly, they are typically deep with a narrow or sometimes absent littoral zone (essential for many limnological functions) that lacks a drainage basin. They are commonly associated with water of a poor quality containing high sulphate and metal concentrations and either very low or high pH values.

With only crude estimates regarding the actual number of these water bodies, they are typically associated with open cast mining (predominantly coal) and came about prior to the introduction of reclamation legislation in South Africa. Consequently the bulk of pit lakes are considered ownerless and hence part of the country's mining legacy problem.

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Fortunately many of these pit lakes are quite old and the possibility of these water bodies providing useful services cannot be excluded. However, given the extent of the pit lake restoration challenge and budgetary constraints from government and mining companies, a need arise to identify pit lakes worthy of restoration. Here, the term “worthy” might be interpreted from various perspectives and although a multi-disciplinary decision, monetary valuation of the expected benefits to society remains an important consideration as to decide whether or not to invest in the restoration of a particular pit lake. With no method currently available to compare and rank pit lakes in a consistent way and with legislation now demanding such restoration, a rapid assessment protocol for screening and ranking these water bodies is required to support decision-making in this regard. This work is considered a first attempt towards creating a standardised way (protocol) of assessing the current state of pit lakes paired to a monetary valuation of services to be expected from such water bodies which is then used for comparative purposes. The tool should be used to identify those pit-lakes worthy of restoration.

We make use of a pit lake index (PLI) to determine the ecological status of pit lakes. The index is based on appearances and measures of ecological processes of the pit lake including surface morphology, hydro-chemical characteristics, biological communities and external environmental and anthropogenic stressors. The index makes use of selected pit lake characteristics of type, landform, size and buffer zone. We explain the protocol that was used to first assess the eco-status of a pit lake where after a categorical score was allocated to the pit lake. This information is used to categorise the anticipated extent to which these water bodies can provide services. The categorical scores were then fed into a model to derive estimates of the monetary value to be expected from services of the specific pit lake in question. We illustrate the tool by means of a South African case study and conclude with a discussion of the potential application and current limitations of the tool.

2. Assessment protocol to determine the eco-status of pit lakes

Blanchette and Lund (2016) present two reasons why pit lakes (also refered to as cut lakes) remains problematic. Firstly, they argue that widespread confusion regarding suitable use of these water bodies remains, mainly because of the absence of a standard protocol for deciding what to do with these water bodies. Secondly, the apparent lack of an integrated transdisciplinary approach for managing pit lakes stand in the way of effective restoration. We do not contest any of these as our work aims to feed into this wider debate on ways to increase the effective management of mining legacies such as pit lakes.

No standard protocol currently exists to assess the ecological integrity of pit lakes and this is a first attempt to apply an index which can be standardised to allow inter pit lake comparisons. The PLI contains several ecological, hydrological and geomorphological water body characteristics: (Table 1):

(a) Pit lake types – we employed a modified version of Kumar (2009) to classify pit lakes.
(b) slope determines the formation of littoral zones where sunlight penetrate to bottom sediment creating most productive zone in terms of habituating rooted and benthic plants and phytoplankton.
(c) Pit lake size – we used 1:50 000 maps to estimate the surface area of a pit lake, after which we applied the geomorphic scale of Semeniuk (1987) to categorise the water body
(d) Pit lake buffer zones – we applied Mitsch and Gosselink (2000) and Gerber et al. (2004) to determine the cross-section distance of pit lakes.
(e) Hydro-period – the amount of time a pit lake is filled with water depends on rainfall and evaporation loss, recharge and discharge characteristics, and shape of the pit lake (Semeniuk and Semeniuk, 1995).

We employed the chemical, physical and biological indicators of the above-mentioned characteristics, to evaluate the structural and functional properties of pit lakes. This information was subsequently used to establish the ‘eco-status’ of pit lakes. The indicators included:

(a) Bank stability – we applied Spencer (1998) to assess bank erosion
(b) Width of fringing vegetation strip – in the case of wetlands, the width of the vegetation fringe is based on visual estimates of the strip using at least four cross-section points of the water body (Castelle et al., 1994; Bren, 1993; Dallas et al., 1993). However, the side slope of pit lakes vary substantially; hence we rather used flood height to determine the width of the riparian vegetation strip. We considered a 5 m wide strip as minimal protection to maintain aquatic functionality, whilst a strip greater than 20 m was considered to provide good protection to maintain aquatic functions (Barling and Moore, 1994; Macfarlane and Bredin, 2016).
(c) pH – was measured with a Hach sension TM 156 portable multiparameter (Loveland, USA). pH intervals were derived from changes in biodiversity (Kalff, 2001) where measurements below 6 and greater than 8 were considered as the thresholds for a drop in biodiversity.
(d) Electrical conductivity - strongly relates to the diversity and abundance of freshwater plants (Gómez Mercado et al., 2012). We employed Hillman (1986) and Crabb (1997) to define the conductivity range.
(e) Turbidity – we measured turbidity with a Hach 2100P Turbidimeter (Loveland, USA).
(f) Bottom sediment – we sampled with a sediment corer to a depth of 10 cm to analyse the extent of dissolved organic matter in bottom sediment.
(g) Dissolved oxygen – we categorized dissolved oxygen concentrations according to Alabaster and Lloyd (1982).
(h) Aquatic vegetation cover – we applied Pressey (1987) and Mitchell (1990) to determine the percentage of the water surface been covered with aquatic vegetation. We note that a pit lake which is completely covered with aquatic vegetation, may be due to nutrient enrichment and were allocated a low(er) score, whereas vegetation cover of 51–85 percent was allocated the highest score.
(i) Near surface suspended chlorophyll-a was used as an indicator of pit lake primary production according to Kalff (2001). Suspended chlorophyll a was measured in the field using a OTT Hydrolab DS5 multiparameter water quality probe. The categories used to establish productivity potential for the index were as follows: 1) > 25 = hypertrophic; 2) 9–25 = eutrophic; 3) 3.5–9 = mesotrophic; and 4) < 3.5 = oligotrophic. Measurements were collected in triplicate at each sampling site. We used a Van Dorn sampler (1 L) to collect planktonic algae at the surface and 2 m below surface. These samples were pooled and assessed. We sedimented samples in an algae chamber and used an inverted microscope at 1250× magnification to analyse by means of the strip-count method (APHA 1992, Truter 1987; Wehr and Sheath 2003; Van Vuuren et al., 2006; Taylor et al., 2007).

Table 1
Environmental characteristics used to develop the PLI.

Pit lake Types	Slope	Pit lake size	Pit lake buffer zone	Hydro-period
Acidic pit lake: low pH and toxic concentrations of metals. Primarily Al toxicity due to the low buffer capacity of the natural environment, rather than high acidity inputs	Slope of <1°: little or no relief or diffuse margins; large littoral zone if evident.	Megascale: more than 10 km × 10 km. Macroscale: 1000 m × 1000 m up to 10 km × 10 km.	Grassland zone: temporarily wet and usually dominated by a mixture of plant species that may also occur in non-wetland areas, and hydrophylic plant species that are usually restricted to temporarily and seasonally wet areas.	Permanently inundated: permanently flooded; water covers the bottom throughout the year; usually governed by rain and groundwater.
Saline pit lakes: evaporation exceeds precipitation, while surface inflow is largely restricted to direct precipitation which can result in brackish to hyper-saline lakes due to high rates of evapo-concentrations.	Slope of 25°: defined margin and small littoral zone is evident.	Mesoscale: 500 m × 500 m up to 1000 m × 1000 m. Microscale: 100 m × 100 m up to 500 m × 500 m.	Wet meadow zone: seasonally wet and dominated by hydrophylic plant species (usually sedges and grasses < 1 m tall); usually restricted to seasonally or temporarily wet areas.	Seasonally inundated: surface water is present for extended periods, especially during the early part of the growing season, but is absent in the dry season usually governed by rain water.
Neutral pit lakes: generally good water quality; well suited to a variety of end uses as individual contaminants can often be readily remediated or treated.	Slope of 45°: no littoral zone	Leptoscale: less than 100 m × 100 m.	Marsh zone: usually dominated by tall emergent herbaceous plants such as reeds (e.g. Phragmites Australis; usually >1 m tall); consists of permanent or semi-permanent wet areas.	Intermittently inundated: substrate usually exposed, but surface water present at various times with no definite seasonal period; usually pit lakes governed by rain and groundwater only.
			Open water zone: usually dominated by free-floating plants on the water surface; free floating plants beneath the surface; emergent plants in substrate with floating leaves; submerged plants (anchored in substrate).	Seasonally waterlogged: pit lake soils saturated with water, but where the water does not inundate or cover the soil surface; usually governed by groundwater.

(j) Spatial heterogeneity of macrophytes – we applied Williams (1983) and Oberholster et al. (2010) to classify the layers of aquatic vegetation.

A field assessment sheet (see Fig. 1) is used to capture information and data regarding the above-mentioned variables by means of a combination of field observations, measurements and samples for laboratory measurements. Four representative sites are chosen per pit lake. The average between the sites is then taken as a representative measure of each variable.

Field sheet data was then converted to Lickert-based scores for each variable (see Fig. 2, aggregated and presented as a percentage in terms of the standard ecological categories of the South African Department of Water Affairs' (DWA, 2004; DWAF, 2007) (see Table 2).

The category label obtained was considered to be an acceptable indication of the ecological state and hence ability of the pit lake to yield services.

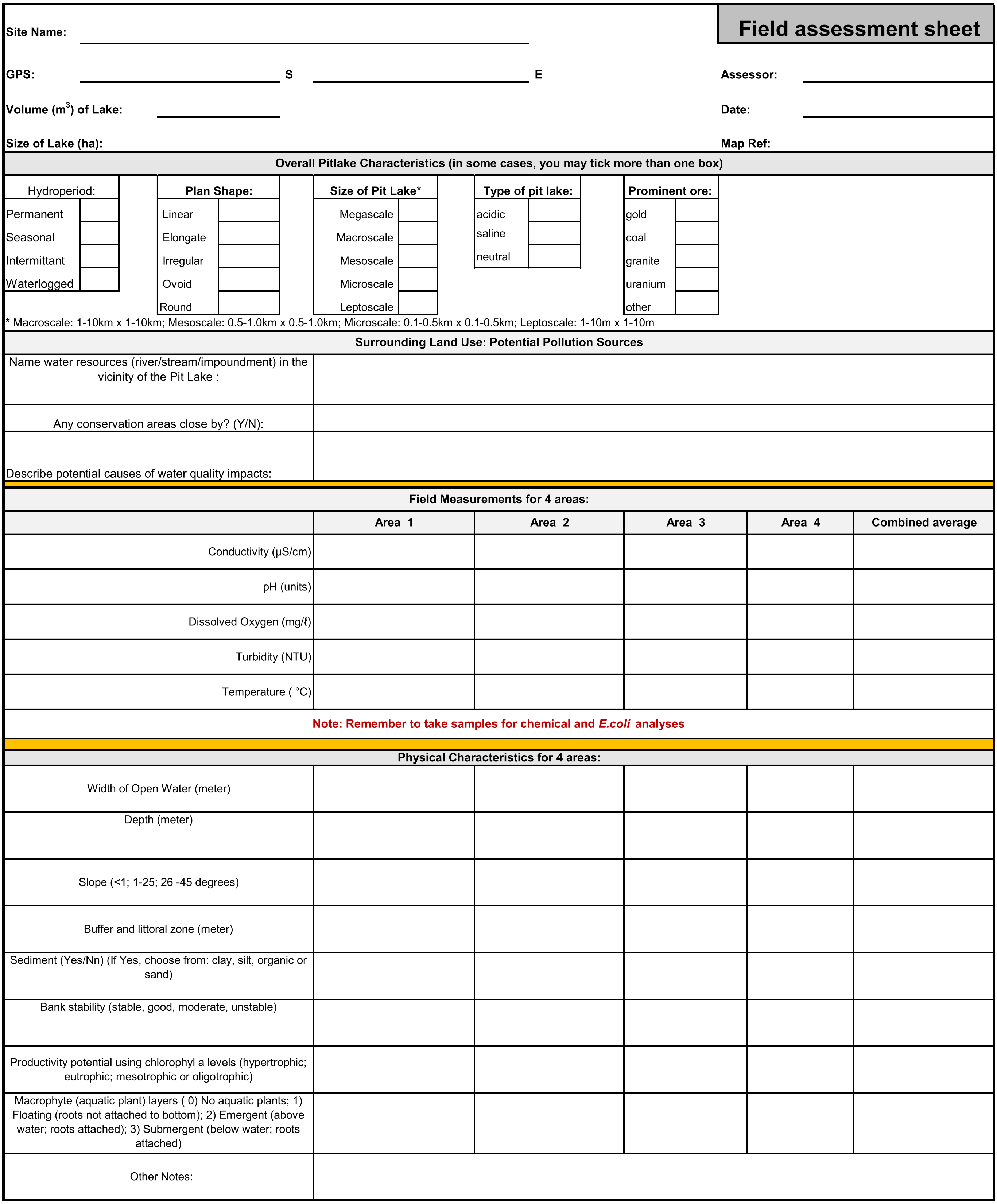
For example a categorical score of 60–80 percent implied the pit lake to considered as an ecological category “C” water body which is considered as moderated modified. Loss and changes of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged. The categorical scores were then used as an adjustment weight in the valuation process. We illustrate this process by means of a case study in the next section.

3. Deriving the value of pit lake services: A South African case study

Monetary valuation of non-market goods and services often plays an important part in balancing trade-offs via redistribution mechanisms to those who are adversely affected by economic development. Such mechanisms include various forms of taxes and/or payments of services. Valuation studies informs price setting via assessing the willingness and ability to pay for such services to affect a change in their delivery. Valuation studies have also confirmed that wherever the optimal situation for society differ from the preferred situation of individuals, monetary incentives are often more effective to achieve the desired social goals as compared to regulatory (so-called command and control) measures alone (Arrow, 1950). It thus becomes necessary to create monetary incentives to make damaging behaviour less profitable for individuals. Overall, valuation studies improve our understanding in terms of why people degrade landscapes, and assist in developing incentives for people to engage in more sustainable use patterns.

Benefit transfer is not a valuation method in a true sense, but rather a method for transferring existing estimates of non-market values from one study site to another. The method requires appropriate adjustments to accommodate contextual differences between study sites (Eshet et al., 2005). The value estimates used in the method are obtained via any non-market valuation method (Eshet et al., 2005; Nahman et al., 2009; Vo et al., 2012; Parks and Gowdy, 2013). Benefit transfer methods are subdivided in two broad categories. The first being ‘unit value transfer’, which involves the direct transfer of value estimates from source studies to the study area with limited or no adjustment. Secondly, ‘function transfers’ involves the transfer of parameterized benefit function which is adjusted with independent variables from the study area to (Johnston and Rosenberger, 2010; Rolfe, 2006).

An obvious limitation of the method lies within the accuracy of the adjustment process (Bergstrom and Taylor, 2006; Wilson and Hoehn, 2006; Moeltner et al., 2007). Here it becomes necessary that the methods being followed for the adjustment process is made explicit and that the process is done in a transparent way (Bergstrom and De Civita, 1999; Bergstrom and Taylor, 2006; Hoehn, 2006; Johnston et al., 2015; Moeltner et al., 2007; Rosenberger and Loomis, 2000; Smith and Pattanayak, 2002; Shrestha and Loomis, 2001, 2003; Wilson and Hoehn, 2006). Furthermore, the method has been subject to many applications that sacrifice scientific rigour in ways that provide inaccurate information on ecosystem values (Johnston and Wainger, 2015) that



Field assessment sheet

Site Name: ____________________

GPS: ____________ **S** ____________ **E**

Assessor: ____________

Volume (m^3) of Lake: ____________

Date: ____________

Size of Lake (ha):

Map Ref:

Overall Pitlake Characteristics (in some cases, you may tick more than one box)

Hydroperiod:		**Plan Shape:**		**Size of Pit Lake***		**Type of pit lake:**		**Prominent ore:**	
Permanent	☐	Linear	☐	Megascale	☐	acidic	☐	gold	☐
Seasonal	☐	Elongate	☐	Macroscale	☐	saline	☐	coal	☐
Intermittant	☐	Irregular	☐	Mesoscale	☐	neutral	☐	granite	☐
Waterlogged	☐	Ovoid	☐	Microscale	☐			uranium	☐
		Round	☐	Leptoscale	☐			other	☐

* Macroscale: 1-10km x 1-10km; Mesoscale: 0.5-1.0km x 0.5-1.0km; Microscale: 0.1-0.5km x 0.1-0.5km; Leptoscale: 1-10m x 1-10m

Surrounding Land Use: Potential Pollution Sources

Name water resources (river/stream/impoundment) in the vicinity of the Pit Lake :	
Any conservation areas close by? (Y/N):	
Describe potential causes of water quality impacts:	

Field Measurements for 4 areas:

	Area 1	**Area 2**	**Area 3**	**Area 4**	**Combined average**
Conductivity (µS/cm)					
pH (units)					
Dissolved Oxygen (mg/ℓ)					
Turbidity (NTU)					
Temperature (°C)					

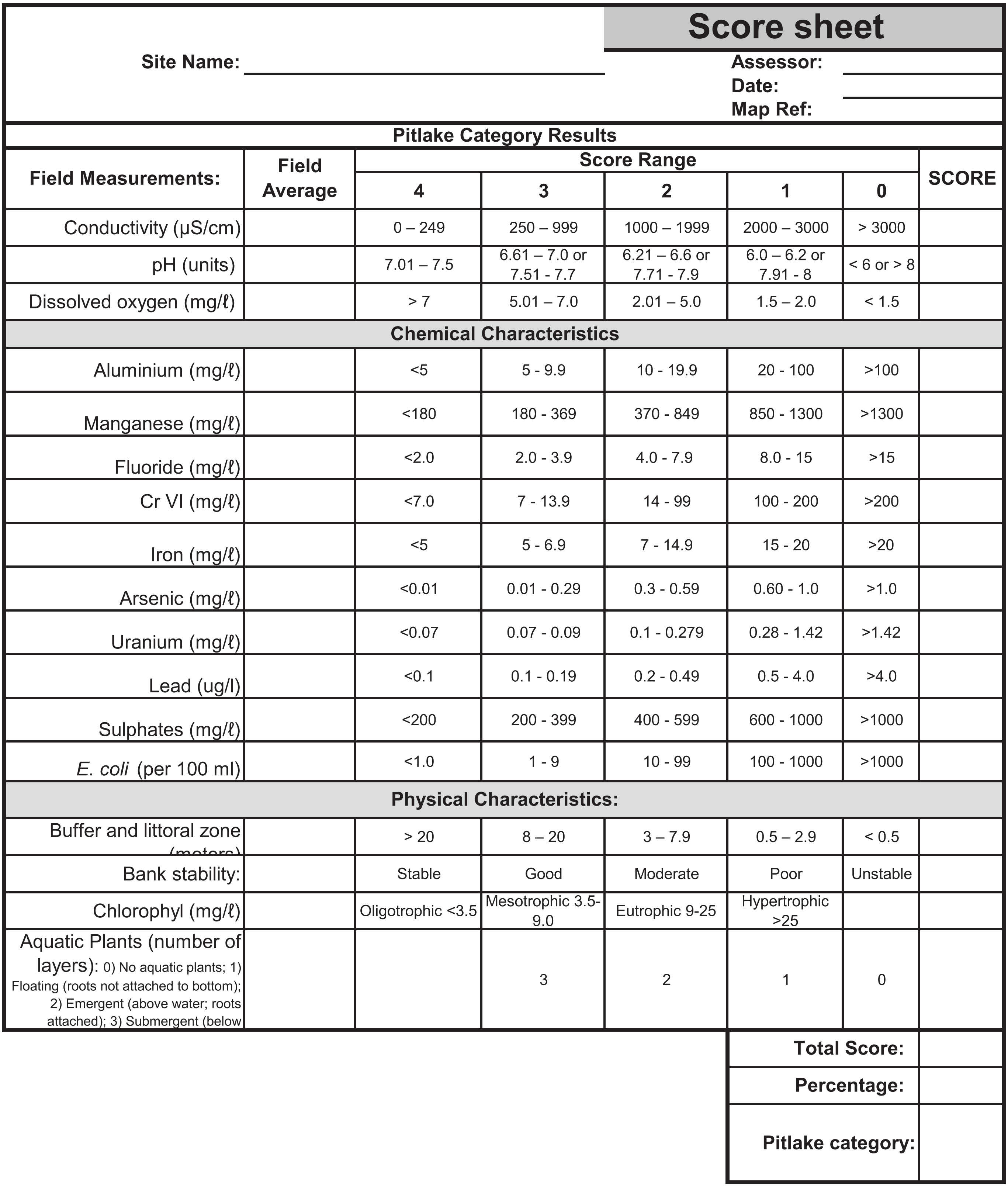
Note: Remember to take samples for chemical and *E.coli* analyses

Physical Characteristics for 4 areas:

Width of Open Water (meter)					
Depth (meter)					
Slope (<1; 1-25; 26 -45 degrees)					
Buffer and littoral zone (meter)					
Sediment (Yes/Nn) (If Yes, choose from: clay, silt, organic or sand)					
Bank stability (stable, good, moderate, unstable)					
Productivity potential using chlorophyl a levels (hypertrophic; eutrophic; mesotrophic or oligotrophic)					
Macrophyte (aquatic plant) layers (0) No aquatic plants; 1) Floating (roots not attached to bottom); 2) Emergent (above water; roots attached); 3) Submergent (below water; roots attached)					

Other Notes:	

Fig. 1. Field assessment sheet been used to assess eco functionality of pit lakes.



Score sheet

Site Name: ____________________

Assessor: ____________
Date: ____________
Map Ref:

Pitlake Category Results

Field Measurements:	Field Average	Score Range					SCORE
		4	3	2	1	0	
Conductivity (µS/cm)		0 – 249	250 – 999	1000 – 1999	2000 – 3000	> 3000	
pH (units)		7.01 – 7.5	6.61 – 7.0 or 7.51 - 7.7	6.21 – 6.6 or 7.71 - 7.9	6.0 – 6.2 or 7.91 - 8	< 6 or > 8	
Dissolved oxygen (mg/ℓ)		> 7	5.01 – 7.0	2.01 – 5.0	1.5 – 2.0	< 1.5	
Chemical Characteristics							
Aluminium (mg/ℓ)		<5	5 - 9.9	10 - 19.9	20 - 100	>100	
Manganese (mg/ℓ)		<180	180 - 369	370 - 849	850 - 1300	>1300	
Fluoride (mg/ℓ)		<2.0	2.0 - 3.9	4.0 - 7.9	8.0 - 15	>15	
Cr VI (mg/ℓ)		<7.0	7 - 13.9	14 - 99	100 - 200	>200	
Iron (mg/ℓ)		<5	5 - 6.9	7 - 14.9	15 - 20	>20	
Arsenic (mg/ℓ)		<0.01	0.01 - 0.29	0.3 - 0.59	0.60 - 1.0	>1.0	
Uranium (mg/ℓ)		<0.07	0.07 - 0.09	0.1 - 0.279	0.28 - 1.42	>1.42	
Lead (ug/l)		<0.1	0.1 - 0.19	0.2 - 0.49	0.5 - 4.0	>4.0	
Sulphates (mg/ℓ)		<200	200 - 399	400 - 599	600 - 1000	>1000	
E. coli (per 100 ml)		<1.0	1 - 9	10 - 99	100 - 1000	>1000	
Physical Characteristics:							
Buffer and littoral zone (meters)		> 20	8 – 20	3 – 7.9	0.5 – 2.9	< 0.5	
Bank stability:		Stable	Good	Moderate	Poor	Unstable	
Chlorophyl (mg/ℓ)		Oligotrophic <3.5	Mesotrophic 3.5-9.0	Eutrophic 9-25	Hypertrophic >25		
Aquatic Plants (number of layers): 0) No aquatic plants; 1) Floating (roots not attached to bottom); 2) Emergent (above water; roots attached); 3) Submergent (below			3	2	1	0	

Total Score:	
Percentage:	
Pitlake category:	

Fig. 2. Score sheet to determine pit lake category result.

misinform policies which could reduce human welfare on the long term. One particular area of concern relates to the choice of transferring unit values or the underlying function of such value (Loomis and Rosenberger, 2006). Although, function transfers allow for adjustments to be made according to a variety of factors that can influence values and although the literature suggests that function transfers outperform unit value transfers in terms of representivity and inclusiveness (Kaul et al., 2013), actual evidence for this

Table 2
Description of the A-F ecological categories (adapted from Kleynhans, 1996, 1999; Kleynhans and Louw, 2007).

Ecological category	Score (%)	Description
A	90–100	Unmodified, natural
B	80–90	Largely natural with few modifications. A few small-scale changes in natural habitats and biota may have taken place but the ecosystem functions are essentially unchanged.
C	60–80	Moderated modified. Loss and changes of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D	40–60	Largely modified. A large loss of natural habitat, biota and basic ecosystem function has occurred.
E	20–40	Seriously modified. The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	0–20	Critically modified. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural habitat and biota.

preference in practice is mixed (Johnston and Rosenberger, 2010). Indeed, Bateman et al. (2011) argues that unit value transfers are appropriate when source studies are within the same socio-economic context as target sites, but that function transfers becomes more appropriate as contextual differences increase. Context similarity is therefore important, but the exact point as to when to use unit value transfer as opposed to functional transfer remains somewhat obscure. It is however clear that unit value transfers are simpler to use and often the only approach available when source studies are limited or when benefit functions are not reported in source studies (Rolfe et al., 2015).

The academic literature has also highlighted the problem of divergence between transfer practices recommended in the literature and those applied in practice. Unit value transfer is often the preferred practice (it is simpler) although it could be less accurate than functional transfer. However, although benefit transfer is subject to these conceptual and empirical limitations, the method is still widely applied (especially by government agencies) in policy design and implementation (Bergstrom and De Civita, 1999).

Not disregarding its limitations, we employed the method because of an increasing need for utilising more cost effective valuation methods in South Africa and because several studies has been done on describing, mapping, physical quantification and monetary valuation of wetland ecosystem services in southern Africa. This has allowed the confident use of the method, but with special attention to adjust wetland values to serve as estimates for pit lake values. We opted for unit value transfer since we consider it as been acceptable to be used as preliminary value estimate within similar socio-economic contexts.

There are no natural lakes and no natural waterbodies with comparable bio-physical characteristics to that of pit lakes in South Africa. Furthermore, no 'ecosystem' service valuation studies were found in the southern African literature focusing exclusively on man-made waterbodies such as dams and reservoirs (all existing valuation studies are either on water basins as a whole or a river (including dams) making differentiation of attributable values to dams only, impossible). Consequently we have decided to test the idea of using the PLI to adjust the results of wetland valuation studies (of which there are many in the southern African literature), which is then used as a proxy for the value of pit lake services. This paper assesses and illustrates the extent to which this can be done subject to the current knowledge base. We argued that because socio-economic context is a major value determinant, the similarity in socio-economic context of comparing southern African studies would provide a more representative estimate of the value of pit lake services compared to using international literature on natural and man made lakes, dams/reservoirs and pit lakes as proxy for South African pit lakes.

We acknowledge that pit lakes and wetlands are fundamentally different and that a man-made water body such as a pit lake is technically not a natural ecosystem and therefore cannot provide true ecosystem services. However, although pit lakes are not able to substitute wetlands, they can and does provide some comparable services to that of natural wetlands.

Furthermore, the implementation of reclamation legislation for the South African mining sector has increased the political urgency coupled to the pit lake challenge and the consequent demand for information on environmental services to support and improve environmental policies and management decisions. With practitioners slow to respond, an interim solution needed to be found to inform immediate policy needs. On this basis, and given the absence of pit lake valuation studies in the southern African literature, we employed the pit lake index (Oberholster et al., 2017, 2014) together with unit value transfers to identify those pit

Table 3
Examples of provisioning value of wetlands from Southern Africa.

Study area	Reference	Type or service	USD per hectare per year
Olifants River, Mpumalanga	Palmer et al., 2002	Riparian wetlands	7
		Seepage wetlands	250
		Pans	372
		Artificial wetlands	209
	DWA, 2010	Livestock grazing	405
		Food and firewood	417
Rufiji floodplain and delta, Tanzania	Turpie, 2000	Rivers and lakes	42
		Flood plain	67
		Mangroves	17
Knysna estuary	Napier et al., 2009		36
Okavango Delta, Botswana	Turpie, 2006		2
Barotse flood plain, Zambia	Turpie et al., 1999		16
Chobe-Caprivi, Namibia	Turpie et al., 1999		16
Lower Shire, Malawi	Turpie et al., 1999		82
Zambezi Delta, Mozambique	Turpie, 2000		7
Lake Chilwa wetland, Malawi	Schuyt, 2005		86

lakes worthy of restoration. It is considered an interim solution for preliminary screening of pit lakes within comparable socio-economic contexts until more sophisticated, inclusive models becomes available.

4. What are wetlands worth in southern Africa?

Wetlands are complex hydro-ecological systems, which provide ecosystem services that are a function of the direct or indirect use of the bio-physical characteristics of wetlands. The Millennium Ecosystem Assessment (2005) classifies these services into provisioning, regulating and cultural services with intermediate supporting services. A vast amount of literature is available on wetland valuation from all over the world. However, given the challenges associated with benefit transfer studies mentioned earlier, we focused on studies from southern Africa where wetlands are recognised as being valuable ecosystems as these waterbodies play an important role in sustaining peoples' livelihoods. We now present those studies been used in the benefit transfer for this study.

Several studies have been carried out on the provisioning values of wetlands in southern Africa (Table 3).

Recreational values are often reflected in changes in the value of property due to its proximity to a wetland, i.e. the same/similar property has a different value due to proximity to the wetland. Alternatively, these values can be reflected in terms of actual expenditure (or stated willingness to pay) of visiting wetlands. We found a number of South African studies on recreational and tourism values of wetlands (Table 4).

Table 4
Studies on the recreational and tourism value of wetlands from southern Africa.

Study area	Reference	USD per hectare per year
Cape Town metro	Turpie et al., 2001	360
Sandvlei, Cape Town	Van Zyl and Leiman, 2002	525
Knysna estuary	Turpie and Joubert, 2004	40 442
Linyati-Chobe, Zambezi basin	Seyam et al., 2001	1
Okavango Delta, Botswana	Turpie et al., 2006	159
Olifants WMA	DWA, 2010	15

Table 5
Examples of regulating values of wetlands in southern Africa.

Study area	Reference	Service	USD per hectare per year
Cape Town metro	Turpie et al., 2001	Water storage and purification	2213
Knysna estuary	Turpie and Clark, 2007	Fish nursery areas (refugia)	5423
Barotse flood plain, Zambia	Turpie et al., 1999	Groundwater recharge, carbon sequestration and water purification	80
Chobe-Caprivi, Namibia	Turpie et al., 1999	Groundwater recharge, carbon sequestration and water purification	72
Lower Shire, Malawi	Turpie et al., 1999	Groundwater recharge, carbon sequestration and water purification	151
Zambezi Delta, Mozambique	Turpie et al., 1999	Groundwater recharge, carbon sequestration and water purification	45
Olifants WMA	DWA, 2010	Groundwater recharge	22
		Carbon sequestration	13
		Flow regulation	42
		Water purification	31
Okavango Delta, Botswana	Turpie et al., 2006	Groundwater recharge	2
		Carbon sequestration	12
		Wildlife refuge	11
		Water purification	0
		Education and scientific value	3

Table 6
Relevant services for the study sites.

Service		Description
Provisioning	Food	Pit lake's ability to facilitate production of fish, wild game, fruits and grains.
	Freshwater	Pit lake's ability as to provide storage and retention of water for domestic, industrial and agricultural use.
	Fibre and Fuel	Pit lake's ability to produce logs, fuelwood, peat and fodder.
	Biochemical	Extent to which medicines and other biochemical materials from biota can be extracted from the pit lake.
	Genetic material	Pit lake's ability to provide genetic material for selection for resistance to plant pathogens, ornamental species, etc.
Regulating	Climate regulation	Extent to which the pit lake acts as source and sink for greenhouse gases; influences local and regional temperature, precipitation and other climate processes.
	Water regulation	Extent to which the pit lake recharges/discharges groundwater
	Erosion regulation	Extent to which pit lake facilitate retention of soils and sediments
	Natural hazard regulation/flood control/attenuation	Extent to which the pit lake facilitates flood control and storm protection.
	Water purification and waste treatment	Extent to which the pit lake facilitates retention, recover and removal of excess nutrients and other pollutants.
	Refugia	Extent to which the pit lake provides habitat, breeding and feeding habitat for plants and animals.
Cultural	Spiritual and inspiration/aesthetic	Extent to which the pit lake serve as a sources of inspiration; spiritual and religious values and aesthetic beauty.
	Recreational (e.g. angling and tourism)	Extent to which the pit lake facilitates recreational activities (e.g. angling, sport and tourism).
	Educational	Extent to which the pit lake provides opportunities for education and training.

Table 7
Median representative values drawn from southern Africa studies to be weighed and reconciled with pit lake index (2015 USD values).

Ecosystem Services		Description	USD per hectare per year
Provisioning	Food	Pit lake's ability to facilitate production of fish, wild game, fruits and grains.	201 (Letseng-la-Letsie, Turpie et al., 1999) 1612 (Mfuleni, Turpie et al., 1999) 33 (Knysna, Napier et al., 2009) 309 (Olifants WMA, DWA, 2010) median: 255
	Freshwater	Pit lake's ability to provide storage and retention of water for domestic, industrial and agricultural use.	1669 (Cape Town Metro, Turpie et al., 2001) 11 (Olifants river, Palmer et al., 2002) 425 (Upper Olifants WMA, Palmer et al., 2002) 634 (Middle Olifants WMA, Palmer et al., 2002) 356 (Lower Olifants WMA, Palmer et al., 2002) median: 425
	Fibre and Fuel	Pit lake's ability to produce logs, fuelwood, peat and fodder.	2 (Okavango delta, Turpie et al., 2006) 19 (Barotse floodplain, Turpie et al., 1999) 19 (Chobe National Park, Turpie et al., 1999) 98 (LowerShire, Turpie et al., 1999) 8 (Zambezi river, Turpie et al., 1999) 79 (Lake Chilwa, Schuyt, 2005) 54; 86 and 22 (Rufiji floodplain, Turpie, 2000) 318 (Olifants WMA, DWA, 2010) median: 38
	Biochemical	Extent to which medicines and other biochemical materials from biota can be extracted from the pit lake.	1 (no data)
	Genetic material	Pit lake's ability to provide genetic material for selection for resistance to plant pathogens, ornamental species, etc.	1 (no data)
Regulating	Climate regulation	Extent to which the pit lake acts as source and sink for greenhouse gases; influences local and regional temperature, precipitation and other climate processes.	12 (Okavango delta, Turpie et al., 2006) 32 (Barotse floodplain, Turpie et al., 1999) 29 (Caprivi, Turpie et al., 1999) 60 (Lower Shire, Turpie et al., 1999) 18 (Zambezi delta, Turpie et al., 1999) 10 (Olifants WMA, DWA, 2010) median: 23
	Water regulation	Extent to which the pit lake recharges/dischargse groundwater.	2 (Okavango delta, Turpie et al., 2006) 32 (Barotse floodplain, Turpie et al., 1999) 29 (Caprivi, Turpie et al., 1999) 61 (Lower Shire, Turpie et al., 1999) 19 (Zambezi delta, Turpie et al., 1999) 17 (Olifants WMA, DWA, 2010) median: 23
	Erosion regulation	Extent to which the pit lake facilitates retention of soils and sediments.	1 (no data)
	Natural hazard regulation/ flood control/attenuation	Extent to which the pit lake facilitates flood control and storm protection.	803 (Nylsvlei, Turpie et al., 1999) 32 (Olifants WMA, DWA, 2010) median: 417
	Water purification and waste treatment	Extent to which the pit lake facilitates retention, recover and removal of excess nutrients and other pollutants.	1557 (Cape Town, Turpie et al., 1999) 0.3 (Okavango, Turpie et al., 2006) 1669 (Turpie et al., 2001) 32 (Barotse floodplain, Turpie et al., 1999) 29 (Caprivi, Turpie et al., 1999) 60 (Lower Shire, Turpie et al., 1999) 18 (Zambezi delta, Turpie et al., 1999) 4390 (Zaalklap wetland, Harris and Crafford, 2014) 24 (Olifants WMA, DWA, 2010) median: 32
	Refugia	Extent to which the pit lake provides habitat, breeding and feeding habitat for plants and animals.	1238 (Knysna, Turpie and Clark, 2007) 11 (Okavango delta, Turpie et al., 2006) median: 625
Cultural	Spiritual and inspiration/ aesthetic	Extent to which the pit lake serves as a source of inspiration; spiritual and religious values and aesthetic beauty.	168 (South Africa, Turpie and Clark, 2007) 9 (Barotse floodplain, Turpie et al., 1999) median: 88
	Recreational (e.g. angling and tourism)	Extent to which the pit lake facilitates recreational activities (e.g. angling, sport and tourism).	543 (Cape Town metro, Turpie et al., 2001) 792 (Sandvlei, Van Zyl and Leiman, 2002) 9778 (Knysna, Turpie and Joubert, 2004) 1 (Linyati, Seyam et al., 2001) 149 (Okavango delta, Turpie et al., 2006) 678 (Nylsvlei, Turpie et al., 1999) 13 (Olifants WMA, DWA, 2010) median: 543
	Educational	Extent to which the pit lake provide opportunities for education and training.	3 (Okavango delta, Turpie et al., 2006)

Table 8
Substitutability (based on Table 2) levels between pit lake and wetland values based on the pit lake index.

Index rating	Index score	Substitutability for wetland value (%)
A	90–100	95
B	80–90	85
C	60–80	70
D	40–60	50
E	20–40	30
F	0–20	10

Regulating values are often indirect and refer to those benefits that people receive indirectly from wetlands. Beneficiaries are often unaware of the benefits derived from regulating services. We present studies on the indirect use value of wetlands from southern Africa in Table 5. It should be noted that these estimates are often somewhat contentious because of the assumptions employed in the underlying valuation methods that determined these values.

Considerably fewer studies were found focusing on non-use value (e.eg existence and bequest value) of wetlands. Turpie and Clark, 2007 and Turpie and Joubert, 2004 assessed a number of South African wetlands and calculated an average value of USD 185 per hectare per year. Turpie et al., 1999 assessed the non-use values of the Barotse flood plain in Zambia and estimated the average value for this area on USD 8 per hectare per year.

We are aware that all of above-mentioned studies have different underlying assumptions and that these measures should be considered as partial.

5. Deriving values for pit lake services

The following table (Table 6) was compiled by the project team (applying the Millennium Ecosystem Assessment, 2005 categorisation) and was consequently taken as a basic point of departure to identify relevant services to be included in the benefit transfer.

A value for each service as per Table 6 was derived via a benefit transfer exercise based on several studies as presented in above. The values are presented in Table 7. The focus was exclusively on southern African studies, albeit at different times and different base years. The main reason for selecting only studies from southern Africa (study sites were located in Namibia, South Africa, Botswana, Zambia, Mozambique and Malawi) was to draw from studies from a comparable socio-economic and bio-physical context as to that of the case study area in which the index was applied (see later). One of the valuation studies was done within the same water management area (DWA, 2010). Values were, where necessary, inflated against the consumer price index up to 2015 values and foreign currency values where exchanged against prevailing annual exchange rates. It should be evident that unit valuations of ecosystem services are limited and show wide variance. Consequently we have used median value estimates and not mean values (Rolfe et al., 2015) as representative unit reference values.

The results of the estimates show that more 80 percent of the total value is explained by four services namely: water provisioning (17 percent) for which there was five unit values ranging between $12 and $1668; flood control (17 percent) with two unit values ($803 and $32); recreational services (22 percent) for which there was 7 unit values between $1 and $10,000; and refugia (25 percent) which had two unit values ($11 and $1238).

It should be noted that by employing benefit transfer to derive pit lake values from wetlands without any form of reconciliation, implicitly assumes perfect substitutability between the ecosystem services of wetlands and pit lakes. This is obviously not the case and these wetland value estimates were therefore needed to be

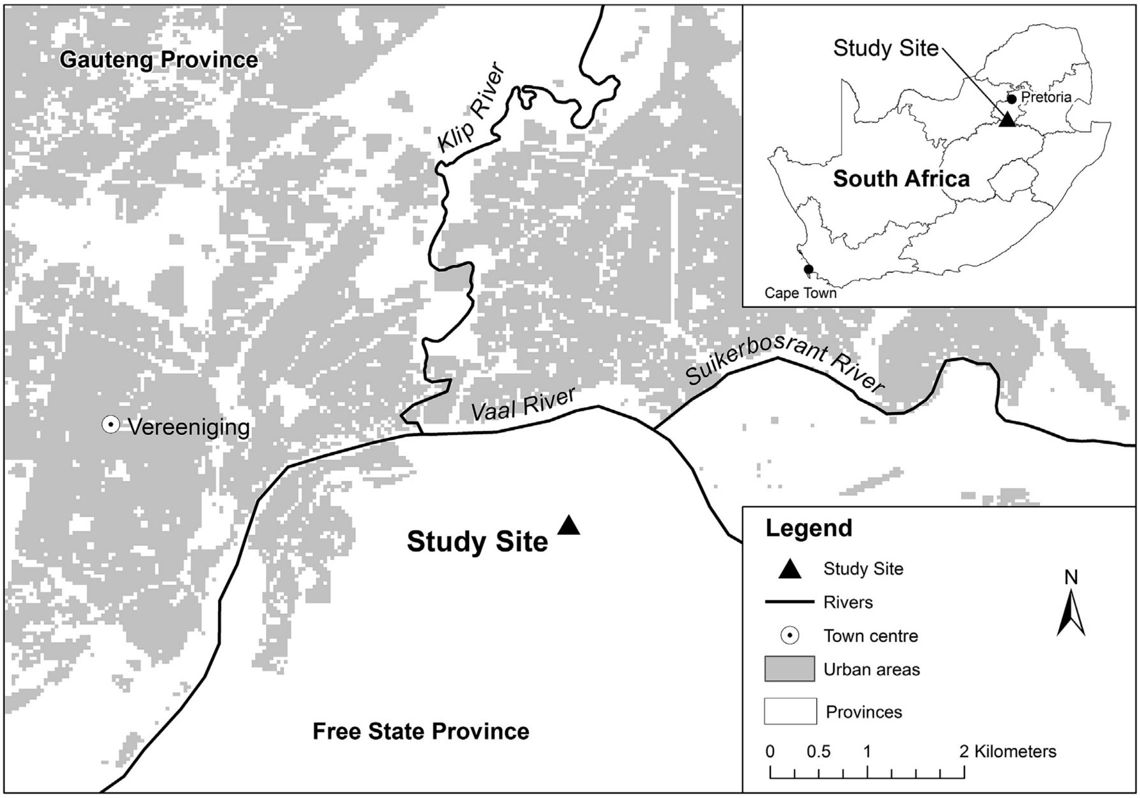
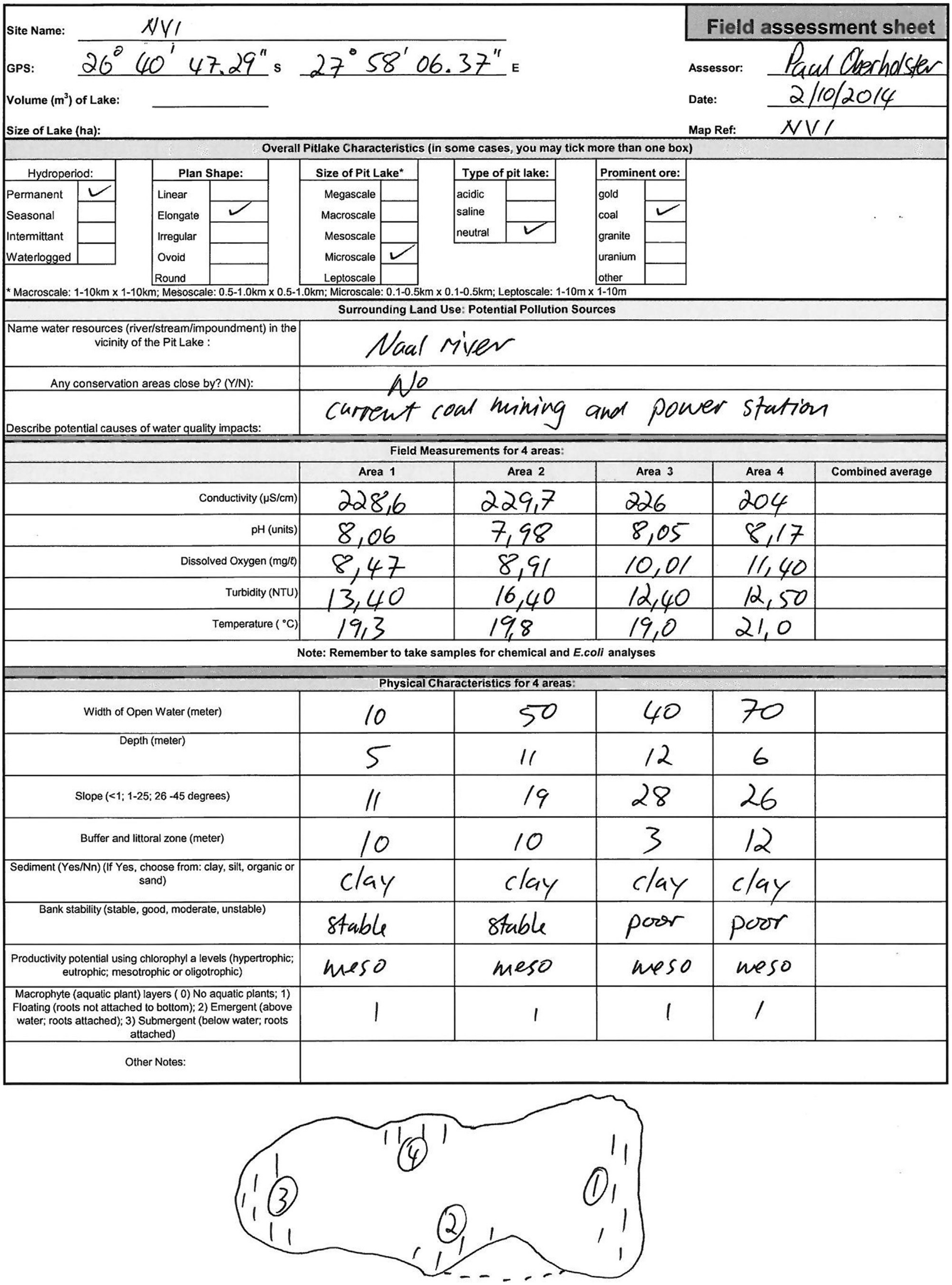


Fig. 3. The New Vaal colliery is a restored pit lake, created as a result of coal mining activities.



Field assessment sheet

Site Name: NV1

GPS: 26° 40' 47.29" S 27° 58' 06.37" E

Assessor: Paul Oberholster

Volume (m^3) of Lake:

Date: 2/10/2014

Size of Lake (ha):

Map Ref: NV1

Overall Pitlake Characteristics (in some cases, you may tick more than one box)

Hydroperiod:		Plan Shape:		Size of Pit Lake*		Type of pit lake:		Prominent ore:	
Permanent	☑	Linear	☐	Megascale	☐	acidic	☐	gold	☐
Seasonal	☐	Elongate	☑	Macroscale	☐	saline	☐	coal	☑
Intermittant	☐	Irregular	☐	Mesoscale	☐	neutral	☑	granite	☐
Waterlogged	☐	Ovoid	☐	Microscale	☑			uranium	☐
		Round	☐	Leptoscale	☐			other	☐

* Macroscale: 1-10km x 1-10km; Mesoscale: 0.5-1.0km x 0.5-1.0km; Microscale: 0.1-0.5km x 0.1-0.5km; Leptoscale: 1-10m x 1-10m

Surrounding Land Use: Potential Pollution Sources

Name water resources (river/stream/impoundment) in the vicinity of the Pit Lake :	Vaal river
Any conservation areas close by? (Y/N):	No
Describe potential causes of water quality impacts:	current coal mining and power station

Field Measurements for 4 areas:

	Area 1	Area 2	Area 3	Area 4	Combined average
Conductivity (μS/cm)	228,6	229,7	226	204	
pH (units)	8,06	7,98	8,05	8,17	
Dissolved Oxygen (mg/ℓ)	8,47	8,91	10,01	11,40	
Turbidity (NTU)	13,40	16,40	12,40	12,50	
Temperature (°C)	19,3	19,8	19,0	21,0	

Note: Remember to take samples for chemical and *E.coli* analyses

Physical Characteristics for 4 areas:

Width of Open Water (meter)	10	50	40	70	
Depth (meter)	5	11	12	6	
Slope (<1; 1-25; 26 -45 degrees)	11	19	28	26	
Buffer and littoral zone (meter)	10	10	3	12	
Sediment (Yes/Nn) (If Yes, choose from: clay, silt, organic or sand)	clay	clay	clay	clay	
Bank stability (stable, good, moderate, unstable)	stable	stable	poor	poor	
Productivity potential using chlorophyl a levels (hypertrophic; eutrophic; mesotrophic or oligotrophic)	meso	meso	meso	meso	
Macrophyte (aquatic plant) layers (0) No aquatic plants; 1) Floating (roots not attached to bottom); 2) Emergent (above water; roots attached); 3) Submergent (below water; roots attached)	1	1	1	1	
Other Notes:					

Fig. 4. Field assessment sheet for Maccauvlei.

reconciled in order to adjust for the difference in the relative functionality between pit lakes and wetlands. This was done by means of a PLI which was used as weight indicating the relative substitutability of pit lake services for wetland services. The relative performance of a particular pit lake in terms of its ability to substitute for wetland services was determined by pairing the categories of the output sheet of the PLI (Table 2) with assumed substitutability levels between wetlands and pit lakes (Table 8).

While we acknowledge the non-linearity of ecosystem functionality and value approximation, a perfect substitute in terms of functionality infer an almost equal value (i.e. 95% of wetland value), whilst a PLI score of between 20 and 40 implies 20–40% functionality of a pristine wetland inferring a 30% substitutability of the wetland value.

The next section describes the use of the PLI and substitutability weights in a South African case study.

6. South African case study

A pit lake in the New Vaal colliery (see Fig. 3) was used as a case study. New Vaal colliery is situated next to the Vaal River in the Maccauvlei area, south of the town of Vereeniging of South Africa. The colliery was established in the early 1980s to mine coal reserves to supply low grade coal for generating electricity until 2030. The mine operates according to the open-cut strip method to extract remaining coal left from underground mining that took place in the area during the 1960s. It produces approximately 18 million tonnes per year.

The research team conducted a field assessment of the study site in 2015 (see Fig. 4).

The results of the assessment showed that the selected pit lake was categorized according to the standard ecological categories of the South African Department of Water Affairs' (DWA, 2004; DWAF, 2007) as "Class D" (i.e. largely modified) with its surrounding catchment revealing a range of possible causes contributing to its state. The most important cause turned out to be salinity, as reflected in above average electrical conductivity values. High salinity triggered a chain of events which led to a reducing in phytoplankton productivity, and subsequent life forms. A class "D" rating implies a 50% substitutability of services and associated values (see Table 9).

If it is assumed that all of the services presented in Table 9 are mutually exclusive (which of course is not the case), it means the value could be aggregated to a theoretical value for pit lake services of USD 1238 per hectare per year. This figure could then be extrapolated based on the size of a pit lake in order to yield the estimated value of the pit lake as a whole. However, the level of exclusivity between services varies because of the interlinked nature of ecosystem services and because many supporting services (intentionally excluded from this study) simultaneously serves as input for several 'final' services. A simple aggregation would therefore be an over estimate due to double-counting. However, appropriate service-specific proportional weighing to account for double-counting, and deciding on whether or not to include a particular service in an aggregation of the total value derived from the pit lake, is an area-specific question and study for which the current tool does not allow for. We present and discuss more limitations in the next section.

7. Conclusion

The implementation of reclamation legislation for the South African mining sector has increased the political urgency and the consequent demand for information on environmental services to support and improve the management of pit lakes. With currently no protocol in place to compare and rank pit lakes, we designed an interim solution for preliminary screening of these water bodies within comparable socio-economic contexts until more sophisticated, inclusive models becomes available.

We employed a pit lake index together with unit value transfers to identify those pit lakes worthy of restoration. As far as could be established, this is the first attempt of creating a standardised way of assessing the current state of pit lakes paired to a monetary valuation of services to be expected from such water bodies which can then be used for ranking purposes. However, the results with regard to the valuation per se as presented in this rapid assessment should be interpreted with caution as the base values originated from several studies focusing on wetlands which should be considered an over-estimate of the values for pit lakes. Weighing was done by means of the PLI and although the main reason for applying the index, was an attempt to account for this limitation, it does not replace the need for dedicated site-specific valuation case-studies once the pit lakes to be focused on has been identified. Furthermore, two meta-analyses on wetland studies have concluded that there are no predictive trends in monetary value (Brouwer et al., 1999; Woodward and Wui, 2001), which strengthens the case for caution when deriving values for pit lakes from wetland based studies. Care should be taken in selecting appropriate studies to be used for these benefit transfer estimates.

The reader should note that the focus of the study was not on

Table 9
Index rating and corresponding substitutability values for pit lake "NV1".

Service type	Service	Index rating	Substitutability for wetland value (%)	weighed value (USD per hectare)
Provisioning	Food	D	50	127
	Freshwater	D	50	212
	Fibre and Fuel	D	50	19
	Biochemical	D	50	0.5
	Genetic material	D	50	0.5
Regulating	Climate regulation	D	50	12
	Water regulation	D	50	12
	Erosion regulation	D	50	0.5
	Natural hazard regulation/flood control/attenuation	D	50	209
	Water purification and waste treatment	D	50	16
	Refugia	D	50	312
Cultural	Spiritual and inspiration/aesthetic	D	50	44
	Recreational (e.g. angling and tourism)	D	50	271
	Educational	D	50	1
Total				1238

the inclusive valuation of pit lake services as the full inclusive valuation of pit lakes are not required for making consistent comparisons between these water bodies. Multi-Criteria decision theory (Belton and Stewart, 2002) confirms that the minimum amount of information required to facilitate a choice between options is that amount of information that will allow comparison, i.e. that marginal difference that present the trade-offs between options. In depth assessments of the ecological condition of the target sites and fully inclusive valuation of service will add to the accuracy of measurement and will be useful to monitor the performance of restoration initiatives, but will not improve the consistence of comparison. It is therefore not necessary to benchmark measurement and valuation accuracy if the objective is to 'compare' and if the same protocol is used in a consistent way to compare options. In fact, consistency is an absolute requirement for comparison, hence the development of a protocol, i.e. standardised/consistent way of comparing.

The index is not currently able to differentiate on service level, i.e. if a pit lake is allocated a score of "D", all subsequent services from the pit lake are scored a "D", implying a 50% substitutability of service delivery and associated value. I.e. service level differentiation is currently not possible, e.g. allocate a "D" score for 'food provisioning', but an "E" for 'freshwater'. Last-mentioned can be improved upon by refining the index to enable such differentiation, which will require a significant expansion of field assessment sheets. Furthermore, the integrated nature of the intermediate inputs of the services and the causal impacts of the state of the pit lake on these inputs makes for complex modelling. Accurate attributebility of impacts on intermediate input, becomes a major challenge, and last-mentioned is a topic of ongoing research. For the interim the tool can be used to identify those pit-lakes worthy of restoration.

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References

Alabaster, J.S., Lloyd, R., 1982. Water Quality Criteria for Freshwater Fish, second ed., ISBN 9780408108492, p. 261 London.

Arrow, K., 1950. A difficulty in the concept of social welfare. J. Polit. Econ. 58, 328–346.

Barling, R.D., Moore, I.D., 1994. Role of buffer strips in management of waterway pollution: a review. Environ. Manag. 18, 545–558.

Bateman, I.J., Brouwer, R., Ferrini, S., Schaafma, M., Barton, D., Dubgaard, A., 2011. Making benefit transfers work: deriving and testing principles for value transfers for similar and dissimilar sites using a case study of non-market benefits of water quality improvement across Europe. Environ. Resour. Econ. 50, 365–387.

Belton, V., Stewart, T.J., 2002. Multiple Criteria Decision Analysis: an Integrated Approach. Kluwer Academic Press, London.

Bergstrom, J.C., Taylor, L.O., 2006. Using meta-analysis for benefits transfer: theory and practice. Ecol. Econ. 60, 351–360.

Bergstrom, J.C., De Civita, P., 1999. Status of benefits transfer in the United States and Canada: a review. Can. J. Agric. Econ. 47, 79–87.

Blanchette, M.L., Lund, M.A., 2016. Pit lakes are a global legacy of mining: an integrated approach to achieving sustainable ecosystems and value for communities. Curr. Opini.Environ. Sustain. 23, 28–34.

Bren, L.J., 1993. Riparian zone, stream, and floodplain issues: a review. J. Hydrol. 150, 277–299.

Brouwer, R., Langford, I.H., Bateman, I.J., Turner, R.K., 1999. A meta-analysis of wetland contingent valuation studies. Reg. Environ. Change 1, 47–57.

Castelle, A.J., Johnson, A.W., Conolly, C., 1994. Wetland and stream buffer size requirements - a review. J. Environ. Qual. 23, 878–882.

Crabb, P., 1997. Murray-darling Basin Resources. Murray-Darling Basin Commission. CSIRO publishing, Canberra, ISBN 9781875209583, p. 308.

Dallas, H.F., Day, J.A., 1993. The Effect of Water Quality Variables on Riverine Ecosystems: a Review. Water Research Commission Report No. TT 61/93, Pretoria.

DWA, 2010. The Nature, Distribution and Value of Aquatic Ecosystem Services of the Olifants, Inkomati and Usutu to Mhlatuze Water Management Areas. Contract Report by Anchor Environmental Consultants for Department: Water Affairs, 362 pp. http://www.anchorenvironmental.co.za/Documents/Pdfs/EGSA%20Final%20report.pdf. (Accessed 6 July 2017).

DWA, 2004. Development of a Framework for the Assessment of Wetland Ecological Integrity in South Africa, Phase 1: Situation Analysis, Resource Quality Services. Department of Water Affairs and Forestry, Pretoria, South Africa, p. 192. http://www.dwa.gov.za/iwqs/reports/Wetlands/WetIndex_FIN_Sep042-edits.pdf. (Accessed 6 July 2017).

DWAF, 2007. Manual for the Assessment of a Wetland Index of Habitat Integrity for South African Floodplain and Channelled Valley Bottom Wetland Types. Department of Water Affairs and Forestry, Pretoria. Report No. N/0000/WEI/0407, Resource Quality Services. http://www.dwa.gov.za/iwqs/rhp/wetlands/WETLAND_IHI_final.pdf. (Accessed 6 July 2017).

Eshet, T., Ayalon, O., Shechter, M., 2005. A critical review of economic valuation studies of externalities from incineration and landfilling. Waste Manag. Res. 23, 487–504.

Genthe, B., Oberholster, P.J., De Lange, W.J., 2017. Evaluation of the Post Coal Mining Landscapes in Mpumalanga for Realistic Mitigation Options to Regain Wetland Losses and Reduce Human Health Impacts. CSIR report number: CSIR/NRE/WR/IR/2017/0038/B, Pretoria.

Gerber, A., Cilliers, C.J., Van Ginkel, C., Glen, R., 2004. Easy Identification of Aquatic Plants. Department of Water Affairs and Forestry, Pretoria, South Africa, p. 73. http://www.dwa.gov.za/iwqs/biomon/aquaplantsa/DWAF_2004_Easy_identification_of_Aquatic_Plants_web.pdf. (Accessed 6 July 2017).

Gómez-Mercado, F., Del Moral Torres, F., Giménez, Luque, E., De Haro Lozano, S., 2012. Salinity tolerance of the hygrophilus plant species in the wetlands of the south of the Iberian Peninsula. Not. Bot. Horti Agrobot. Cluj-Napoca 40, 18–28.

Harris, K., Crafford, J., 2014. Limiting and Mitigating the Impact of Coal Mines on Wetlands. Report Prepared for Coaltech by Prime Africa, Pretoria. http://www.wrc.org.za/Knowledge%20Hub%20Documents/Briefs/Briefs%202016/TB_2230_Limiting%20the%20impact%20of%20coal%20mines%20on%20wetlands.pdf. (Accessed 6 July 2017).

Hillman, T.J., 1986. Billabongs. In: De Decker, P., Williams, W.D. (Eds.), Limnology in Australia,. Dr W. Junk Publishers, CSIRO, the Netherlands, Melbourne, Australia.

Hoehn, J.P., 2006. Methods to address selection effects in the meta regression and transfer of ecosystem values. Ecol. Econ. 60, 389–398.

Johnston, R.J., Rolfe, J., Rosenberger, R.S., Brouwer, R., 2015. Benefit Transfer of Environmental and Resource Values: a Guide for Researchers and Practitioners. Springer Media, Dordrecht, ISBN 978-94-017-9929-4.

Johnston, R.J., Wainger, L.A., 2015. Benefit transfer of ecosystem service valuation: an introduction to theory and practice. In: Johnston, R.J., Rolfe, J., Rosenberger, R.S., Brouwer, R. (Eds.), 2015 Benefit Transfer of Environmental and Resource Values: a Guide for Researchers and Practitioners. Springer Media, Dordrecht, ISBN 978-94-017-9929-4.

Johnston, R.J., Rosenberger, R.S., 2010. Methods trends and controversies in contemporary benefit transfer. J. Econ. Surv. 24, 479–510.

Kalff, J., 2001. Limnology: Inland Water Ecosystems. Prentice Hall, Upper Saddle River, New Jersey, USA.

Kaul, S., Boyle, K.J., Kuminoff, N.V., Parmeter, C.F., Pope, J.C., 2013. What can we learn from benefit transfer errors? Evidence from 20 years of research on convergent validity. J. Environ. Econ. Manag. 66, 90–104.

Kleynhans, C.J., Louw, M.D., 2007. Module a: Eco-classification and Eco-status Determination in River EcoClassification: Manual for Eco-status Determination. Water Research Commission Report No. TT329/08, Pretoria.

Kleynhans, C.J., 1996. A qualitative procedure for the assessment of the habitat integrity status of the Luvuvhu River. J. Aquat. Ecosys. Health 5, 41–54.

Kleynhans, C.J., 1999. A Procedure for the Determination of the Ecological Reserve for the Purpose of the National Water Balance Model for South African Rivers. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria. http://www.dwa.gov.za/iwqs/rhp/eco/EcoStatus/ModuleA_EcoStatus/ModuleA_EcoClassification.pdf. (Accessed 6 July 2017).

Loomis, J.B., Rosenberger, R.S., 2006. Reducing barriers in future benefit transfers: needed improvements in primary study design and reporting. Ecol. Econ. 60, 343–350.

Macfarlane, D.M., Bredin, I.P., 2016. Buffer Zone Guidelines for Rivers, Wetlands and Estuaries. Water Research Commission Report No. TT 610/14, Pretoria. 163 pp.

Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: a Framework for Assessment. Millennium Ecosystem Assessment. Island Press, Washington D.C., 245 pp.

Mitchell, P., 1990. The Environmental Conditions of Victoria Streams. Department of Water Resources, Melbourne, Victoria, ISBN 072417267X, p. 65. http://www.epa.vic.gov.au/~/media/Publications/909.pdf. (Accessed 6 July 2017).

Mitsch, W.J., Gosselink, J.G., 2000. Wetlands 3, third ed. John Wiley& Sons Inc, New York.

Moeltner, K., Boyle, K.J., Paterson, R.W., 2007. Meta-analysis and benefit transfer for resource valuation: addressing classical challenges with Bayesian modelling. J. Environ. Econ. Manag. 53, 250–269.

Nahman, A., Wise, R., De Lange, W.J., 2009. Environmental and resource economics in South Africa – status quo and lessons for developing countries. South Afr. J. Sci. 105, 350–355.

Napier, V., Turpie, J.K., Clark, B., 2009. Value and management of the subsistence fishery at Knysna estuary, South Africa. Afr. J. Mar. Sci. 31, 297–310.

Oberholster, P.J., Genthe, B., Hill, L., 2017. Development of a Mine Pit Lake Index (PLI) for Management of Water Resources. CSIR report number CSIR/NRE/WR/IR/2017/0038/B, Pretoria.

Oberholster, P.J., McMillan, P., Durgapersad, K., Botha, A.M., De Klerk, A., 2014. The development of a wetland classification and risk assessment index for non-wetland specialists for the management of natural freshwater wetland ecosystems. Water Air Soil Pollut. https://doi.org/10.1007/s11270-013-1833-5.

Oberholster, P.J., Blaise, C., Botha, A.M., 2010. Phytobenthos and phytoplankton community changes upon exposure to a sunflower oil spill in a South African protected freshwater wetland. Ecotoxicology 19, 1426–1439.

Palmer, R.W., Turpie, J., Marnewick, G.C., Batchelor, A.L., 2002. Ecological and Economic Evaluation of Wetlands in the Upper Olifants River Catchment, South Africa. Water Research Commission Report No. 1162/1/02. Pretoria. 138 pp.

Parks, S., Gowdy, J., 2013. What have economists learned about valuing nature? A review essay. Ecosyst. Serv. 3, 1–10.

Pressey, R.L., 1987. A Survey of Wetlands of the Lower Macleay Floodplain, New South Wales. New South Wales National Parks and Wildlife Service, Melbourne, ISBN 9780730520191, p. 244.

Rosenberger, R.S., Loomis, J.B., 2000. Using meta-analysis for benefit transfer: in-sample convergent validity tests of an outdoor recreation database. Water Resour. Res. 36, 1097–1107.

Rolfe, J., 2006. A simple guide to choice modelling and benefit transfer. In: Rolfe, J., Bennett, J. (Eds.), Choice Modelling and the Transfer of Environmental Values. Edward Elgar, Cheltenham.

Rolfe, J., Windle, J., Johnston, R.J., 2015. Applying benefit transfer with limited data: unit value transfer in practice. In: Johnston, R.J., Rolfe, J., Rosenberger, R.S., Brouwer, R. (Eds.), 2015 Benefit Transfer of Environmental and Resource Values: a Guide for Researchers and Practitioners. Springer Media, Dordrecht, ISBN 978-94-017-9929-4.

Schuyt, K.D., 2005. Economic consequences of wetland degradation for local populations in Africa. Ecol. Econ. 53, 177–190.

Semeniuk, C.A., 1987. Wetlands of the Darling system – a geomorphic approach to habitat classification. J. Roy. Soc. West Aust. 69, 95–112.

Semeniuk, C.A., Semeniuk, V., 1995. A geomorphic approach to global classification for inland wetlands'. Vegetatio 118, 103–124.

Seyam, I.M., Hoekstra, A.Y., Ngabirano, G.S., Savenije, H.H.G., 2001. The Value of Freshwater Wetlands in the Zambezi Basin. Value of Water Research Report Series No. 7. International Institute for Infrastructural, Hydraulic, and Environmental Engineering, Delft, 2001. https://www.utwente.nl/en/et/wem/staff/hoekstra/reports/report7.pdf. (Accessed 6 July 2017).

Shrestha, R.K., Loomis, J.B., 2001. Testing a meta-analysis model for benefit transfer in international outdoor recreation. Ecol. Econ. 39, 67–83.

Shrestha, R.K., Loomis, J.B., 2003. Meta-analytic benefit transfer of outdoor recreation economic values: testing out-of-sample convergent validity. Environ. Resour. Econ. 25, 79–100.

Smith, V.K., Pattanayak, S.K., 2002. Is meta-analysis a Noah's Ark for non-market valuation? Environ. Resour. Econ. 22, 271–296.

Turpie, J., Barnes, J., Arntzen, J., Nherera, B., Lange, G.M., Buzwani, B., 2006. Economic Value of the Okavango Delta, Botswana, and Implications for Management. Okavango Delta Management Plan. 139 pp. Report available: http://www.the-eis.com/data/literature/jwwREPDelta%20Okavango%20Delta%20Valuation%20Study%20FINAL%20REPORT.pdf.

Turpie, J., Joubert, A., van Zyl, H., Harding, B., Leiman, A., 2001. Valuation of Open Space in the Cape Metropolitan Area. A Pilot Study to Demonstrate the Application of Environmental and Resource Economics Methods for the Assessment of Open Space Values in Two Case Study Areas: Metro South and Metro South-east. Report to the City of Cape Town. 104 pp.

Turpie, J., Smith, B., Emerton, L., Barnes, J., 1999. Economic Value of the Zambezi Basin Wetlands. Report to IUCN. 199 pp. Report available: https://portals.iucn.org/library/sites/library/files/documents/1999-098.pdf.

Turpie, J.K., Clark, B.M., 2007. The Health Status, Conservation Importance, and Economic Value of Temperate South African Estuaries and Development of a Regional Conservation Plan. Water Research Commission Report No. TT441/09, Pretoria.

Turpie, J.K., Joubert, A.J., 2004. Estimating the recreational use value of estuaries: a case study of the Knysna estuary. In: Turpie, J.K., Hosking, S. (Eds.), Proceedings of a National Workshop on Resource Economics as a Tool for the Management and Conservation of Estuaries in South Africa. Report by Anchor Environmental Consultants for Department of Environmental Affairs and Tourism. 120 pp. https://www.overstrand.gov.za/en/documents/town-planning/legislation/national-environmental-management-integrated-coastal-management-act-24-of-2008/1281-no-9-guideline-economic-value-oct-2007/file. (Accessed 6 July 2017).

Turpie, J.K., 2000. The Use and Value of Natural Resources of the Rufiji Floodplain and Delta, Tanzania. Rufiji Environmental Management Project and IUCN – Eastern Africa Regional Office. Ecological and Resource Economics Consulting, 116 pp. http://www.cf.tfcg.org/pubs/REMP%2020%20TR17%20Value%20of%20Natural%20Resources.pdf. (Accessed 6 July 2017).

Turpie, J.K., 2006. Kromme/seekoei Catchments Reserve Determination Study – Technical Component. Socio-economics Report. Prepared by Anchor Environmental Consultants for Coastal and Environmental Services. Report no. RDM/K90/00/CON/1105. 91 pp. http://www.dwa.gov.za/rdm/Projects_SeekoeiKrommeRiver.aspx. (Accessed 6 July 2017).

Van Zyl, H., Leiman, A., 2002. Hedonic approaches to estimating the impacts of open spaces: a case study in the Cape. S. Afr. J. Econ. Manag. Sci. 5, 379–394.

Vo, Q.T., Kuenzer, C., Minh, Q., Moder, F., Oppelt, N., 2012. Review of valuation methods for mangrove ecosystem services. Ecol. Econ. 23, 431–446.

Williams, W.D., 1983. Life in Inland Waters. Blackwell Scientific publications, Melbourne.

Wilson, M.A., Hoehn, J.P., 2006. Valuing environmental services using benefit transfer: the state-of-the art and science. Ecol. Econ. 60, 335–342.

Woodward, R.T., Wui, Y., 2001. Analysis: the economic value of wetland services: a meta-analysis. Ecol. Econ. 37, 257–270.