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Methodological and empirical considerations when assessing freshwater ecosystem service provision in a developing city context: Making the best of what we have

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ABSTRACT

This study contributes to both the methodological and empirical literature by developing an integrative approach to assessing temporal and spatial change in riparian ecosystem service delivery by drawing on available and diverse data sets. These data sets act as multiple lines of evidence in supporting comparisons between data sets to test the validity of developed methods and the application of such methods. In order to synthesise these data as well as to determine the fluctuations in riparian ecosystem service provision a scoring system was developed. Methodologically, the scoring system proved informative across the majority of ecosystem services categories, showing close to 80% similarity in outcomes when comparing the scoring method to trends in long-term water quality measurements. Other benefits of the scoring system included its design simplicity, cost-effectiveness, and applicability and replicability across various urban settings. Empirically, the data sets used support the findings of the ecosystem services scoring exercise and suggests that fluctuations in ecosystem service delivery through time and across the river reaches are linked to land-use change and other human activities. Findings suggest that as water leaves an urban protected area and travels across transformed and impacted landscapes, the results are poor water quality and diminished ability of rivers to yield ecosystem services the further the river flows into the urban setting. Urbanisation and changes in land-uses in developing city contexts is therefore shown to affect potential ecosystem services benefits, necessitating increasing management interventions.

1. Introduction

Since the first half of the twentieth century, there has been a significant transition from undisturbed to human-dominated landscapes across many areas of the globe (Sánchez-Azofeifa et al., 2003; Tscharntke et al., 2005). This transition has greatly impacted the functioning of ecosystems by altering their ability to meet human physical and social needs (Larondelle and Haase, 2013; Pickett et al., 2004). Demands on natural capital and ecosystem services (ES) keep growing steadily (Gómez-Baggethun et al., 2013) and we increasingly recognise that these human actions are the principal threat to the ecological and physical integrity of landscapes and ecosystems. Freshwater ecosystem systems are particularly vulnerable because rivers are dynamic and have recurrent disturbances (Everard and Moggridge, 2012; Nilsson and Bergren, 2000) with human demands and actions such as changes in land cover impacting on ecological processes, habitat and biota (Brown and Vivas, 2005), water quality, as well as the supply of specific ES (Burkhard et al., 2012) via numerous and complex pathways (Allan, 2004; Townsend et al., 2003) and across multiple scales. Although most urban river systems are heavily degraded (Everard and Moggridge, 2012; Findlay and Taylor, 2006), these systems are recognised as important natural ecological networks, providing critical cultural, provisioning and regulating services to city residents (Loomis et al., 2000; Zander and Straton, 2010).

River ecologists have long recognised that rivers and streams are influenced by the landscapes through which they flow (Allan, 2004; Everard and Moggridge, 2012). Protected areas within urban areas, such as national parks, contain ecological infrastructure including freshwater ecosystems, which provide valuable ES (Bolund and Hunhammar, 1999; Gómez-Baggethun et al., 2013; Larondelle and Haase, 2013). As water moves from these natural spaces into more disturbed and altered landscapes, the ecological and physical characteristics of the rivers typically change both through space, and as the urban land use and land cover develops and changes, through time, impacting on the ES that urban resi-

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dents receive (Costanza et al., 2006; Reeves et al., 1995). However, it is difficult to assess the impacts on ES delivery as a result of land-use change so that approaches need to be developed to achieve a better understanding of these changes over time (Large and Gilvear, 2015; Wong et al., 2015).

Quantitative and/or qualitative data that allow us to understand change over time relating to the contribution of urban rivers and streams to the delivery of ES is scarce (Lundy and Wade, 2011). There is often a lack of long-term data for effective analyses, mapping and modelling of systems (Bertzky and Stoll-Kleemann, 2009; Large and Gilvear, 2015; Raudsepp-Hearne et al., 2010). This may be as a result of the expense of recording and measuring environmental variables, as well as a lack of capacity for data gathering and storage in developing regions (Millennium Ecosystem Assessment, 2005). Additionally, there is often little research focused on the influence of land use on the state and functioning of aquatic ecosystems, resulting in deficient, inadequate or non-existent data (Wong et al., 2015). This hinders our understanding of what ES are delivered under anthropogenically altered conditions (Bennett et al., 2009; Large and Gilvear, 2015). These data shortcomings make researching the impacts of land-use change on freshwater ecosystems that much more challenging, requiring creative and novel methodological research approaches in cities (Keeler et al., 2012).

This study contributes to both the empirical and methodological literature by exploring how anthropogenic-driven changes in urban riparian landscapes in a developing region impact on the supply of ES. There were two objectives in this study. The first considered the development of a novel assessment approach, using available and diverse data sets. These data sets acted as multiple lines of evidence, supporting the outcomes from comparisons between the assessment approach and long-term water quality data. The second objective was to validate the assessment approach by applying it to case-study rivers in a developing city context. We integrate land-use changes and contrast these with long-term water-quality data to assess the levels of ES provision of three case study rivers in the city of Cape Town, South Africa, across a multidecadal period. These rivers flow from a protected area into the metropolitan environment where the impacts of land-use change and the ability of measured indicators to capture change can be assessed. Gradients of landscape change and variations in water quality over time and along river reaches are related to the capacity of these freshwater systems to supply ES.

2. Study area

2.1. Cape Town

The city of Cape Town is located on the south-western tip of southern Africa (Fig. 1) and occupies an area of roughly 2460 km^2 with a population of 3.7 million people (StatsSA, 2011). The city has a varied topography, with mountain ranges in the south-west and east, a low-lying highly-urbanised region in the centre known as the Cape Flats, coastal areas on the southern and western borders and agricultural areas in the north-east (Rebelo et al., 2011). Considerable changes to the landscapes around Cape Town have occurred since European arrival in the 1600s. Much of the native forests and natural vegetation has been removed, making way for agriculture, formal and informal residential areas, as well as commercial and industrial centres (Anderson and O'Farrell, 2012). Changes to the landscape through development and urban sprawl, such as an increase in hard surfaces (Trombulak and Frissell, 2000) continue to impact on natural areas in Cape Town (Turok and Watson, 2001). The amount of natural versus disturbed vegetation cover is also of concern as there are high incidences of plant species which are threatened with extinction (Rebelo et al., 2011).

The waterways and waterbodies of Cape Town have been pivotal in the history of the Cape shaped by the region's political and social history as well as by nature and technology (Brown and Magoba, 2009). These water systems have provided numerous ES and were a driving factor in historic engagements with the region (Anderson and O'Farrell, 2012; O'Farrell et al., 2012). This social engagement has placed tremendous demands on natural resources and urban infrastructure in and around the rivers of Cape Town and has had a substantial effect on the ecological integrity and functioning of the city's riparian landscapes and systems (Brown and Magoba, 2009). River courses have also been redirected, excavated, canalized and silted up with eroded sediment (Water Research Commission, 2007). These changes to freshwater systems are further compounded by pollution which is often discharged via stormwater outlet pipes or washed directly into rivers. Further, the hardening of the catchments has increased peak stormwater runoff during rainstorms well beyond natural levels (Brown and Magoba, 2009; Lundy and Wade, 2011) so compounding many other land-management issues. Many of Cape Town's rivers are described as being in a poor state with efforts to rehabilitate them often hampered by the duration and scale of change since their pre-disturbance condition (Anderson and O'Farrell, 2012).

2.2. Rivers under review

This study focused on three rivers in Cape Town, namely the Liesbeek, Sand and Silvermine Rivers (Fig. 1). These rivers were selected because their headwaters are in Table Mountain National Park (TMNP), their varying degrees of anthropogenic impacts over time and the availability of municipal records of water-quality monitoring.

2.2.1. Liesbeek River

The Liesbeek River, which is approximately 9 km long, is situated in the oldest urbanised river valley in South Africa. Records of indigenous use are limited, but major extraction and use was seen from the 1650s (Brown and Magoba, 2009). The headwaters of the Liesbeek River flow from the eastern slopes of Table Mountain where the vegetation is largely indigenous and undisturbed. The course of the Liesbeek River follows a north-north-east striking fault zone (Brown and Magoba, 2009). Water abstraction occurs along much of the river's path causing the flow to reduce during the summer months (Water Research Commission, 2007). Approximately 40% of the river's course is canalized (City of Cape Town, 2005).

2.2.2. Sand River

The Sand River is approximately 4 km long (City of Cape Town, 2005). The Sand River catchment area is located in TMNP and feeds a number of other rivers in the area. There are confluences with the Diep River and Brommersvlei Stream in the upper reaches of the catchment. The gentle gradient of the landscape in which the Sand River is located allows the river to follow the course of the underlying palaeovalleys (Brown and Magoba, 2009), flowing in a southerly direction. A reduction in summer flow in the Sand River is due to invasive tree species and water abstraction. Approximately 75% of this river is canalized (City of Cape Town, 2005).

2.2.3. Silvermine River

The Silvermine River is approximately 11 km long. The river's headwaters are in TMNP. The river course is controlled by the major lineaments in the surrounding geomorphology (Brown and Magoba, 2009) and flows in a south-westerly direction. There is a reduction in summer flows in the Silvermine River as a result of water abstraction (City of Cape Town, 2005). Alien invasive plants reduce flow all year round (Brown and Magoba, 2009). Although

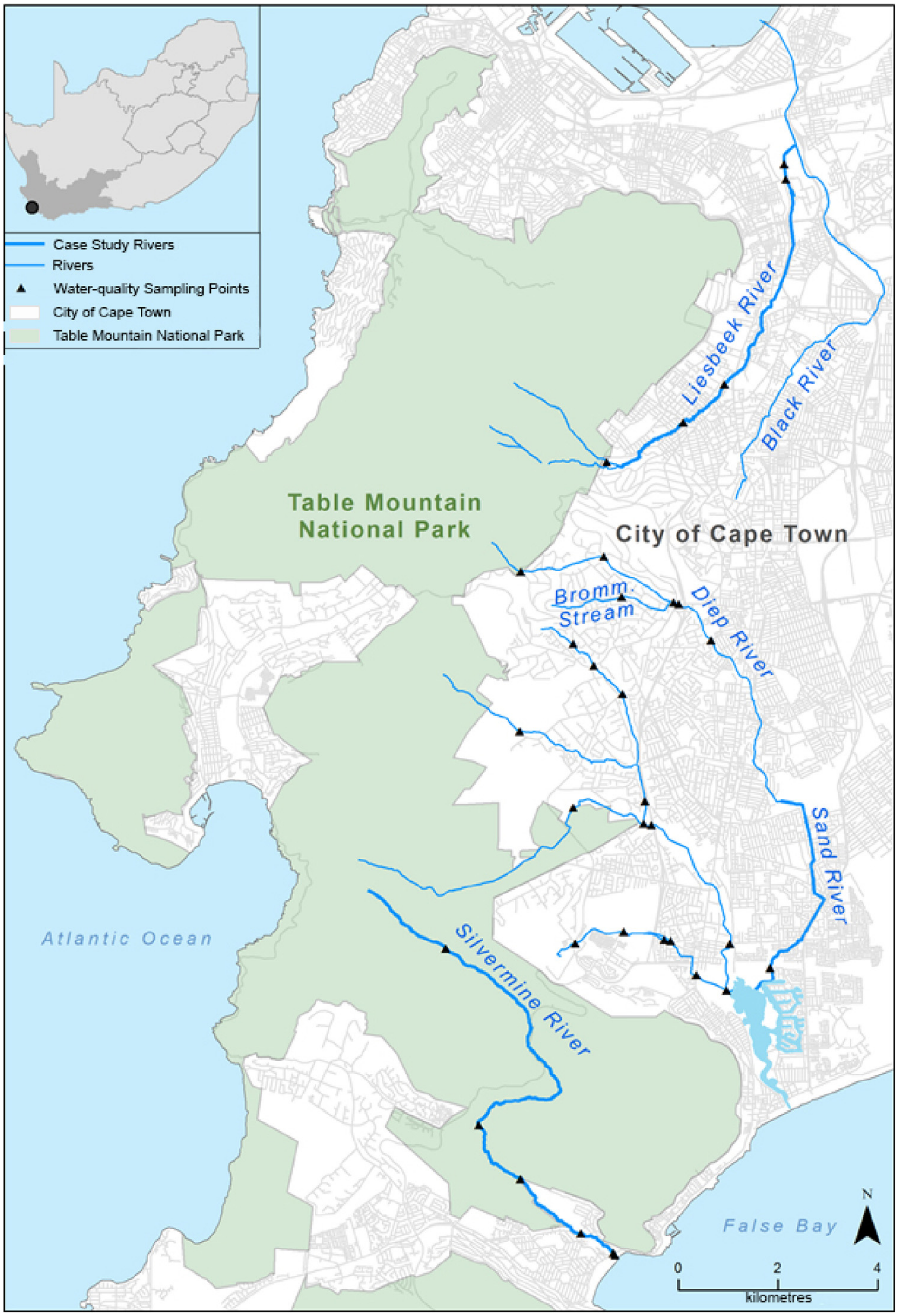

Fig. 1. Location of the Liesbeek, Sand and Silvermine Rivers in Cape Town, South Africa. The Brommersvlei Stream is abbreviated to Bromm. Stream.

alien-vegetation clearing has taken place in the middle reaches of the Silvermine River, garden-variety exotics pose a threat to its habitat diversity, the recovery of indigenous vegetation and aquatic life (City of Cape Town, 2005). No part of the Silvermine River is canalized.

3. Methods and materials

The methods developed and materials used in this study integrate numerous and varied data sources. These include the use of aerial photographs and geographic information systems (GIS) to determine levels of land-use change within a river buffer zone, as well as the selection of freshwater ES based on various literature. Using these data, this study developed a novel scoring system to determine ES change over temporal and spatial scales. Historical water-quality data are used as another line of evidence which suggest changes in ES over time. A flowchart of the steps followed in this study is presented in Fig. 2.

3.1. Assessing land-use change

Available aerial photographs of the study areas were obtained from the Department of Rural Affairs and Land Reform for 1977, 1988, 2001 and 2010. Only one photograph per area per time

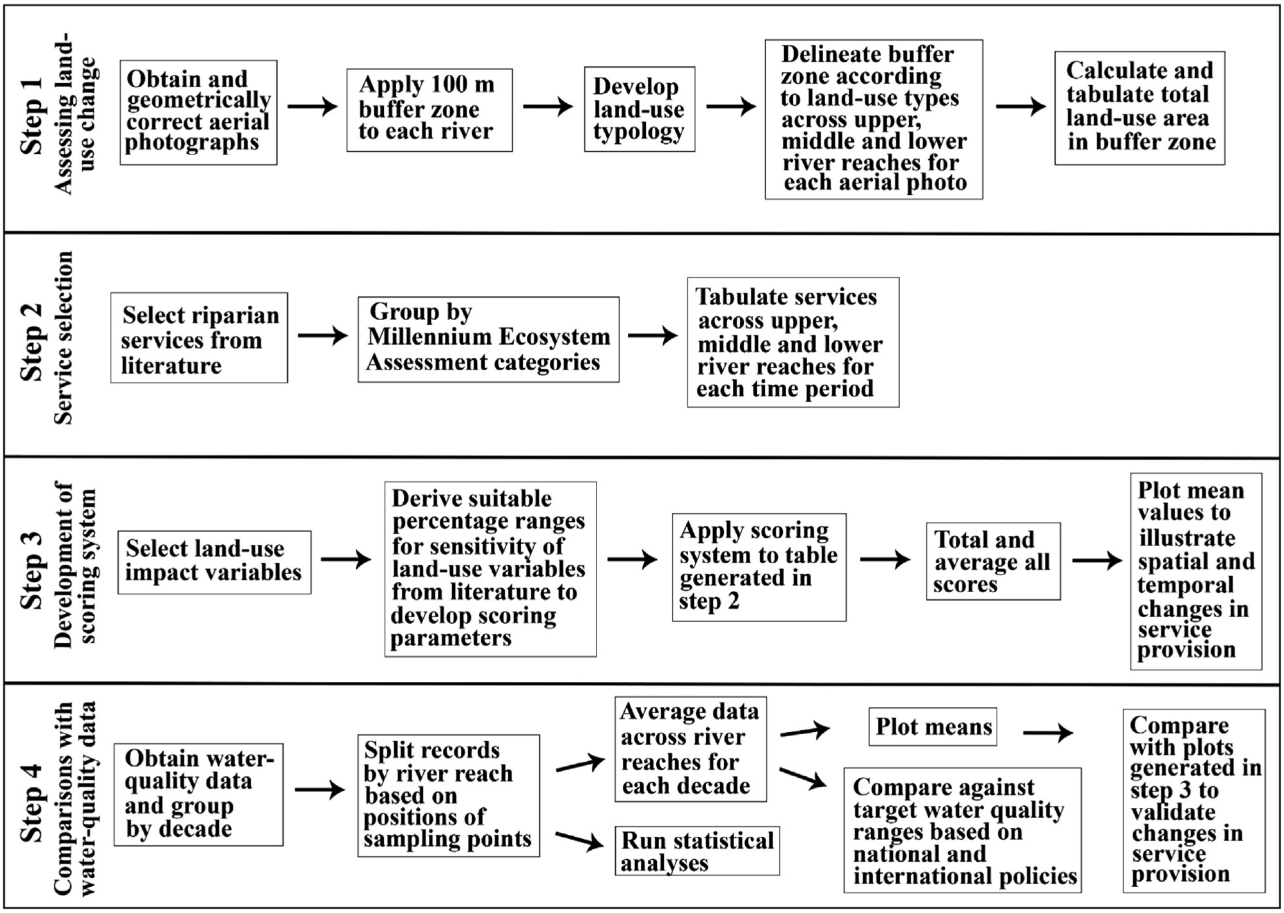

Fig. 2. Methodological framework used to determine levels of change in freshwater ecosystem services in Cape Town, South Africa.

period was captured. The average time period between aerial photographs used in this study is 11 years. Aerial photographs were geometrically corrected to ensure that the scale of the study sites was uniform and the photographs were georeferenced using Esri's ArcGIS against the 2010 aerial photographs. The aerial photographs for 1977, 1988 and 2001 had been radiometrically corrected. The aerial photographs for 2010 were received as orthophotographs and had already been topographically corrected. The resolution of the 1977, 1988 and 2001 imagery is 50 cm while that for 2010 is 12.5 cm. Aerial photographs were mosaicked into a single image for each river.

A 100-m buffer zone was assigned to each side of the case-study rivers using the mosaicked aerial photographs for the four time periods. A buffer zone of this size is sufficient to capture surrounding land-use effects, it is suitable for local-scale research (Allan, 2004; Brown and Vivas, 2005) and it is believed to be the area with the greatest impact on water quality (Gergel et al., 2002). Within the buffer zones land use was delineated according to six land-use types based on the Cape Town Spatial Development Framework (City of Cape Town, 2012). A land-use typology was developed based on activities occurring in the buffer zone. The use types are residential, industrial, commercial, natural vegetation, disturbed land and open space/recreation. Polygons of each land-use category were created along the buffer zone according to the upper, middle and lower reaches of the case-study rivers. The total area of each land-use category was calculated for each of the four time periods (Table A1 in Appendix A). Overall changes across the river reaches for the three case study rivers are reflected in Table A2 (Appendix A).

3.2. Selecting services

The selection of ES is based on those reported by Burkhard et al. (2012), De Groot et al. (2002) and De Groot (2006) and grouped according to the Millennium Ecosystem Assessment's (MA) ES categories (Millennium Ecosystem Assessment, 2005). Regulating and supporting services were combined as these are believed to be interdependent. Only services related to or influenced by freshwater systems were selected (Table B1 in Appendix B) and provide a broad overview of the types of services offered by case study rivers in each of the MA categories. Scores for each ES are reported for the upper, middle and lower reaches across each of the four time periods, resulting in 12 scores for each ES over the study period.

3.3. Land-use change scoring system

A scoring system was developed to determine the impacts to freshwater ES due to changes in land cover over time. Scoring was determined by the changes in land use within the buffer zone over time between 1977, 1988, 2001 and 2010 for the upper, middle and lower reaches across the three case-study rivers using six variables. Each land-use variable was chosen according to its sensitivity to land-use change (Table 1). Kroll et al. (2011) have recommended that the target of this type of study should be a good compromise of precision, broad applicability to a variety of landscapes and adaptability to varying data availability. Scoring in this study involves a methodological approach which aims to determine whether the scoring system is an acceptable or valid approach to determining transitions in service provision across time periods and across landscapes.

Table 1
Rank scores for land-use variables, canalization and pollution points.

Variables	Value	Score
Amount of natural vegetation cover in 100 m buffer	51%–100%	4
	26%–50%	3
	11%–25%	2
	0%–10%	1
Amount of disturbed vegetation cover in 100 m buffer	0%–10%	4
	11%–25%	3
	26%–50%	2
	51%–100%	1
Amount of hard surfaces in 100 m buffer	0%–10%	4
	11%–25%	3
	26%–50%	2
	51%–100%	1
Amount of soft surfaces in 100 m buffer	51%–100%	4
	26%–50%	3
	11%–25%	2
	0%–10%	1
Amount of river canalized	0%–10%	4
	11%–25%	3
	26%–50%	2
	51%–100%	1
Storm-water drains/pollution points	1–5	4
	6–10	3
	11–15	2
	16+	1

The percentage ranges of the variables (Table 1) were adapted from studies reported by Chin (2006), Findlay and Taylor (2006), Klein (1979), Ladson (2004) and Paul and Meyer (2001). Scoring of ES was done on a ranking scale where 1 point is allocated to high levels of impact or negative land-use attributes, such as a decrease in natural vegetation within a wetland area between two time periods. A score of 4 was allocated where surrounding land use had a positive influence on ES between time periods, such as an increase in natural vegetation cover within the river buffers which were previously degraded. Each ES (e.g. microclimate regulation) was scored for each of the six variables along the upper, middle and lower reaches across each of the four time periods. To limit the possibility of having each ES score replicated across the individual ES in each category due to the land-use variable percentage or value (e.g. each cultural service awarded the same score in a given time period based on percentage natural vegetation cover), consideration was given to the influence of social-ecological factors based on the literature and expert knowledge.

For each social-ecological factor considered a point was either added or subtracted to the score obtained from the variables listed in Table 1. Individual ES can be influenced by more than one social-ecological factor and can have numerous points added or subtracted accordingly. Social-ecological considerations are critical in studies considering the provision of ES in urban settings (Chan et al., 2012) and in landscapes containing freshwater systems (Everard and Moggridge, 2012; Gilvear et al., 2013; Large and Gilvear, 2015; Wong et al., 2015). A list of the social-ecological factors influencing each ES considered in this study is given in Table C1 in Appendix C. The social-ecological factors influenced by changes in land use are context specific and must be adapted to specific settings based on geographic locations (e.g. cities versus rural settings) and levels of development (e.g. global South versus global North). The scores for each of the six land-use variables were combined with the social-ecological factors for each of the 17 ES along each river reach. Mean values were derived which were used to determine the changes in service provision over the river reaches and time periods. An example of how the scoring exercise was implemented is shown in Table C2 in Appendix C. A total of 1176 entries was collected for each river across the four time periods. Variables were evenly weighted. Microclimate regulation had four entries as this service is not influenced by river canalization or the number of storm-water drains. Disturbance prevention and noise reduction were influenced by five variables, with no influence from storm-water drains.

3.4. Analyses of water-quality data

Historical water-quality data were obtained from the Catchment, Stormwater and River Management Branch of the City of Cape Town. Eleven water-quality indicators were measured at various locations along each of the case study rivers. These indicators are conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; unionised ammonia; total phosphorous; total suspended solids; and water temperature. As the main thrust of the paper is ES provision and not the analyses of water quality variables, mean changes in water quality variables are recorded in Appendix D.

Data sets for the three rivers spanned different periods, with water-quality measurements collected from January 1976, March 1978, and August 2000 until December 2010 for the Liesbeek, Sand, and Silvermine Rivers respectively. The start dates for collection of some indicators was later than the commencement of water sampling in some rivers, for example *E. coli* sampling. In these cases, mean decadal values for these water-quality variables were reported for decades in which sampling occurred. For the purpose of this study, records were grouped by decadal periods (1980s, 1990s and 2000s) as these are believed to best capture the impacts from preceding land use. Data preceding 1980 were not included.

River reaches were sectioned into upper, middle and lower reaches according to the locations of municipal water-quality sampling points (Fig. 1) as these created the end points on which to measure indicators from the river reach above. The number of water-quality testing locations is not equal in each river reach. Where multiple testing stations are present in a single river reach, a mean total was reported. Decadal means for each variable across the three rivers (Tables D1–D3 in Appendix D) were compared against target water quality ranges (TWQR) based on guidelines laid down by the national Department of Water Affairs, as adopted from Environmental Protection Agency guidelines (Department of Water Affairs and Forestry, 1996).

To establish significant changes in water quality across the spatial landscape and through time, data were subjected to Levene's test of homogeneity of variances, followed by analysis of variance (ANOVA) and Kruskal-Wallis tests. Tukey post hoc tests further explored levels of significance between variables where applicable. Tables D4 and D5 in Appendix D record significance of water-quality variables.

3.5. Validation of water quality with the land-use change scoring system

Keeler et al. (2012) caution that a lack of appropriate data to describe the link between changes in water quality and changes in the provision of ES that directly affect ecosystem functioning and human well-being often limits the potential to successfully integrate biophysical data sets into workable models and methods. In this study changes in water quality over the study period were used to complement or contrast the findings from the developed land-use change scoring method, thus evaluating the effectiveness of the method. Overall, changes in the means of the 11 water quality variables (i.e. an overall increase in dissolved oxygen concentrations over time) were compared to the overall result from the land-use change scoring system (i.e. an overall increase in provisioning services over time) for each reach of the Liesbeek and Sand Rivers. If the number of overall changes to water-quality variables supporting the land-use change scoring system exceeded 50%, the result was deemed to complement the scoring system. Table B1

(Appendix B) lists the water-quality variables associated with each ES. An example of how the validation exercise was implemented is shown in Table D6 in Appendix D. Eventually, 906 entries representing the overall changes in mean water quality were compared to the outcomes of the land-use change scoring system. Variables were evenly weighted.

4. Results

4.1. Assessing land-use change over time

Broadly, the most significant positive change was noted in the upper stretches of all three case-study rivers. The lower and middle stretches show change in land-use categories which negatively affect ES provision over time across the majority of land-use categories. A summation of land cover changes across the reaches of the three rivers is given in Table A2 in Appendix A.

4.1.1. Regulating and supporting services

Changes to eight regulating and supporting services provided by the three case study rivers are described here, based on changes to land use over time. Changes to service provision were more noticeable across all three reaches of the Sand and Silvermine Rivers with declines noted over time in many service categories. Little change was observed along the Liesbeek River (Fig. 3).

4.1.1.1. Liesbeek River. No change was detected for the river's upper reaches for six of the ES between 1977 and 2010, namely microclimate regulation, disturbance prevention, water regulation, waste removal, ecological integrity and noise reduction. A decrease in waste treatment occurred over time, while nutrient regulation increased. The middle and lower reaches of the Liesbeek showed far more variation in ES provision due to changes in land-use variables over the study period. Along the middle reaches, declining service provision is noted in microclimate regulation, disturbance prevention and noise reduction. Improvements are seen in water regulation, nutrient regulation, waste treatment and waste removal, with little change observed in ecological integrity. The lower portion of the river shows a downward trajectory for microclimate regulation and disturbance prevention, while improvements are observed across water regulation and waste-removal services, with little change noted across the remaining five services.

4.1.1.2. Sand River. Along the upper reaches declining service provision is observed in noise reduction as opposed to increases across waste treatment, waste removal and ecological integrity. Marginal changes between microclimate regulation, disturbance prevention, waste treatment and noise reduction were noted with no change observed across the remaining four services over the study period. The lower reaches revealed the highest levels of declining service levels with seven categories showing negative trajectories. A slight increase is noted in disturbance prevention.

4.1.1.3. Silvermine River. Increases are observed in ES provision along the upper reaches of the Silvermine River across all categories. The converse is evident in the lower reaches. The middle reaches recorded seven negative scores, with only water regulation improving over the study period.

4.1.2. Provisioning services

Changes to the four provisioning services provided by the three case study rivers are reported here. Overall, the Liesbeek River showed an increase in provisioning services over time, with little change observed across the Sand River (Fig. 4). The Silvermine River showed similar increases and decreases for provisioning services.

4.1.2.1. Liesbeek River. Little change is noted across service categories in the upper reaches of the Liesbeek River. Increases in services provision are observed across water supply and material supply in the middle reaches with declines noted in refuge functions. No change is observed in the provision of habitable spaces across the study period. The lower stretches of the river showed increases across all services over time.

4.1.2.2. Sand River. Increased levels of ES provision are observed in the upper reaches across material supply and refuge function, with little to no change recorded for the other two services. Overall, change is limited across three categories in the middle reaches, with a slight decline seen in levels of human habitation over time. Declines are observed for material supply and refuge function along the lower reaches, with no change recorded in the other two categories.

4.1.2.3. Silvermine River. Levels of provisioning services increased across all categories along the upper reaches over the study period. The middle stretch shows no change in water supply and material supply but increases in human habitation and declines in refuge functions. Service provision declined across all categories along the lower reaches of the river.

4.1.3. Cultural services

Cultural-service provision by the Liesbeek, Sand and Silvermine Rivers are presented in this section. The Liesbeek River shows an overall increase in the provision of cultural ES over time, while the Silvermine River shows the converse (Fig. 5). The Sand River shows the least change in service provision over the study period.

4.1.3.1. Liesbeek River. Apart from a slight increase in aesthetics over time, there was no change observed for cultural ES provision along the upper reaches of the Liesbeek River. Increases in service provision were noted in all the service categories along the lower reaches of the river, whereas all service levels declined marginally in the middle reaches.

4.1.3.2. Sand River. Increasing cultural ES provision is noted for aesthetics and cultural and historical services along the upper Sand River catchment with recreation and spiritual and religious services reporting no change. Science and education services show a decline. Declines were also noted in the provision of aesthetics and science and education along the middle stretches of the river, with no change observed in recreation or cultural and historical services over the study period. An increase in spiritual and religious services was identified. The same trends were noted along the lower reaches.

4.1.3.3. Silvermine River. The Silvermine River shows increased levels of cultural ES provision over time across all services in the upper reaches. Apart from a decrease in aesthetics along the middle reaches, little to no change was recorded across the other cultural-service categories. A decline is noted across all cultural services along the lower reaches of the Silvermine River.

4.2. Comparisons between changes in water quality and ecosystem service scores

Mean changes to water-quality variables over the study period were used as indicators of river health as well as being used to support the outcomes of ES scores from the developed land-use change scoring system. The fluctuations in water quality variables across

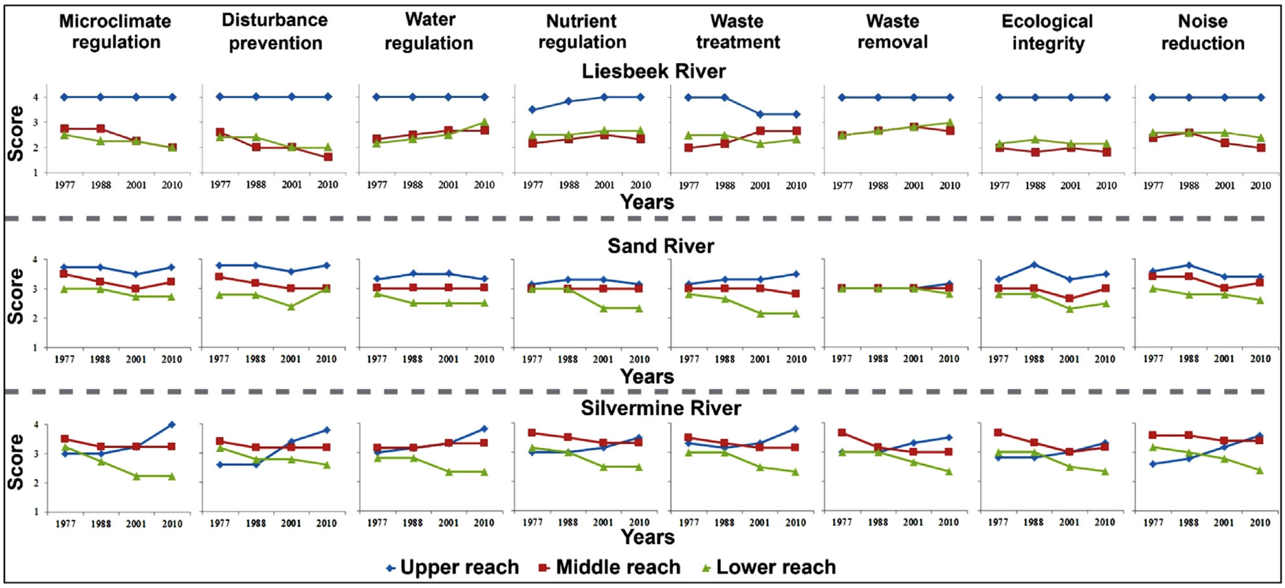

Fig. 3. Regulating and supporting ecosystem service scores in 1977, 1988, 2001 and 2010 for the upper, middle and lower reaches of the Liesbeek, Sand and Silvermine Rivers.

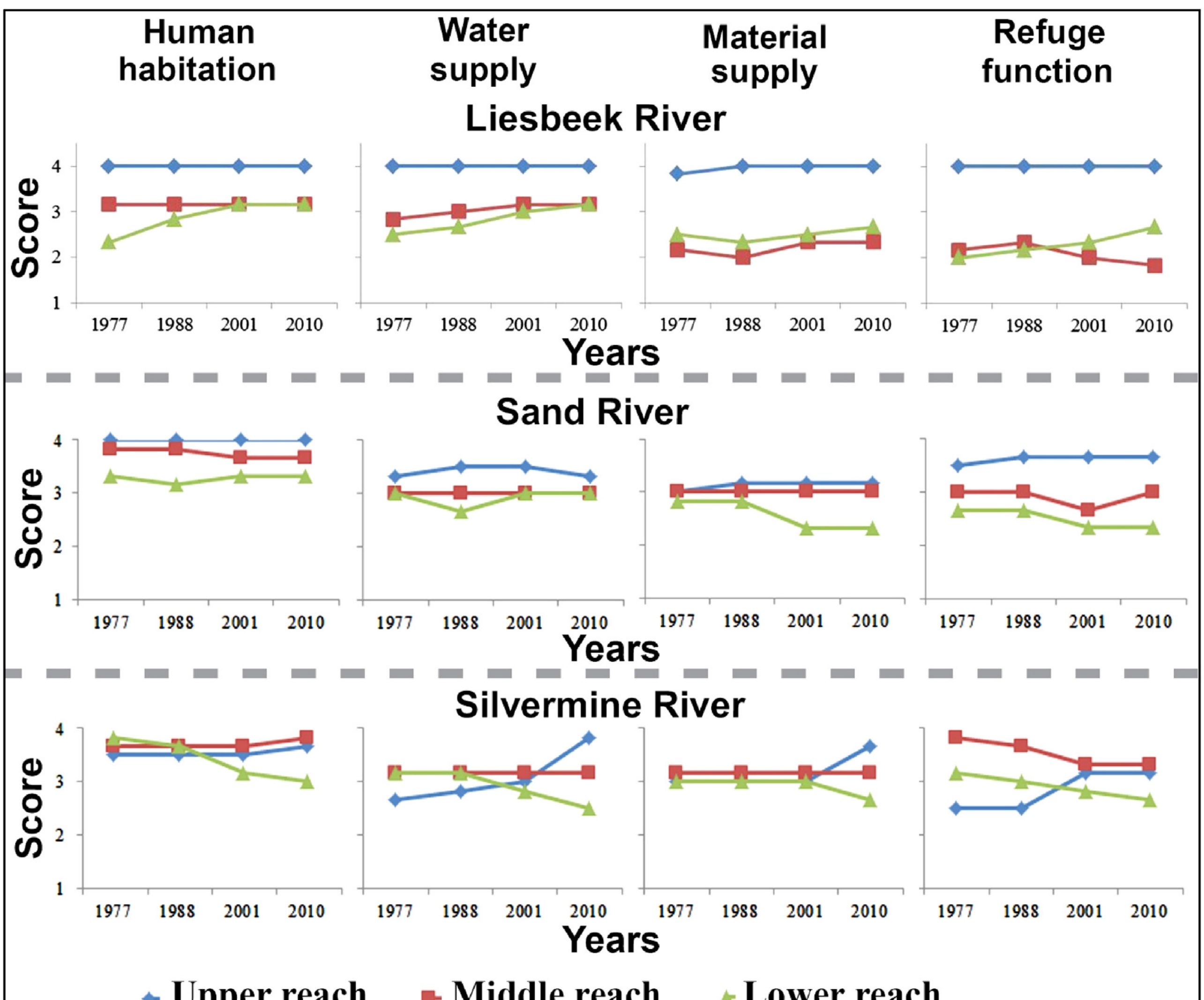

Fig. 4. Provisioning ecosystem service scores in 1977, 1988, 2001 and 2010 for the upper, middle and lower reaches of the Liesbeek, Sand and Silvermine Rivers.

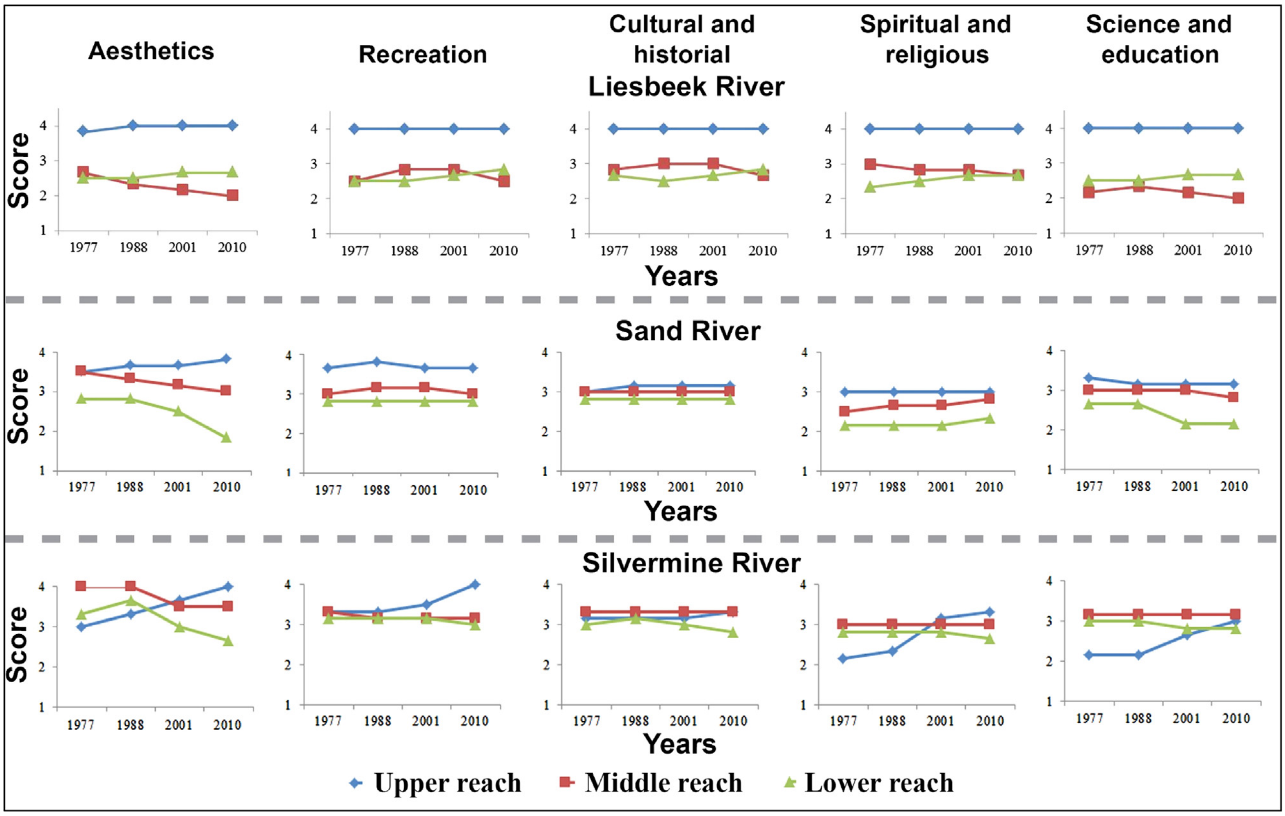

Fig. 5. Cultural ecosystem service scores in 1977, 1988, 2001 and 2010 for the upper, middle and lower reaches of the Liesbeek, Sand and Silvermine Rivers.

the upper, middle and lower reaches for the Liesbeek and Sand Rivers over the 1980s, 1990s and 2000s are reported in Figs. 6 and 7 respectively. Sixteen entries are reported for each of the reaches of the Liesbeek and Sand Rivers which correspond with 16 of the 17 ES under review. Noise regulation is not influenced by water quality. There were 34 increases and 26 decreases in ES provision noted in this study, with a further 36 instances of no change in service provision over time across the three river reaches for the Liesbeek and Sand Rivers. Due to the limited availability of long-term water-quality data for the Silvermine River, comparisons between changes in water quality and ES provision were not possible.

4.2.1. Cross-validation of water-quality changes and ES provision across river reaches

Overall, the cross-validation of trends in water quality and ES provision over the study period reported a 79.2% similarity in outcomes. The upper reaches of the Liesbeek and Sand Rivers showed that 96.9% (n = 31) of mean changes in water quality variables supported the findings from the developed land-use change scoring system. The middle reaches showed less accord, with 62.5% (n = 20) of the overall water quality trends supporting the ES scoring outcomes. Trends in water quality variables along the lower reaches supported the outcomes of the land-use change scoring system with close to 80% congruence (n = 25; 78.1%).

The Liesbeek River reported 100% accord between the trends noted in water quality compared to those derived from the ES scoring system across both the upper and lower reaches of the river. The middle reaches of this river recorded only 56.3% support. The upper reaches of the Sand River showed the greatest level of congruence between water quality and ES provision, with 93.8% in accord. The middle reaches showed 68.8% agreement, while the lower reaches recorded 56.3% accordance between trends in water quality when compared to outcomes from the developed land-use change scoring system. An example of the method used to determine the level of congruence between developed scoring system and water quality variables is shown in Table 2.

4.2.2. Cross-validation of water-quality trends and changes in ES provision

Comparisons between the directional trends (i.e. increases, no change or decreases) in water quality variables over time against the outcomes of the scoring system yielded an overall congruence of 74.4%. The changes to water quality variables showed 100% support for both increases in service provision over time as well as in instances where no change was noted in the amount of ES provision across the different reaches of the Liesbeek and Sand Rivers. Water quality variables did not support the findings in instances where decreases in ES provision were noted, showing only 23.1% (n = 6) accordance. Decreases in both provisioning and cultural service showed 100% discord between trends in water quality variables and the outcomes from the ES scoring system, while decreases in regulating services showed only 53.8% discord.

5. Discussion

This study focussed on the integration of existing data sets to develop a new method for identifying trends in ES provision derived from urban rivers. These data sets act as multiple lines of evidence in supporting the new method. The research shows an overall decline in regulating and supporting services over time with little to no change in provisioning services. Cultural service provision showed the greatest level of varied change over time. Examined spatial trends showed an increase in ES provision along the upper reaches of the rivers, with declines recorded along the middle and lower reaches. Water-quality data supported the outcomes from the scoring system confirming that the scoring system is sensi-

Table 2
Example of cross-validation exercise testing whether the overall changes noted in 11 water-quality variables support the outcomes of the scoring system across the upper, middle and lower reaches of the Liesbeek and Sand Rivers.

Ecosystem service	River	River reach	Outcome of scoring system	Conductivity	Dissolved oxygen	*E. coli*	Faecal coliforms	Nitrates and nitrites	pH	Soluble ammonia	Total phosphorous	Total suspended solids	Unionised ammonia	Water temperature	No. of water quality variables supporting scoring system	Percentage contribution
Human habitation	Liesbeek	Upper	→	↗	↗	↘	↗	↘	↗	↗	↗	↘	↗	↗	7	63.6
		Middle	→	↗	↗	↗	↘	↘	↗	↗	↗	↘	↗	↗	7	63.6
		Lower	↗	↘	↗	↗	↗	↘	↘	↘	↗	↘	↘	↗	7	63.6
	Sand	Upper	→	↗	↗	↗	↗	↘	↘	↗	↘	↘	↗	↘	7	63.6
		Middle	↘	↘	↗	↘	↘	↘	↘	↗	↘	↘	↘	↘	2	18.2
		Lower	→	↗	↗	↗	↗	↘	↘	↗	↗	↘	↘	↘	7	63.6
Water supply	Liesbeek	Upper	→	↗	↗	↘	↗	↘	↗	↗	↗	↘	↗		6	60.0
		Middle	↗	↗	↗	↗	↘	↘	↗	↗	↗	↘	↗		6	60.0
		Lower	↗	↘	↗	↗	↗	↘	↘	↘	↗	↘	↘		7	70.0
	Sand	Upper	→	↗	↗	↗	↗	↘	↘	↗	↘	↘	↗		6	60.0
		Middle	→	↘	↗	↘	↘	↘	↘	↗	↘	↘	↘		8	80.0
		Lower	→	↗	↗	↗	↗	↘	↘	↗	↗	↘	↘		7	70.0
Material supply	Liesbeek	Upper	↗	↗	↗			↘	↗	↗	↗		↗	↗	6	75.0
		Middle	↗	↗	↗			↘	↗	↗	↗		↗	↗	6	75.0
		Lower	↗	↘	↗			↘	↘	↘	↗		↘	↗	7	87.5
	Sand	Upper	↗	↗	↗			↘	↘	↗	↘		↗	↘	5	62.5
		Middle	→	↘	↗			↘	↘	↗	↘		↘	↘	5	62.5
		Lower	↘	↗	↗			↘	↘	↗	↗		↘	↘	3	37.5
Refuge function	Liesbeek	Upper	→	↗	↗	↘	↗	↘	↗	↗	↗	↘	↗	↗	7	63.6
		Middle	↘	↗	↗	↗	↘	↘	↗	↗	↗	↘	↗	↗	3	27.3
		Lower	↗	↘	↗	↗	↗	↘	↘	↘	↗	↘	↘	↗	7	63.6
	Sand	Upper	↗	↗	↗	↗	↗	↘	↘	↗	↘	↘	↗	↘	7	63.6
		Middle	→	↘	↗	↘	↘	↘	↘	↗	↘	↘	↘	↘	9	81.8
		Lower	↘	↗	↗	↗	↗	↘	↘	↗	↗	↘	↘	↘	5	45.5

Increases are denoted by a ↗, decreases by a ↘ and no change by a →.

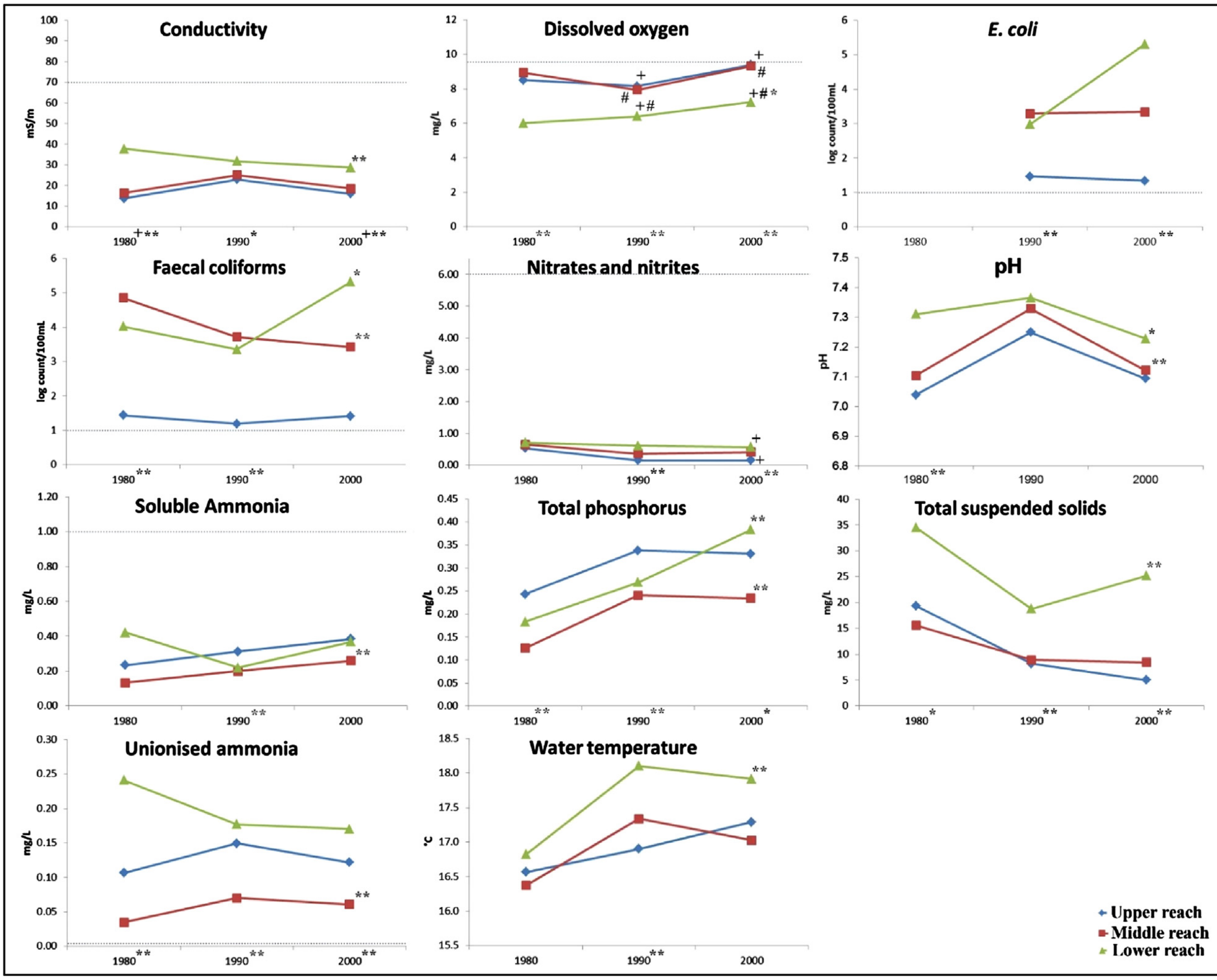

Fig. 6. Mean values of water quality variables in the 1980s, 1990s and 2000s for the upper, middle and lower Liesbeek River. An * indicates significant difference ($p < 0.05$), ** indicates highly significantly different ($p < 0.005$), and + indicates significance between two decadal periods or between two rivers. The dotted line indicates the national threshold (where applicable).

tive enough to indicate changes in freshwater ES provision over the study period and across the spatial extent of the three case-study rivers. We believe that this method can be replicated in other urban catchments as long as minimum data requirements are met.

5.1. Methodological considerations: integration, viability and repeatability

5.1.1. Opportunities and issues with data integration to create viable ecosystem service outputs

The strength of this paper is in trying to integrate multiple lines of evidence to support newly developed methods to determine changes in riparian ES over time and across space. This study integrates existing sources of data (Liss et al., 2013) with a view to "making the best of what we have". By using aerial photographs to determine land-use change over time it was possible to develop an ES scoring index which was sensitive enough to pick up changes in the levels of ES provision. These scoring outputs were confirmed by water-quality measures which constituted long-term census data about chemical indicators and provided a strong comparative data set with which to verify outcomes from the scoring system. This comparison was prone to a level of error because water quality is not always directly related to land-use activities (Young et al., 2005) and there is no general framework for linking changes in water quality to changes in multiple ES (Keeler et al., 2012). Determining the relationships between water quality and riparian ES is particularly challenging. Nevertheless, the findings of this study suggest that the methods applied are robust enough to calculate the changes in ES provision in the riparian buffer zones over time and across space. It is hoped that this study stimulates exploration into the use of multidata-set methodologies in other urban rivers in developing regions with similar data constraints.

5.1.2. Repeatability of the land-use scoring system

This study used a simple scoring rubric which is easily adapted to and replicable in other riparian landscapes. Some assumptions about rivers were made regarding the links between riparian land-use changes and ES delivery. Even where these assumptions are scientifically valid locally, there may be a degree of uncertainty regarding universal applicability (Large and Gilvear, 2015). The six variables considered in this study are applicable in any developing-city context where the aim is to create spatially-relevant ES outputs. These can be adapted to the urban riparian landscape in which this method is applied, with additional variables added where necessary.

To ensure that studies of this nature are replicable across different urban settings, one needs to address the concerns of designing and implementing such methodologies. Concerns relate to ease

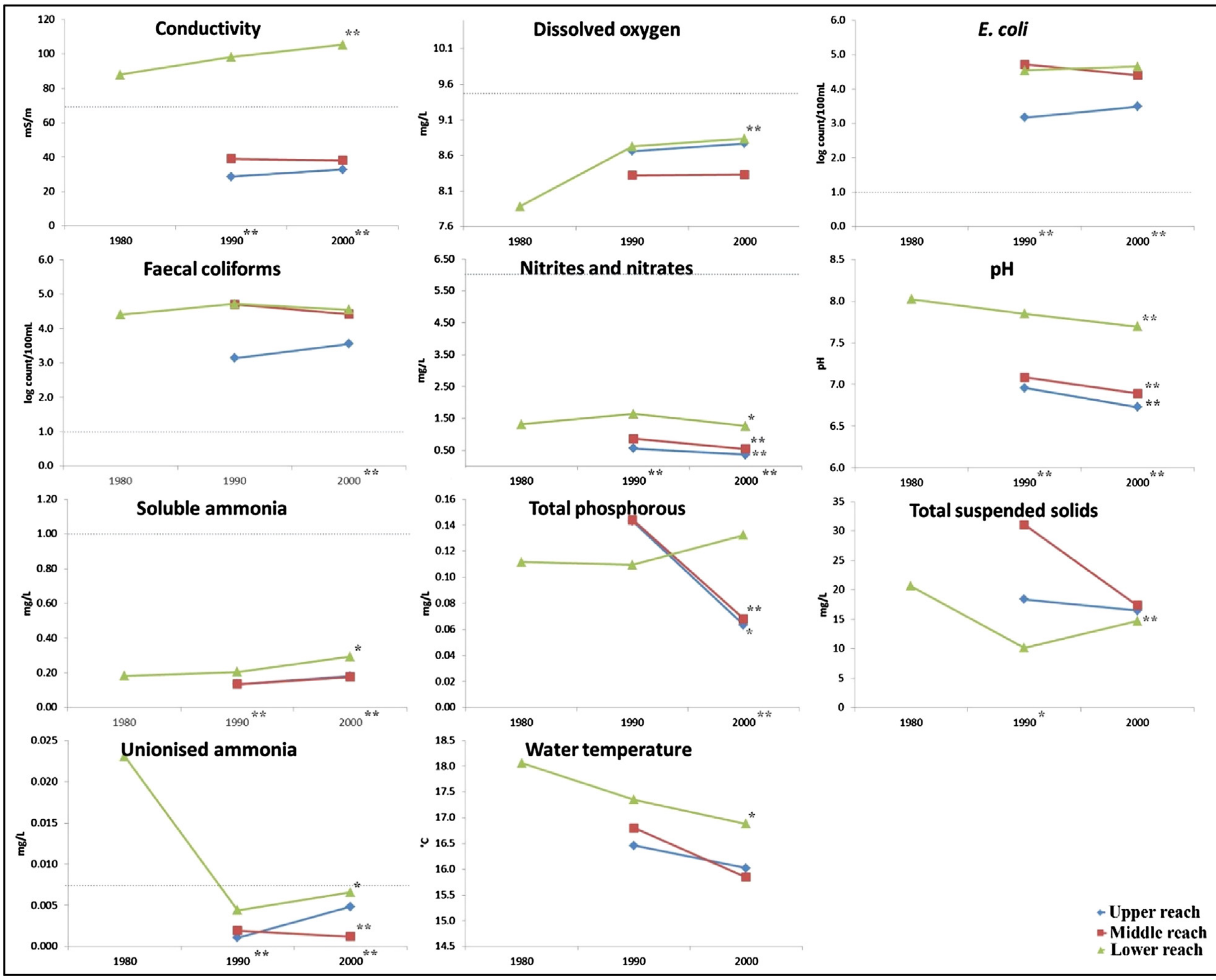

Fig. 7. Mean values of water quality variables in the 1980s, 1990s and 2000s for the upper, middle and lower Sand River. An * indicates significant difference ($p < 0.05$), ** indicates highly significantly different ($p < 0.005$), and + indicates significance between two decadal periods or between two rivers. The dotted line indicates the national threshold (where applicable).

of development, data interpretation and the subjectivity of categories and classes (Larondelle and Haase, 2013; Raudsepp-Hearne et al., 2010). Scoring systems should be simple in design, yet robust enough to generate effective outcomes. However, caution should be taken not to oversimplify the interactions between landscape variables existing across temporal and spatial scales (Dobbs et al., 2011). There may also be concerns about the degree to which the land-use scoring system is repeatable in different settings. A first concern is that aerial photographs and landscape images may be insufficiently detailed and not readily available (Large and Gilvear, 2015), especially in some developing countries. This could create problems in differentiating between some land-use and land-cover types. In such cases, it may be advisable to use multiple land-use and land-cover visualization tools that combine traditional options like aerial photographs with digital options such as Google Earth (Large and Gilvear, 2015). A second concern relates to the wide range of approaches used to define and measure freshwater ES indicators based on the different environmental and social phenomena being studied (Liss et al., 2013). Ecosystem service interpretation is influenced by several factors, including the discipline of the researchers, their interpretation of ES, their perspective on social-ecological interactions, as well as the objectives of a given study (Boyd and Banzhaf, 2007; Liss et al., 2013). To enhance the repeatability of the presented method and the potential to compare findings, multidisciplinary teams comprising of a variety of other researchers, local experts and planners could be drawn together to define the ES, determine the suitability of variables and social-ecological factors, and to assess and interpret data and scoring outcomes (Larondelle and Haase, 2013). Differences in definitions in ES research is a general limitation and can restrict comparisons between studies, limit agreement on trends and patterns, and reduce the effectiveness of ecosystem-management strategies based on ES assessments (Liss et al., 2013). However, as long as the choice of methods and measurement is well reasoned, defensible and explicit, allowance will be made for some level of bias (Liss et al., 2013). A final concern regarding repeatability relates to the cost implications of studies (Raudsepp-Hearne et al., 2010). Scoring systems need to be inexpensive to ensure their uptake in research and management. Existing data sets that are accessible, easily collected and readily available are favoured (Liss et al., 2013), as was the case in this study.

5.2. Empirical findings: changes in ecosystem service provision over time and across river reaches

5.2.1. Land-cover and land-use changes through time

This study has shown an overall decline in regulating and supporting services over time, which suggests that the provision of these services is controlled by historical modifications of land in the riparian buffer zones. This is in accord with findings by O'Farrell et al. (2012). Many of these declines, as noted for the Sand and Silvermine Rivers, are in part due to expanding residential areas, industrial zones and recreational spaces. These findings are in support of those reported previously by Harding (1994). This is further supported by water-quality records which show significant changes in numerous measures reflecting negative changes to water quality all of which are associated with the expansion of residential and industrial areas and human activities in these areas (Brown and Magoba, 2009; Dent et al., 2002; Dodds, 2007).

Little to no change was noted for provisioning services in the three case-study rivers. The exception being increases in service provision along the Liesbeek River, which historically has had high provisioning value (Bhikha, 2013). This may imply that the values assigned to provisioning services along these rivers are stable and not impacted significantly by changes in land use over the study period. These findings support previous research, suggesting that the delivery of regulating services is often more likely to show varied degrees of change due to alterations in land use over time and less so for provisioning services, at least in the short term (Andrés et al., 2012; Lavorel et al., 2011; Mace et al., 2012). This is significant for the health and well-being of individuals and communities in developing cities where some of the beneficiaries of provisioning services are those in most vulnerable and economically marginal communities in cities (O'Farrell et al., 2012). Improvements in water chemistry over time, such as increases in dissolved oxygen and decreases in nitrates and nitrates, total phosphorus, and total suspended solids indicate a decline in nutrient loads, which in turn result in fewer ecological phenomena, such as algal blooms, thus improving the provisioning functions of urban river systems (Dent et al., 2002; Dodds, 2007). However, relationship between algal blooms and nutrient loading is not constant as there are a number of other physical and biological mechanisms which are likely to modify responses to nutrient loadings (Keeler et al., 2013). This applies to most water-quality indicators whereby a single action that affects water quality may cause a change in another attribute, such as water clarity, or have a direct effect on the provision of various ES that affect different groups of beneficiaries (Keeler et al., 2012). Moreover, activities that impact on water quality today can affect water quality far into the future, with the consequent challenge of predicting future ES provision and values (Keeler et al., 2012).

Cultural-service provision showed the greatest variability of change over time with different directional change along different rivers. The Liesbeek River yielded an increase in cultural services over time, probably as a result of rehabilitation projects along the middle and lower stretches of the river (Brown and Magoba, 2009). This finding is supported by improvements in water chemistry which relate to healthier aquatic systems (Dodds, 2007). Little change in the levels of cultural services provision were noted across the Sand River catchment over time, while there was a marked decline in cultural services provision along the Silvermine River over the study period, despite efforts to remove alien vegetation in the upper reaches (Van Wilgen, 2012).

The method developed in this study shows that the relationship between water quality and ES scores was positive and robust for improvements or where there was no change in service provision, but the relationship falls down for decreasing ES scores and water quality trends. The method may need to be improved to address finer-scale land-use change variables when looking at the degree of change in ES provision versus water quality trends (Loomis et al., 2000). Researchers should consider the scale of change when comparing ES provision and water quality over time to identify the actual level of difference between the factors being compared. It is sensible to reconsider the social-ecological factors relating to increases and decreases in ES to ensure that these adequately cover the full range of factors which affect ES scoring. In addition, greater engagement with other researchers and experts is well advised to assess the nature of ES declines (Boyd and Banzhaf, 2007; Liss et al., 2013). Finally, it is of course quite possible that ES provision is actually not declining along some reaches of the case study rivers over time and that service levels may be stable or even be increasing. A refinement of the method developed in this study will need to consider all these options.

5.2.2. Land-cover and land-use change over space

The findings of this study indicate an overall increase in ES provision along the upper reaches of the case-study rivers due to these areas undergoing conservation efforts or corrective management (Van Wilgen, 2012). This implies that the closer the urban riparian area is to its headwaters, which in this study are inside a protected area, the higher the potential for ES provision. The majority of water-quality indicators support this finding by showing only slight fluctuations in mean values over the multidecadal period along the upper-river reaches.

As the water exits TMNP it flows across landscapes which have been modified, resulting in impacted river quality further diminishing the ability for urban rivers to yield ES. This is the case in the middle and lower reaches where overall declines in service provision were noted. Many of these areas have become highly modified (O'Farrell et al., 2012) and they are affected by historical practices such as expanding residential, commercial and industrial areas, farming practices, dumping and the spread of alien vegetation (Bhikha, 2013). The middle and lower reaches recorded significantly worse water quality compared to the upper reaches of the three rivers, as a function of their urban status and this negatively affects the ability to provide ES. The increases in service outputs noted in the middle reaches of the Liesbeek River could be associated with riparian improvement practices (Brown and Magoba, 2009). Water-quality data supports this finding with value changes that allude to a healthier riverine system (Dodds, 2007).

This study contributes to the call made by Mitchell et al. (2013) for empirical tests to determine how spatial factors, such as connectivity between different river reaches, affect ES provision so as to accurately model and manage ES provision across human-dominated landscapes. An important consideration when assessing the spatial attributes of ES provision derived from land-use change is to understand the nature of connectivity between upstream and downstream systems (Jackson and Pringle, 2010; Mitchell et al., 2013; Thorp et al., 2010; Wohl et al., 2005). Keeler et al. (2012) suggest that an approach that considers upstream drivers and downstream beneficiaries is important to understanding how biophysical change to the landscape influences water quality and ES provision. Changes in water quality affect many aspects of ecosystem functions and human well-being as well as the benefits and/or costs accruing to different groups of beneficiaries at varying spatial (and temporal) scales (Mitchell et al., 2013; Wohl et al., 2005). Consideration of landscape connectivity in this regard is called for because of the important management implications (Jackson and Pringle, 2010; Mitchell et al., 2013), such as the maintenance of habitat, biological diversity and system complexity (Amoros and Bornette, 2002; Bornette et al., 1998; Freeman et al., 2007; Ward, 1998), spatial heterogeneity of river systems (Amoros and Bornette, 2002; Ward, 1998), as well as possible social and economic implications such as the implementation of payment for ES schemes (Casey et al., 2006; Lambert, 2003; Loomis et al., 2000).

6. Conclusion

Rapid urbanization within developing country contexts is significantly altering urban landscapes, particularly by impacting urban rivers and reducing their ability to deliver important ES. Identifying the impacts of land-use change on ES provision at fine scales is complex, time consuming and not fully explored either methodologically or empirically in the literature. This study aimed to contribute to both by developing an integrative approach to assessing temporal and spatial change in ES delivery by drawing on available data. In order to integrate and synthesise this data and develop an understanding of ES provision a scoring system was developed to determine the fluctuations in ES provision. These data sets acted as multiple lines of evidence. A major benefit of designing and implementing a scoring system such as the one used in this study is that it is simple in design, cost-effective and replicable across various urban settings. This allows for application in other freshwater systems in urban centres. Empirically, the data sets used support the findings of the ES scoring system and suggest that fluctuations in ES delivery through time and across the river reaches are linked to land-use change and other human activities. As water flows out of an urban protected area and travels through transformed and impacted landscapes, the resultant effect is a decline in water quality and a diminishing ability of rivers to yield ES with increasing distance from the protected area. Urbanisation and its associated changes in land uses in developing-city contexts affects potential ES benefits, and highlights the potential need for creating management interventions such as restoration.

Acknowledgements

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Appendix A.

Table A1
Land-use area (m^2) in 100-m buffer across river reaches of the Liesbeek, Sand and Silvermine Rivers in 1977, 1988, 2001 and 2010.

River Reach	Land-use category	1977			1988			2001			2010		
		Liesbeek	Sand	Silvermine	Liesbeek	Sand	Silvermine	Liesbeek	Sand	Silvermine	Liesbeek	Sand	Silvermine
Upper	Natural vegetation	293 588	118 988	288 471	300 213	101 321	356 395	311 492	103 567	587 424	328 197	110 627	740 464
	Disturbed land	76 995	213 769	548 430	70 370	218 691	480 505	59 091	211 608	249 477	42 386	201 151	96 436
	Residential	170 773	593 958	0	170 773	604 899	0	170 773	607 335	0	170 773	609 905	0
	Commercial	0	18 209	0	0	20 802	0	0	22 159	0	0	22 691	0
	Industry	0	0	0	0	0	0	0	0	0	0	0	0
	Open space/recreation	186 685	195 234	0	186 685	194 445	0	186 685	195 489	0	186 685	195 784	0
Middle	Natural vegetation	22 102	16 430	544 237	19 907	12 857	624 740	18 071	8 220	706 082	17 912	6 462	716 145
	Disturbed land	16 833	331 338	278 408	17 998	332 287	197 904	19 203	334 111	116 562	19 043	334 648	106 499
	Residential	596 984	600 982	0	597 086	601 032	0	598 218	603 357	0	600 247	605 702	0
	Commercial	23 590	68 330	0	24 951	69 576	0	25 162	71 501	0	26 302	72 479	0
	Industry	0	53 140	0	0	54 222	0	0	56 148	0	0	57 768	0
	Open space/recreation	68 532	69 938	0	68 098	70 184	0	67 387	66 821	0	64 537	63 098	0
Lower	Natural vegetation	19 679	17 643	144 690	17 016	16 245	134 652	14 849	13 897	130 853	12 649	12 988	109 972
	Disturbed land	186 478	303 963	353 389	187 102	305 530	362 700	188 124	306 996	362 755	189 078	307 337	373 902
	Residential	371 876	639 990	104 964	372 056	649 174	105 691	372 102	652 157	108 177	372 314	652 956	117 910
	Commercial	109 948	91 689	0	110 079	85 722	0	110 948	85 168	0	111 753	86 883	0
	Industry	0	0	0	0	0	0	0	0	0	0	0	0
	Open space/recreation	40 060	86 873	218 764	41 788	83 486	218 764	42 018	81 940	220 022	42 247	79 995	220 022
		2 184 123	**3 420 474**	**2 481 351**	**2 184 122**	**3 420 474**	**2 481 351**	**2 184 124**	**3 420 474**	**2 481 351**	**2 184 123**	**3 420 474**	**2 481 351**

Table A2
Increases (↗), decreases (↘) or no change in land-use categories over the study period across river reaches in the Liesbeek, Sand and Silvermine Rivers. Non-applicable (n/a) is stated where a land-use category is not present along a river reach.

River Reach	Land-use category	Liesbeek	Sand	Silvermine
Upper	Natural vegetation	↗	↘	↗
	Disturbed land	↘	↘	↘
	Residential	No change	↗	n/a
	Commercial	n/a	↗	n/a
	Industry	n/a	n/a	n/a
	Open space/recreation	No change	No change	n/a
Middle	Natural vegetation	↘	↘	↗
	Disturbed land	↗	↗	↘
	Residential	↗	↗	n/a
	Commercial	↗	↗	n/a
	Industry	n/a	↗	n/a
	Open space/recreation	↘	↘	n/a
Lower	Natural vegetation	↘	↘	↘
	Disturbed land	↗	↗	↗
	Residential	↗	↗	↗
	Commercial	↗	↘	n/a
	Industry	n/a	n/a	n/a
	Open space/recreation	↗	↘	↗

Appendix B.

Table B1
Examples of ecosystem services selected in each service category and water-quality variables which affect services

Ecosystem service category	Ecosystem service	Example in freshwater systems	Water-quality indicators affecting service provision
Regulating and supporting services	Disturbance prevention	Reduction in riverbank erosion	Conductivity; dissolved oxygen; pH; total suspended solids; water temperature
	Ecological integrity	Maintaining riparian biological diversity	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Microclimate regulation	Reducing heat-island effects	Dissolved oxygen; water temperature
	Noise reduction	Absorbing noise from residential areas	–
	Nutrient regulation	Dispersing nutrients throughout river reach	Dissolved oxygen; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Waste removal	Dilution of waste products in water column	Dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Waste treatment	Microbial breakdown of wastes	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Water regulation	Ensuring flow of water and materials	Dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
Provisioning services	Human habitation	Providing habitable spaces	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Material supply	Provisioning of medicinal plants	Conductivity; dissolved oxygen; nitrates and nitrites; pH; soluble ammonia; total phosphorous; unionised ammonia; water temperature
	Refuge functions	Supplying refuge for local fauna and flora	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Water supply	Providing fresh water for irrigation	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia
Cultural services	Aesthetics	Offering scenic environments	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Cultural and historical	Contributing to urban history	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Recreation	Spaces for walking and running	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Science and education	Opportunities for scientific discoveries	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature
	Spiritual and religious	Areas for meditation and spiritual rituals	Conductivity; dissolved oxygen; *E. coli*; faecal coliforms; nitrates and nitrites; pH; soluble ammonia; total phosphorous; total suspended solids; unionised ammonia; water temperature

Appendix C.

Table C1
Social-ecological factors influencing ecosystem service provision along riparian buffer zones.

Variable	Social-ecological factors	
	Positive	Negative
Amount of natural vegetation cover in 100-m buffer	Rehabilitation/revegetation projects can improve ecosystem service delivery and biodiversity (e.g. Gilvear et al., 2013; Large and Gilvear, 2015; Loomis et al., 2000; Maron et al., 2012; Trabucchi et al., 2012) Preference for natural and indigenous vegetation (e.g. Cronk and Fuller, 2014; Helfand et al., 2006; Hitchmough, 2011; Kendle and Rose, 2000; Van Wilgen 2012) An increase in natural vegetation can enhance the feeling of being in nature even in cities (e.g. Dean et al., 2011; Özgüner et al., 2007; Puppim de Oliveira et al., 2011).	Removal of existing or alien vegetation can cause conflict (e.g. Bullock et al., 2011; Helfand et al., 2006; Hitchmough, 2011; Kendle and Rose, 2000; Özgüner et al., 2007; Van Wilgen 2012) Non-natural vegetation can disrupt ecosystem functions e.g. increased water uptake (e.g Cronk and Fuller, 2014; Gilvear et al., 2013; Keeler et al., 2012; Van Wilgen 2012).
Amount of disturbed vegetation cover in 100-m buffer	Rehabilitation/revegetation projects can improve ecosystem service delivery and biodiversity (e.g. Bullock et al., 2011; Gilvear et al., 2013; Large and Gilvear, 2015; Loomis et al., 2000; Maron et al., 2012; Trabucchi et al., 2012; Van Wilgen 2012).	Areas of disturbance may reduce an areas ability to provide ecosystem services (e.g. Gilvear et al., 2013; Maron et al., 2012; Puppim de Oliveira et al., 2011). Disturbed areas can result in increased erosion and siltation in and around rivers (e.g. Bakker et al., 2005, 2008; Cebecauer and Hofierka, 2008; Jackson and Pringle, 2010).
Amount of hard surfaces in 100-m buffer	Built infrastructure such as hard surfaces can enhance some ecosystem service provision (e.g. Mitchell et al., 2013; Schäffler and Swilling, 2013; Tzoulas et al., 2007). Hard surfaces can allow for greater access to some areas improving some ecosystem service provision, especially cultural services (e.g. Newell et al., 2013).	Hard surfaces increase runoff and surface pollution transfer (e.g. Barnes et al., 2000; Everard and Moggridge, 2012; Göbel et al., 2007). The amount of hard surfaces can negatively influence provisioning surfaces such as microclimate regulation, noise reduction and waste removal (e.g. Everard and Moggridge, 2012; Robinson and Lundholm, 2012).
Amount of soft surfaces in 100-m buffer	The amount of soft surfaces can positively influence ecosystem services provision, such as microclimate regulation, noise reduction, waste removal and many cultural services (e.g. Bullock et al., 2011; Everard and Moggridge, 2012; Keeler et al., 2012; Large and Gilvear, 2015; Maron et al., 2012; Mitchell et al., 2013; Naiman and Decamps, 1997; Robinson and Lundholm, 2012). Increased soft surfaces allow for greater rainfall and runoff regulation (e.g. Robinson and Lundholm, 2012; Zhang et al., 2012).	An increase in soft surfaces may create conflicts (e.g. Bullock et al., 2011; Helfand et al., 2006; Hitchmough, 2011; Kendle and Rose, 2000; Özgüner et al., 2007; Van Wilgen 2012).
Amount of river canalized	Built infrastructure can enhance some ecosystem service provision (e.g. Munné et al., 2003; Tzoulas et al., 2007). Canalized rivers may provide habitat/refuge for some species (e.g. Chester and Robson, 2013; Munné et al., 2003).	Canalized rivers can be perceived as non-natural and affect cultural service provision (e.g. Medina-Vogel et al., 2003). A decrease in permeability of riverbanks limits regulating services such as waste removal (e.g. Everard and Moggridge, 2012; Gilvear et al., 2013; Naiman and Decamps, 1997). Canalization removes natural habitat for riparian/aquatic species (e.g. Munné et al., 2003).
Storm-water drains/pollution points	Outlet pipes and other man-made infrastructure may provide habitat/refuge for some species (e.g. Chester and Robson, 2013; Munné et al., 2003).	An increase in pollution points results in greater transfer of pollutants in to rivers (e.g. Burton and Pitt, 2001; Everard and Moggridge, 2012). Outlet pipes may have negative consequences on biodiversity and ecosystem service provision, notably aesthetics (e.g. Everard and Moggridge, 2012; Naiman and Decamps, 1997).

Table C2
Example of scoring exercise using six land-use variables to determine changes in cultural ecosystem service provision across the upper (U), middle (M) and lower (L) reaches over case study rivers. A + or − indicate where social or cultural factors have enhanced or reduced the overall score based on land-cover variables. Scoring exercises were undertaken for each ecosystem service category (regulating and supporting, provisioning, cultural) and across each decadal period (1977, 1988, 2001 and 2010) for each river.

Land-cover variables	Value (Score)	Score	Cultural ecosystem services														
			Aesthetics			Recreation			Cultural and historical			Spiritual and religious			Science and education		
			U	M	L	U	M	L	U	M	L	U	M	L	U	M	L
Amount of natural vegetation cover in 100-m buffer	51%–100%	4	4			4			4			4			4		
	26%–50%	3		3			3	3^{+}									
	11%–25%	2			2					2^{-}	2		2^{-}			2^{-}	2
	0%–10%	1												1^{-}			
Amount of disturbed vegetation cover in 100-m buffer	0%–10%	4	4			4			4			4			4		
	11%–25%	3															
	26%–50%	2		2	2		2	2		2	2		2			2	2
	51%–100%	1												1^{-}			
Amount of hard surfaces in 100-m buffer	0%–10%	4				4			4	4^{+}	4^{+}	4	4^{+}	4^{+}	4		
	11%–25%	3	3^{-}	3	3			3									3
	26%–50%	2					2^{-}									2^{-}	
	51%–100%	1															
Amount of soft surfaces in 100-m buffer	51%–100%	4	4	4^{+}		4			4			4			4		
	26%–50%	3			3		3	3		3	3		3	3		3	3
	11%–25%	2															
	0%–10%	1															
Amount of river canalized	0%–10%	4	4			4			4			4	4^{+}	4^{+}	4		
	11%–25%	3			3		3	3		3	3						3
	26%–50%	2		2^{-}												2^{-}	
	51%–100%	1															
Stormwater drains/pollution points	1–5	4	4			4			4			4			4		
	6–10	3								3^{+}			3^{+}				
	11–15	2		2	2		2				2					2	2
	16+	1						1^{-}						1^{-}			
TOTAL			23	16	15	24	15	15	24	17	16	24	18	14	24	13	15
AVERAGE			4	3	3	4	3	3	4	3	3	4	3	2	4	2	3

Appendix D.

Conductivity

Conductivity in the Liesbeek River showed mean levels well below the TWQR of 70 mS/m (Fig. 5). There was a slight increase over time across the middle and upper reaches, while a decrease is observed along the lower reaches over time. The Sand River shows an increase in conductivity measures across all river reaches over time (Fig. 6). The lower reaches of the Sand recorded mean values that exceeded the TWQR. Although none of the river reaches along the Silvermine River produced mean decadal values that exceeded the TWQR, there is a definite increase of conductivity measures from the upper to lower river reaches.

Dissolved oxygen

The Liesbeek River showed an overall increase in dissolved oxygen means over the study period. The upper and middle reaches of the Liesbeek fall either within or close to the optimal range of between 9 and 10 mg/L. The lower river reaches fall short of this range. All reaches in the Sand and Silvermine Rivers fell short of the ideal range over the entire multi-decadal period.

E. coli

Logged means across all reaches of the three case study river exceed the TWQR of between 0 and 1 count/100 mL. The lower river reaches across all three rivers under review reveal the highest counts of *E. coli*. The upper Liesbeek shows the lowest count of *E. coli* across all case study river reaches, and shows decreasing logged mean counts over the study period.

Faecal coliforms

Logged mean values across all river reaches exceeded the TWQR count of between 0 and 1. The upper Liesbeek shows the lowest count, while the lower Sand River shows the highest.

Nitrates and nitrites

The means for nitrates and nitrites were below the TWQR across all rivers and river reaches. There is an overall decline in means over time for the Liesbeek and Sand Rivers. The values for this water quality variable are fairly constant across the three Silvermine River reaches.

pH

All pH means fall within the ideal range of between 6 and 9 for the rivers under review. Marginal increases in pH are noted in the upper and middle reaches of the Liesbeek, with a slight decrease observed along the lower reach. All river reaches along the Sand show a slight decrease in pH over time. The Silvermine River shows that pH increases from the upper to lower reaches.

Soluble ammonia

An increase in mean soluble ammonia is observed along the upper and middle reaches in both the Liesbeek and Sand Rivers over the period under investigation. An increase over time is also noted in the mean soluble ammonia measure in the Sand River, while this decreased in the Liesbeek over the study period. Soluble ammonia decreased from the upper to lower reaches in the Silvermine River.

Total phosphorus

The Liesbeek River shows definite increases in mean total phosphorus over time across all three river reaches. The converse is true for the upper and middle reaches of the Sand River, while the lower reaches increases over time. The Silvermine River shows the lowest total phosphorus means across the three case study rivers. No recorded means exceed the TWQR of 5 mg/L.

Total suspended solids

The means of total suspended solids decreased over the multi-decadal period in both the Liesbeek and Sand Rivers. The upper reach in the Sand River shows higher mean values over time compared to the lower reaches in that river from the early 1990s to end of the 2000s, which is not reflected in any of the other rivers in this study.

Table D1
Water quality variable means across the upper (U), middle (M) and lower (L) reaches for three decadal periods for the Liesbeek River

Variable		1980			1990			2000		
		U	M	L	U	M	L	U	M	L
Conductivity	Mean	13.7	16.4	37.8	23.0	25.2	31.8	16.0	18.5	28.7
	SD	3.5	4.2	29.0	33.6	34.9	22.6	5.0	5.1	12.5
Dissolved oxygen	Mean	8.5	8.9	6.0	8.2	7.9	6.4	9.4	9.3	7.2
	SD	3.1	1.9	2.8	2.0	2.1	2.2	3.6	3.4	3.3
E.coli	Mean				29.0	1 940.9	962.0	21.9	2 182.7	203 312.6
	SD				72.6	4 141.8	3 649.2	54.2	4 875.0	2 449 358.3
	Logged mean				1.5	3.3	3.0	1.3	3.3	5.3
Faecal coliforms	Mean	27.5	71 424.7	10 437.6	15.6	5 197.7	2 282.9	26.1	2 697.5	207 021.9
	SD	23.3	625 547.8	69 670.8	18.5	41 210.9	8 343.8	54.7	5 783.4	2 465 820.1
	Logged mean	1.4	4.9	4.0	1.2	3.7	3.4	1.4	3.4	5.3
Nitrites and nitrates	Mean	0.54	0.65	0.71	0.16	0.36	0.62	0.15	0.42	0.57
	SD	0.45	0.49	0.60	0.12	0.23	0.61	0.08	0.30	0.34
pH	Mean	7.0	7.1	7.3	7.3	7.3	7.4	7.1	7.1	7.2
	SD	0.3	0.3	0.5	0.7	0.4	0.5	0.7	0.6	0.7
Soluble Ammonia	Mean	0.23	0.13	0.42	0.31	0.20	0.22	0.39	0.26	0.37
	SD	0.36	0.11	2.00	0.24	0.22	0.28	0.23	0.33	0.28
Total phosphorous	Mean	0.24	0.13	0.18	0.34	0.24	0.27	0.33	0.23	0.38
	SD	0.09	0.22	0.15	0.19	0.26	0.23	0.19	0.24	0.48
Total suspended solids	Mean	19.3	15.6	34.5	8.2	8.9	18.8	5.0	8.5	25.2
	SD	45.0	47.6	75.3	11.5	19.4	29.1	5.2	14.6	77.1
Unionised ammonia	Mean	0.11	0.03	0.24	0.15	0.07	0.18	0.12	0.06	0.17
	SD	0.02	0.09	0.20	0.13	0.10	0.15	0.05	0.08	0.16
Water temperature	Mean	16.6	16.4	16.8	16.9	17.3	18.1	17.3	17.0	17.9
	SD	4.2	3.5	3.4	3.3	3.2	3.7	3.6	3.7	3.7

Table D2
Water quality variable means across the upper (U), middle (M) and lower (L) reaches for three decadal periods for the Sand River

Variable		1980			1990			2000		
		U	M	L	U	M	L	U	M	L
Conductivity	Mean			87.91	28.71	39.14	98.16	32.89	38.15	105.16
	SD			57.65	15.81	11.55	58.47	22.78	11.41	140.79
Dissolved oxygen	Mean			7.88	8.66	8.32	8.73	8.77	8.33	8.83
	SD			2.17	2.17	2.14	2.15	2.87	2.15	2.89
E.coli	Mean				1 493.14	52 047.10	34 817.79	3 096.55	25 548.47	44 865.68
	SD				5 474.19	228 521.23	205 244.68	12 348.00	100 327.05	152 826.08
	Logged mean				3.17	4.72	4.54	3.49	4.41	4.65
Faecal coliforms	Mean			25 584.67	1 381.44	50 597.82	51 750.99	3 605.72	26 465.17	35 171.23
	SD			75 755.83	5 183.31	234 510.02	347 431.51	14 281.54	102 811.43	77 971.53
	Logged mean			4.41	3.14	4.70	4.71	3.56	4.42	4.55
Nitrites and nitrates	Mean			1.31	0.56	0.86	1.64	0.36	0.54	1.27
	SD			0.63	0.40	0.53	0.95	0.25	0.20	0.54
pH	Mean			8.02	6.96	7.08	7.85	6.73	6.89	7.69
	SD			0.59	0.34	0.28	0.41	0.45	0.37	0.42
Soluble Ammonia	Mean			0.18	0.13	0.13	0.20	0.18	0.18	0.29
	SD			0.21	0.14	0.10	0.19	0.19	0.26	0.35
Total phosphorous	Mean			0.11	0.14	0.14	0.11	0.06	0.07	0.13
	SD			0.09	0.28	0.14	0.13	0.19	0.07	0.14
Total suspended solids	Mean			20.63	18.38	31.07	10.19	16.49	17.40	14.73
	SD			22.63	14.94	35.17	9.80	20.21	29.68	17.42
Unionised ammonia	Mean			0.023	0.001	0.002	0.004	0.005	0.001	0.007
	SD			0.066	0.000	0.001	0.006	0.030	0.001	0.013
Water temperature	Mean			18.06	16.46	16.80	17.35	16.02	15.85	16.88
	SD			3.67	2.11	1.93	3.34	2.48	3.19	3.89

Table D3
Water quality variable means across the upper (U), middle (M) and lower (L) reaches for three decadal periods for the Silvermine River

Variable		1980			1990			2000		
		U	M	L	U	M	L	U	M	L
Conductivity	Mean							15.8	31.3	54.0
	SD							11.5	16.2	70.5
Dissolved oxygen	Mean							8.0	9.0	8.1
	SD							2.2	2.1	2.2
E.coli	Mean							336.5	860.8	1 398.4
	SD							1043.0	5418.2	5709.7
	Logged mean							2.5	2.9	3.1
Faecal coliforms	Mean							348.2	281.8	1066.1
	SD							1075.7	882.1	6570.9
	Logged mean							2.5	2.4	3.0

Table D3 (*Continued*)

Variable		1980			1990			2000		
		U	M	L	U	M	L	U	M	L
Nitrites and nitrates	Mean							0.13	0.24	0.19
	SD							0.08	0.76	0.14
pH	Mean							4.8	5.1	6.8
	SD							1.0	1.1	0.9
Soluble Ammonia	Mean							0.16	0.15	0.11
	SD							0.12	0.20	0.11
Total phosphorous	Mean							0.04	0.04	0.05
	SD							0.06	0.05	0.05
Total suspended solids	Mean							6.0	10.5	7.6
	SD							5.4	22.4	14.7
Unionised ammonia	Mean							0.0011	0.0010	0.0011
	SD							0.0006	0.0001	0.0006
Water temperature	Mean							15.1	16.0	15.5
	SD							2.7	3.3	3.6

Unionised ammonia

The means along all three reaches of the Liesbeek River exceeded the national TWQR of 0.007 μg/L. All other rivers fell below this guideline.

Water temperature

The Liesbeek River showed increases in temperature across each decadal period for all of the river reaches. The converse is observed along the Sand River. Mean decadal temperatures were similar for both of these rivers. The Silvermine River recorded the lowest mean temperatures, with the highest mean recorded along this river occurring in the middle reaches.

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