Received: 4 March 2016 | Revised: 21 September 2016 | Accepted: 28 October 2016

DOI: 10.1002/aqc.2739

WILEY

RESEARCH ARTICLE

Small dams need consideration in riverscape conservation assessments

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Abstract

1. Small, off-channel dams are generally ignored in impact assessments owing to limited information and spatial resolution issues. Previous research on South African rivers showed correlative links between high density of small dams and associated reductions in low flows, poorer water quality, and impoverished aquatic macroinvertebrate communities that were dominated by opportunistic taxa instead of specialist groups.
2. Since small dams are usually associated with catchment transformation (for example, vineyards, stock farming and exotic timber plantations), they are convenient surrogates of the impacts of catchment transformation on river functionality. Here, an index of cumulative small dams for South Africa, Lesotho and Swaziland is presented and evaluated.
3. Fifty-two per cent of the water management catchments in the study region exceeded the threshold for the cumulative small dams density (SDD) index above which river functionality is compromised. This estimate of potentially affected catchments is considered to be conservative for reasons discussed.
4. The index results are compared with a recent systematic biodiversity planning exercise for setting biodiversity targets for freshwater areas of South Africa. Although the systematic planning included in-stream small dams within 50 m of a river, analysis showed that 36% of all quaternaries that have high SDD score overlap with river reaches classified as 'natural' or 'largely natural'.
5. Disregarding dams outside the 50 m buffer area equates to ignoring the majority of small dams (94%) in South Africa, and it is recommended that aquatic conservation assessments include the SDD index as a cost layer for prioritizing rivers for rehabilitation and conservation.

KEYWORDS

abstraction, agriculture, catchment management, cumulative impacts, macroinvertebrates, small dams density index

1 | INTRODUCTION

Freshwater ecosystems contribute significantly to global biodiversity and ecosystem services, despite their relatively small footprint and, therefore, the threats and challenges facing these ecosystems are of global concern (Dudgeon et al., 2006; Millennium Ecosystem Assessment, 2005a, b). Longitudinal connections of rivers, and breakages in this connectivity by the presence of large in-channel impoundments, can be easily visualized using remote sensing. This aspect of disconnectivity has been the focus of many global studies (Lehner et al., 2011; Nilsson, Reidy, Dynesius, & Revenga, 2005; World Commission on Dams, 2000) but linking rivers with human activities in the catchment, the interactions of the river surface water with groundwater (vertical connectivity), and the associated changes to hydrographs or thermographs, is not as simple (Ward, 1989). This paper contextualizes such impacts within the 'riverscape' (*sensu* Allan, 2004), with lotic response typically reflected in reduced lateral, vertical and temporal connectivity (Brierley, Fryirs, & Jain, 2006; Rivers-Moore, Mantel, Ramulifho, & Dallas, 2016). The focus is on small dams (defined here in the broadest sense as a structure

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that stores water either on or off-stream, and holding a volume below the threshold for large dams (< 3 Mm^3) as defined by the World Commission on Dams, 2000), which are associated with catchment activities such as cultivation, cattle rearing, small-scale mining and timber plantations in South Africa, and their presence is postulated as a surrogate measure of catchment transformation.

A comprehensive review of the causes and consequences of river fragmentation (Fuller, Doyle, & Strayer, 2015) notes that dams and impoundments are the most important human agents among an extensive range of impacts. In-stream dams affect river baseflows and flooding regimes that have impacts on river water quality, dilution of pollutants, and habitat availability (Mantel, Hughes, & Muller, 2010a; Mantel, Muller, & Hughes, 2010b; McCully, 2001; Poff, Olxden, Merritt, & Pepin, 2007) and have led to more than half of the world's large river systems being fragmented (Nilsson et al., 2005). In South Africa, 84% of 112 ‘main rivers’ (main channel of the river that connects water management areas) have been assessed to be ‘critically endangered’, ‘endangered’ or ‘vulnerable’ because of human modification (Nel et al., 2007). The Global Reservoir and Dam Database (GRanDv1) stresses the importance of connectivity and the need to mitigate the impacts of dams (Lehner et al., 2011). The authors estimated that there are 16.7 million reservoirs globally of which 99.5% could be considered as small dams with reservoir surface area < 0.1 km^2 (or maximum volume of 3.38 Mm^3 using Equation (2) in Lehner et al., 2011). While small dams are important for farming-related activities (Ashraf, Kahlown, & Ashfaq, 2007), particularly in areas where water resources are highly variable, as in South Africa, they have demonstrable impacts on stream-flow connectivity, catchment runoff, sediment delivery, river habitat structure, macroinvertebrate communities and water temperature changes (Callow & Smetten, 2009; Lessard & Hayes, 2003; Mantel et al., 2010a, 2010b; Verstraeten & Prosser, 2008). From a catchment water resources perspective, the cumulative amount of evaporation from small dams is of concern (4–10 mm d^{-1}, in India, Zimbabwe and Australia: Craig et al., 2007; Mugabe, Hodnett, & Senzanje, 2003; Sur, Bhardwag, & Jindal, 1999). Recent South African research showed that annual evapotranspiration values derived from MODIS-ET (MOD16), in two catchments in the Eastern Cape Province, for grassland areas with high numbers of small dams was either similar to or significantly higher than nearby grassland areas that receive similar rainfall (unpublished research by the first author). These results suggest that small dams are potentially having an indirect effect on the MODIS-ET values through the seepage of water from the dams to bordering vegetation.

A recent global review of 94 studies (Mbaka & Mwaniki, 2015) showed that there are significant impacts of small dams – both positive and negative – on the richness and density of aquatic macroinvertebrates, with the effects varying by the type of impoundment. While useful, the study failed to evaluate cumulative downstream impacts of small dams, a gap which this research addresses. The current study originates from research in two regions of South Africa where impacts of reduced baseflows and increased total dissolved salts (Mantel et al., 2010a), in addition to shifts in macroinvertebrate communities to more opportunistic and slow-current taxa (Mantel et al., 2010b) were correlated with high densities of small dams. River baseflows, in addition to floods, droughts and high pulses, are important drivers that maintain river connectivity, and reduction in baseflows can result in streams or tributaries either becoming non-perennial or reducing flow predictability, leading to a higher ‘stress’ index for inhabiting invertebrates and fishes (Hughes & Louw, 2010; Richter, Baumgartner, Wigington, & Braun, 1997). Notably, reduced low flows not only affect the local stream and its biota, but can also have adverse impacts further downstream at the stream's confluence with an impounded river by preventing the resetting of the river's water quality and fauna (Serial Discontinuity Concept: Stanford & Ward, 1989, 2001; Ward, 1989).

Januchowski-Hartley et al. (2013) have noted that a necessary first step for any region to restore aquatic ecosystem connectivity where there are impacts from small dams and culverts, is a detailed inventory. For the present study, a recently released spatial dataset of hydrological areas was useful for extracting the location of small dams and evaluating the spatial variation of the small dams density (SDD) index for the south African region (South Africa, Lesotho and Swaziland). The index values are useful to identify areas where the SDD might be high enough to compromise river functionality (Mantel et al., 2010a). This paper discusses the relevance of the results in the context of the South African National Freshwater Ecosystem Priority Areas (NFEPA) assessment for identifying critical habitats for conservation planning purposes (Driver et al., 2011) and implications for river management and conservation planning.

2 | METHODS

The locations and areas of the small dams covering South Africa, Lesotho and Swaziland were obtained from the national hydrological areas spatial dataset (Chief Directorate: National Geo-Spatial Information (NGI), 2014), from which all ‘Dam’ features were extracted. Three 1:50 000 sheets of the NGI (2014) dataset had missing data, and thus an older dataset of small dams (Chief Directorate of Surveys and Land Information, 1999) was merged with the more recent database to estimate the total number of small dams in the region. South Africa has 1946 ‘quaternaries’, which are the principal water management units in South Africa and are based on a standardized runoff measure per unit area (Midgley, Pitman, & Middleton, 1994). The SDD index value was calculated as defined by Mantel et al. (2010a) for each quaternary in the 22 primary catchments (i.e. the entire drainage basin of a main river and its associated tributaries). The cumulative number of small dams for each quaternary, which includes all small dams in the upstream catchment of the river if the river originated outside the quaternary, was quantified using ESRI ArcMap 10 (‘Spatial Join’ analysis). The cumulative value for each quaternary was standardized by the square root of the catchment area in km^2 (referred to as √catchment area) to reduce catchment size bias. We acknowledge that the SDD index value might be underestimated for the northern catchments of South Africa with rivers or tributaries originating in neighbouring countries (Zimbabwe, Botswana and Namibia; Figure 1 inset) because the dataset for small dams does not extend to these countries. Where this was the case, the cumulative catchment area

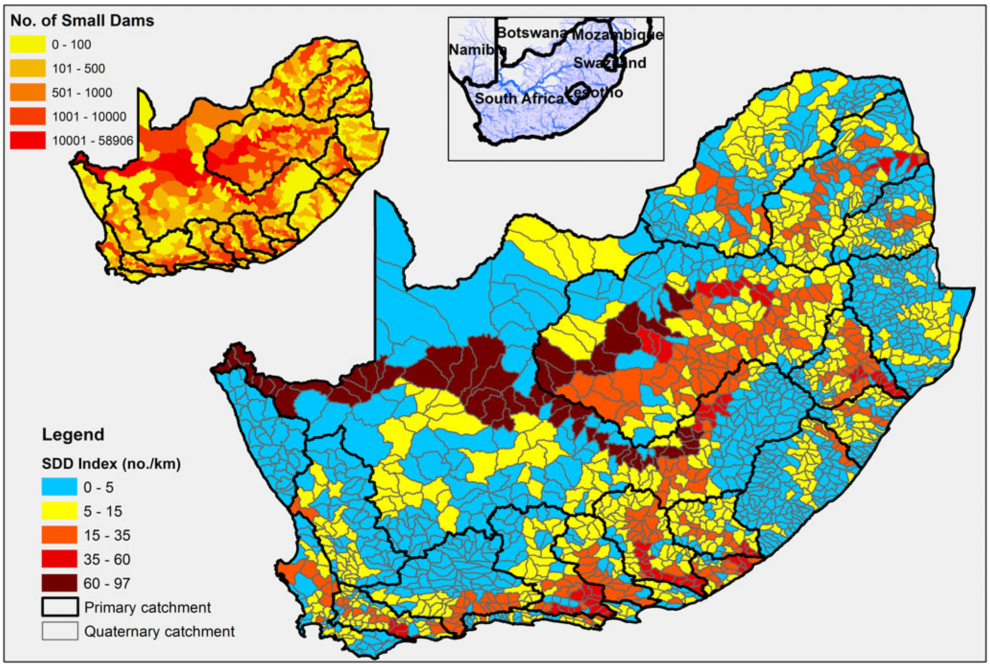

FIGURE 1 Map showing the small dams density (SDD) index for quaternaries in South Africa, Lesotho and Swaziland. The small inset shows the transboundary rivers shared by South Africa with Mozambique, Zimbabwe, Botswana and Namibia (boundaries denoted by the black lines). The larger inset shows the cumulative number of small dams at quaternary catchment level

was adjusted to include only the area of the quaternaries in South Africa for the calculation of the SDD index so that the index is not biased by the catchment area outside South Africa.

The SDD index was compared with the NFEPA assessment, which includes in-stream dams within 50 m of a river. The NFEPA assessment included a process of systematic biodiversity planning for setting biodiversity targets for freshwater areas of South Africa, using the principles of representation and persistence (Driver et al., 2011). These areas were chosen as they are considered important for maintaining key ecological processes and for conserving ecosystem types and species that are associated with rivers, wetlands and estuaries.

An Overlay Analysis (using ArcMap function 'Select by Location'), similar to a spatial intersection, was conducted between quaternaries with high SDD (>5 small dams km^{-1}) and river reaches defined as having good river condition under NFEPA. These are 'natural' or 'largely natural' categories for reaches defined from a 1:500 000 river network to identify those evaluated as being 'largely natural' or better, but which lie in quaternaries with a high SDD index. One of the outcomes of the NFEPA classification process was the identification of free-flowing rivers, which has been defined by the World Wide Fund for Nature (2006) as 'a river that flows undisturbed from its source to its mouth, at either the confluence with a larger river, an inland sea or at the coast'. From these, 19 flagship free-flowing rivers were identified as top priority rivers that are representative of free-flowing rivers in South Africa and their ecosystem processes and biodiversity are important. Thus, a second Overlay Analysis was conducted to identify those flagship free-flowing rivers that flow through quaternaries having high SDD. These analyses helped develop recommendations for conservation planning of flagship free-flowing rivers in the region.

3 | RESULTS

The small dams dataset (NGI, 2014, with missing data filled using the 1999 data) contained more than 165 000 dams of which just over 600 are large dams. Although most small dams are located in the south, centre and east of the country, the cumulative number of small dams in the catchment presented at a quaternary level tended to be associated with coastal areas and the Orange River, which is the longest river in the region that runs through the middle of South Africa towards the western coast and which has 58 906 small dams in the catchment (Figure 1).

The SDD index values by quaternary (Figure 1) range from 0 to 96.5 small dams km^{-1}. Of the 1946 quaternaries, 1020 (or 52% quaternaries primarily located in the centre and the south west of the country) exceed the SDD threshold value for the cumulative SDD. This estimate of quaternaries with potential impacts is considered to be conservative since the spatial dataset for small dams used in the analysis is for South Africa, Lesotho and Swaziland only, and therefore the calculated index values are biased for the quaternaries with transboundary rivers to the north of South Africa (Figure 1). The sensitivity of the SDD index to increases in the number of small dams is noted through the strong positive polynomial relationship between SDD and the natural log of the cumulative number of small dams (Figure 2).

The Overlay Analysis showed that 36% of all quaternaries that have high SDD scores overlap with river reaches that are classified under NFEPA as 'natural' or 'largely natural'. The NFEPA assessment includes small dams but only within a 50 m buffer zone; the number of small dams in the GIS spatial dataset that are located outside this zone was calculated to be 94% from a total of 165 781. In addition, eight of the 19 flagship free-flowing rivers identified by NFEPA lie within quaternaries with high SDD scores. An example of such a case is the Mzimkhulu River catchment in the province of KwaZulu-Natal

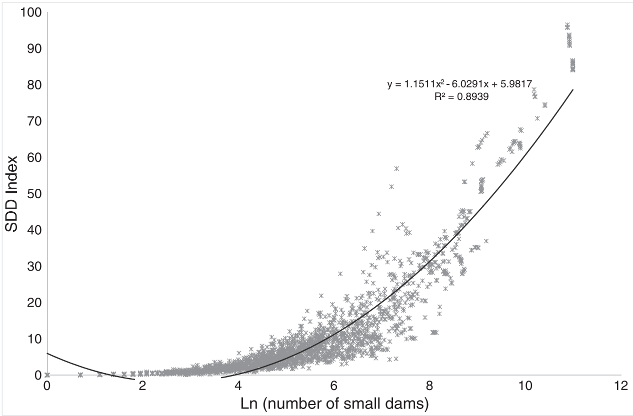

FIGURE 2 Polynomial regression relationship between SDD and natural log of the cumulative number of small dams in the catchment using the dataset presented in this study (n = 1946)

on South Africa's eastern coast (Figure 3). The Mzimkhulu catchment has 1283 small dams of which only 37 are within the 50 m buffer zone used by NFEPA, and all of the river reaches that have been defined as flagship free-flowing run through quaternaries with SDD index >5. The potential reasons and implications of these discrepancies for river conservation are discussed below.

4 | DISCUSSION

The analyses of small dams density in South Africa, Lesotho and Swaziland indicated that a large percentage (52%) of quaternaries have high SDD scores above the threshold where river functionality is compromised according to previous research (Mantel et al., 2010a, 2010b). A limitation of the SDD index is that the small dams spatial dataset does not encompass upstream areas for Primary Catchments A and D that are shared with neighbouring countries (Zimbabwe, Botswana and Namibia) and is thus biased by available data for the south African region (South Africa, Lesotho and Swaziland). However, as noted in the methods, the standardizing total catchment area was adjusted to include only the catchment area where information on small dams was available; thus, the bias should be minimal.

The correspondence of 36% quaternaries that have high SDD with rivers that are considered 'natural' or 'largely natural' under NFEPA highlights the mismatch between the two assessments. In addition, a high percentage (eight out of 19) of the NFEPA flagship rivers that were identified as top priority for retaining their free-flowing character have sections that lie in quaternaries with high SDD. Some of these flagship rivers have upstream reaches that are below the SDD

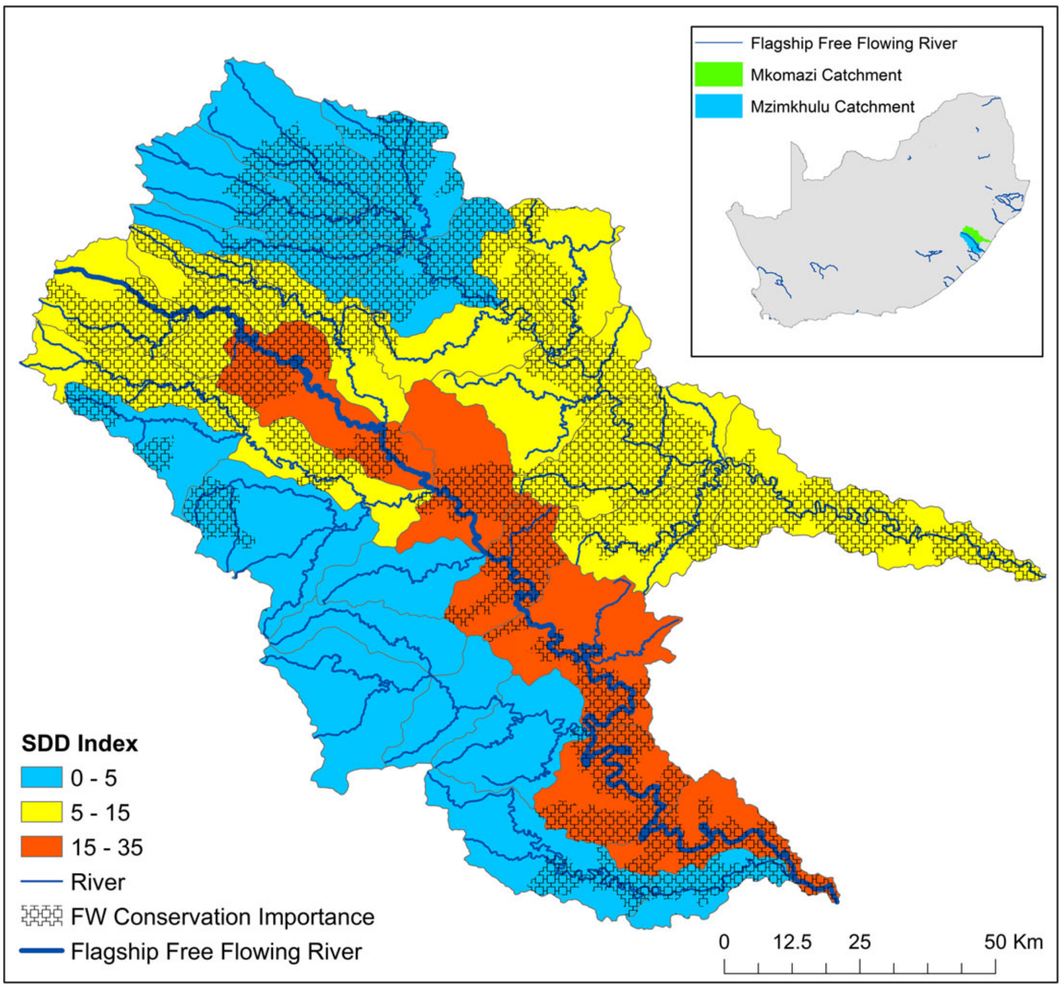

FIGURE 3 Two adjacent free-flowing rivers (Mzimkhulu and Mkomazi) with the former defined as a NFEPA flagship free-flowing river, and the important areas of freshwater conservation defined by Rivers-Moore et al. (2011). Note that all of the mainstream reaches of Mzimkhulu River fall in sub-catchments (=quaternary catchments) with a high SDD index

threshold but their lower reaches are located in quaternaries with high SDD. We suggest that these river reaches be re-evaluated considering the SDD or be prioritized for rehabilitation, e.g. Mohlapitse River in Limpopo, Kraai River in Eastern Cape, and Mkuze River in Kwa-Zulu Natal. The discrepancies between the two national level evaluations could arise from the different spatial scales of the assessments; the SDD was determined at a quaternary level while the river reach assessment for NFEPA is at a sub-quaternary level. This hypothesis is supported by the presence of reaches with different NFEPA river condition in a single quaternary. However, a second, and more significant, reason for the discrepancy could be that the NFEPA assessment only considers in-stream dams within 50 m of a river to define 'free-flowing rivers' (WWF, 2006), so that most small dams (94%) are overlooked. Thus, the NFEPA assessment underestimates the catchment level impacts in contrast to the SDD index. Disregarding dams outside the 50 m buffer area equates to ignoring the catchment transformation impacts associated with these small dams which could cause a reduction in the natural flow rate as indicated by previous research (Mantel et al., 2010a). We are proposing the SDD index, therefore, as a surrogate for catchment transformation and flow modification.

Rivers defined as flagship free-flowing under NFEPA are those that are priorities for conservation. In Australia, free-flowing rivers are defined as Heritage Rivers, and the Heritage Rivers Act 1992 prohibits construction of any barrier to the movement of freshwater fauna, and in some cases restricts diversion of water (http://www.austlii.edu.au/au/legis/vic/consol_act/hra1992171/; accessed 23 February 2016). The present analysis suggests that South African flagship free-flowing rivers should be considered not only for protection from future development and making them resilient to climate change (Dallas & Rivers-Moore, 2014), but also considered as priorities for restoration. One measure towards restoration could be partial or complete decommissioning of dams, similar to that in countries such as Australia and the USA (ArcGIS Online, 2015; Gangloff, 2013; Hart & Poff, 2002; International Rivers, 2011). Literature suggests that some species can recover following the removal of small dams, particularly if there are populations elsewhere in the stream, or adult stages that can re-colonize, although other changes might be irreversible or take an extremely long time to recover (Doyle et al., 2005; Stanley, Luebke, Doyle, & Marshall, 2002). Benefits from removal need to be balanced against the positive effects of small dams – e.g. increasing the diversity of mussel species, controlling the invasion of exotic species, and increasing habitat heterogeneity (Fuller et al., 2015; Gangloff, 2013). In South Africa, limited research has been conducted on benefits from these small dams, with the exception of Samways (1989) who denoted them as 'nature reserves' for dragonfly adults particularly at low and middle elevation of the Drakensberg Mountains. Thus, a holistic, and if possible evidence-based, argument and implementation plan would need to be developed to support dam removals in South Africa.

At a catchment level, the SDD index can be overlain with the NFEPA free-flowing rivers (both flagship and other free-flowing rivers) in conservation plans to help set priorities for river conservation or rehabilitation. This can assist with pairwise manual assessments of free-flowing rivers. Alternatively, at a regional level, the SDD index would be useful as an ancillary layer in defining a 'cost' surface in freshwater conservation planning exercises. This would facilitate conservation planning software to select targets or features (such as free-flowing rivers) preferentially that fall within more natural riverscapes (Rivers-Moore, Goodman, & Nel, 2011). For example, two adjacent free-flowing rivers on the eastern side of South Africa – the Mzimkhulu and Mkomazi Rivers (Figure 3) – were both selected as areas of high aquatic conservation value by a provincial scale assessment (Rivers-Moore et al., 2011); neither river falls within formal protected areas except in the upper escarpment zones. Both rivers have been earmarked for the construction of future in-channel impoundments. The Mzimkhulu River, a NFEPA flagship free-flowing river, has historical data available for it (Kemp, Chutter, & Coetzee, 1976) which adds context for future river studies, but it falls within sub-catchments with higher SDD index values relative to Mkomazi River. Thus, in this case the Mkomazi River is a better choice for conservation planning given its lower SDD values, even though the mainstem of the Mzimkhulu River is given a higher priority as a flagship river by NFEPA.

Systematic conservation planning can assist with stemming the degradation of rivers by conserving and preserving rivers that exhibit natural flow signatures which include the frequency, duration, magnitude and timing of flow events (Richter, 2010). Rolls, Ellison, Faggotter, & Roberts (2013) reviewed quantitative methods that may be used for assessing alterations in connectivity on fish populations or assemblages owing to the presence of barriers such as dams, weirs and culverts. These methods include comparisons of reaches above and below barriers; control versus impact areas; before and after barrier removal comparisons; and methods such as species distribution modelling. A systematic decision-support tool that accounts for the costs and benefits would need to be developed for assessing and prioritizing rivers for rehabilitation; this tool could be similar to the hierarchical multi-criteria tool developed by Hoenke, Kumar, & Batt (2014) that used social, water quality, ecological and hydrological criteria. A catchment management tool for South Africa could feed into such a decision-support tool, using environmental filters and organismal traits (Poff, 1997) to predict the species composition of macroinvertebrates (which are widely used for river health assessments in South Africa) to diagnose catchment-level human impacts for resource assessments and planning.

In many developing countries, the principle of environmental flows is recognized in state policy, but there is limited, if any, practical implementation (Le Quesne, Kendy, & Weston, 2010; Tharme, 2003). For example, environmental water requirements (EWR) are enshrined in the South African National Water Act (No. 36 of 1998), with a considerable body of research that has subsequently focused on identifying rivers that need conservation and implementation strategies for conservation and management (Nel et al., 2004; Nel, Reyers, Roux, & Cowling, 2009; Nel, Roux et al., 2009; Rivers-Moore, Goodman, & Nkosi, 2007). For researchers and practitioners working on South African rivers, the GIS shapefile is hosted on the website of the Institute for Water Research (http://www.ru.ac.za/iwr/downloads/#d.en.163488) and the values by quaternary are listed in Supplementary material (Table S1). The SDD index has been integrated into a River Connectivity Index incorporating both longitudinal (large dams and natural waterfalls) and lateral (using the SDD index and land-use fragmentation) connectivity components (Dallas, Rivers-Moore, Ross-Gillespie, Ramulifho, & Reizenberg, 2015; Rivers-Moore et al., 2016). This provides the basis for holistically assessing cumulative catchment-wide disconnectivity. The River Connectivity index can be a tool for assessing the vulnerability of aquatic biota to the effects of climate change in South Africa, and for use in conservation decision-making. While acknowledging the large uncertainty in predicting future climate, significant reductions in river runoff are projected for some areas in southern Africa (Todd et al., 2011). Key challenges in quantifying the impacts of small dams are, first, the difficulty in evaluating their impact on downstream hydrological regimes owing to the uncertainty associated with the volumes of water and the abstraction patterns (Hughes & Mantel, 2010) and the limited (if any) information related to wall height, age and condition; and second, the resolution of GIS datasets that may limit a precise assessment of the location of small dams relative to rivers (Fuller et al., 2015). Irrespective of the issues that need resolution, systematic planning of water resources, which balances protection and use as embedded in the South African National Water Act (No. 36 of 1998), is necessary to meet the UN Sustainable Development Goals for a sustainable future.

ACKNOWLEDGEMENTS

We thank the two anonymous referees and the editor for their comments, which significantly improved the manuscript. The original work on the index was conducted under the guidance of Professor Denis Hughes and Dr Nikite Muller of the Institute for Water Research, Rhodes University and was supported by the Rhodes Postdoctoral Fellowship.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

How to cite this article: Mantel SK, Rivers-Moore N, Ramulifho P. Small dams need consideration in riverscape conservation assessments. *Aquatic Conserv: Mar Freshw Ecosyst*. 2017;27:748–754. https://doi.org/10.1002/aqc.2739