Ecological impacts of small dams on South African rivers Part 1: Drivers of change – water quantity and quality

Sukhmani K Mantel*, Denis A Hughes and Nikite WJ Muller
Unilever Centre for Environmental Water Quality - Institute for Water Research (UCEWQ-IWR), Rhodes University, PO Box 94, Grahamstown, South Africa

Abstract

Impacts of large dams are well-known and quantifiable, while small dams have generally been perceived as benign, both socially and environmentally. The present study quantifies the cumulative impacts of small dams on the water quality (physico-chemistry and invertebrate biotic indices) and quantity (discharge) of downstream rivers in 2 South African regions. The information from 2 South African national databases was used for evaluating the cumulative impacts on water quality and quantity. Physico-chemistry and biological data were obtained from the River Health Programme, and discharge data at stream flow gauges was obtained from the Hydrological Information System. Multivariate analyses were conducted to establish broad patterns for cumulative impacts of small dams across the 2 regions – Western Cape (winter rainfall, temperate, south-western coast) and Mpumalanga (summer rainfall, tropical, eastern coast). Multivariate analyses found that the changes in macroinvertebrate indices and the stream's physico-chemistry were more strongly correlated with the density of small dams in the catchment (as a measure of cumulative impact potential) relative to the storage capacity of large dams. T-tests on the data, not including samples with upstream large dams, indicated that the high density of small dams significantly reduced low flows and increased certain physico-chemistry variables (particularly total dissolved salts) in both the regions, along with associated significant reductions in a macroinvertebrate index (SASS4 average score per taxon). Regional differences were apparent in the results for discharge reductions and the macroinvertebrate index. The results suggest that the cumulative effect of a high number of small dams is impacting the quality and quantity of waters in South African rivers and that these impacts need to be systematically incorporated into the monitoring protocol of the environmental water requirements.

Keywords: cumulative impacts, regional comparison, macroinvertebrate indices, measures of small-dam impact potential, average score per taxon

Introduction

Impacts of large dams have been quantified in terms of changes in the flow regime, water quality, sediment transport and channel structure, which affect the fauna and flora (periphyton, macrophytes, invertebrates and fishes) assemblages of rivers (e.g. Petts, 1984; Pringle et al., 2000; WCD, 2000; SADC et al., 2002). Large dams provide a 'significant contribution to human development', although at 'an unacceptable and often unnecessary' social and environmental price (WCD, 2000). Globally, 59% of all global large river systems are moderately or strongly impacted by river fragmentation and flow regulation by large dams (Nilsson et al., 2005). These modifications have resulted in the loss of regionally distinct flow regimes and helped the proliferation of cosmopolitan species through reduced magnitude and modified timing of ecologically important flows in US rivers (Poff et al., 2007). Therefore, there has been an increased momentum for the removal of dams (particularly those that are no longer operational) in some countries (Bednarek, 2001; Poff and Hart, 2002).

South African river ecosystems experience high variability in rainfall and runoff (Davies et al., 1995). On average, South Africa receives 497 mm of rainfall (vs. a global average of 860 mm) with western areas receiving much lower amounts relative to eastern parts that receive ~1 000 mm rainfall (DWAF, 1986). The effects of the low rainfall are exacerbated by the high potential evaporation rates (1 100 to 3 000 mm range; DWAF, 1986), leading to a value of mean annual precipitation to mean annual runoff of only 8.6%, similar to Australia (9.8%) but much lower than other parts of the globe (e.g. Canada 65.7%) (Davies et al., 1995). Nevertheless, environmental water requirements (EWR) are enshrined in South African legislation (National Water Act, No. 36 of 1998) and they represent 'the water provided within a river, wetland or coastal zone to maintain ecosystems and the benefits they provide to people' (GEFN, 2008). Inter-basin transfers and large dams have been emphasized as solutions to improve water security in the past in South Africa. Their impacts on South African rivers (geomorphology, physical and biological parameters, distribution of pest species) have been investigated (e.g. O'Keeffe and De Moor, 1988; O'Keeffe et al., 1990; Palmer and O'Keeffe, 1990a; b; c; 1995; Rivers-Moore et al., 2007). In comparison, the environmental impacts (particularly the cumulative effects) of small dams (<15m height or <$3x10^6$ m^3 storage capacity if 5 to 15 m in height; WCD, 2000) have been generally ignored (Davies et al., 1993; Hart and Hart, 2006), although they comprise the vast majority of impoundments (>500,000 with ~600 being large dams; DWAF, 1986). South African research on small dams has primarily focused on their hydrological impacts (Maaren and Moolman, 1985; Pitman and Pullen, 1989),

* To whom all correspondence should be addressed.
☎ +2746 622 4014; fax: +2746 622 9427;
e-mail: s.mantel@ru.ac.za
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with the exception of in-depth studies on 2 small dams in the headwaters of 2 rivers that recorded changes in temperature, nutrients, chlorophyll a and biotic macroinvertebrate indices (Byren and Davies, 1989; Palmer and O'Keeffe, 1989; 1990a; 1990b; O'Keeffe et al., 1990; Dallas, 1997). Studies elsewhere on small dams have noted changes in habitat structure through capturing sediment (Stanley et al., 2002), changed species composition of riparian flora by disrupting dispersal of species with poor floating capacity (Jansson et al., 2000), reduced density of cold-water fishes, such as trout, and shift in macroinvertebrate community composition due to increases in mean summer temperatures below dams (Lessard and Hayes, 2003).

Regional and global surveys have hypothesized that small dams can have a significant impact on river systems because of their large numbers and the total area covered (e.g. Rosenberg et al., 2000; Resource Planning and Development Commission, 2003). Although catchment wide hydrological models assessing farm dam impacts are being developed (e.g. Schreider et al., 2002), cumulative impacts of small dams and weirs on water quantity and quality of rivers have not been quantified on a regional scale as far as we are aware. The Serial Discontinuity Concept (Stanford and Ward, 2001) has emphasized the cumulative impacts of primarily large dams with deep or hypolimnial releases, which contrast with small dams and weirs, which are generally surface releasing. Additionally, some of the impacts of large dams (e.g. altered temperature regimes, oxygen depletion) and their implications (e.g. absent or altered thermal cues for invertebrate fauna) might not be directly transferrable to small dams (Cortes et al., 1998; Poff and Hart, 2002).

Given the paucity of analyses of cumulative impacts of small dams on river ecosystems (within the context of environmental flows), our study aims to investigate their impacts on river water quality and quantity in 2 South African regions utilising data from 2 national databases maintained by the South African Government's then Department of Water Affairs and Forestry (DWAF, now the Department of Water Affairs). Although a proper scientific investigation of the impacts on biota and physico-chemistry variables should be based on a focused field study, systematic experimental design and long-term programmes of focused data collection are frequently beyond the available funding and personnel capacities in developing countries, such as South Africa. The legislation and resource management imperatives, on the other hand, require decisions to be made in the short-term. This paper aims to investigate regional effects, instead of focusing on small site-specific studies that possibly could not be extrapolated to a larger scale. Therefore, while accepting that the data available from the national databases have limitations with respect to the objectives of this study, it must be recognised that these are the best data currently available. This paper argues that these data can nevertheless contribute to more accurately defining generalisations about anthropogenic impacts that will be useful for managing water resources using the precautionary principle. The hypotheses derived from this study can be further tested in the medium- and long-term and their scientific results applied using adaptive management.

The study was divided into 2 components. The 1st component, presented in this paper, analysed the water quantity (discharge statistics) and quality changes (physicochemical variables plus biotic macroinvertebrate indices), while a companion study investigated the invertebrate community changes that underlie the variation in the biotic indices (Mantel et al., 2010).

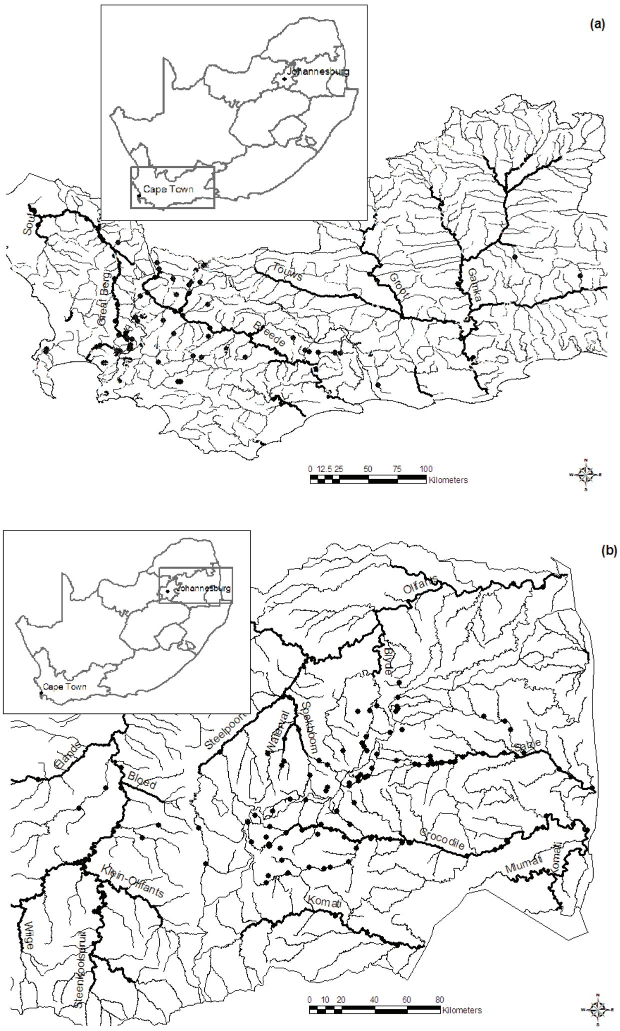

Figure 1
Maps of the (a) Western Cape and (b) Mpumalanga regions of South Africa showing the 92 and 126 sampling sites respectively. Inserts show location of the study regions relative to each other.

Methods

Data were obtained from 2 national DWAF databases: biomonitoring data from the River Health Programme (RHP, 2006) and stream flow data from the Hydrological Information System (HIS, 2006). Our analyses were conducted in 2 provinces – Western Cape and Mpumalanga – as these 2 regions comprised the majority of the RHP database. The Western Cape, located on the southwest coast (Fig. 1a), has a temperate climate and receives winter rainfall, while Mpumalanga, located in the eastern part of the country (Fig. 1b), has a subtropical climate with summer rainfall. Both regions have an abundance of small dams that are associated with vineyards and other cultivation (Western Cape) and with stock farming, cultivation and exotic timber plantations (Mpumalanga). The data used in the analyses are described below.

Biological data

The RHP reports biological data collected using the rapid river health monitoring protocol SASS (South African Scoring System; Chutter, 1998), which is an index based on

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the sensitivity of macroinvertebrate families to pollution and disturbance. This index is equivalent to those used in the UK (Biological Monitoring Working Party (BMWP); Armitage et al., 1983) and in Australia (Stream Invertebrate Grade Number Average Level, SIGNAL; Chessman et al., 1997) and the history of the development of the index is provided by Dickens and Graham (2002). The macroinvertebrate indices for the data used in our analyses were collected using the SASS4 (SASS Version 4) methodology and comprise SASS score (the sum of the sensitivities of the taxa present), number of taxa (at family level) and Average Score per Taxon (ASPT, which is SASS score divided by the number of taxa).

Physico-chemistry data

The physicochemical variables in the RHP database are not consistently reported because data are collected by various researchers. The dataset was therefore reduced to include only those variables that had the most reported values. For the Western Cape 217 samples from 92 sampling sites collected between February 1993 and November 1996 were used for analysis and for Mpumalanga, 361 samples from 126 sampling sites collected between February 1993 and September 1999.

Classification of the impact potential of dams

We have utilised the WCD's (2000) definition to distinguish between small and large dams, to highlight the significance of these small dams to rivers, and because of the simplicity of this classification and the availability of dam attribute data. The impact potential of large ($\geq 3x10^6\,m^3$; WCD, 2000) and small dams was quantified for each RHP sampling site separately. The impact potential of large dams was assessed from the storage capacity of the large dams in the catchment area above the sample sites (referred to as LDC). The total storage volume was standardised to the sampling site's mean annual runoff (MAR), estimated from the national database of Midgley et al. (1994). Data for the location and area of the small dams were obtained from a dams GIS coverage produced by the Chief Directorate of Surveys and Land Information (1999). The storage capacity of most of the small dams is unknown and therefore, the impact potential of small dams was estimated using 2 different methods for comparison: the number of small dams in the catchment of the sampling site, and secondly, the area covered by the small dams in the catchment, estimated using ESRI ArcMap 8.2 functions. Both of these small-dam impact potential measures were standardised to the square root of the catchment area in km^2 (referred to as √catchment area) to reduce catchment size bias. The √catchment area was used for standardisation instead of the catchment area, since division by the latter would have reduced the values of the small-dam impact potential measures to near zero in most cases. The former measure of the small-dam impact potential (using the number of small dams or density) is referred to as SDD, while the latter (the area covered by the small dams) is referred to as SDA. Since the small-dam density represents continuous values, it has been arbitrarily classified into the following levels for ease of interpretation of results: Level 0 (0 to5 small dams·km^{-1}), Level 1 (>5 to 15 small dams·km^{-1}), Level 2 (>15 to 25 small dams·km^{-1}), Level 3 (>25 to 35 small dams·km^{-1}) and Level 4 (>35 small dams·km^{-1}) and these levels are referred to as SDD0, SDD1, SDD2, etc., respectively.

Discharge data

Stream gauges with flow values recorded for at least an 8-year period and with less than a year gap in the reported data were utilised in the analyses. Forty-seven stream gauges in the Western Cape (Western Cape; 8 to 70 years of data, median of 36 years) and 59 gauges in Mpumalanga (Mpumalanga; 14 to 99 years of data, median of 38 years) fit these criteria. Daily discharge data were input into SPATSIM (Spatial and Time Series Information Modelling Software; Hughes and Forsyth, 2006) to obtain the following discharge statistics from the flow duration curve for each gauging station: mean daily flow (MDF), Q90 (i.e. flow which is exceeded 90% of the time), Q75, Q50 and Q10. Q10 has been assumed to be a measure of moderate high flow events as this represents the flow which is equalled or exceeded on average 36 days of the year. Note that the gauge data should represent impacted conditions since we assume that the majority of the dams have been present for a long period of time based on assessment of historical topographical maps. Estimates of the natural MAR (mean annual runoff, $10^6\,m^3$) for each gauge were calculated using a method proposed by Hughes (2004) for catchments smaller than the quaternary catchment scale used in Midgley et al. (1994). For each stream gauge, the impact of small and large dams was calculated using the methodology described in the impact potential section above. The discharge statistics (MDF, Q90, Q75, Q50 and Q10) of the gauges were standardised by the gauged catchment area.

Analysis of the impact potential of dams on water chemistry and rapid biomonitoring macroinvertebrate indices

Principal Component Analysis (PCA, which reduces the dimensionality of the data to orthogonal axes with high variance) were conducted on the water physico-chemistry data that were common between the regions (i.e. pH and TDS) and macroinvertebrate biological indices using Statistica (StatSoft, 2003). These multivariate analyses were undertaken to establish the existence of broad patterns in order to describe cumulative impacts of small dams across the 2 regions, Western Cape and Mpumalanga. For statistical significance testing, the impacts of small dams were isolated from those due to large dams by removing samples that were collected from sites with LDC of >2% from the database. Removal of sites with LDC <2% would have reduced the database size dramatically, and, therefore, it has been assumed that the effect of large dams below this level is minimal. This is a reasonable assumption as this low percentage value generally resulted when large dams were located in the headwaters of the sampling site catchment, which presumably allows the river sufficient 'recovery distance' (cf. Stanford and Ward, 2001). All variables were compared at sites with low vs. high density of small dams for significant differences using Student's t-test or Mann-Whitney U test (the latter in cases where the assumptions of normality and homoscedascity were not met). Before testing for significance, each regional database was divided into 3 subsets based on the sampling site's 'subregion', as previous research found distinct invertebrate assemblages by subregions for mountain and foothill-cobble streams vs. lowland streams (Dallas, 2004). Subregions are geomorphological zones at the river-channel scale that are distinguished by the stream gradient and the dominance of various substrate types, such as boulders, bedrock and cobble (Dallas, 2000). Our study database contained

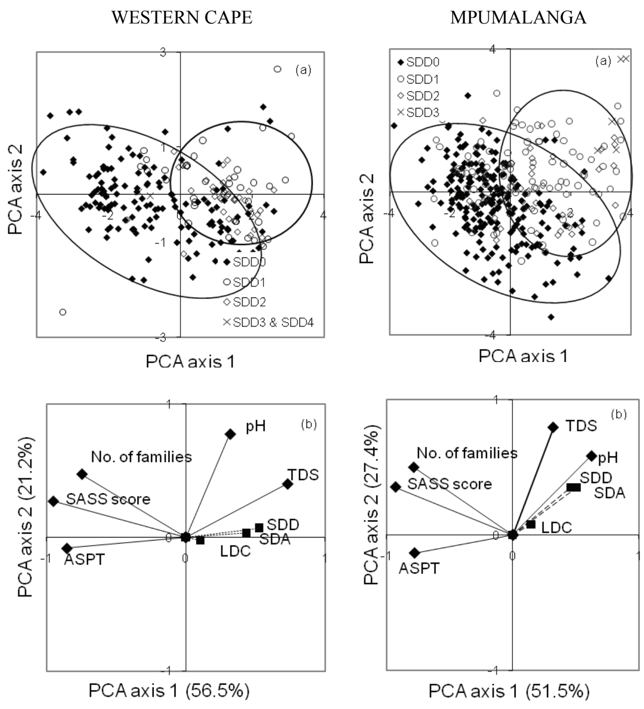

Figure 2

(a) Principal Component Analysis (PCA) for the Western Cape and Mpumalanga data showing the SDD (i.e. the number of dams per √catchment area) level for each sampled point and the 2 clusters mentioned in the text. (b) Correlation biplots for the first 2 axes of the PCA with primary (dashed lines) and supplementary (solid lines) variables entered in the analysis. The measures of small-dam density in the catchment of the sampling sites are denoted as SDD and of small-dam area as SDA. The measure of large dam impact is denoted as LDC.

sampling sites from 3 subregions: mountain stream, foothill-cobble and foothill-gravel. In order to remove the influence of inherent subregional variation, testing for differences in physico-chemistry variables and macro-invertebrate indices at low versus high dam density were conducted separately by subregions.

Results

The dams GIS coverage contained 131 042 natural and man-made water bodies (including both small and large dams) in the entire country. The Western Cape had 14 257 of these bodies while the Mpumalanga region contained 10 040 of them.

The PCA and correlation biplots for the Western Cape and Mpumalanga, shown in Fig. 2, display very similar results. SDD consistently showed better correlation with the PCA Axis 1 in comparison to the large dam storage capacity (see LDC in Fig. 2b for both regions). For this reason the SDD level is displayed for the sampling sites in the PCA outputs of the 2 regions (Fig. 2a for the 2 regions) instead of LDC. Area of small dams (SDA) on the other hand, had comparatively lower (for Western Cape) or slightly higher (for Mpumalanga) correlation values relative to SDD with the PCA Axis 1 (Fig. 2b). Since SDD is a simpler measure to determine in future analyses compared to SDA, it has been used here to display the output of the PCA.

For the Western Cape and Mpumalanga, the first 2 PCA axes explained 78% of the data variation in the macroinvertebrate indices and the physico-chemistry variables (Fig. 2a and b). Eigenvalues of 2.83 and 1.06 for PCA Axes 1 and 2 for the Western Cape, and of 2.58 and 1.37 for Mpumalanga, were obtained. Two clusters of sampled data are observable in the PCA plot in both regions – one cluster primarily includes samples with low small-dam density (SDD0, referred to as SDLo in the rest of this paper) and the second has samples from sites with higher small-dam density (SDD1-SDD4, collectively referred to as SDHi in the following text) (Fig. 2a). The 2 clusters are separated along PCA Axis 1, and an increasing level of SDD correlates with a decrease in the scores obtained for macroinvertebrate indices and with an increase in water chemistry measurement values, i.e. lower water quality overall (Fig. 2a, b).

The differences in macroinvertebrate indices and physico-chemistry variables between the 2 clusters of low and high small-dam density were tested using Student's t-test or Mann-Whitney U test. Sites with large-dam impact (with storage capacity/MAR of >2%) were removed from the database before the analyses, and the database was then subdivided by subregions, as described under the Methods section. Table 1 shows the number of samples for the 2 main subregions (foothill-cobble and foothill-gravel) after removal of sampling sites with large dams in their catchment in the Western Cape and Mpumalanga. Samples from mountain streams were not analysed statistically, due to an insufficient number of sites with high small-dam density in these streams in both the Western Cape (n = 0 for high small-dam density samples) and Mpumalanga (n = 1). The number of dams in the catchment, stream order, and MAR for the samples in low vs. high small-dam density categories in the foothill-cobble and the

Table 1
Comparison of the number of dams per kilometre of √catchment area, the stream order and the mean annual runoff (MAR) for low small-dam density (SDLo) and high small-dam density (SDHi) samples in the foothill-gravel and the foothill-cobble streams of the (a) Western Cape and (b) Mpumalanga regions. Data for median (range) are shown. Sampling sites with large dams in their catchment (LDC >2%) have been removed from the dataset.

WESTERN CAPE		Foothill-cobble	Foothill-gravel
Number of samples	**SDLo**	48	12
	SDHi	17	13
Number of dams.km^{-1} Median (range)	**SDLo**	0.0 (0.0 - 4.5)	0.2 (0.2 - 3.4)
	SDHi	5.9 (5.1 - 17.6)	10.1 (6.0 - 15.0)
Stream order Median (range)	**SDLo**	1 (1 - 3)	1 (1 - 3)
	SDHi	2 (1 - 3)	3 (1 - 3)
MAR (10^6 m^3) Median (range)	**SDLo**	39.4 (3.7 - 144.2)	6.4 (0.3 - 48.7)
	SDHi	181.3 (20.3 - 382.5)	75.8 (0.8 - 984.5)
MPUMALANGA		**Foothill-cobble**	**Foothill-gravel**
Number of samples	**SDLo**	82	20
	SDHi	14	19
Number of dams.km^{-1} Median (range)	**SDLo**	2.4 (0.0 - 4.6)	2.6 (0.2 - 4.8)
	SDHi	7.5 (5.5 - 16.7)	6.4 (5.1 - 7.8)
Stream order Median (range)	**SDLo**	2 (1 - 3)	2 (2 - 3)
	SDHi	2 (2 - 2)	3 (1 - 3)
MAR (10^6 m^3) Median (range)	**SDLo**	68.5 (5.3 - 374.9)	136.7 (119.0 - 686.7)
	SDHi	55.4 (55.4 - 373.8)	73.9 (36.8 - 838.0)

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Table 2
Results of Student's t-test or Mann-Whitney U test (latter indicated by + next to the test statistic value) for the physico-chemistry variables and macroinvertebrate biomonitoring indices in low (SDLo) and high (SDHi) small-dam density in foothill-cobble streams in the Western Cape. Median, 25th and 75th percentile values are given. The number of samples (n) for the low density group was 48 (with the exception of Cl and SO_4 with n of 47) and for the high density group was 17. Significance is denoted as P > 0.05, ns; P < 0.05, *; P < 0.01, **; P < 0.001, *.**

	SDLo Median	SDLo 25%	SDLo 75%	SDHi Median	SDHi 25%	SDHi 75%	*t* or *Z* statistic	Signi-ficance
SASS4 score	98.5	58.8	122.8	75.0	45.0	97.0	1.7	ns
No. of invertebrate families	13.0	9.8	17.0	13.0	9.0	17.0	0.4 +	ns
ASPT	7.1	5.5	7.9	5.9	5.6	6.7	2.3 +	*
Ca	2.0	0.9	3.0	3.0	2.0	5.0	-3.2 +	**
Cl	10.7	5.5	14.4	14.6	11.6	22.2	-3.0 +	**
K	0.7	0.2	1.2	1.0	0.7	2.5	-2.7 +	**
Mg	0.7	0.4	1.7	2.0	1.7	2.7	-3.4 +	***
Na	5.4	3.7	7.3	8.1	7.1	11.9	-3.2 +	**
NO_3-N	0.1	0.0	0.2	0.1	0.1	0.5	-1.3 +	ns
pH	6.0	5.1	6.7	6.6	6.3	7.1	-2.8 +	**
SO_4	1.7	1.1	3.7	4.2	3.3	9.2	-3.7 +	***
TDS	28.8	19.5	49.4	54.0	35.5	86.1	-2.7 +	**
Temperature	17.3	15.0	19.8	18.5	16.5	22.4	-1.5	ns
TSS	1.1	0.6	3.5	2.4	1.5	2.7	-2.0 +	ns

Table 3
Results of Student's t-test or Mann-Whitney U test (latter indicated by + next to test statistic value) for the physico-chemistry variables and macroinvertebrate biomonitoring indices in low (SDLo) and high (SDHi) small-dam density in foothill-gravel streams in the Western Cape. Median, 25th and 75th percentile values are given. The number of samples (n) for the low density group was 12 and for the high density group was 13 (with the exception of TDS with n of 10 and 12 respectively). Significance is denoted as P > 0.05, ns; P < 0.05, *; P < 0.01, **; P < 0.001, ***

	SDLo Median	SDLo 25%	SDLo 75%	SDHi Median	SDHi 25%	SDHi 75%	*t* or *Z* statistic	Signi-ficance
SASS4 score	90.0	54.0	124.5	48.0	44.0	58.0	2.1 +	*
No. of invertebrate families	12.5	9.0	17.0	11.0	10.0	14.0	0.8	ns
ASPT	6.7	5.0	7.4	4.2	3.9	4.4	3.6 +	***
Ca	4.5	2.0	7.0	11.9	8.0	56.0	-2.6 +	*
Cl	25.3	19.1	39.3	66.0	41.5	132.8	-2.0 +	ns
K	1.1	0.5	3.3	4.6	2.2	11.4	-2.0 +	*
Mg	3.4	2.2	5.7	7.4	4.1	96.7	-1.8 +	ns
Na	20.0	14.5	28.6	63.8	37.0	252.3	-1.7 +	ns
NO_3-N	0.2	0.0	0.3	0.2	0.0	0.4	-0.7 +	ns
pH	6.4	5.8	6.9	7.8	7.0	8.0	-2.4 +	*
SO_4	3.5	2.4	5.6	25.0	11.9	69.6	-2.5 +	*
TDS	85.1	64.9	190.5	468.9	173.2	1734.9	-1.4 +	ns
Temperature	18.7	15.1	23.3	21.0	19.7	23.0	-0.9	ns
TSS	3.0	1.5	7.7	6.0	3.6	7.0	-1.3 +	ns

foothill-gravel subregions are also given in Table 1. Note the overlap in the ranges of stream orders for the samples in the low and high small-dam density groups.

There was a significant decrease in ASPT associated with an increase in the small dam density in all 4 subregional groups tested, although no significant change was detected in the number of invertebrate families collected (Tables 2 to 5). SASS4 score showed significant reduction only for foothill-gravel streams in the Western Cape. The changes in ASPT were associated with a significant increase in pH (all groups except foothill-cobble streams in Mpumalanga) and in TDS (all groups except foothill-gravel streams in the Western Cape). The increase in TDS corresponded with an increase in concentrations of various salts and ions, with the exception of a decrease in Cl in foothill-cobble streams in Mpumalanga as shown in Tables 2 to 5.

Since discharge statistics for many of the RHP sites were not available (because they do not coincide with the locations of the stream gauges), the impact potential of small dams on the water quantity was tested on the discharge statistics of the stream gauges in the catchments. Stream gauges with LDC >2% were excluded from the analysis, similarly to the RHP sample sites as described in the Methods section. The results showed significant reduction in all discharge statistics

Table 4
Results of Student's t-test or Mann-Whitney U test (latter indicated by + next to test statistic value) for the physico-chemistry variables and macroinvertebrate biomonitoring indices in low (SDLo) and high (SDHi) small-dam density in foothill-cobble streams in Mpumalanga. Median, 25th and 75th percentile values are given. The number of samples (n) for the low density group was 82 and for the high density group was 14. Significance is denoted as P > 0.05, ns; P < 0.05, *; P < 0.01, **; P < 0.001, ***

	SDLo Median	SDLo 25%	SDLo 75%	SDHi Median	SDHi 25%	SDHi 75%	*t* or *Z* statistic	Significance
SASS4 score	155.0	136.3	179.0	151.5	108.5	166.0	0.8 +	ns
No. of invertebrate families	22.5	19.3	25.0	23.0	20.0	25.0	-0.7	ns
ASPT	7.1	6.6	7.4	6.2	5.8	6.9	3.4 +	***
Ca	7.0	4.0	10.0	8.0	7.0	8.8	-0.09 +	ns
$CaCO_3$	41.0	27.3	60.0	58.0	54.5	64.8	-2.8 +	**
Cl	10.0	10.0	10.0	4.0	3.0	10.0	2.3 +	*
F	0.1	0.1	0.2	0.1	0.1	0.2	-1.1 +	ns
K	0.5	0.3	0.8	0.8	0.6	1.0	-3.3 +	**
Mg	5.0	3.0	7.0	8.5	7.3	9.0	-3.7 +	***
Na	3.0	2.0	5.0	4.0	3.3	4.0	-1.2 +	ns
NH_4-N	0.04	0.04	0.04	0.04	0.04	0.04	-0.3 +	ns
NO_3+NO_2-N	0.1	0.1	0.3	0.1	0.1	0.2	1.3 +	ns
pH	7.8	7.6	8.1	7.7	7.3	8.0	1.4 +	ns
PO_4-P	0.01	0.01	0.02	0.01	0.01	0.01	1.1 +	ns
Si	6.5	4.9	7.5	8.2	7.6	8.8	-3.3 +	**
SO_4	4.0	4.0	5.8	4.0	4.0	5.8	-0.5 +	ns
TDS	72.0	56.0	103.0	98.0	94.3	110.3	-2.3 +	*

Table 5
Results of Student's t-test or Mann-Whitney U test (latter indicated by + next to test statistic value) for the physico-chemistry variables and macroinvertebrate biomonitoring indices in low (SDLo) and high (SDHi) small-dam density in foothill-gravel streams in Mpumalanga. Median, 25th and 75th percentile values are given. The number of samples (n) for the low density group was 20 and for the high density group was 19. Significance is denoted as P > 0.05, ns; P < 0.05, *; P < 0.01, **; P < 0.001, ***

	SDLo Median	SDLo 25%	SDLo 75%	SDHi Median	SDHi 25%	SDHi 75%	*t* or *Z* statistic	Significance
SASS4 score	136.0	95.3	165.3	104.0	75.5	131.0	1.7	ns
No. of invertebrate families	21.0	16.0	24.0	17.0	14.0	20.0	1.3 +	ns
ASPT	6.4	5.8	6.8	5.5	5.3	6.1	2.1	*
Ca	8.0	7.0	9.3	26.0	9.0	31.0	-3.9 +	***
$CaCO_3$	54.5	48.0	58.3	127.0	58.0	158.0	-3.5 +	***
Cl	11.0	5.0	12.3	9.0	5.5	15.5	0.7 +	ns
F	0.2	0.1	0.2	0.3	0.2	0.5	-2.0 +	*
K	0.8	0.6	1.0	2.0	1.0	2.8	-3.3 +	***
Mg	4.5	4.0	6.0	12.0	6.0	17.5	-3.9 +	***
Na	13.0	6.0	17.3	15.0	8.5	26.0	-1.4 +	ns
NH_4-N	0.04	0.04	0.04	0.04	0.04	0.06	-1.3 +	ns
NO_3+NO_2-N	0.1	0.0	0.1	0.2	0.1	0.3	-3.7 +	***
pH	7.8	7.7	7.9	8.2	8.0	8.2	-3.6 +	***
PO_4-P	0.02	0.01	0.02	0.02	0.01	0.02	-0.2 +	ns
Si	7.1	5.4	7.9	6.7	5.1	8.0	-0.4	ns
SO_4	5.0	5.0	7.0	10.0	6.0	26.0	-2.9 +	**
TDS	112.5	93.0	118.3	227.0	116.5	320.5	-3.3 +	***

(standardised to catchment area) for the Western Cape gauges and reduced Q90 values for Mpumalanga at sites with high small-dam density (Table 6; Fig. 3). To test whether these results are affected by the different periods of recorded data at the different stream gauges (i.e. 8 to 77 years in the Western Cape and 14 to 99 years in Mpumalanga), we picked 1 gauge in each region with no large- or small-dam impact, and with a long recording period of over 50 yr, and then recalculated the Q10 and Q90 discharge statistics using the minimum recording period for the region (8 yr in the Western Cape and 14 yr in Mpumalanga) for 8 semi-random time periods. The results showed that the variability in time periods in the Western Cape region is unlikely to affect the significance of differences in Q10 and Q90 between low and high small-dam density gauges that are given in Table 6. However, the estimates of Q10 and Q90 in the Mpumalanga region appear to be strongly affected

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Table 6
Results of Mann-Whitney U test for the discharge statistics standardised to the catchment area (CA) in units of 10^{-6} m·s^{-1} for low (SDLo) and high (SDHi) small-dam density samples in the Western Cape and Mpumalanga streams. Median, 25th and 75th percentile values are given and the number of samples (n) is indicated. Significance is denoted as P > 0.05, ns; P < 0.05, *; P < 0.01, **

WC	SDLo (n = 24)			SDHi (n = 8)			*Z* statistic	Significance
	Median	25%	75%	Median	25%	75%		
MDF / CA	0.012	0.003	0.031	0.001	0.001	0.005	2.6	*
Q90 / CA	0.001	0.000	0.003	0.0000	0.0000	0.0001	2.4	*
Q75 / CA	0.002	0.000	0.004	0.0002	0.0000	0.0004	2.4	*
Q50 / CA	0.003	0.001	0.008	0.0003	0.0001	0.0015	2.3	*
Q10 / CA	0.020	0.006	0.049	0.0017	0.0007	0.0104	2.5	*

MPL	SDLo (n = 27)			SDHi (n = 7)			*Z* statistic	Significance
	Median	25%	75%	Median	25%	75%		
MDF / CA	0.004	0.002	0.007	0.002	0.001	0.003	1.9	ns
Q90 / CA	0.014	0.010	0.027	0.004	0.003	0.005	3.1	**
Q75 / CA	0.001	0.0000	0.002	0.0001	0.0000	0.0005	1.2	ns
Q50 / CA	0.001	0.0001	0.003	0.0002	0.0001	0.0009	1.3	ns
Q10 / CA	0.002	0.001	0.004	0.001	0.0003	0.002	1.2	ns

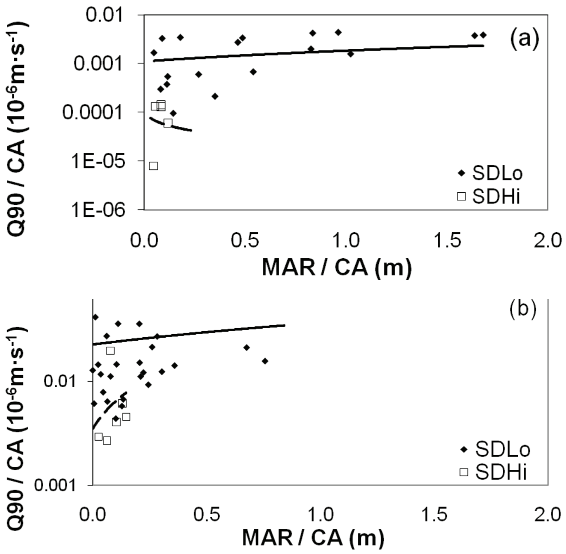

Figure 3
Comparison of the change in Q90 discharge statistic for stream gauges with low and high small-dam density in the (a) Western Cape (n = 32) and (b) Mpumalanga (n = 35) regions of South Africa respectively. Both Q90 and the MAR have been standardised by the catchment area (CA). Sites with large dams in their catchment have not been included in the analyses.

by the record period, making it difficult to interpret the differences in the impacts of small-dam development on water quantity in this region.

Discussion

The present study investigated the impacts of small dams on the water quality and quantity in 2 South African regions (Western Cape and Mpumalanga) using data available from national databases. The results of multivariate analyses indicated that the measure of small- dam impact potential based on the density of small dams in the catchment of the sampling sites was a consistently better predictor of changes in macroinvertebrate indices and physico-chemistry variables (as suggested by its high correlation value), in comparison to the measure based on the storage capacity of large dams. A 2nd measure of small-dam impact potential, based on the area of the small dams, which is analogous to the storage capacity of the dams, was either a worse (in Western Cape) or a slightly better predictor (in Mpumalanga) than the measure based on the density of small dams. The analyses were therefore conducted using the density of small dams, instead of their area, as a measure of small-dam impacts, since it is an easier measure of cumulative impacts to implement in future analyses and in water resource management programmes.

Discussion of water quality effects

Physicochemical changes were noted in three of the sub-regional groups investigated, with TDS increasing at high small-dam density sites located in foothill-cobble streams in the Western Cape and in both types of foothill streams in Mpumalanga. The increase in TDS at sites with a high small-dam density could be due to 2 main reasons. Firstly, changes in the flow-water quality relationships (e.g. increase of salts and other chemical concentration possibly due to evaporation losses from dams) could lead to higher concentrations downstream. Secondly, changes in the quality inputs related to anthropogenic activities, such as agriculture and stock farming, which are associated with the building of small dams and generally result in increased salt and nutrient input (e.g. Schofield and Ruprecht, 1989; Brainwood et al., 2004; Hart and Hart, 2006). As an example, the status of the Berg River in the Western Cape has deteriorated due to a 10-fold increase in inorganic nitrogen and phosphorus content due to agricultural runoff and sewage effluent, further exacerbated by reduced runoff, over the past 20 years (De Villiers, 2007).

ASPT decreased at sites with high small-dam density in their catchment, in both types of foothill streams in both regions. SASS4 score was not significantly reduced in 3 of the 4 groups tested, but this could be because SASS4 score is not as consistent a measure of river health and impacts as ASPT (Chutter, 1998; Dickens and Graham, 2002). Palmer et al. (2005) noted the following general guidelines for ASPT scores: natural (>7), good (6 to 7), fair (5 to 6) and poor (<5). Comparison of the median ASPT scores for the low and high small-dam density sites indicates that the Western Cape streams changed more drastically (from natural/good status to fair/poor categories) than the Mpumalanga streams (from natural/good to good/fair categories). Various authors have suggested that river flows are a major determinant for invertebrate distribution (e.g. Richter et al., 1997; Bunn and Arthington, 2002). The regional difference in ASPT change found in our study might be due to the magnitude of discharge reduction, as well as due to regional climatic differences (winter rainfalls and higher evaporation rates in Western Cape vs. summer rainfall in Mpumalanga). It can therefore be presumed that the aquatic organisms in the Western Cape rivers face greater stress compared to those in Mpumalanga rivers where low flows are experienced naturally in the winter season. Additionally, parameters linked to reduced flow, such as reduced wetted perimeter, increased concentration of pollutants due to reduced dilution, and modified transport rates for various kinds of organic and inorganic matter, might contribute to these changes.

Since our analysis was conducted using the RHP data, which are collected by various researchers during different seasons, there was a concern that the observed patterns found in this study might be influenced by seasonal differences in the time of data collection. Review of the data sets used for t-test analyses indicated that the data were collected from 3 to 4 seasons for each subregional group that was tested; however, t-tests could not be conducted for each season separately due to lack of sufficient replicates. Therefore, assessment of the general pattern was conducted by redrawing the PCA results with the collection season shown for the low and high small-dam density levels. The results showed that small-dam density remained the dominant factor regardless of any seasonal differences in sample collection. Additional support is provided by the results of a study by Dallas (1997) which found that the influence of the Nuweberg Dam (Palmiet River) was greater than the seasonal variation in the SASS4 score and ASPT values.

Discussion of water quantity effects

Our study found a significantly reduced magnitude of low flows (Q90/catchment area) in both the regions at sites with high small-dam density, suggesting that the cumulative impacts of small dams are significant for baseflows (Q90). The effect of different recording periods on Q10 and Q90 for the stream gauges, however, indicates that the results for the effects on baseflows in Mpumalanga might not be reliable. River flows (including floods, droughts, high pulses, and baseflows) serve different functions in moulding the available habitat and dictating which organisms are found where, and they are considered to be key drivers that maintain the longitudinal and the lateral river connectivity (Petts, 1984; Richter et al., 1997; Bunn and Arthington, 2002). Previous studies on individual small dams have shown reduction in flows, sometimes no flow or flow during the wrong season (due to water diversion) and, therefore, environmental flow assessments need to be aware of the implications for biodiversity (O'Keeffe et al., 1990; Lake, 2003), such as for fishes that prefer faster flows (Lamouroux et al., 2006) and for riparian woody vegetation (O'Connor, 2001). In our study, the Western Cape stream gauges showed an additional reduction in the other discharge statistics tested (MDF, Q75, Q50, Q10 standardised to catchment area) compared to Mpumalanga where only Q90 flows were significantly different. The difference in response between the 2 regions (i.e. reduction in all discharge statistics in Western Cape compared to Mpumalanga) is believed to be linked to the climatic differences between the regions, since the Western Cape experiences higher temperatures and evaporation rates during the summer low flow season.

Threshold between low and high small-dam density

The validity of the threshold of 5 small dams per √catchment area used in this study, which distinguished the low and high small-dam density sites, is at present questionable as it might be an arbitrary division based on the results of multivariate analyses and t-tests. To assess if this threshold is ecologically meaningful, ASPT and SASS4 scores at low small-dam density sites were compared with the results of Dallas's (2004) study on macroinvertebrates from reference sites in the same 2 regions. In the Western Cape, the sub-regional groupings of Dallas (2004) contain mountain and lowland streams and therefore cannot be compared with our 2 groups (foothill-cobble and foothill-gravel). Dallas (2004) found 2 distinct groups for the Mpumalanga region. Group 1 consisted of majority of foothill-gravel streams with a median ASPT of 6.2 and SASS4 score of 182. In our study, the ASPT for the low small-dam density foothill-gravel streams (6.4) is comparable to this group, although the SASS4 score is lower (136). The 2nd group in the Mpumalanga region in Dallas (2004) had 4 subgroups, 2 of which (sub-groups 2B and 2C) had >50% foothill-cobble streams. The median ASPT of these 2 sub-groups was 6.5 and 7.1, which is comparable to the ASPT value in our study for the foothill-cobble streams with low small-dam density with a median ASPT of 7.1, suggesting that the sites included in the SDLo category in the Mpumalanga region might be classifiable as reference sites. The SASS4 scores of these 2 sub-groups were higher than in our study for foothill-cobble streams in Mpumalanga, which might arise from the lower consistency of SASS score relative to ASPT (Chutter, 1998; Dickens and Graham, 2002). Therefore, we suggest that the closeness of the ASPT values of the Mpumalanga reference sites of Dallas (2004) to the ASPT values for our SDLo samples in foothill-cobble and foothill-gravel streams indicates that the threshold of 5 small dams has some ecological basis. However, determining the exact threshold would require field research, especially since the data in our study was a continuum of the density of small dams in the catchment and this translated into a continuum of values for the associated measured variables. This threshold, once confirmed by field studies, can in future be incorporated into EWR (environmental water requirement) studies by investigating the change in river health measures by the presence of small dams at a river or ecoregion level. Future studies would also need to conduct field investigations to understand the mechanisms behind the reductions in baseflows (such as effects of water diversions, evaporation from small dams), water quality changes (linked to land use and water quantity reductions) and the associated changes in biodiversity (due to habitat changes, water quality degradation, baseflow reductions).

Limitations and conclusions

This research has found some generalisations about the cumulative impacts of small dams on rivers in 2 South African regions, in terms of baseflow reductions, increases in the concentrations of some water quality variables and reductions in a macroinvertebrate biomonitoring index. Secondly, the changes in the macroinvertebrate index and the physico-chemistry were more strongly correlated with the density of small dams in the catchment relative to the storage capacity of large dams. Some regional differences were also noted with the impacts on discharge reduction and the changes in the macroinvertebrate index being greater in the Western Cape region than in Mpumalanga.

There are limitations, however, to the interpretation of our research results. Firstly, although the results could isolate the small-dam impact by excluding sites with large dams in their catchment, other anthropogenic land-use impacts, such as agriculture and forestry that are correlated with the building of small dams were ignored; these could be alternative and/or additional reasons for the changes noted in our study. Our results are of interest in light of a recent publication which reported that small dams were not as good a predictor of instream habitat integrity as the percentage area of natural vegetation and the number of mines (Amis et al., 2007). We believe our study appears to contradict these results due to the use of different indicators (habitat and fish versus invertebrate assemblage) and it could be argued that the comparatively sedentary nature of invertebrates, relative to fish, suggests that invertebrates are a better indicator of local changes relative to fish that are more mobile.

A 2nd limitation of our study was the GIS dam coverage utilised for determining the small-dam density. This coverage was obtained from 1:50 000 topographical maps (Chief Directorate of Surveys and Land Information, 1999), which contained a total of only 131 042 water bodies, while the DWAF has reported an estimate of >500 000 dams (DWAF, 1986). This large discrepancy could be due to the absence of some farm dams (i.e. small dams that do not require a licence) in the GIS coverage or due to the DWAF figure being an overestimate. The latter reason might be more realistic as a comparison of Google Earth images of 2 small catchments in the Western Cape indicated that the GIS coverage was generally correct in capturing the location of farm dams.

South Africa, with a semi-arid climate (<500 mm annual rainfall) and high irrigation demand, has a progressive water legislation which visualizes a balance between equity (human needs) and sustainability (including ecological needs) of the water resource, best described by the slogan 'some, for all, forever' (Palmer et al., 2002). Environmental water requirements, as laid out in the National Water Act (Act No. 36 of 1998), refers to the amount of water, both quantity and quality, required to protect the aquatic ecosystems. Our understanding of the links between water quantity and quality is, however, limited, and therefore, the quality and quantity components of the EWR are presently conducted semi-independently. The present study has highlighted the need for systematic collection of data, both quantity and quality and by season, which can assist in proper EWR assessments. The importance of dams for providing water for human use in a semi-arid country cannot be underestimated. This paper is not suggesting that all small dams are ecologically bad, but instead provides an insight into their cumulative impacts that can lead the way forward in balancing the needs of the environment with those of humans, by determining the threshold at which the water quality necessary for biodiversity conservation, as well as for human use, is impacted. This is particularly important in light of freshwater conservation planning occurring in South Africa, Australia and the US (e.g. Stein et al., 2002; Abell et al., 2007; Nel et al., 2007).

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