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## Evidence for the effectiveness of nature-based solutions to water issues in Africa

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There is increasing global interest in employing nature-based solutions, such as reforestation and wetland restoration, to help reduce water risks to economies and society, including water pollution, floods, droughts and water scarcity, that are likely to become worse under future climates. Africa is exposed to many such water risks. Nature-based solutions for adaptation should be designed to benefit biodiversity and can also provide multiple co-benefits, such as carbon sequestration. A systematic review of over 10 000 publications revealed 150 containing 492 quantitative case studies related to the effectiveness of nature-based solutions for downstream water quantity and water quality (including sediment load) in Africa. The solutions assessed included landscape-scale interventions and patterns (forests and natural wetlands) and site-specific interventions (constructed wetlands and urban interventions e.g. soakaways). Consistent evidence was found that nature-based solutions can improve water quality. In contrast, evidence of their effectiveness for improving downstream water resource quantity was inconsistent, with most case studies showing a decline in water yield where forests (particularly plantations of non-native species) and wetlands are present. The evidence further suggests that restoration of forests and floodplain wetlands can reduce flood risk, and their conservation can prevent future increases in risk; in contrast, this is not the case for headwater wetlands. Potential trade-offs identified include nature-based solutions reducing flood risk and pollution, whilst decreasing downstream water resource quantity. The evidence provides a scientific underpinning for policy and planning for nature-based solutions to water-related risks in Africa, though implementation will require local knowledge.

**1. Introduction**

Globally, for the period between 2001 and 2018 floods and droughts affected over three billion people and caused total economic damage of almost US\$700 billion. (UNESCO 2020). For the period between 1995 and 2015, droughts accounted for 5% of natural disasters, affecting 1.1 billion people, killing 22 000, and causing US\$100 billion in damage (UNISDR 2015, Wallemacq and Below 2015). Africa is experiencing many serious water issues including floods (Di Baldassarre *et al* 2010, Ekwezuo and Ezeh

2020, Lumbroso 2020), droughts (Haile *et al* 2019) and river pollution (Fayiga *et al* 2018), presenting major risks to economies and societies. Furthermore, these issues may worsen in the future as the climate changes (De Wit and Stankiewicz 2006, Douglas *et al* 2008). Seven African countries are in the recent top ten rank of countries with the highest risk of drought for combined agricultural systems of rain-fed and irrigated crops (Meza *et al* 2020). Floods are associated with a 35% decrease in total and food per-capita consumption and 17 percentage point increase in extreme poverty (Azzarri and Signorelli

2020). Consequences will continue to impair economic development and poverty alleviation, increasing risks linked to conflict and migration (Scholes *et al* 2018).

There is increasing interest in Africa, as well as globally, in employing nature-based solutions to help address water issues (Boelee *et al* 2017, Kalantari *et al* 2018, Frantzeskaki *et al* 2019, Seddon *et al* 2020). These can include protection and/or restoration of naturally occurring systems, such as regrowth of natural forests, removal of non-native vegetation, reconnecting floodplains with their rivers and constructed interventions, including installing green roofs and creating artificial wetlands. Past studies have shown how landscape elements, such as natural wetlands (Bullock and Acreman 2003) and forests (Dadson *et al* 2017, Filoso *et al* 2017), can alter the hydrological cycle, and how site-based interventions, such as constructed wetlands (Kivaisi 2001) can be effective for wastewater treatment in developing countries.

A widely acknowledged definition of nature-based solutions, used by IUCN, is 'Actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits' (Cohen-Shacham *et al* 2019). In contrast, other solutions, such as dams, embankments or pipelines to transfer water between catchments often disrupt natural processes and lack biodiversity benefits. Nature-based solutions for adaptation can also produce multiple additional benefits, such as carbon sequestration (Reid *et al* 2006), thus addressing the Triple Challenge of simultaneously minimising climate change, restoring biodiversity and addressing food security and other development priorities (Baldwin-Cantello *et al* 2020). Nature-based solutions are increasingly attracting the attention of governments and non-state actors in climate, conservation and natural resource management arenas. For instance, they feature in national climate change adaptation policies in African countries (Seddon *et al* 2021). Yet, there is a lack of scientific evidence on nature-based solutions and their effectiveness, particularly in Africa (FAO 2015) and limited meta-analysis of available evidence; this has led to the emergence of 'popular narratives', such as in forest hydrology, that are not consistent with the best available scientific evidence (Gilmour 2014).

This paper presents the results of a systematic review of the available evidence for nature-based solutions to water-related risks in Africa. Systematic reviews were designed specifically to find, classify and analyse all available scientific evidence in a comprehensive, objective, transparent and repeatable manner. We focus on blue water issues of floods and water resources in rivers and aquifers (Falkenmark and Rockström 2006); we do not cover green water in soils and solutions such as conservation agriculture. We considered solutions at the landscape scale,

(forests and natural wetlands) and site-specific scale (constructed wetlands and urban interventions). This evidence provides the basis for identifying the potential for nature-based solutions to current and future water risks in Africa and can guide policy development, strategic planning and investments.

## 2. Method

Whilst most studies start with an assessment of past literature, reviews can vary enormously in methods employed and quality. In some cases, specific evidence may be selected to justify a pre-determined viewpoint at the exclusion of contrary evidence (Goldacre 2009) or interpreted in a manner to create fake science (Hopf *et al* 2019). Systematic evidence reviews provide a means of collating in a comprehensive and unbiased manner all available science to produce conclusions and summary statements supported by an audit trail back to original studies. They originated in medical research (Cook *et al* 1997), have been widely accepted as best practice to develop health policies and are now applied to environmental issues, including effectiveness of protected areas for freshwater biodiversity conservation (Acreman *et al* 2019) and impacts of riverine aggregate mining on freshwater ecosystems (Koehnken *et al* 2020).

We undertook a systematic evidence review to answer focused questions (table 1), by applying the preferred reporting items of systematic reviews and meta-analyses (Moher *et al* 2009) and guidance produced by the UK Government's Department of Environment, Food and Rural Affairs (Collins *et al* 2015). Our review included search and selection protocols based on the population, intervention, comparator and outcome framework (table 1). The search strategy, search terms and inclusion/exclusion criteria were peer-reviewed and amended before searching.

We searched the Web of Science database (including SciELO) and Google Scholar, made requests to experts and institutions and scanned reference lists of review papers and books (termed 'snow-balling') to obtain publications containing evidence of the effectiveness of nature-based solutions in Africa. Throughout the rest of this paper, the term 'searches' refers to this activity. These searches returned a range of information including published papers and unpublished reports and brochures from conservation organisations, UN agencies and development banks. Some documents referred to more than one study area or water metric (e.g. nitrate concentration or flood peak magnitude); these were each recorded as separate case studies. Only those containing primary quantitative evidence related to the effectiveness of nature-based solutions to downstream water issues (floods, water quality, water resource quantity) were retained. This meant rejecting other documents that reported the same study results. We also rejected publications that reported confounding factors,

Table 1. PICO elements.

PICO element	Inclusion	Exclusion
Primary question: ‘are nature-based solutions effective in mitigating specific water risks to societies and economies in Africa?’ Secondary question: ‘What are the characteristics of nature-based solutions (e.g. type of ecosystem, landscape location, level of management) that are effective in mitigating specific water risks?’		
Population. The subject or unit of study	Any country in Africa. In terrestrial and freshwater systems e.g. forests, wetlands, urban areas, where quantitative results have been published in searchable databases	Other developing countries not in Africa. Other ecosystems such as coastal and marine areas. Reviews, personal opinions and unpublished material.
Intervention. Exposure applied or investigated	Actions to alter ecosystems at landscape scale (e.g. deforestation, reforestation, restoring wetlands) or presence/absence of these ecosystems that provide insight into effectiveness of interventions. Local scale interventions (e.g. constructed wetlands and sustainable urban drainage) that could be nature-based solutions to water issues (e.g. floods, water resource quantity, droughts, water quality).	Engineered solutions, such as large dams and inter-basin transfers through pipes. Solutions to risks other than climate-water issues, e.g. increased temperature, CO <sub>2</sub> concentration or atmospheric pollution.
Comparator. Control with no intervention	Pre- and post-intervention. Post- compared to reference location representing pre-implementation conditions. Measurement of processes and simulation of reference conditions within a computer model. Comparison of catchments with and without forests and wetlands or other nature-based solutions to water issues.	Implementation of interventions where there is no comparator, control or reference counter-factual. Studies where pre- and post-implementation are both modelled and not based on local data. Presence of confounding factors that question associations.
Outcome. The effect of the intervention	Quantified change in blue water metrics downstream such as floods, droughts, water resource quantity and water quality, including sediment, demonstrated with recorded data.	Green water issues, such as soil moisture. Qualitative or inferred change in water issues without data. Changes in other metrics e.g. CO <sub>2</sub> concentration. Wholly model-based studies within new observed data. Impacts outside the catchment of intervention.

which precluded unambiguous, firm conclusions; for example where recorded hydrological changes could have resulted either from deforestation or from concurrent urban development. Documents that reported other hydrological metrics, such as evaporation or infiltration rates, from which floods or water resource quantity had to be inferred, were also discarded. Furthermore, we rejected documents recording metrics downstream of wetlands or forests that lacked comparative data for reference sites (without wetlands or forests) or before interventions. The exception to this was for process studies that clearly demonstrated the link between interventions and hydrological metrics, particularly related to groundwaters. Modelling studies not supported by data were excluded from the review. However, studies were included where pre-intervention reference conditions were simulated using a model, but where post-intervention data were employed. Because we were primarily interested in local and landscape-scale effects of nature-based solutions, the review excluded studies of regional or

continental processes, such as deforestation in the tropics altering the hydrology of higher latitudes. Key information was recorded for each case study (table 2).

Water resource quantity metrics were of three types: ‘annual flow volume’, ‘dry season flow volume’, ‘wet season flow volume’. The flood metrics are predominantly peak flow during flood events. Water quality metrics were primarily percentage removal of pollutants (e.g. nutrients, biological oxygen demand (BOD), chemical oxygen demand (COD), cadmium, zinc, pharmaceuticals, coliforms, petroleum products and sediment).

In this paper we use the term afforestation to refer to planting of trees where the species would not have occurred naturally, such as use of non-native species or planting any species on land that would have been grassland in the past. We use reforestation to refer to planting of native trees where they would have existed or allowing natural regrowth of native trees.

Table 2. Meta-data collected for each case study.

**All case studies**

Authors, publication reference, country, catchment/location, ecoregion (Olson *et al* 2001), period of study, key species, size of intervention, water metric and direction of change (increase, decrease, unchanged), notes (e.g. compounding factors)

**For forest and natural wetland case studies**

Ecosystem type (e.g. native forest, fen wetland), catchment area

**For natural wetland case studies**

Major freshwater habitat type (Abell *et al* 2008)

**For constructed wetlands**

Inflow rate

### 3. Overall results

The searches returned 10 633 publications. After applying inclusion/exclusion criteria, we were left with 150 publications containing 492 case studies from across Africa (table 3), all meta-data for which are provided in the supplementary file (available online at [stacks.iop.org/ERL/16/063007/mmedia](https://stacks.iop.org/ERL/16/063007/mmedia)). Only 13 case studies were explicitly referred to by the authors as ‘nature-based solutions’, five were urban and eight rural. They covered a range of intervention types, such sustainable urban drainage.

Of the 133 forest case studies, 50 were of native forests, 45 related to non-native forests, whilst 14 were mixed native and non-native. In 24 forest case studies the forest type was not specified. These 133 case studies reported mainly downstream water resource quantity metrics, though a small number reported impacts on floods and sediment loads.

Afforestation case studies totalled 35, with 31 explicitly planting non-native trees, two planting a mix of native and non-native and in two cases the tree species were not specified. Only two studies involved reforestation. Deforestation case studies totalled 92 studies, with 50 involving removal of native trees, 10 removal of non-native trees, 12 removal of mixed tree species, whilst in 20 case studies the tree species were unspecified.

The 144 natural wetland case studies reported a range of water resource quantity and quality parameters and groundwater interactions. The 202 constructed wetland case studies only reported water quality parameters comparing input concentrations of pollutants with outputs from the wetland to calculate effectiveness of removal.

In the following sections we present the numbers of case studies grouped according to different associations between land cover and hydrological metrics; we also provide graphs of the associations. The cases studies of various species, at different scales and employing a range of analysis techniques and method of inference. Furthermore, the majority were

single observational studies rather than experimentally designed with replicates, and few provided statistical significance of their results. Therefore, we avoid making definitive conclusions but indicate tendencies in the evidence found.

## 4. Hydrological response to forest

### 4.1. Forests and water resource quantity

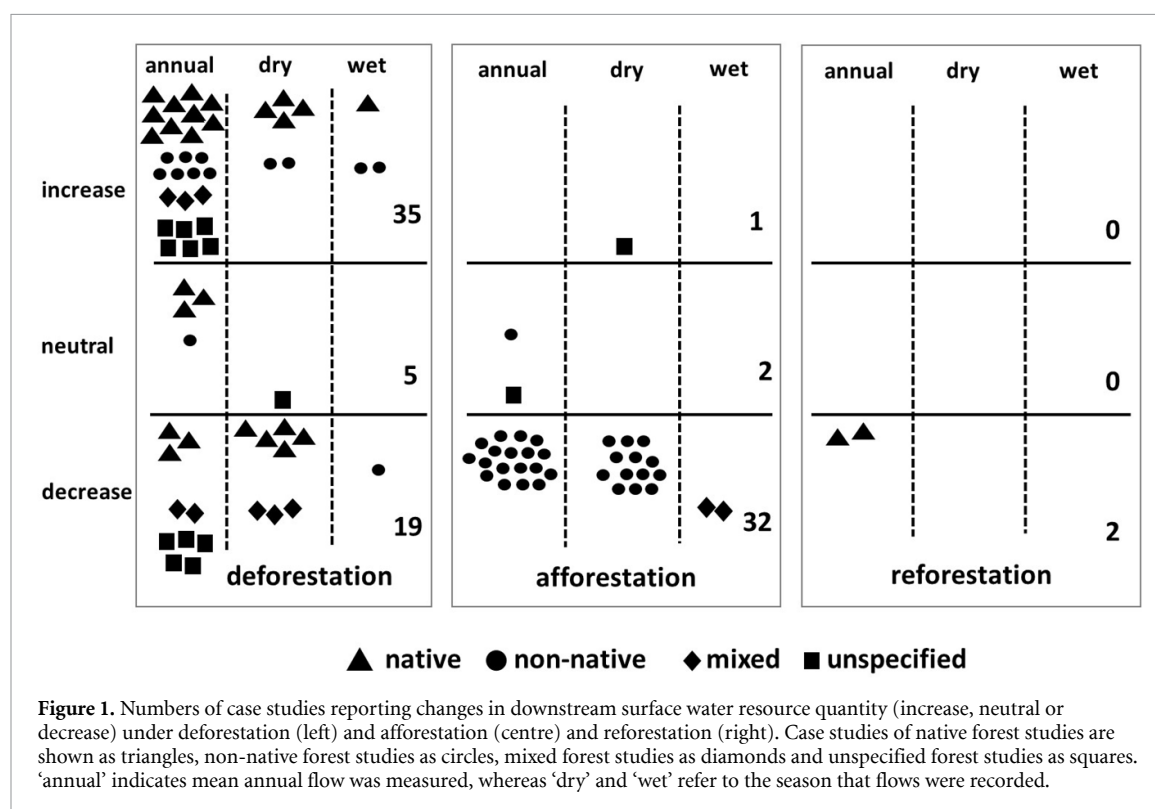
Of the 133 case studies involving forests, 97 reported effects on downstream surface water resource quantity. Most (32 of the 35) afforestation case studies showed decreased downstream surface water quantity, with 30 non-native species examples and two mixed forest types (figure 1). Most studies were for a single time period, and only a few reported flow changes at different stages of tree growth. For example, after replanting of pine trees (following clear-felling and flow increases) in Jonkershoek, South Africa, flows reduced to preclearing levels within 12 years, with the peak decrease after 20 years; thereafter the reduction was less (Scott *et al* 2000). The two reforestation case studies in Ethiopia were of exclosures that allowed natural tree regrowth, without replanting; they reported a significant decrease in runoff generation, which continued for 20 years (Descheemaeker *et al* 2006).

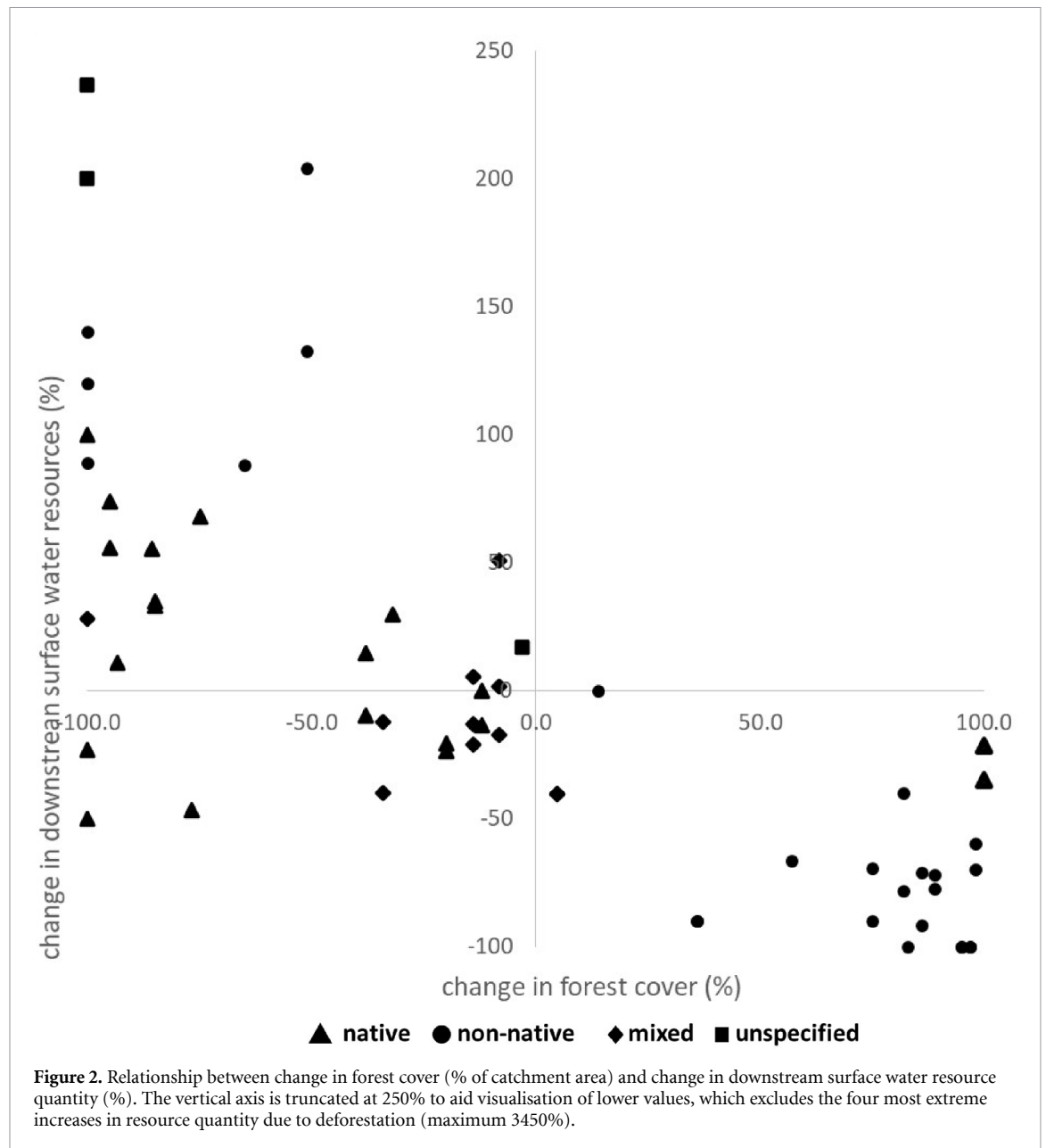
Deforestation was reported to increase downstream surface water resource quantity, in almost 60% (35 of 59) of case studies. Most studies considered only one time period, so changes in hydrological impact over time were not present, but studies directly after deforestation showed effects were immediate. Of these 35, 15 case studies concerned native species, 11 non-native, three mixed species and six unspecified. Almost one third (19 of 59) of deforestation case studies reported decreased surface water quantity. Of the 19, eight were native species studies, one non-native, five mixed and five unspecified. Of the case studies reporting dry season flows, just over half (8 of 15) recorded a decrease following deforestation, whilst 40% (6 of 15) recorded an increase. Considering only studies of native or mixed forests, twice as many (8) showed a decrease in dry season flows in response to deforestation as those that showed an increase (4).

A subset of case studies reported the percentage changes in water resources. Of these, more than 70% (17 of 24) of the case studies of afforestation show decreases in surface water resource quantity of greater than 60%. Changes were less consistent for deforestation. Most (7 of 8) case studies of native tree deforestation reported increased water quantity of greater than 80%, with one reporting a decrease of over 80%. Almost half (13 of 28) of the case studies of non-native deforestation (e.g. Scott *et al* 2000) showed increases in water quantity of greater than 40%, whereas one third (9 of 28) show decreases.

**Table 3.** Numbers of case studies in African countries.

	Nature-based solutions	Forests	Natural wetlands	Constructed wetlands	Total
Algeria				4	4
Benin		2			2
Botswana			6		6
Burkina Faso	1	1			2
Burundi		2			2
Cameroon			2	5	7
Chad			2		2
Congo		1			1
Egypt			2	29	31
Ethiopia		38	9	35	82
Ghana		2	6	16	24
Kenya	2	9	1	3	15
Madagascar			2		2
Malawi		10	10		20
Mali			4		4
Morocco				10	10
Namibia	1				1
Nigeria		2	5	19	26
Rwanda				2	2
Senegal			5		5
Sierra Leone			3		3
South Africa	9	37	14	10	70
Sudan			3		3
Tanzania		16	3	19	38
Tunisia			1	18	19
Uganda			21	27	48
Zambia		9	28		37
Zimbabwe		3	13		16
More than one country		1	4	5	10
Total	13	133	144	202	492





A few studies showed maps of forest cover change, which were distributed across the catchment, but most simply reported the percentage change within the catchment. Therefore, it was not possible to assess the differing impacts of forest change in different locations, such as in headwaters or along the main channel. All case studies reported at a single measuring point at the outlet of the catchment under study, so it was not possible to determine how changes in water resources might propagate downstream.

Figure 2 shows the percentage change in surface water resource quantity for a given change in percentage of the catchment forested for the subset of the case studies that reported both values. The maximum decrease in surface water quantity from deforestation was 50% from clear-felling native trees in Tanzania

(Lundgren 1980), though this was from a micro-plot study of 12 m<sup>2</sup>. In contrast, several studies reported 100% decrease (drying of the river) from afforestation. The general trend was for increasing water resource quantity as the percentage of the catchment covered by forests decreases and decreasing water resource quantity as the percentage of the catchment forested area increased. Changes in water resource quantity were generally greater for non-native than for native species. Case studies covered a range of ecoregions and forest types found in Africa, but two types found on the continent and not represented in the literature were tropical rainforests and cloud forests. There was no clear pattern of the direction of change in water resource quantity with native forest type or ecoregion (table 4).



**Table 4.** Type of native forests (ecoregion from Olson *et al* 2001) in case studies of deforestation impacts on water resource quantity Reproduced with permission from Olson *et al* (2001). CC BY-NC 3.0.

	Country	Forest type	Catchment area km <sup>2</sup>	reference
<b>Annual flow volume</b>				
Increase in water availability	Tanzania	Montane evergreen forest	5	Lorup and Hansen (1997)
	Malawi	Montane forest	95 750	Calder <i>et al</i> (1995)
	Kenya	Montane forest	690	Mwangi <i>et al</i> (2016)
	Benin	Forest-savannah mosaic	3	Giertz <i>et al</i> (2005)
	Tanzania	Miombo woodland	24 620	Kashaigili (2008)
	Zambia	Miombo woodland	1	Mumeka (1986)
	Kenya	Forest-savannah mosaic	1	Recha <i>et al</i> (2012)
Neutral	Ethiopia	Montane forest	266	Gebrehiwot <i>et al</i> (2010)
Decrease in water availability	Tanzania	Eastern arc forests	0.00001	Lundgren (1980)
<b>Dry season flow volume</b>				
Increase in water availability	Tanzania	Montane evergreen forest	5	Lorup and Hansen (1997)
	Malawi	Miombo woodland	534	McCartney <i>et al</i> (2013)
	Zambia	Miombo woodland	3699	McCartney <i>et al</i> (2013)
Decrease in water availability	Tanzania	Acacia woodlands	164	Chiwa (2012)
	Ethiopia	Montane forest	47	Kidane <i>et al</i> (2018)
	Zambia	Miombo woodland	17742	McCartney <i>et al</i> (2013)
<b>Wet season flow volume</b>				
Increase in water availability	Ethiopia	Montane forest	46.6	Kidane <i>et al</i> (2018)

#### 4.2. Forests and floods

The 20 case studies of flood response to changes in forest cover were from a range of catchment sizes from >17000 km<sup>2</sup> to <1 km<sup>2</sup> and show a diverse pattern of responses. Three quarters (12 of 16) of deforestation case studies reported an increase in downstream flood peak flow (e.g. Mumeka 1986), whilst three showed no effect (e.g. Mwendera 1994). The afforestation case studies reported increases (1 of 4), decreases (1 of 4) and no effect (2 of 4) on flood magnitude. Sub-dividing the case studies into native and non-native did not reveal strong trends, partly due to the small numbers of studies.

The ten case studies providing numerical values for percentage change in flood magnitude and percentage in catchment area forested are shown in figure 3; there were no studies providing quantitative results of afforestation effects on floods. Although data were limited, they suggested that greater deforestation was associated with a greater increase in flood magnitude.

Most case studies reported flood metrics at a single time period after deforestation. One exception was in Kapchorwa, Kenya, where the conversion from forest to agricultural land in the first 5 years caused half of the total increases in flood discharge (Recha *et al* 2012).

#### 4.3. Forests and sediment yield

There were 11 case studies of change in sediment yield in response to alterations in forest cover. Most (9 of 11) case studies indicated that deforestation was associated with increases in sediment yield downstream and one showed decreasing sediment yield with afforestation. One study reported higher sediment loads in naturally forested catchment than a savannah catchment in the Congo (Coynel *et al*

2005), but sediment concentrations from both catchments were very low, so the difference may not be significant.

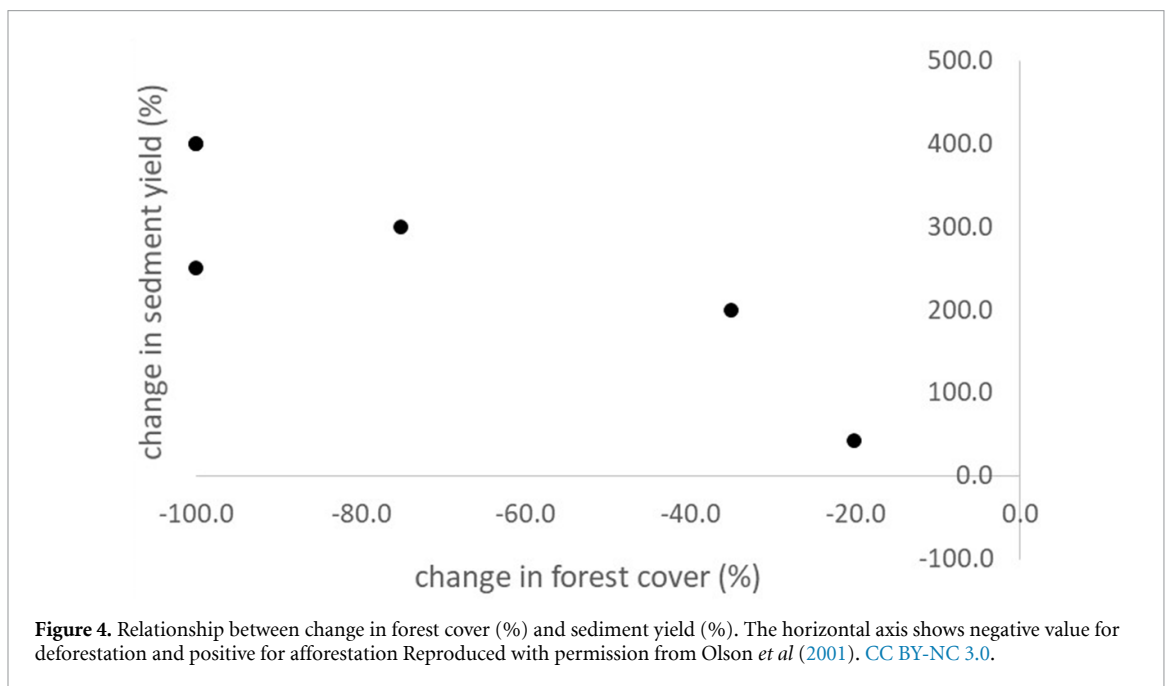
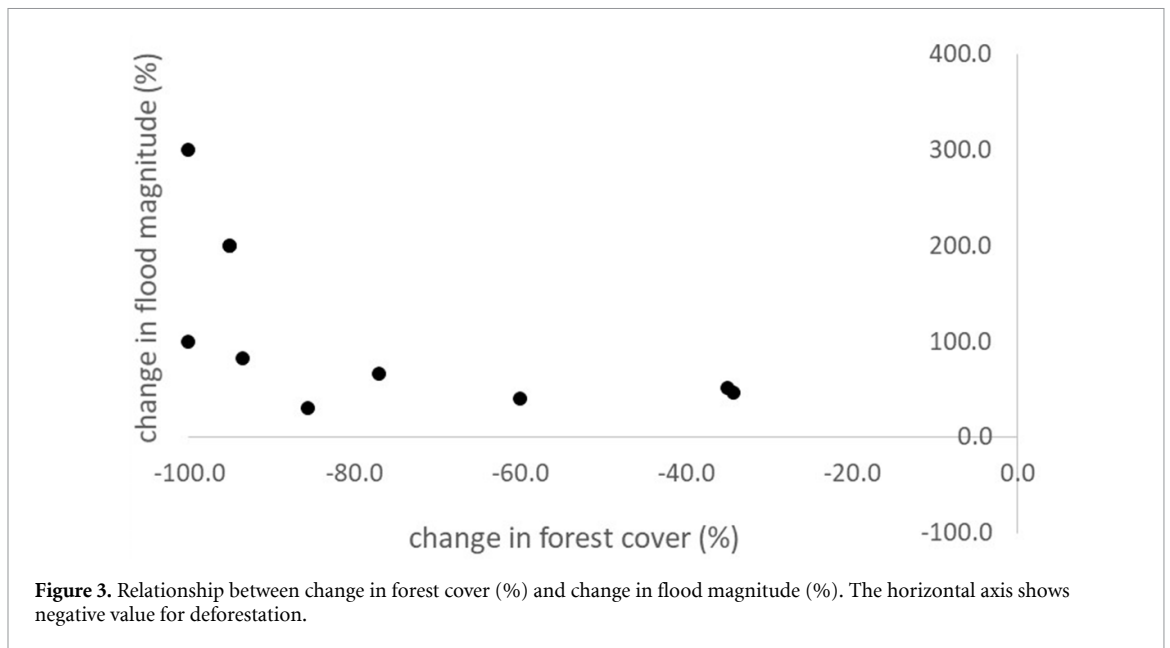
Only 5 of the 11 case studies reported the percentage change in sediment yield and percentage in catchment area forested (figure 4). Their data suggested sediment yield increases with decreasing forest cover, with up to a four-fold increase in sediment following clear-felling.

## 5. Hydrological response to natural wetlands

#### 5.1. Classification of natural wetlands

The searches returned 144 case studies reporting changes to water metrics associated with the presence of natural wetlands within catchments ranging in size from >300 000 km<sup>2</sup> to <1 km<sup>2</sup>. Although a range of wetland types was represented (characterised by different vegetation and soils), the vast majority were referred to by the authors as one of two types: (a) headwater wetlands including dambos and headwater peat swamps and (b) floodplains including lowland papyrus wetlands, inland deltas and lowland valley swamps. Catchment location is a long-standing simple method of classifying wetlands for functional assessment (Novitski 1978). Three case studies involved a statistical analysis of many wetlands of various types, but the remaining 141 studies were divided into the two broad categories: headwater wetlands and floodplains.

Most case studies recorded metrics immediately downstream of the wetland, compared to immediately upstream or on a similar catchment without a wetland. A few studies used chemical tracers to define hydrological processes. All case studies reported at



a single measuring point, none reported changes in metrics at different distances downstream, so it was not possible to determine how an effect might propagate downstream. No case studies reported how metrics varied over time or with different types of wetland management, such as grazing or drainage.

## 5.2. Natural wetlands and water resource quantity

The 52 case studies reporting surface water resource quantity metrics that could be classified as headwater or floodplain are shown in figure 5. Most (32 of 52) reported dry season flows, some (17 of 52) reported annual total flows and a few (3 of 52) reported wet season flows. Just over half of the studies (28 of 52) reported that wetlands (of both types) were associated with reduced surface water resources downstream,

with less than a fifth (9 of 52) reporting an increase in surface water resources. Of these, most (8 of 9) were floodplains. For example, floodplains were associated with increased dry season flows on the White Volta River, Ghana (Nyarkoa *et al* 2013). In detailed studies of dambo headwater wetlands in Zimbabwe, it was found that dry season depletion of water is dominated by high evaporation from open water and emergent vegetation, thus limiting contributions to downstream river flow (McCartney and Neal 1999). Similarly, the water balances of large floodplains (Senegal, Sudd, Niger and Okavango) were dominated by high evaporation (Sutcliffe and Parks 1989). The one study reporting an increase in downstream water resource quantity from a headwater wetland in Zambia was for the wet season (Balek and Perry 1973).



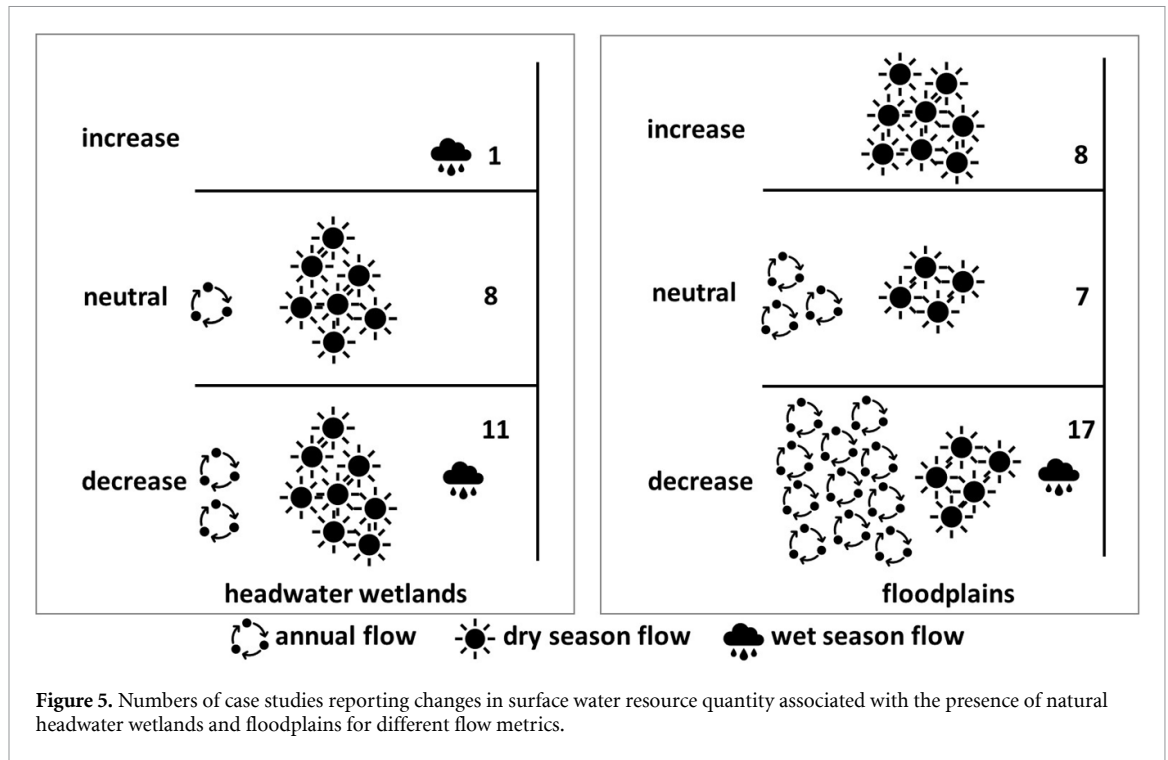


Figure 5. Numbers of case studies reporting changes in surface water resource quantity associated with the presence of natural headwater wetlands and floodplains for different flow metrics.

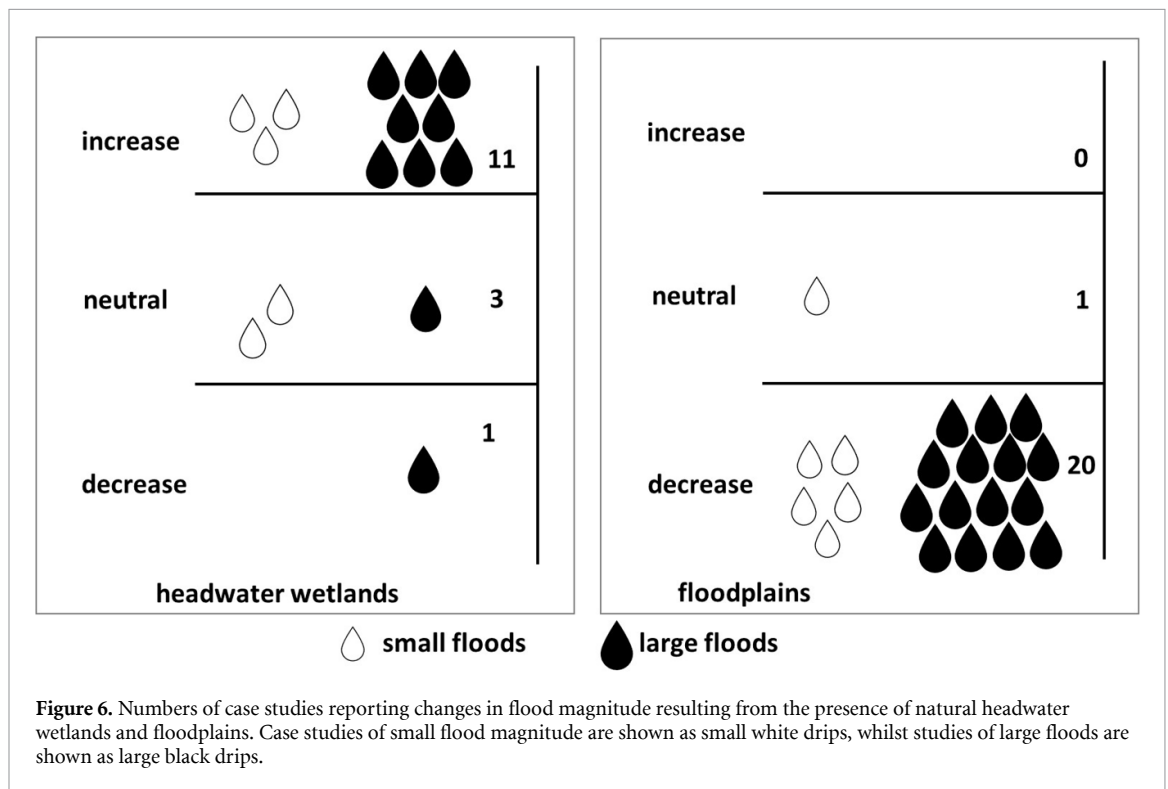


Figure 6. Numbers of case studies reporting changes in flood magnitude resulting from the presence of natural headwater wetlands and floodplains. Case studies of small flood magnitude are shown as small white drips, whilst studies of large floods are shown as large black drips.

### 5.3. Natural wetlands and floods

Of the 38 natural wetland case studies reporting flood metrics, two multiple wetland studies reported increases in small floods in the presence of wetlands. The other 36, of which 15 were studies of headwater wetlands and 21 were studies of floodplains, are shown in figure 6. Almost all (20 of 21) of the floodplain studies reported a decrease in flood magnitude; the one that reported no effect was perhaps due to

the small size of wetland (Lacombe and McCartney 2016).

In contrast, almost three quarters (11 of 15) of headwater wetlands studies showed increased floods associated with their presence, whilst three report no effect. The only case study reporting a decrease in flood magnitude with a headwater wetland present is of a dambo in Malawi (Smith-Carrington 1983); even here there was an apparent duality as the dambo

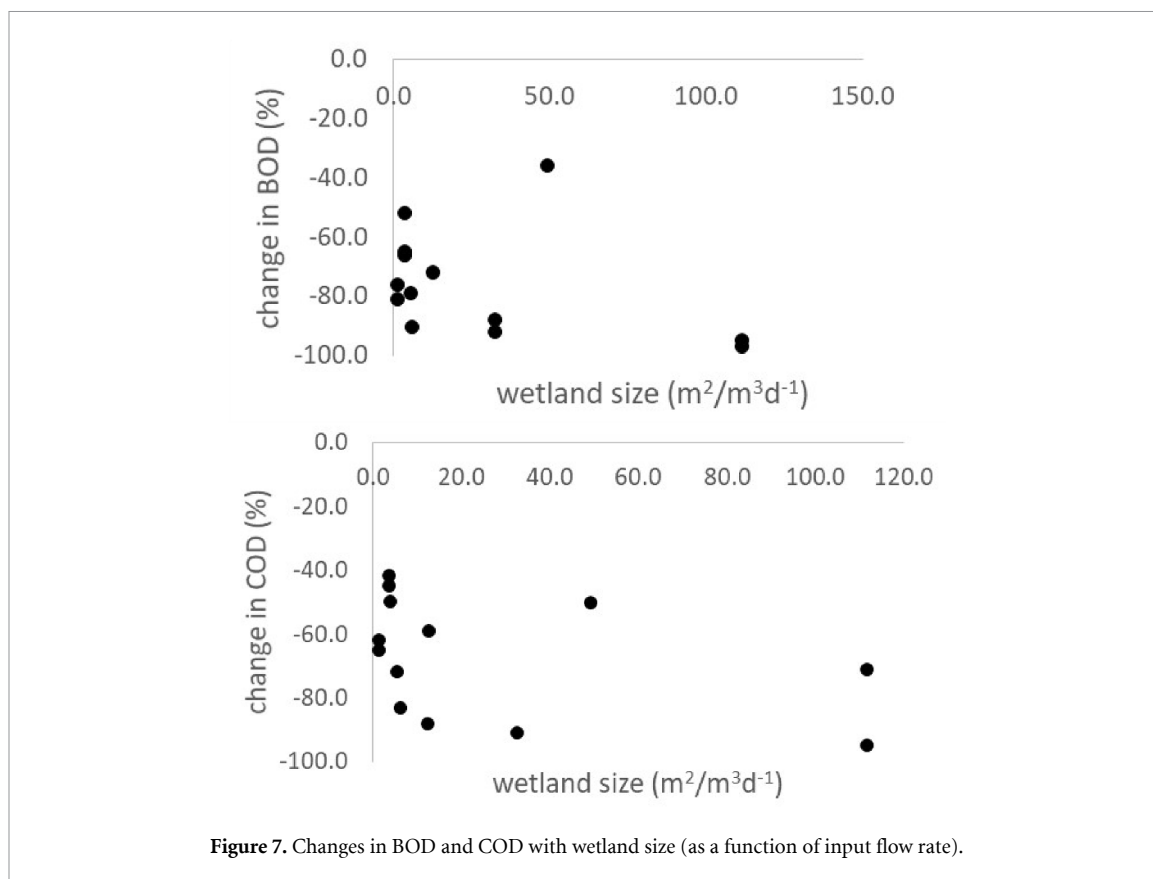


Figure 7. Changes in BOD and COD with wetland size (as a function of input flow rate).

increased flood runoff initially after rainfall before buffering the peak flow. Detailed studies of dambos undertaken in Zimbabwe (McCartney 2000) concluded that these headwater wetlands had a small capacity to absorb rainfall at the start of the wet season, when water table levels were low, but soon became saturated and contributed to flood runoff thereafter.

#### 5.4. Natural wetlands and groundwater

Twenty case studies investigated interactions between natural wetlands and underlying aquifers. Of these, 13 assessed groundwater recharge, with nine finding recharge occurred including floodplains of the Senegal River (Hollis 1996) and Komoguge–Yobe River, Nigeria (Goes 1999); four found recharge did not occur. Seven case studies assessed whether wetlands were groundwater discharge sites; five reported discharge occurred, whilst two reported it did not occur. Overall, the interaction between wetlands and underlying aquifers was site specific and no generalisations can be made from the evidence reported in our case studies.

#### 5.5. Natural wetlands and water quality

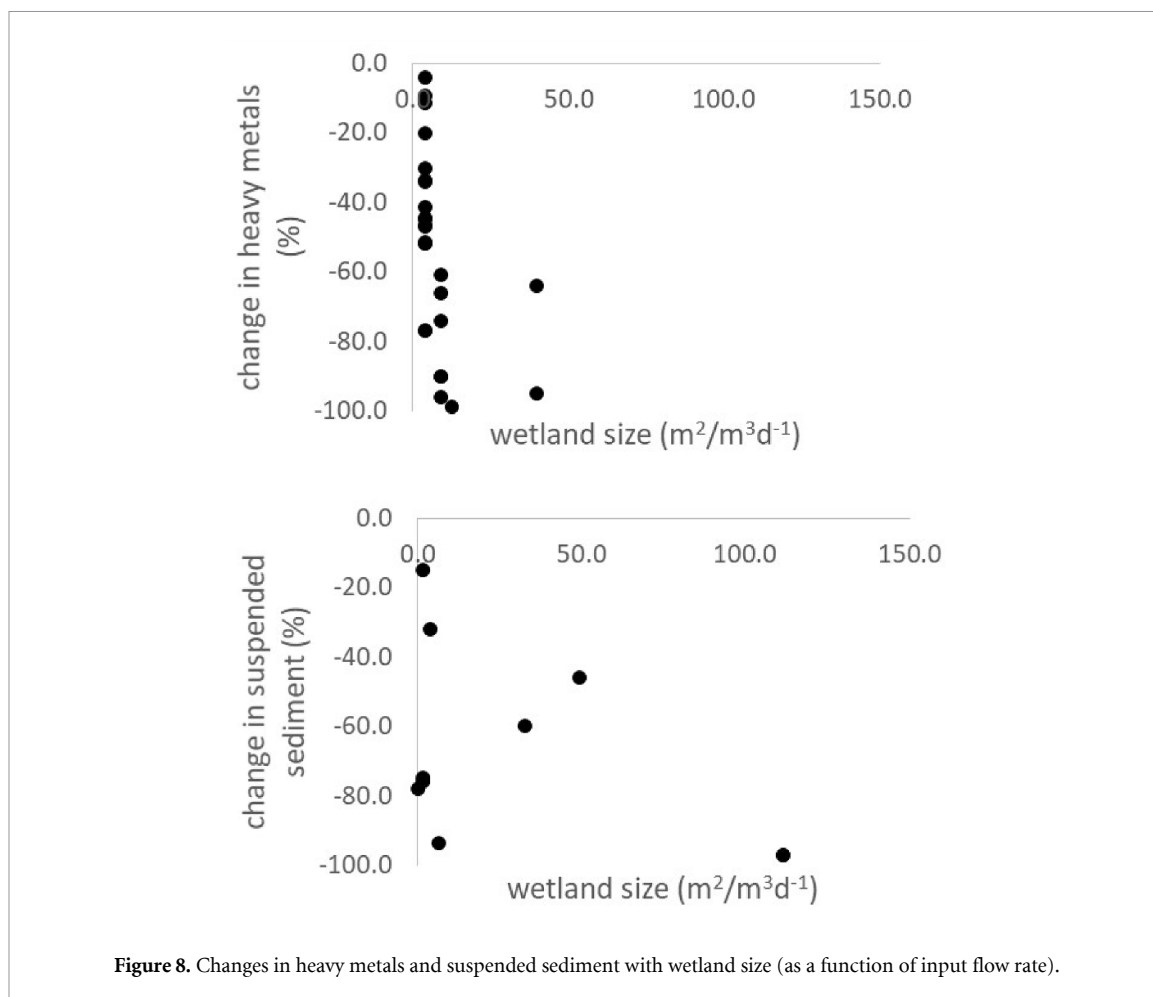
Three case studies of natural wetlands reported changes to sediment in downstream water courses. All reported decreases; two reported  $-70.0\%$  and  $-79.1\%$ , the third study did not provide data. Seven case studies of natural wetlands reported changes to total nitrogen in downstream water course; all were decreases. Five of these reported numerical values,

which ranged from  $-33.0\%$  to  $-53.0\%$ . Six case studies of natural wetlands reported changes to total phosphorus in downstream water courses; three reported decreases from  $-5.0\%$  to  $-50.0\%$ , one study of Natete wetland, Uganda (Kanyiginya *et al* 2010) reported an increase due possibly to remobilisation of phosphorus from sediments. Eight case studies of natural wetlands reported changes in heavy metals (cadmium, copper, iron, lead, manganese, uranium and zinc) in downstream water courses; all were decreases ranging from  $-61\%$  to full removal ( $-100\%$ ).

## 6. Hydrological response to constructed wetland interventions

The searches produced 202 case studies reporting changes to water metrics resulting from the construction of wetlands. Metrics included sediment, ammonia, nutrients (nitrogen and phosphorus), BOD, COD, heavy metals (e.g. cadmium, lead, zinc, copper, iron, manganese, mercury), oil and grease, *Escherichia coli*, parasite eggs, *Salmonellae* and faecal coliforms. All case studies reported reductions in these metrics. Many case studies were concerned with the relative removal rates of pollutants from different designs of constructed wetlands or types of vegetation employed.

Figures 7 and 8 show some relationship between effectiveness of pollutant removal and wetland size. As catchment area is not a relevant variable, to compare case studies, the wetland size ( $m^2$ ) was



standardised by the input flow rate ( $\text{m}^3 \text{d}^{-1}$ ). There was a tendency towards improved pollutant removal with larger wetlands.

## 7. Hydrological response to other nature-based interventions

The searches returned 1218 publications referring explicitly to nature-based solutions, that tended to be constructed interventions rather than restoration of naturally occurring systems. These included green roofs, sustainable urban drainage and river channel restoration. However, the vast majority focused on direct and local water/climate impacts such as reducing temperatures, draining flood water or collecting water for public use or agriculture. Only nine publications provided quantitative results of impacts on downstream floods, water resource quantity or water pollution, yielding 13 case studies.

Three case studies of greenways linking cities and forests reported reduced runoff coefficients, reduced flood risk, and increased replenishment of subterranean water sources (Sy *et al* 2014). Three case studies of sustainable urban drainage, including semi-vegetated channels, soakaways and miniature bio-retention areas, showed reductions in nitrate, phosphate and COP (Fitchett 2017).

## 8. Discussion

### 8.1. Utility of the database

Most analyses of nature-based solutions have been based on case studies in north America or Europe (e.g. Kabisch *et al* 2017) and previous reviews have found only a few studies in Africa (Hanson *et al* 2017). However, the current review has revealed 492 case studies undertaken in African countries. It significantly extends existing databases, such as the global review of nature-based solutions for climate change adaptation (Chausson *et al* 2020), which contains 16 examples addressing water issues in Africa.

The conclusions drawn in this paper are based upon the results of studies found in the searches. We recognise the danger of over-generalisation and implying cause-effect, so use terms such 'generally associated with' to convey the balance of scientific evidence found. Forest and wetland land classes cover a vast range of ecosystem types, which do not necessarily work hydrologically in the same way, so results cannot always be transferred between types. Furthermore, Africa is very diverse in terms of climate, geology, topography, soils and other characteristics, such that the hydrological response to land cover alterations will vary in different settings, so local data and scientific understanding are vital to underpin

local decisions and actions (Bullock and Acreman 2003).

Although it cannot replace robust context-specific analysis, the evidence for hydrological response to afforestation, reforestation and deforestation provides general guidance for the effectiveness of removing or planting trees or allowing forest regrowth. The action of restoring forests is associated with reduced risks from floods and sediment loads but often also reduced water resource quantities, potentially increasing risks of downstream water scarcity. A notable limitation of the current review was the lack of studies of tropical rain forests, particularly cloud forests, especially compared to the many studies in Amazonia (Chishugi *et al* 2017). Many of the forest studies were of deforestation and there were few of native forest restoration (reforestation). This is a significant research gap. However, if a nature-based solution involves restoration of natural forests, results of studies of deforestation of native trees could be used 'in reverse' to some extent, to assess the potential effects of reforestation, such as reduced sediment delivery in forested areas. However, outcomes may depend on the restoration process, as tree planting, for example, may cause some soil erosion or compaction in the short term, whereas natural regeneration may avoid this issue.

The evidence that forests, particularly non-native trees, can reduce water resource quantity supports the action of removing alien trees as a nature-based solution. This is consistent with the studies in South Africa (Van Wilgen *et al* 2012, 2020, Le Maitre *et al* 2016) that have demonstrated the detrimental impacts of alien species, including reductions in water resources, which underpins non-native vegetation removal as a nature-based solution within the Working for Wetlands programme supported by the South African government. Careful practices can avoid side-effects of vegetation removal, such as soil erosion or soil compaction. It should further be noted that planting any trees, whether native or not, in areas not naturally forested, e.g. in grasslands, or savannas, would not meet the IUCN definition of a nature-based solution as it could have negative impacts on biodiversity.

Whilst the presence of headwater wetlands is associated with larger downstream floods than when they are absent, the implication for a nature-based solution is not clear because headwater wetlands cannot readily be created or removed and there is little evidence on the effects of altered management (see section 8.5). In contrast, many floodplains have effectively been lost by building of embankments that separate floodplains from their rivers or dredging the river to increase its depth. The results of floodplain case studies can be used to assess flood risk reduction from reconnecting floodplains with their rivers, such as by removing embankments (e.g. Acreman *et al* 2003), though this may also reduce downstream water resource quantity.

We have classified the change in water metrics simply as increase, decrease or unchanged (with quantitative values given where available). The societal implications of metric change will depend on many factors, such as the vulnerability of people to increases in flood flows in a river and the type of local water resource management infrastructure. For example, water supplies reliant on direct river abstraction will be vulnerable to during dry seasons, whereas annual flow volumes will be more critical for water supplied from reservoirs. Furthermore, flooding in the wrong place, e.g. homes, factories, hospitals and most agricultural land, is seen as negative, but in the right place floods can be very beneficial to African people, such as supporting floodplain fisheries and flood-recession agriculture (Acreman 1996).

We focus this review on blue water issues and did not cover green water, i.e. water in soils and vegetation, for which a wider set of nature-based solutions exist such as conservation agriculture (e.g. Assefa *et al* 2019). We recognise the need to consider all types of water on the planet—in the atmosphere, soil, surface water, ground water and ice (Gleeson *et al* 2020)—in relation to global limits to anthropogenic water cycle modifications (Zipper *et al* 2020).

Finally, it should be noted that we did not attempt to address nature-based solutions in coastal or marine environments, although we recognise that coastal ecosystems, such as saltmarshes, mangroves and reefs, can play a vital role in protecting from coastal flooding, erosion and salt water intrusion.

## 8.2. Comparison of results with other reviews

The evidence found from the searches is consistent with previous reviews. A systematic review of impacts of forest restoration on water yield (Filoso *et al* 2017) found that most studies reported a decrease in water yield resulting from an increase in forest area, including regrowth of native trees. In a general global assessment (Farley *et al* 2005), annual runoff was found to be reduced on average by 44% ( $\pm 3\%$ ) and 31% ( $\pm 2\%$ ) when grasslands and shrublands were afforested, respectively. To observe increases in low-flows following tree planting, the increase in evaporation must be smaller than the increase in infiltration—the 'infiltration trade-off hypothesis' (Bruijnzeel 2004); evidence outside Africa shows that this may occur only in limited cases for specific tree species, soil types, soil conditions (degraded or compacted), initial vegetation types and climate conditions (e.g. Bonell *et al* 2010, Roa-Garcia *et al* 2011, Zhang *et al* 2019). As noted above, we found in Africa that 8 out of 12 studies of deforestation of native or mixed forests resulted in decreases in dry season flow. Planting of fast-growing non-native species, such as eucalyptus and pines, has been widely reported to reduce water yield (Smith *et al* 2017, Chausson *et al* 2020). We found strong evidence of this in Africa. Eucalyptus trees are known to be high water users as their

deep roots can continue to take up water as they lower the water table (Calder *et al* 1993). The high water use of trees has been incorporated within water policy in South Africa, where afforestation is classified as a Streamflow Reduction Activity (SFRA) under the National Water Act of 1998 (Gush *et al* 2002), such that no forestry can be practiced without an SFRA licence (Edwards and Roberts 2006). The IPBES report on land degradation and restoration (Scholes *et al* 2018) reported that land degradation through loss of biodiversity can increase flood risk and soil erosion and also that planting trees in previously non-forested areas, such as grasslands and savannahs can result in loss of water yield.

Previous reviews have found that at small spatial scales (<20 km<sup>2</sup>) forests can reduce flood flows, but not for the most extreme floods, and measured data for impacts in larger catchments (>100 km<sup>2</sup>) are lacking (Dadson *et al* 2017). Stratford *et al* (2017) also found that studies of forest cover changes on large catchments were limited to modelling due to lack of empirical data.

A review of evidence of the role of wetlands in hydrological cycles (Bullock and Acreman 2003) and follow-up research (Acreman and Holden 2013) concluded that the relationship between wetlands and floods depends largely on available water storage. Catchments containing headwater wetlands, such as damboes in Africa, have greater floods than catchments without headwater wetlands. This is because the combination of rainfall, topography and soils leads to ground saturation at the start of the wet season simultaneously creating wetlands and generating rapid runoff (McCartney 2000). In contrast, downstream floodplains reduce floods as they tend to be dry before floods and have large storage volumes. The evidence we found from Africa was consistent with these findings.

A review of the potential for constructed wetlands for wastewater treatment and reuse in developing countries (Kivaisi 2001) found these to be effective and efficient for wastewater treatment, and additionally they are low cost, easily operated and maintained, and have a strong potential for application in developing countries, particularly by small rural communities. African case studies support this finding.

### 8.3. Forest types for which no studies were found in Africa

Some forest types for which case studies were lacking in Africa, including tropical rainforests and cloud forests, have been investigated elsewhere, although results may not be readily transferable because, for example, the climate of African rainforests is, on average, much drier than rainforests on other continents (Malhi *et al* 2013). For tropical forests, analysis by Bruijnzeel (1989, 1990, 2004) concluded that deforestation and conversion to annual cropping or grazing is generally followed by increased surface runoff

during the wet season, and often by increased base flow water yield, though this is not always the case. Sometimes dry season streamflows decrease in catchments with extensive deforestation. Bruijnzeel (2004) concluded that this may be due to a higher proportion of impermeable surfaces within the catchment due to development (including urban areas), or to compaction and degradation of soils during deforestation or subsequent agricultural use, rather than loss of the trees *per se*.

Some studies show that evapotranspiration in cloud forests is low and large amounts of water are captured by trees from fog, which can make a significant contribution to water yield downstream (e.g. Gomez-Peralta *et al* 2008). Other studies have recorded a loss of water yield downstream following cloud forest clearance (López-Ramírez *et al* 2020). However, it is difficult to draw generic conclusions due to a complex dependency on local climate and other factors. A Mexican cloud forest at the drier end of the spectrum, with higher evapotranspiration and lower cloud water capture, had lower annual water yield than an adjacent catchment that was converted to pasture but higher dry season base flows, as well as lower runoff during storm events (Bruijnzeel *et al* 2011, Asbjornsen *et al* 2017); while conversion of cloud forest to pasture in northern Costa Rica had little effect on streamflow, although local storm flows were doubled (Bruijnzeel *et al* 2010). Extrapolation of results from elsewhere to Africa is thus extremely difficult. Sáenz and Mulligan (2013) used computer models to explore the role of cloud-affected forests in African river basins containing dams but did not explore the impact of forest loss in the delivery of water.

### 8.4. Comparison with modelling studies

In the absence of direct measurements of the effects of deforestation and afforestation, particularly at large scale, researchers have turned to the use of mathematical computer models. Modelling of catchments in Indonesia, Sri Lanka, Brazil and Tanzania (miombo woodland) found that the impacts of forest removal are highly seasonal; whilst typically increasing mean annual water yield, dry-season flows can decrease depending on pre- and post-forest removal surface conditions and groundwater response times (Peña-Arancibia *et al* 2019). Modelling of reforestation in Brazil generally decreased water quantity throughout the whole basin, though increases were noted in some parts of the basin (Ferreira *et al* 2019). Computer simulated deforestation of the Amazon region more generally could reduce discharge by 6%–36% (Stickler *et al* 2013). None of these model predictions were tested with observed data.

### 8.5. Management interventions

Most case studies of wetlands and a few of forests found for Africa concerned the presence or absence



of features or interventions compared with a reference catchment, e.g. wetland v. no wetland, forest v. grassland. Associated management of forests and wetlands, such as pre-forestation ploughing, thinning of trees or removal of undergrowth and draining or heavy grazing vegetation of natural wetlands, was rarely mentioned, so their hydrological implications could not be assessed. This is a significant research gap.

Much of the current discussion of nature-based solutions has focused on the benefits and disbenefits of active planting of trees or removal of non-native species. The evidence suggests that protection of existing native forests and other native vegetation types (i.e. no active intervention) could be effective in preventing the increased flood risk and sedimentation that would be associated with deforestation. Also avoidance of afforestation of land that is naturally grassland or savannah can prevent water resource quantity losses.

The type of vegetation planted in constructed wetlands can play an important role in their performance. In Uganda wetlands planted with *Cyperus papyrus* had higher COD removal rates than those planted with *Phragmites mauritianus* (Okurut *et al* 1999). Likewise, in Ethiopia, the nutrient removal efficiency of *Typha* was higher than *Phragmites australis* and *Scirpus* (Timotewos *et al* 2017).

Some wetlands are so effective at removing nutrients that these can build-up in the wetland soil to high levels and exceed the concentrations in the water input, therefore turning the wetland from a sink to a source. Because of this, water exiting the Natete wetland, Uganda, was found to have higher phosphorous than water entering (Kanyiginya *et al* 2010). This can be alleviated by periodical mechanical removal of sediment from the wetland.

### 8.6. Spatial and temporal aspects of nature-based solutions

Most studies found in this review reported downstream hydrological changes for specific single periods, so it was generally not possible to assess the evolution of effects over long periods. This is another research gap. Only a few studies reported how flow reductions resulting from afforestation varied with the age of the trees, such as the continued reduction in flows for 20 years after planting of pine trees in South Africa (Scott *et al* 2000). Similarly, most studies using flood metrics reported a single time period after deforestation. One exception was in Kapchorwa, Kenya, where the conversion from forest to agricultural land in the first five years caused about half of the total observed increases in discharge in relation to rainfall (Recha *et al* 2012).

In case studies of constructed wetlands, residence time was reported as important. For example, the effectiveness of COD reduction increased as retention

times increased from 0.5 to 5 days in Arusha, Tanzania (Mtavangu *et al* 2017).

No studies reported hydrological metrics for more than one location, so it was not possible to assess the changes upstream or downstream of this point. Forest cover was usually reported as a percentage change across the catchment so neither the specific location of changes in forest cover (e.g. headwaters) nor an index of fragmentation could be defined. The only exceptions were case studies reporting clear-felling.

### 8.7. Inter-catchment and regional scale impacts of nature-based solutions

Whilst this review focuses only on the direct downstream hydrological implications of water-related nature-based solutions, hydro-meteorological models have been employed to study water circulation at regional and global scales. For example, regional scale evaporation from agricultural activities and irrigation in the Sahel and Nile basin have been shown to increase moisture supply to the Yangtze, Yensisei, and Niger basins (Wang-Erlandsson *et al* 2018). Furthermore, deforestation of tropical regions has been reported to significantly affect precipitation at mid- and high latitudes (Avisar and Worth 2005). Results vary according to the scale of analysis; whilst deforestation within the Xingu River basin (a tributary of the Amazon) increased discharge locally, deforestation across the whole Amazon region reduced rainfall, decreasing discharge within the basin (Strickler *et al* 2013). It has been suggested that evaporation from the Sudd wetlands in South Sudan is important for rainfall generation in the Ethiopian Highlands (Hurst 1938). However, it has been argued more recently that the impact of Sudd evaporation on the regional hydrological budget of the Nile Basin is insignificant compared to the inter-annual rainfall variability, owing to the relatively small area covered by the wetland (Mohamed *et al* 2006).

## 9. Knowledge gaps

Previous authors have identified knowledge gaps on the effectiveness of nature-based solutions, especially on trade-offs and synergies concerning water management, biodiversity, human health, social and economic issues (Kabisch *et al* 2017), and on case studies in the Global South, as well as comparisons with non-nature-based alternatives (Chausson *et al* 2020). Most studies of changes in forest cover in Africa have been of commercial non-native species; more work on reforestation using native species is required. Published studies tend to describe binary situations, i.e. with/without interventions, and there is little information on the impacts of management, such as changing water levels within wetlands. More work is also needed on effects of the location and scale of nature-based solutions within catchments and how



any resultant hydrological alterations may vary in space and time.

Many nature-based solutions are forms of naturalising engineering (rather than engineering nature), including green roofs and sustainable urban drainage. Only a few examples were found for Africa that assessed impacts of these types of intervention on downstream water metrics. No studies assessed the benefits of integrating nature-based solutions with traditional engineering approaches, such as using embankments, sluice gates and weirs to enhance floodplain flood water retention.

Key topics for future research include:

- hydrological effects of native forest protection and reforestation, including cloud forests and rainforests, and native savannah restoration
- effects of management such as grazing, drainage, tree thinning, undergrowth removal
- effects of the location of nature-based solutions within a catchment
- monitoring downstream at various locations to assess propagation of effects
- long term monitoring to assess changes over time following interventions, including seasonal and inter-annual variability
- studies of channel restoration, including reintroduction of meanders and woody debris, reconnection of rivers and floodplains
- continental scale assessment of hydrological effects beyond the catchment of interventions
- effects of combining nature-based solutions with traditional engineering solutions, including sustainable drainage systems, and other water management interventions.

## 10. Conclusions

This review considered evidence related to nature-based solutions to water risks in terrestrial and freshwater environments across Africa. It found 10 633 publications related to this topic. Of these, 150 reported primary empirical information on the effectiveness of water-related nature-based solutions, generating 492 case studies with a wide distribution across Africa. In general, forests and floodplain wetlands provide a potential nature-based solution for reducing floods and sediment generation, whilst constructed wetlands readily reduce water pollution. Generally, the presence of headwater wetlands and non-native forests was associated with reduced water resource quantity downstream, whilst the evidence is inconsistent for native forests, and there is a lack of evidence in Africa for cloud forests and tropical rainforests. Although there is a need for more studies, including more information on temporal and spatial scales of effects, the results from these publications collectively provide a basis for assessing the likely effectiveness of different nature-based solutions

to water risk issues that can support policy and planning decisions.

A strategic approach to landscape or catchment management should consider all potential benefits and disbenefits of nature-based solutions, including water and non-water issues, such as carbon sequestration, food and fuel supply, as well as intrinsic benefits in terms of biodiversity and cultural value. However, local policy and management decisions should ideally be based on finer-scale, context-specific analysis using local knowledge. Our review can provide a guiding frame for such an analysis but should not be a substitute for it. Decisions should also be guided by socio-economic, cultural and political considerations as much as by an understanding of the biophysical dynamics of landscapes and catchments. Stakeholder views will be especially important in influencing policy and management decisions. Even so, an understanding of biophysical dynamics, including this review, can help to draw up potential portfolios of solutions and can provide foundational inputs to the policy discourse.

## Data availability statement

The data that support the findings of this study are available upon request from the lead author.

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## References

- Abell R *et al* 2008 Freshwater ecoregions of the world: a new map of biogeographic units for freshwater biodiversity conservation *BioScience* **58** 403–14
- Acreman M C 1996 Environmental effects of hydro-electric power generation in Africa and the potential for artificial floods *Water Environ. Manage.* **10** 429–34
- Acreman M C, Booker D J and Riddington R 2003 Hydrological impacts of floodplain restoration: a case study of the river Cherwell, UK *Hydrol. Earth Syst. Sci.* **7** 75–86
- Acreman M C and Holden J 2013 Do wetlands reduce floods? *Wetlands* **33** 773–86
- Acreman M, Hughes K, Arthington A, Tickner D and Duenas M-A 2019 Protected areas and freshwater biodiversity: lessons for effective conservation *Conserv. Lett.* **13** e12684

- Asbjornsen H, Manson R H, Scullion J J, Holwerda F, Munoz-Villers L E, Alvarado-Barrientos M S and Bruijnzeel L A 2017 Interactions between payments for hydrologic services, landowner decisions, and ecohydrological consequences: synergies and disconnection in the cloud forest zone of central Veracruz, Mexico *Ecol. Soc.* **22** 25
- Assefa T, Jha M, Reyes M, Tilahun S and Worqlul A W 2019 Experimental evaluation of conservation agriculture with drip irrigation for water productivity in sub-Saharan Africa *Water* **11** 530
- Avissar R and Werth D 2005 Global hydroclimatological teleconnections resulting from tropical deforestation *J. Hydrometeorol.* **6** 134–45
- Azzarri C and Signorelli S 2020 Climate and poverty in Africa South of the Sahara *World Dev.* **125** 104691
- Baldwin-Cantello W et al 2020 The Triple Challenge: Synergies, Trade-offs and Integrated Responses to Meet our Climate, Food and Biodiversity Goals (Working: WWF-UK) (available at: [www.wwf.org.uk/sites/default/files/publications/Oct20/WWF%20TRIPLE%20CHALLENGE%20REPORT\\_1.pdf](http://www.wwf.org.uk/sites/default/files/publications/Oct20/WWF%20TRIPLE%20CHALLENGE%20REPORT_1.pdf)) or simply [www.wwf.org.uk/triple-challenge](http://www.wwf.org.uk/triple-challenge)
- Balek J and Perry J E 1973 Hydrology of seasonally inundated African headwater swamps *J. Hydrol.* **19** 227–49
- Boelee E, Janse J, Le Gal A, Kok M, Alkemade R and Ligtoet W 2017 Overcoming water challenges through nature-based solutions *Water Policy* **1**–17
- Bonell M, Purandara B K, Venkatesh B, Krishnaswamy J, Acharya H A K, Singh U V and Chappell N 2010 The impact of forest use and reforestation on soil hydraulic conductivity in the Western Ghats of India: implications for surface and sub-surface hydrology *J. Hydrol.* **391** 49–64
- Bruijnzeel L A 1989 (De)forestation and dry season flow in the humid tropics: a closer look *J. Trop. For. Sci.* **1** 229–43
- Bruijnzeel L A 1990 *Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review* (Paris: UNESCO International Hydrological Programme)
- Bruijnzeel L A 2004 Tropical forests and environmental services: not seeing the soil for the trees? *Agric. Ecosyst. Environ.* **104** 185–228
- Bruijnzeel L A, Kappelle M, Mulligan M and Scatena F N 2010 Tropical montane cloud forests: state of knowledge and sustainability perspectives in a changing world *Tropical Montane Cloud Forests: Science for Conservation and Management* ed L A Bruijnzeel, F N Scatena and L S Hamilton (Cambridge: Cambridge University Press) pp 691–740
- Bruijnzeel L A, Mulligan M and Scatena F N 2011 Hydrometeorology of tropical montane cloud forests: emerging patterns *Hydrol. Process.* **25** 465–98
- Bullock A and Acreman M C 2003 The role of wetlands in the hydrological cycle *Hydrol. Earth Syst. Sci.* **7** 75–86
- Calder I R, Hall R L, Bastable H G, Shela O, Chirwa A and Kafundu R 1995 The impact of land use change on water resources in sub-Saharan Africa: a modelling study of Lake Malawi *J. Hydrol.* **170** 23–135
- Calder I R, Hall R L and Prasanna K T 1993 Hydrological impact of *Eucalyptus* plantation in India *J. Hydrol.* **150** 635–48
- Chausson A, Turner C B, Seddon D, Chabaneix N, Girardin C A J, Key I, Smith A C, Woroniecki S and Seddon N 2020 Mapping the effectiveness of nature-based solutions for climate change adaptation *Glob. Change Biol.* **26** 6134–55
- Chishugi J B, Amani C, Nzabandora C K, Mokoso J M, Chishugi D U and Gasuga B M 2017 Forest management and water in the democratic Republic of Congo *Forest Management and the Impact on Water Resources: A Review of 13 Countries* IHP—VIII/Technical document N° 37 Latin America and the Caribbean ed P A Garcia-Chevesich, D G Neary, D F Scott, R G Benyon and T Reyna (Paris: UNESCO) pp 67–89
- Chiwa R 2012 Effect of land use and land cover changes on the hydrology of the Weruweru-Kiladeda sub-catchment on Pangani River basin, Tanzania MSc thesis Kenyatta University, Nairobi
- Collins A M, Coughlin D, Miller J and Kirk S 2015 The production of quick scoping reviews and rapid evidence assessments: a how to guide (London: Department for the Environment, Food and Rural Affairs) p 63
- Cook D J, Mulrow C D and Haynes R B 1997 Systematic Reviews: Synthesis of Best Evidence for Clinical Decisions *Ann. Intern. Med.* **126** 376–80
- Coynel A, Seyler P, Etcheber H, Meybeck M and Orange D 2005 Spatial and seasonal dynamics of total suspended sediment and organic carbon species in the Congo River *Glob. Biogeochem. Cycles* **19** 4
- Dadson S et al 2017 A restatement of the natural science evidence concerning catchment-based ‘natural’ flood management in the United Kingdom *Proc. R. Soc. A* (<https://doi.org/10.1098/rspa.2016.0706>)
- De Wit M and Stankiewicz J 2006 Changes in surface water supply across Africa with predicted climate change *Science* **311** 1917–21
- Descheemaeker K, Nyssen J, Poesen J, Raes D, Haile M, Muys B and Deckers S 2006 Runoff on slopes with restoring vegetation: a case study from the Tigray Highlands, Ethiopia *J. Hydrol.* **331** 219–41
- Di Baldassarre G, Montanari A, Lins H, Koutsoyiannis D, Brandimarte L and Blöschl G 2010 Flood fatalities in Africa: from diagnosis to mitigation *Geophys. Res. Lett.* **37** L22402
- Douglas I, Alam K, Maghenda M, McDonnell Y, McLean L and Campbell J 2008 Unjust waters: climate change, flooding and the urban poor in Africa *Environ. Urban.* **20** 187–205
- Edwards M B P and Roberts P J 2006 Managing forests for water: the South African experience *Int. For. Rev.* **8** 65–71
- Ekwezu C S and Ezeh C U 2020 Regional characterisation of meteorological drought and floods over west Africa *Sustain. Water Res. Manage.* **6** 1–11
- Falkenmark M and Rockström J 2006 The new blue and green water paradigm: breaking new ground for water resources planning and management *J. Water Res. Plann. Manage.* **132** 129–32
- FAO 2015 *Towards effective national forest funds* FAO Forestry Paper No. 174. Rome, Italy Authored by Matta R (available at: [www.fao.org/3/a-i4359e.pdf](http://www.fao.org/3/a-i4359e.pdf))
- Farley K A, Jobbágy E G and Jackson R B 2005 Effects of afforestation on water yield: a global synthesis with implications for policy *Glob. Change Biol.* **11** 1565–76
- Fayiga A O, Ipinmoroti M O and Chirenje T 2018 Environmental pollution in Africa *Environ. Dev. Sustain.* **20** 41–73
- Ferreira P, Van Soesbergen A, Mulligan M, Freitas M and Vale M M 2019 Can forests buffer negative impacts of land-use and climate changes on water ecosystem services? The case of a Brazilian megalopolis *Sci. Total Environ.* **685** 248–58
- Filoso S, Bezerra M O, Weiss K C B and Palmer M A 2017 Impacts of forest restoration on water yield: a systematic review *PLoS One* **12** e0183210
- Fitchett A 2017 SuDS for managing surface water in Diepsloot informal settlement, Johannesburg, South Africa *Water Sci. Technol.* **43**
- Frantzeskaki N et al 2019 Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making *BioScience* **69** 455–66
- Gebrehiwot S G, Taye A and Bishop K 2010 Forest cover and stream flow in a headwater of the Blue Nile: complementing observational data analysis with community perception *Ambio* **39** 284–94
- Giertz S, Junge B and Diekkrüger B 2005 Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa *Phys. Chem. Earth* **30** 485–96
- Gilmour D 2014 Forests and water: a synthesis of the contemporary science and its relevance for community forestry in the Asia-Pacific region RECOFTC Issue Paper

- No. 3. RECOFTC—The Center for People and Forests, Bangkok, Thailand
- Gleeson T *et al* 2020 The water planetary boundary: interrogation and revision *One Earth* **2** 223–34
- Goes B 1999 Estimate of shallow groundwater recharge in the Hadejia–Nguru Wetlands, semi-arid northeastern Nigeria *Hydrogeol. J.* **7** 294–304
- Goldacre B 2009 *Bad Science* (London: Fourth Estate)
- Gomez-Peralta D, Oberbauer S F, McClain M E and Philippi T E 2008 Rainfall and cloud-water interception in tropical montane forests in the eastern Andes of Central Peru *For. Ecol. Manage.* **255** 1315–25
- Gush M B, Scott D F, Jewitt G P W, Schulze R E, Hallowes L A and Görgens A H M 2002 A new approach to modelling streamflow reductions resulting from commercial afforestation in south Africa *South. Afr. For. J.* **196** 27–36
- Haile G G, Tang Q, Sun S, Huang Z, Zhang X and Liu X 2019 Droughts in East Africa: causes, impacts and resilience *Earth Sci. Rev.* **193** 146–61
- Hanson H, Veerkamp C, Nordin A, Lazarova T, Hedlund K, Olsson P and Schipper A 2017 Assessment of biophysical and ecological services provided by urban nature-based solutions: a review Deliverable 1.3 Part II *Report to European Commission Horizon 2020*
- Hollis G E 1996 Hydrological inputs to management policy for the Senegal River and its floodplain *Water Management and Wetlands in sub-Saharan Africa* ed M C Acreman and G E Hollis (Gland: IUCN) pp 176
- Hopf H, Krief A, Mehta G and Matlin S A 2019 Fake science and the knowledge crisis: ignorance can be fatal *R. Soc. Open Sci.* **6** 5
- Hurst H E and Phillips P 1938 The hydrology of the Lake Plateau and Bahr el Jebel *The Nile Basin Volume V* (Cairo: Government Press)
- Kabisch N, Korn H, Stadler J and Bonn A 2017 Nature-based solutions to climate change adaptation in urban areas *Linkages between Science, Policy and Practice* (Berlin: Springer)
- Kalantari Z, Santos Ferreira C S, Keesstra S and Destuni G 2018 Nature-based solutions for flood-drought risk mitigation in vulnerable parts of East Africa *Curr. Opin. Environ. Sci. Health* **5** 73–8
- Kanyiginya V, Kansime F, Kimwaga R and Mashauri D A 2010 Assessment of nutrient retention by Natete wetland Kampala, Uganda *Phys. Chem. Earth* **35** 657–64
- Kashaigili J J 2008 Impacts of land-use and land-cover changes on flow regimes of the Usangu wetland and the Great Ruaha River, Tanzania *Phys. Chem. Earth* **33** 640–7
- Kidane M, Tolessa T, Bezie A, Kessete N and Endrias M 2018 Evaluating the impacts of climate and land use/land cover (LU/LC) dynamics on the hydrological responses of the Upper Blue Nile in the central highlands of Ethiopia *Spatial Inf. Res.* **27** 151–67
- Kivaisi A K 2001 The potential for constructed wetlands for wastewater treatment and reuse in developing countries: a review *Ecol. Eng.* **16** 545–60
- Koehnken L, Goichot M, Tickner D, Loftus A-C and Acreman M C 2020 Impacts of riverine aggregate mining on freshwater ecosystems: a review of the scientific evidence and guidance for future research *River Res. Appl.* **36** 362–70
- Lacombe G and McCartney M 2016 Evaluating the flow regulating effects of ecosystems in the Mekong and Volta river basins (Colombo: International Water Management Institute Research Report 166) (<https://doi.org/10.5337/2016.202>)
- Le Maitre D C, Forsyth G G, Dziki S and Gush M B 2016 Estimates of the impacts of invasive alien plants on water flows in South Africa *Water S.A.* **42** 4
- López-Ramírez S M, Sáenz L, Mayer A, Muñoz-Villers L E, Asbjornsen H, Berry Z C, Looker N, Manson R and Gómez-Aguilar L R 2020 Land use change effects on catchment streamflow response in a humid tropical montane cloud forest region, central Veracruz, Mexico *Hydrol. Process.* **34** 3555–70
- Lorup S K and Hansen E 1997 Effect of land use on the streamflow in the southwestern highlands of Tanzania sustainability of water resources under increasing uncertainty *Proc. of the Rabat Symp.* (IAHS Publication no. 240)
- Lumbroso D 2020 Flood risk management in Africa *J. Flood Risk Manage.* **13** 3
- Lundgren L 1980 Comparison of surface runoff and soil loss from runoff plots in forest and small-scale agriculture in the Usambara *Geogr. Ann. Ser. A* **62** 113–48
- Malhi Y, Adu-Bredu S, Asare R A, Lewis S L and Mayaux P 2013 African rainforests: past, present and future *Phil. Trans. R. Soc. B* **368** 20120312
- McCartney M P 2000 The water budget of a headwater catchment containing a dambo *Phys. Chem. Earth* **25** 611–6
- McCartney M P and Neal C 1999 Water flow pathways and the water balance within a headwater catchment containing a dambo; inferences drawn from hydrochemical investigations *Hydrol. Earth Syst. Sci.* **3** 581–91
- McCartney M, Cai X and Smakhtin V 2013 Evaluating the flow regulating functions of natural ecosystems in the Zambezi River basin IWMI Research Report 148 (Colombo: IWMI)
- Meza I *et al* 2020 Global-scale drought risk assessment for agricultural systems *Nat. Hazards Earth Syst. Sci.* **20** 695–712
- Mohamed Y A, Savenije H H G, Bastiaanssen W G M and Van Den Hurk B J J 2006 New lessons on the Sudd hydrology learned from remote sensing and climate modelling *Hydrol. Earth Syst. Sci.* **10** 507–18
- Moher D, Liberati A, Tetzlaff J and Altman D G 2009 Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement *PLoS Med.* **6** e1000097
- Mtavangu S, Rugaika A M, Hilonga A and Njau K N 2017 Performance of constructed wetland integrated with sand filters for treating high turbid water for drinking *Water Pract. Technol.* **12** 1
- Mumeka A 1986 Effect of deforestation and subsistence agriculture on runoff of the Kafue River headwaters, Zambia *Hydrol. Sci. J.* **31** 543–54
- Mwangi H M, Patil S D, McDonald M A and Feger K-H 2016 Relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya *J. Hydrol.: Reg. Stud.* **5** 244–60
- Mwendera E J 1994 Effect on the water yield of the Luchelemu catchment in Malawi of replacing indigenous grasses with timber plantations *Forest Ecology and Manage.* **65** 75–80
- Novitski R P 1978 Hydrologic characteristics of Wisconsin's wetlands and their influence on floods, streamflow and sediment *Wetland Functions and Values: The State of Our Understanding* (Minneapolis, MN: Amer. Water. Resour. Assoc.) pp 377–88
- Nyarkoa B K, Eghanb J M, Essumang D K, Amankwahd H K and Osae S 2013 Riverine wetland-rivers flow synergy: an isotopic study of the White Volta basin, Ghana *Isotopic Age and Composition of Streamflow as Indicators of Groundwater Sustainability* (International Atomic Energy Agency Water Resources Programme) pp 83–110
- Okurut T O, Rijs G B J and Van Bruggen J J A 1999 Design and performance of experimental constructed wetlands in Uganda planted with *Cyperus papyrus* and *Phragmites mauritianus* *Water Sci. Technol.* **40** 265–71
- Olson D M *et al* 2001 Terrestrial Ecoregions of the World: a new map of life on Earth *BioScience* **51** 933–8
- Peña-Arancibia J L, Bruijnzeel L A, Mulligan M and Van Dijk A I J M 2019 Forests as 'sponges' and 'pumps': assessing the impact of deforestation on dry-season flows across the tropics *J. Hydrol.* **574** 946–63
- Recha J W, Lehmann J, Walter T, Pell M, Verchot A and Johnson M 2012 Stream discharge in tropical headwater catchments as a result of forest clearing and soil degradation *Earth Interact.* **16** 1–18
- Reid W *et al* 2006 Nature: the many benefits of ecosystem services *Nature* **443** 749

- RIN 1985 Evaluation of forest land, Kali Konto upper watershed, East Java II. Area, methods and organization (Leersum: Research Institute for Nature Management (RIN)) p 30
- Roa-García M C, Brown S, Schreier H and Lavkulich L M 2011 The role of land use and soils in regulating water flow in small headwater catchments of the Andes *Water Resour. Res.* **47** W05510
- Sáenz L and Mulligan M 2013 The role of cloud affected forests (CAFs) on water inputs to dams *Ecosyst. Serv.* **5** 69–77
- Scholes R J *et al* (eds) 2018 Assessment report on land degradation and restoration of the intergovernmental science-policy platform on biodiversity and ecosystem services (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) (available at: [www.ipbes.net/system/tdf/spm\\_3bi\\_ldr\\_digital.pdf?file=1&type=node&id=2833](http://www.ipbes.net/system/tdf/spm_3bi_ldr_digital.pdf?file=1&type=node&id=2833))
- Scott D F, Prinsloo F W, Moses G, Mehloimakulu M and Simmers A D A 2000 A re-analysis of the South African catchment afforestation experimental data (WRC Pretoria: Report to the Water Research Commission)
- Seddon N *et al* 2020 Global recognition of the importance of nature-based solutions to climate change impacts *Glob. Sustain.* **3** e15
- Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, House J, Srivastava S and Turner C B 2021 Getting the message right on nature-based solutions to climate change *Glob. Change Biol.* (<https://doi.org/10.1111/gcb.15513>)
- Smith A C *et al* 2017 How natural capital delivers ecosystem services: a typology derived from a systematic review *Ecosyst. Serv.* **26** 111–26
- Smith-Carrington A K 1983 Hydro-geological bulletin for the Bua catchment Water Resource Unit number 5 (Lilongwe: Department of Land, Valuation and Water)
- Stickler C M, Coe M T, Costa M H, Nepstad D C, McGrath D G, Dias L C P, Rodrigues H O and Soares-Filho B S 2013 Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales *Proc. Natl Acad. Sci.* **110** 9601–6
- Stratford C *et al* 2017 *Do Trees in UK-relevant River Catchments Influence Fluvial Flood Peaks?* (Wallingford: NERC/Centre for Ecology & Hydrology) pp 46
- Sutcliffe J and Parks Y 1989 Comparative water balances of selected African wetlands *Hydrol. Sci. J.* **34** 49–62
- Sy M, Bagueian H and Gahi N 2014 Multiple use of green spaces in Bobo-Dioulasso, Burkina Faso *Urban Agric.* **27** 33–6
- Timotewos M T, Kassa K and Reddythota D 2017 Selection of mesocosm to remove nutrients with constructed wetlands *J. Ecol. Eng.* **18** 42–51
- UNESCO 2020 UN-water united nations world water development report (UNWWDR): water and climate change, facts and figures (Paris: UNESCO) (available at: <https://unesdoc.unesco.org/ark:/48223/pf0000372985.locale=en>) (Accessed 2 February 2021)
- UNISDR 2015. The Human costs of major related disasters 1995–2015. A global perspective. UN office for disaster risk reduction (available at: [www.unisdr.org/2015/docs/climatechange/COP21\\_WeatherDisastersReport\\_2015\\_FINAL.pdf](http://www.unisdr.org/2015/docs/climatechange/COP21_WeatherDisastersReport_2015_FINAL.pdf))
- Van Wilgen B W, Forsyth G G, Le Maitre D C, Wannenburgh A, Kotzé J D F, Van Den Berg E and Henderson L 2012 An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa *Biol. Conserv.* **148** 28–38
- Van Wilgen B W, Measey J, Richardson D M, Wilson J R and Zengeya T A (eds) 2020 *Biological Invasions in South Africa; Invading Nature* (Berlin: Springer)
- Wallemacq P and Below R 2015 *The Human Cost of Natural Disasters: A Global Perspective* (Brussels: Centre for Research on the Epidemiology of Disasters) pp 1–55
- Wang-Erlandsson L, Fetzer I, Keys P W, Van Der Ent R J, Savenije H H G and Gordon L J 2018 Remote land use impacts on river flows through atmospheric teleconnections *Hydrol. Earth Syst. Sci.* **22** 4311–28
- Zhang J, Bruijnzeel L, Tripoli A R and Van Meerveld H J 2019 Water budget and run-off response of a tropical multispecies ‘reforest’ and effects of typhoon disturbance *Ecohydrology* **12** e2055
- Zipper S C *et al* 2020 Integrating the water planetary boundary with water management from local to global scales *Earth's Future* **8** e2019EF001377