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EVIDENCE OF THE EFFECTIVENESS OF NATURE-BASED WATER SOLUTIONS IN AFRICA

PART OF THE PROJECT ‘SCALING-UP NATURE-BASED SOLUTIONS ACROSS AFRICA’

Report title: Evidence for the effectiveness of nature-based water solutions in Africa

Project title: Scaling-up nature-based solutions across Africa

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Customer: WWF-UK, WWF-DK

Task title: 1 A systematic review of the contribution of nature-based solutions

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Executive summary

1. **The study of nature-based solutions in Africa is important**. The African continent has regularly suffered major floods and droughts, but these may be increasing as our climate and landscape changes. Deforestation, wetland conversion and urban development have exacerbated other water risks, such as soil erosion, river pollution and loss of biodiversity. Globally, there is increasing interest in the potential for nature-based solutions to help address climate and water-related risks to economies and society, such as floods, droughts and increasing water scarcity, whilst restoring vital wildlife habitats. To take this forward, WWF-UK, WWF-DK, ABInBev and other partners are undertaking a spatial analysis of Africa to identify likely hotspots for nature-based solutions to climate-water risks and their overlaps with biodiversity hotspots, particularly freshwater biodiversity, and to identify where policy and regulation enables investment in nature-based solutions, and where it acts as a barrier to such investment.

2. **Scope of project.** This project investigated nature-based solutions for water risks: floods and water resources (both water quantity and water quality/pollution). Other climate related risks, such as temperature changes were not included. The solutions assessed included landscape-scale change (forests and natural wetlands) and site-specific interventions including constructed wetlands and urban interventions such as soakaways, semi-vegetated channels and miniature bio-retention areas. Effectiveness was assessed in terms of downstream changes to water risks.

3. **Scientific evidence is key to this project**. The project required authoritative scientific evidence to support policy makers and public and private investors to scale-up nature-based solutions across Africa, to improve resilience to climate-water risks and enable recovery of freshwater biodiversity. This report describes a systematic review of the evidence-base on the effectiveness of nature-based solutions for mitigating specific climate-water risks to societies and economies in Africa. The review follows international best practice for evidence assessments including the PICO (population, intervention, comparator and outcome) framework and independent peer-review of protocols and outputs.

4. **The evidence review found significant literature**. Searches of global databases (*e.g.* Web of Science), requests to experts and institutions and scans of reference lists of review papers and books were made in three subject areas: forests (both afforestation and deforestation), wetlands (natural and constructed) and a wider search for ‘nature-based solutions’ and related terms (*e.g.* river restoration, green infrastructure, sustainable urban drainage). These searches returned 10 633 publications related to nature-based solutions in Africa. Application of strict selection criteria at title, abstract or full text level identified 150 publications containing 492 case studies that reported new empirical information on the effectiveness of nature-based solutions. These were widely distributed across Africa. This shows that the topic is highly relevant and widely discussed but few publications contribute to new knowledge.

5. **Human and wildlife impacts can be assessed from water metrics**. The results of the evidence review are presented in terms of changes in water metrics (floods, water quality, water quantity). These changes need to be analysed to determine the impacts on people and wildlife. Reductions in pollutants in rivers are normally positive for everyone. Reductions in flooding are positive for people and infrastructure (e.g. roads, hospitals, factories and housing) at risk of flooding, but the same reductions may be negative for flood-dependent ecosystems, such as floodplain wetlands. The human impact of changes in river flow volume depends on how water resources are managed. Increases in wet season flows are beneficial for reservoirs that support irrigation, public

supply or hydropower generation, whereas increases in dry season flows are beneficial where abstractions are made directly from flowing rivers.

6. **Most cases of afforestation reduce water resource quantity downstream**. The evidence search produced 52 publications containing 133 case studies reporting changes to water metrics resulting from changes in forest cover. A total of 97 case studies (of catchments ranging from < 1km^2 to >95,000 km^2) reported alterations to water resource quantity (annual or seasonal flows) downstream resulting from changes in forest cover, split roughly evenly between native and non-native forest types. The case studies covered a range of forest types, though not tropical rainforest or cloud forests. None reported a specific location of the forest within the catchment (e.g. in the headwaters or downstream near the flow measurement point). All reported at a single measuring point, none reported changes in water resources at different distances downstream. The vast majority of studies compared water availability at the same point before and after deforestation or afforestation; just a few compared deforested catchments with a forested reference catchment. Most (32 of the 35) afforestation case studies showed decreased downstream surface water resource quantity due to high canopy interception and evaporation, many by more than 60%, with 30 non-native species examples and two mixed forest types. The remaining studies (3 of 35) reported no effect. The two reforestation case studies in Ethiopia also reported significant decrease in downstream water quantity. Decreases continued for 15 or 20 years after planting. The hydrological effects of forest can be highly seasonal; whilst deforestation typically increases mean annual water flow and wet season flow, dry-season flows can increase or decrease depending on factors such as soil type, geology and topography.

7. **Deforestation can increase or decrease downstream surface water resource quantity** Deforestation was reported to increase downstream surface water resource quantity in three-fifths (35 of 59) of case studies. Of these 35, 15 case studies concerned native species, 11 non-native, 3 mixed and 6 unspecified. However, almost one third (19 of 60) of case studies showed the opposite, reporting that deforestation decreases surface water quantity. Of these 19, 8 were native species studies, 1 non-native, 5 mixed and 5 unspecified. Generally, changes in downstream water resources were greater for non-native than for native species. Five case studies, including three of native trees, reported that deforestation had no hydrological effect.

8. **There is little quantitative information available on interactions between forests and groundwater resources**. Only 3 case studies reported a change in groundwater resources in response to changes in forest cover; these did not show any trend.

9. **Preventing deforestation helps avoid increasing flood risk downstream**. A total of 20 case studies reported flood response to changes in forest cover. Three quarters (12 of 16) of deforestation case studies reported an increase in downstream flood magnitude, whilst three showed no effect. 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.

10. **Greater forest cover results in reduced sediment in downstream watercourses**. Most (9 of 11) case studies reported that deforestation increases sediment yield downstream and one showed decreasing sediment yield with afforestation. Two showed opposite impacts. None reported a specific location of the forest (*e.g.* headwaters). All reported at a single measuring point, none reported changes in sediment at different distances downstream. None reported a specific location of the

forest within the catchment (e.g. in the headwaters or downstream near the sediment measurement point).

11. **Headwater wetlands reduce water resource quantity, some floodplain wetlands increase water resource quantity**. The evidence search produced 55 publications containing 144 case studies reporting changes to water metrics resulting from the presence of a natural wetland. No studies reported on the impacts of management of wetlands, such as drainage of dambo wetlands or separation of floodplains from their rivers by embankments. The case studies were divided into two broad types: headwater wetlands, such as dambos, and floodplains. A total of 49 case studies reported changes to water quantity metrics (seasonal or annual flows) resulting from the presence of a natural wetland. Just over half of the studies (25 of 49) reported that the presence of wetlands (of both types) meant reduced surface water resource quantity downstream (compared to the catchment upstream of the wetland or a similar catchment without a wetland), with less than a quarter (10 of 49) reporting an increase in surface water resources of which most (8 of 10) were floodplains. All reported at a single measuring point, normally at the outlet of the wetland; none reported changes in water resource quantity at different distances downstream.

12. **Floodplain wetlands reduce floods, headwater wetlands increase floods**. A total of 38 case studies of natural wetlands reported flood metrics, most in terms of peak flow; 14 from headwater wetlands and 22 from floodplains (two were studies of groups of wetlands). Almost all (20 of 22) of floodplain studies reported a decrease in flood magnitude due to large available water storage before flood events, whilst two reported no effect. Most (11 of 14) of the headwater wetland studies showed an increase in flood magnitude compared to catchments without headwater wetlands due to saturated soils augmenting surface runoff. Only one study of the 14 reported a decrease in floods, whilst two reported no effect.

13. **Different ecosystems function hydrologically in different ways**. The case studies show that headwater wetlands, such as dambos, have different impacts on floods and water resources than floodplain wetlands. When considering solutions to water issues it therefore beneficial to use more specific terms (such as dambo or floodplain) than the generic term ‘wetlands’ to avoid inference that findings of one type of wetland can be readily transferred to another type of wetland. In a similar way, hydrological processes vary between savannah woodlands, montane woodlands, tropical rainforests, cloud forests and plantations of non-native species, and sometimes operate differently according to soil type, topography and aspect.

14. **Some wetlands interact with underlying aquifers, but relationships are site specific**. Twenty case studies examined interactions between natural wetlands and underlying aquifers. Of the 13 studying recharge, eight simply stated that recharge occurs, three reported recharge did not occur, one reported the wetland increased recharge whilst one reported the wetland decreased recharge. Of the seven examining wetlands as groundwater discharge sites, five stated it occurred and two that it did not occur. Overall, the interaction between wetlands and underlying aquifers is site specific and largely descriptive, so no quantitative generalisations can be made from the evidence reported in the case studies found.

15. **Natural wetlands reduce pollution from sediment, nutrients and heavy metals**. Three case studies reported changes in sediment in water courses downstream of wetlands; all were decreases. Thirteen case studies reported changes in nutrients downstream. Of the seven case studies of nitrogen, all reported decreases. Of the five studies of phosphorus, four reported a decrease and one reported an increase. Eight case

studies report reductions in heavy metal (cadmium, copper, iron, lead, manganese, uranium and zinc) in water courses downstream of natural wetlands.

16. **Constructed wetlands reduce a wide range of pollutants**. The evidence search produced 36 publications containing 202 case studies of changes to water quality metrics resulting from the construction of wetlands. The metrics included sediment, ammonia, nutrients (nitrogen and phosphorus), biological oxygen demand (BOD), chemical oxygen demand (COD), heavy metals (e.g. cadmium, lead, zinc, copper, iron, manganese, mercury), oil and grease, *E. coli*, parasite eggs, Salmonellae and faecal coliforms. All case studies report reductions in metrics.

17. **Greenways can reduce floods and groundwater resources**. The evidence search produced 7 publications containing 13 case studies reporting changes to water metrics resulting from implementation of nature-based solutions other than wetlands and forests. Three case studies of green ways linking cities and forests reported reduced runoff coefficients, potentially reducing flood risk and increasing replenishment of subterranean water sources.

18. **Sustainable urban drainage reduces pollutants**. The three case studies of sustainable urban drainage, including semi-vegetated channels, soakaways and miniature bio-retention areas, showed reductions in nitrate, phosphate and chemical oxygen demand.

19. **The evidence base is consistent with previous reviews**. Other reviews have found a decrease in water yields resulting from an increase in forest area, especially for non-native species. Some studies of tropical rainforest and cloud forests suggest reduced water availability downstream after forest loss whilst others showed an increase or no effect. Some computer models predict that large scale deforestation can alter rainfall patterns across continents, with reduced rainfall and reduced water resource quantity in some areas distant from the altered forest. Previous reviews have found that at small spatial scales (< 20 km^2) forests can reduce flood flows, but are less effective at reducing large floods. Measured data for impacts in larger catchments (> 100 km^2) are lacking and studies depend on modelling. Previous reviews also reported that headwater wetlands, such as dambos, reduce downstream water resources due to high evaporation. These reviews also conclude that upstream wetlands predominantly enhance floods, whilst downstream floodplains reduce floods. Others reviews have found that constructed wetlands are very effective and efficient for wastewater treatment.

20. **There was little evidence available concerning the effects of management of interventions**. The case studies mostly reported the effects of the presence or absence of interventions, such as wetlands and forests. No studies reported on the impact of management, such as wetland drainage, tree thinning or grazing or the enhancement of ecosystem functions, such as building banks or deflectors on floodplains to increase flood water storage.

21. **The review did not cover regional implications of evaporation**. The review focused on downstream implications of nature-based interventions. It did not cover potential links between evaporation and rainfall in other catchments across regional, continental and global scales.

22. **Nature-based solutions can deliver multiple co-benefits, but also generate trade-offs**. Nature-based solutions can support multiple objectives, such as carbon sequestration, climate amelioration and biodiversity enhancement as well as significant flood reduction, sediment reduction and water quality improvement. However, there may be hydrological trade-offs such as reduced water resources.

23. **The database provides good support for the spatial analysis in Africa**. The evidence found can form the basis to identify likely hotspots for nature-based solutions to climate-water risks (Task 2) and to identify overlaps between nature-based solution hotspots and biodiversity hotspots, with particular reference to freshwater biodiversity (Task 3). Spatial analysis should focus especially on forests and floodplains, which provide the most promising nature-based solutions at landscape scale. However, few publications reported on enabling environments for nature-based solutions, so the database provides little support to the analysis of policies, regulations and investment (Task 4).

24. **Further studies are required to strengthen the evidence base**. The finding that only 150 publications out of 10,633 returned by the search suggests an imbalance between science and policy discourse. Africa is a large and diverse continent and the 492 case studies of water risks provide evidence for only some of the processes, issues and implications of nature-based solutions. More studies are required on the effectiveness of nature-based solutions, especially in terms of downstream propagation of effects and management.

Contents

1. Introduction

1.1 Background

The African continent has regularly suffered major floods and droughts, but these may be increasing as our climate and landscape changes. Deforestation, wetland conversion and urban development, have exacerbated other water risks, such as soil erosion, river pollution and loss of biodiversity. Globally, there is increasing interest in the potential for nature-based solutions to help address climate and water-related risks to economies and society, such as floods, droughts and increasing water scarcity. There are many definitions of nature-based solutions, two of most widely used are:

"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" (IUCN - Cohen-Shacham *et al.*, 2019).

"Nature-based solutions aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring more novel solutions, for example, mimicking how non-human organisms and communities cope with environmental extremes" (European Commission, 2015).

However, the current evidence base for the effectiveness of nature-based solutions to contribute, at scale, to enhanced socio-economic resilience is unclear, and there is a need for improved strategic analysis that can guide policy development and public and private sector investments in such solutions. The potential for synergies and/or trade-offs between nature-based solutions and measures to protect and restore biodiversity also requires further research. WWF, ABInBev and other partners require authoritative supporting scientific evidence that can help to inform policy makers and public and private investors, so that they can make strategic decisions about how and where to apply nature-based solutions across Africa to improve resilience to climate-water risks and enable recovery of freshwater biodiversity.

This project investigated nature-based solutions for downstream water issues: floods and water resources (water quantity and water quality/pollution). Other climate risks such as changes in temperature were not within the scope. The solutions assessed include landscape-scale change (forests and natural wetlands), and site-specific interventions including constructed wetlands and urban intervention including soakaways, semi-vegetated channels and soakaways.

1.2 Project aims

The project plan included the following activities.
Task 1: systematic review of the existing evidence for nature-based solutions for water in Africa;
Task 2: spatial analysis of Africa to identify likely hotspots for nature-based solutions to climate-water risks
Task 3: spatial analysis to identify overlaps between nature-based solution hotspots and biodiversity hotspots, with particular reference to freshwater biodiversity;
Task 4: analysis of public policies in selected hotspots identifying where policy and regulation enables investment in nature-based solutions, and where it acts as a barrier to such investment;
Task 5: support WWF and ABinBev in drafting final outputs from the assessment

This report concerns Task 1.

1.3 Specific aims of Task 1.

The aim of Task 1 was to deliver an evidence review that is robust, objective, transparent, repeatable. It was required to provide results in an easily accessible manner that facilitate an audit trail from recommendations to underpinning knowledge. The review design followed recommendations for a Quick Scoping Review (QSR) providing informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to the question (Collins *et al.*, 2015). It should be noted that this method does not include, for example, detailed statistical analysis.

The focus of the review is to provide evidence that informs the selection of parameter values in the spatial analysis in Task 2 and Task 3. The primary objective is to locate, collate and describe information on quantitative effectiveness of nature-based solutions in Africa.

Evidence is also required for Task 4 to analyse public policies in selected hotspots identifying where policy and regulation enables investment in nature-based solutions, and where it acts as a barrier to such investment. There is also a special interest in the relationship between nature-based solutions and human migration, conflict and refugees. It was agreed with the Project Advisory Group that separate searches for literature in this area are not possible given the resources available in Task 1. It was anticipated that literature relevant to Task 4 would be returned from the searches into the effectiveness of nature-based solutions. Any references to enabling conditions and human impacts found in that literature would be collated and passed to the Task 4 team.

To achieve the objectives of Task 1, the evidence review addressed the question

“Are nature-based solutions effective in mitigating specific climate-water risks to societies and economies in Africa?”

In addition, two supplementary questions were posed.

“What are the characteristics of nature-based solutions (e.g. type of ecosystem, landscape location, level of management) that are effective in mitigating specific climate-water risks?” and

“What are the enabling environments required to implement nature-based solutions (e.g. policy and planning frameworks, incentives, private sector involvement, stakeholder participation)?”.

1.4 Structure of the report

Section 2 describes the method used for this evidence review. Section 3 provides the results in terms of numbers of publications and studies found. Section 4 describes the hydrological response to interventions as defined in the case studies found for Africa. Section 5 examines wider literature to put the findings into a broader context. Section 6 provides a brief summary and conclusions of the work.

2. Searching for evidence

2.1 Systematic evidence reviews

Achieving the objective of the study required collation of the quantitative evidence of change in climate-water risks that result from nature-based solutions. The word ‘change’ is used instead of 'impact' to avoid pre-empting a conclusion that nature-based solutions will necessarily ameliorate climate-water risks. In the analysis of the evidence, the degree to which nature-based solutions alter climate-water risks needs be considered in the light of contextual factors, such as type of solution, size, geographical location and its ecological setting. It also needs to compare alterations to climate-water risks against reference conditions, such as before implementation or a similar area without the intervention.

Most studies start with a review, but they can vary enormously in quality and thoroughness. Reviews are often based on pre-existing knowledge of the authors (along with their preferences and biases), papers and books easily available on the authors' shelves or the first that come up from an internet search. Key principles of the analysis reported here are that credible evidence reviews must be comprehensive, robust, objective, transparent and repeatable, with full details of methods used. Reviews should also provide results in an easily accessible manner that facilitates an audit trail from summary statements to underpinning knowledge. Systematic evidence reviews were designed specifically to achieve these outcomes. They originated in medical research (Cook *et al.*, 1997) but have since been adapted to study environmental issues (Fazey, 2004; Pullin & Stewart, 2006; Norris *et al.*, 2012. Such systematic reviews follow strict protocols to answer focused questions. The systematic review process we used follows the PRISMA 2009 checklist (Moher *et al.*, 2009), a recognised standard for conducting Systematic Reviews adapted for ecological and environmental issues.

No review is ever fully complete and never covers all available literature; this is an open-ended task and, indeed, some academics spend their entire careers amassing literature on very focused topics. The degree to which a review can be comprehensive depends on the resources available; all reviews are restricted by time and resources. Formal systematic reviews take many months and can cost £100 000. As part of its evidence-based policy-making, the UK Department for the Environment Food and Rural Affairs (Collins *et al.*, 2015) produced (in collaboration with the Centre for Ecology & Hydrology) a consistent set of evidence review methods. These included two less exhaustive methods than full systematic reviews (SR), namely quick scoping reviews (QSR) and rapid evidence assessments (REA). By using consistent processes, the three types of review use the same robust concepts and can be undertaken in sequence if necessary, with one building on another.

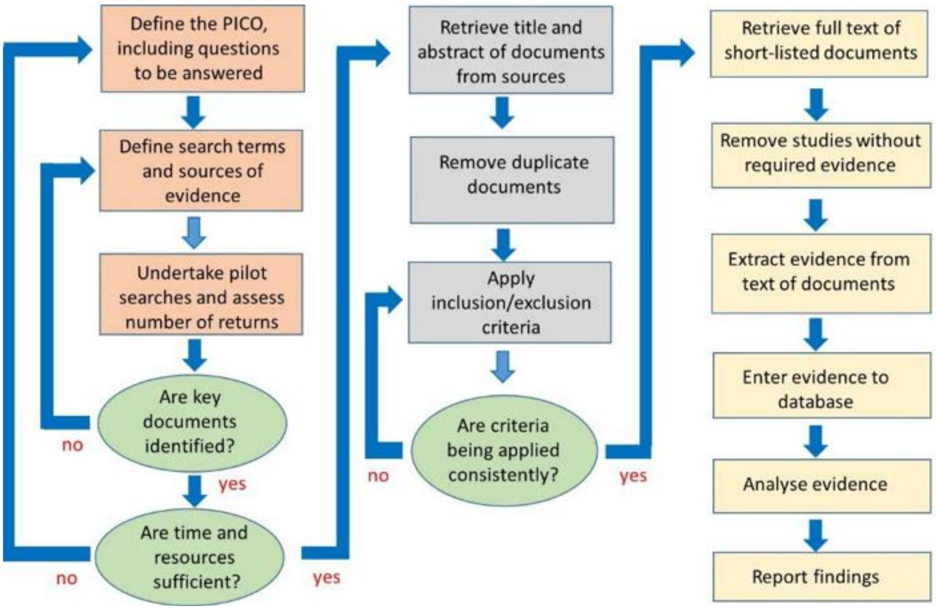

Figure 1. Steps in undertaking a systematic evidence review.

In this study, we undertake a QSR, which is usually based on scales of 3-5 months and funding of £10-30 000 (Collins *et al.*, 2015). A QSR aims to provide an informed conclusion on the volume and characteristics of an evidence base and a synthesis of what that evidence indicates in relation to the question. It is noteworthy that this method does not include detailed statistical analysis of data extracted from sources.

Rather than striving to be completely comprehensive, the approach taken here adheres to the principle of a conditional logic statement "if … then". **If** I apply these terms to a search engine, include/exclude returned publications according to these rules and extract this information from the resulting sub-set, **then** I get this evidence. The search terms, inclusion/exclusion rules and the list of information to be extracted may be subjective, but this is minimised by peer-review and publication of the protocol means the process is replicable and conforms to quality assurance requirements.

The steps followed in the evidence review are described in the Figure 1 and the sections below.

2.2 Selection criteria

The PICO (population, intervention, comparator and outcome) framework for organising selection criteria is widely used in systematic evidence reviews. The elements of the PICO framework (Table 1) define the selection criteria (whether publications are included or excluded in the analysis).

The scope of the study was defined as the terrestrial and freshwater environment of Africa. Studies from other parts of the world and saline systems (coastal and marine) were excluded (see Population in Table 1).

The intervention we were assessing was the implementation of nature-based solutions. Definitions of nature-based solutions include: "the sustainable management and use of nature for tackling societal challenges" (Eggermont et al. 2015) and "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" (IUCN - Cohen-Shacham *et al.*, 2016).

Nature-based solutions can range from landscape-scale alterations to vegetation cover, land use to enhance biodiversity and water management, to small scale interventions such as green roofs to cool city areas during summer or plant-filled depressions to capture storm water or abate pollution. The Project Advisory Group confirmed that the project focus was on landscape-scale nature-based solutions, primarily looking at the role of forests and wetlands in altering floods, water resource quantity and water quality downstream (in terms of sediment for forests and also nutrients, BOD, COD and metals for wetlands). The Group also declared interest in smaller-scale nature-based solutions such as sustainable urban drainage and constructed wetlands. Major engineering solutions, such as large dams were excluded (see Intervention in Table 1). Since many publications relevant to nature-based solutions (such as afforestation or wetland restoration), would not use the term "nature-based solutions", it was decided to undertake separate searches for water functions of forests and wetlands in addition to a search for studies explicitly called nature-based solutions.

The intention of the review was to determine the effectiveness of nature-based solutions by comparison with a baseline, either the situation at that location before implementation or with a similar location where the intervention had not been implemented (see Comparator in Table 1). An increase in water resource quantity or a decrease in flood magnitude or pollutant level constitutes an effective solution.

To define parameter values for the spatial analysis, publications presenting quantitative measures of climate-water risks - floods, surface and groundwater quantity and water quality (sediment, nutrients, BOD, COD, heavy metals) - were included. Publications containing only qualitative measures, personal impressions or inferences beyond the data collected were excluded (see Outcome in Table 1).

Table 1. PICO elements

<table>
<tr><td colspan="3">Primary question:
“Are nature-based solutions effective in mitigating specific climate-water risks to societies and economies in Africa?”</td></tr>
<tr><td colspan="3">Secondary questions:
“What are the characteristics of nature-based solutions (e.g. type of ecosystem, landscape location, level of management) that are effective in mitigating specific climate-water risks?”
“What are the enabling environments required to implement nature-based solutions (e.g. policy and planning frameworks, incentives, private sector involvement, stakeholder participation)?”</td></tr>
<tr><td>PICO element</td><td>Inclusion</td><td>Exclusion</td></tr>
<tr><td>Population. The subject or unit of study</td><td>Any country in Africa. In terrestrial and freshwater systems e.g. forests, wetlands, grasslands (urban areas?) where results have been published in readily findable databases.</td><td>Other developing countries not in Africa. Coastal and marine ecosystems. Reviews, personal opinions and unpublished material.</td></tr>
<tr><td>Intervention. Exposure applied or investigated</td><td>Implementation of nature-based solutions (e.g. afforestation, restoring wetlands, building constructed wetlands and sustainable urban drainage) to climate-water risk (e.g. floods, water resource quantity, droughts, water quality).</td><td>Engineered solutions, such as large dams, solutions to risks other than climate-water.</td></tr>
<tr><td>Comparator. Control with no intervention</td><td>Pre- and post-implementation of nature-based solutions. Post-implementation of nature-based solutions compared to reference location representing pre-implementation conditions. Simulation of reference conditions within a computer model.</td><td>Implementation of nature-based solutions where there is no control or reference counter-factual. Studies where pre and post implementation are modelled and not based on local data.</td></tr>
<tr><td>Outcome. The effect of the intervention</td><td>Quantified change in climate-water risk such as floods, droughts, water resource quantity and water quality. And/or information on enabling environment (e.g. policy, planning, incentives) that supported implementation. Plus any stakeholder perceptions of risk or change in risk.</td><td>Qualitative or inferred change in climate-water risk without data. Model predictions not confirmed by observed data. No information on enabling environment that supported implementation.</td></tr>
</table>

Publications from 1990 to the present in English language were included from global databases, Web of Science and the Scientific Electronic Library Online (SciELO), plus the global search engine Google Scholar. In addition, publications recommended by experts and institutions (e.g. IUCN, IWMI, IHE-Delft, University of Oxford) and from citations/reference lists of previous reviews and books (termed snowballing) were included. This encompassed formally published and grey literature (technical, research and project reports, working papers, issued by government or non-government organisations) from available sources.

2.3 Defining search terms for Web of Science

To retrieve information from global databases, such as Web of Science, the PICO elements must be translated into search terms using the database query language syntax that employs Boolean operators (e.g. AND, NOT, OR).

Box 1. Search terms in Web of Science syntax for nature-based solutions

Web of Science
= (Africa or Algeria or Angola or Benin or Botswana or Burkina or Burundi or Verde or Cameroon or Chad or Comoros or Congo or Ivoire or Djibouti or Egypt or Eritrea or Eswatini or Swaziland or Ethiopia or Gabon or Gambia or Ghana or Guinea or Kenya or Lesotho or Liberia or Libya or Madagascar or Malawi or Mali or Mauritania or Mauritius or Morocco or Mozambique or Namibia or Niger or Nigeria or Rwanda or Principe or Senegal or Seychelles or Leone or Somalia or Sudan or Tanzania or Togo or Tunisia or Uganda or Zambia or Zimbabwe)

AND ("nature-based" or "ecosystem-based" or "ecosystem service*" or "*green infrastructure" or "natural infrastructure" or "sud*" or "sustainable drainage" or "sustainable urban" or "green urban" or ecohydrolog* or "constructed wetland" or "constructed wetlands" or "green roof*" or "recharge basin*" or "natural flood management" or "natural stormwater management" or “water sensitive urban design” or “integrated urban water management” or “river restoration” or “water tower*”)

AND (*water or flood* or *flow* or discharge or runoff or recharge or pollutant* or nutrient* or metal* or nitrate or phosphate)

Different combinations of search terms and different syntax e.g. wildcards $ (one character) or * (any number of characters including spaces) were trialled. Each returned different lists of publications from Web of Science. A set of search terms was selected that returned key publications on the topic that were recommended by experts and the number of publications that could be reviewed within the time and resources of the project. Initial search terms and the PICO table were set out within a protocol, a draft of which was assessed by Dr Alison Smith as part of the independent peer-review process and approved by the Project Advisory Group.

Box 2. Search terms in Web of Science syntax for forests

Web of Science
= (Africa or Algeria or Angola or Benin or Botswana or Burkina or Burundi or Verde or Cameroon or Chad or Comoros or Congo or Ivoire or Djibouti or Egypt or Eritrea or Eswatini or Swaziland or Ethiopia or Gabon or Gambia or Ghana or Guinea or Kenya or Lesotho or Liberia or Libya or Madagascar or Malawi or Mali or Mauritania or Mauritius or Morocco or Mozambique or Namibia or Niger or Nigeria or Rwanda or Principe or Senegal or Seychelles or Leone or Somalia or Sudan or Tanzania or Togo or Tunisia or Uganda or Zambia or Zimbabwe)

AND (woodland or *forest*)

AND (*water or flood* or streamflow or “stream flow*” or discharge or “annual flow*” or runoff or recharge or sediment)

The final set of terms for nature-based solutions is presented in Box 1. To this were added publications retrieved from Google scholar and those recommended by experts that were not found on Web of Science (primarily grey literature) and citations/reference lists from review papers and books (e.g. Cohen-Shacham *et al.*, 2016 and Seddon *et al.* 2019). The final sets of terms for forests and wetlands are presented in Box 2 and Box 3. The number of publications returned from searches are given in Table 1. It is noteworthy that the returns may be different if the same search terms are used on future dates.

Box 3. Search terms in Web of Science syntax for wetlands

Web of Science
= (Africa or Algeria or Angola or Benin or Botswana or Burkina or Burundi or Verde or Cameroon or Chad or Comoros or Congo or Ivoire or Djibouti or Egypt or Eritrea or Eswatini or Swaziland or Ethiopia or Gabon or Gambia or Ghana or Guinea or Kenya or Lesotho or Liberia or Libya or Madagascar or Malawi or Mali or Mauritania or Mauritius or Morocco or Mozambique or Namibia or Niger or Nigeria or Rwanda or Principe or Senegal or Seychelles or Leone or Somalia or Sudan or Tanzania or Togo or Tunisia or Uganda or Zambia or Zimbabwe)

AND (wetland* or swamp* or dambo* or peat* or bog* or fen* or mire* or marsh* or floodplain or fadama or bolis or sudd)

AND (*water or flood* or *flow* or discharge or runoff or recharge or pollutant* or nutrient* or metal* or nitrate or phosphate or sediment)

In Box 2 the terms woodland and forests were used to capture studies of afforestation, reforestation and deforestation. Reference lists from review papers and books (e.g. Filoso *et al.* 2017) were added.

2.4 Applying inclusion/exclusion criteria

First, duplicate publications were removed. Next the title of each publication was read and those not related to the topic were excluded, such papers of studies in Papua New Guinea picked-up by including Guinea in the search terms. Previous review papers were excluded in their own right (unless they included new unpublished data) to avoid mixing different review protocols, duplicating publication and including reviewers' interpretations of other literature, so only primary sources were included. The citation/reference list of reviews were used to find additional publications. Of those included at this stage the abstract was read to ensure the publication was relevant and likely to include quantitative information. Many abstracts contained much of the data required, such as percentage change in a hydrological metric in response to, for example, planting a forest of a given area. Full text was examined to extract all information required for the database.

Table 2. Numbers of publications collated

	Total number of publications returned from Web of Science	Total gross publications (including snowballing, Google scholar, expert recommendations)	No. of publications short-listed (for inclusion in the database)
Nature-based solutions	1203	1218	7
Forests	4521	4548	52
Wetlands	4812	4867	91

2.5 Extraction of information for the database

The characteristics and contextual information important for this review are different for forests, natural wetlands and constructed wetlands. For example, for natural wetlands the freshwater ecosystem type and upstream catchment area are important. In contrast, important information for constructed wetlands includes flow rate and species planted (as they tend to be monocultures).

Some publications contained information on several sites and/or several different parameters. Each site/parameter was considered as a separate case study. The numbers are given in Table 6.

Table 3. Number of case studies

	No. of publications short-listed	No. of case studies from short-listed publications
Nature-based solutions	7	13
Forests	52	133
Natural wetlands	55	144
Constructed wetlands	36	202

The information listed in Table 4 was extracted from all short-listed papers and entered to the database.

Table 4. Records in database common to all records

Column header in database	**Explanation**
paper number	Sequential unique identifier for each publication
case study number	Sequential unique identifier for each cases study
author	Lead author of publication
year	Year of publication
title	Title of publication
reference	Publisher e.g. journal or institution
country	State in Africa
summary statement	Verbatim quotation from publication that summarises findings
catchment/location	Geographical location of study
time frame of study	Calendar years of study, before and after implementation

Slightly different information was extracted for each of the four sets of publications, nature-based solutions, forests, natural wetlands and constructed wetland, as shown in Tables 6, 7 & 8.

Table 5. Additional records in database for nature-based solutions

Column header in database	**Explanation**
ecoregion	Terrestrial ecoregion defined by Olsen *et al.* (2001)
nature-based solution type	Type of nature-based solution implemented
broad setting	Rural or urban
intervention description	Narrative on type of intervention e.g. urban drainage
size of intervention	Area (m2) of intervention
size of catchment	Catchment area (km2) to metric measurement point
outcomes	Narrative of broad results of intervention
metric	Hydrological measure e.g. annual flow volume
% change in metric	How much (%) the metric changes in the presence of the nature-based solution
climate-water risk category	Whether the metric relates to flood, water resource quantity or water quality/pollution
summary standardised measure	Direction of change for risk category following the intervention (increase, decrease or neutral)
enabling environment	Supporting policies or incentives for nature-based solution implementation
notes	Relevant information not held in other columns

Table 6. Additional records in database for forests

Column header in database	**Explanation**
ecoregion	Terrestrial ecoregion defined by Olsen *et al.* (2001)
forest type	Whether trees are predominantly native or non-native
tree species	Specific species present
size of catchment	Catchment area (km^2) to metric measurement point
forest cover change	Forest cover change reported in publication as an absolute figure and as a percentage of the catchment area
nature of action	Whether afforestation, reforestation or deforestation
basis of inference	How the study was formulated e.g. before-after afforestation
metric	Hydrological measure e.g. annual flow volume
% change in metric	How much (%) the metric changes in the presence of the trees compared to fewer or no trees
climate-water risk category	Whether metric relates to flood, water resource quantity or sediment (other pollution was not recorded)
summary standardised measure - afforestation	Direction of change for risk category standardised for afforestation (increase, decrease or neutral)
notes	Relevant information not held in other columns

Table 7. Additional records in database for natural wetlands

Column header in database	Explanation
ecoregion	Freshwater ecoregion defined by Abel *et al* (2008)
major habitat type	Habitat type defined by Abel *et al* (2008)
wetland type	Type of wetland
local name	Local name for type of wetland
size of catchment	Area (km^2) to outlet of wetland
size of wetland	Area (km^2) of wetland (normally maximum extent)
basis of inference	How the study was formulated e.g. upstream-downstream of wetland
metric	Hydrological metric such as annual flow volume at outlet of wetland
% change in metric	How much (%) the metric changes in the presence of the wetland compared to without the wetland
climate risk category	Whether metric relates to flood, water resource quantity or quality/pollution (including sediment)
summary standardised measure – wetland construction/restoration	Direction of change in risk category standardised for wetland construction/restoration (increase, decrease or neutral)
notes	Relevant information not held in other columns

Table 8. Additional records in database for constructed wetlands

Column header in database	Explanation
wetland type	Type of construction
key species	Vegetation species planted
flow rate (m^3 d^{-1})	Rate of flow into the wetland
size of wetland	Area (km^2) of wetland
basis of inference	How the study was formulated e.g. upstream-downstream of wetland
metric	Hydrological metric such as pollutant type
% change in metric	How much (%) the metric changes between inflow and outflow
climate risk category	Whether metric relates to flood, water resource quantity or quality/pollution (including sediment)
summary standardised measure	Direction of change in risk category (increase, decrease or neutral)
notes	Relevant information not held in other columns

2.6 Inclusion/exclusion of modelling studies

Modelling typically involves the simulation of environmental processes in a computer. In particular, the SWAT model has been used to estimate the implications of actions such as deforestation using parameter values based on data from other studies. In such as cases no observed data are used to check the model results. Examples include change in river flows resulting from deforestation in the Upper Shire river catchment, Malawi (Palamuleni *et al.*, 2011), the Nyando River Basin, Kenya (Olang & Fürst, 2010) and the river Niger and Lake Chad basins of West Africa (Li *et al.*, 2007). Whilst such studies may be useful for local land managers or decision-makers they do not add to quantitative scientific evidence, so were excluded from the review.

In some case studies data were collected on interventions and the response of hydrological metrics, but modelling was used to disentangle simultaneous effects of climate variability and land cover change (*e.g*. Pitman, 1978; Kashaigili *et al*., 2006). For some case studies data were available with the intervention in place, but the pre-intervention conditions were simulated using a model (*e.g*. McCartney *et al*. 2013. Such studies were included, but the use of a model was noted.

2.7 Choice of hydrological metrics

The purpose of this study is to find evidence of alteration to downstream floods, water resource quantity and water quality, including sediment. Many other components of the hydrological cycle are often measured, such as canopy interception, infiltration and evaporation. For example, it is widely accepted that the total evaporation from forested areas is greater than from grasslands, largely due to the differences in the amount of rainfall that is intercepted by the forest canopy and to higher transpiration rates (Bulcock & Jewitt, 2012). However, reduction in evaporation from planting trees may be offset by greater infiltration, such that downstream flows are not reduced. Therefore, only studies that provided quantitative records of downstream floods, water resource quantity or water quality are included. Studies were rejected if downstream hydrological implications were inferred from knowledge of other components, such as evaporation.

3. Results of analysis

3.1 Hydrological metrics

Water resource quantity metrics were of three types. First ‘annual flow volume’, which is the total resource available downstream during the year. Most parts of Africa have distinct wet and dry seasons. The two other metrics were ‘dry season flows’, which tend to be low flows (sometimes no flow) during the period of the year with no or low rainfall, and wet season flows which capture flows during the rainy period of the year. These normally incorporate floods, but individual floods still normally deliver only a small part of the wet season flow, so in most cases the metric is quite different from flood metrics.

The flood metrics are predominantly peak flow during flood events, which typically last days or weeks. In a few cases the flood metrics reported were change in percentage of rainfall that contributed to storm runoff. Area flooded was not reported in any studies.

Water quality metrics were primarily percentage removal of pollutants (nutrients, BOD, COD, heavy metals, pharmaceuticals, coliforms, petroleum products and sediment).

3.2 Geographical distribution of case studies, intervention types and metrics

Table 9 shows the number of case studies originating from different African countries. The 10 case studies involving more than one country are not included in the Table. It can be seen that there is a wide distribution across Africa from Morocco and Algeria in the north to South Africa and from Senegal in the west to Madagascar in the east, covering arid, semi-arid, tropical and sub-tropical areas including savannahs and forest zones. The highest number of case studies came from Ethiopia and South Africa, which have a good spread of all four categories. High numbers also come from Egypt, Uganda, Tanzania and Zambia, though the vast majority from Egypt are constructed wetlands. Those from Uganda are all wetlands (both natural and constructed), whereas most case studies from Zambia are natural wetlands. Some case studies involved more than one country so are entered multiple times in Table 9, but some regional studies did not specify the countries so are not included.

Table 9. Number of case studies found per topic and country

	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

Of the 13 case studies explicitly using the term ‘nature-based solutions’, five were urban and 8 rural. They covered a range of intervention types (Table 10). These studies reported mainly downstream annual flow volume, but some also reported groundwater levels, floods and water quality (Table 11).

Table 10. Number of types of nature-based solution case studies

Aquifer recharge	2		Grassed waterways	2
Sustainable urban drainage	3		Storm water harvesting	5
Greenways	1			

Table 11. Number of nature-based solution case studies reporting water quantity and quality parameters

Annual flow volume	3	Chemical oxygen demand	1
Annual groundwater	3	Nitrate	1
Dry season flow volume	1	Phosphate	1
Floods	2	Sediment	1

Table 12. Number of forest case studies reporting water quantity and quality parameters

Annual flow volume	62	Floods	20
Dry season flow volume	29	Groundwater recharge	4
Wet season flow volume	6	Sediment	12

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 case studies the forest type was unspecified. These 133 studies reported mainly downstream annual flow volume, low flow or dry season flow volume (which are collectively referred to as water resource quantity), but some case studies also reported impacts on floods and sediment (Table 12).

Afforestation case studies totalled 35, with 31 explicitly planting non-native trees, 2 planting a mix of native and non-native and in 2 cases the tree species were not specified. Only two studies involved reforestation (growing native forests, where native forests had existed before), in which enclosures had been erected to allow native trees to regrow on land that had been natural forest. No case studies of planting native trees were found.

Table 13. Number of natural wetland case studies reporting water quantity and quality parameters

Annual flow volume	17	Ammonia	1
Annual groundwater discharge	7	Biologcial Oxygen Demand	1
Annual groundwater recharge	13	Colloids	1
Dry period flow duration	3	Faecal coliforms	2
Dry period flow volume	29	Microbes	1
Flood peak high return period	10	Nitrate	1
Flood peak low return period	28	Organic matter	2
Wet period flow volume	2	Pharmaceuticals	1
Wet period groundwater recharge	1	Sediment	3
		Total nitrogen	6
Cadmium	1	Total phosphorus	6
Copper	2		
Iron	1		
Lead	1		
Manganese	1		
Uranium	1		
Zinc	1		

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 and in 20 case studies the tree species were unspecified. The studies methods were of three types: hydrological measures before and after deforestation at the same site; measurements after deforestation compared with measurements from a reference site to indicate pre-deforestation conditions and comparisons between forested and non-forested sites with no deforestation taking place during the study. Clearly afforestation and deforestation are different processes, but if a nature-based solution is defined in terms of restoring native forests to their original condition in their original locations, then the findings of deforestation of native forest can be reversed to inform the likely results of reforestation.

The 144 natural wetland case studies reported a range of water quantity and quality parameters including river flows downstream (during floods, low flows, dry seasons and wet seasons), groundwater interactions and quality of downstream rivers including nutrients (*e.g.* nitrate and phosphate), heavy metals (including cadmium, copper, lead, uranium and zinc) and microbes (Table 13). None of natural wetland case studies reported construction or destruction of wetlands. 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

Table 14. Number of constructed wetland case studies reporting water quality parameters

Ammonia	8		Orthophosphate	2
Biological Oxygen Demand	26		P. aeruginosa	1
Cadmium	3		Parasite eggs	1
Chemical Oxygen Demand	29		Phenol	1
Copper	6		Phosphate	14
E. coli	2		Salmonellae	1
Faecal coliforms	4		Sulphates	1
heavy metals	1		Total coliforms	2
Iron	11		Total Kjeldahl Nitrogen	2
Lead	6		Total nitrogen	12
Listeria monocytogenes	1		Total petroleum	1
Manganese	3		Total phosphorus	11
Mercury	3		Total suspended solids	20
Nickel	2		Turbidity	1
Nitrate	15		Zinc	8
Oil & grease	2			

The 202 constructed wetland case studies reported water quality parameters including biological oxygen demand, chemical oxygen demand, heavy metals, coliforms, petroleum, microbes and nutrients (Table 14). All constructed wetland case studies compared input concentrations of pollutants with outputs from the wetland to calculate removal effectiveness.

4. Hydrological response to interventions

The large number of case studies and complex interactions between interventions and the water metrics preclude full analysis of every example individually. The following sections describe salient features of the case study database. The term water resource quantity is used to summarise a set of metrics: annual flow volume, dry season flow and low flow.

4.1 Forests

The evidence search produced 133 case studies reporting change in water metrics resulting from changes in forest cover. Of these 133, 97 reported downstream surface water resource quantity. Most (32 of the 35) afforestation case studies show decreased downstream surface water quantity, with 30 non-native species examples and two mixed forest types (Figure 1). The two reforestation case studies in Ethiopia involved exclosures to allow natural tree regrowth, without replanting and reported significant decrease in runoff generation, which continued for 15 or 20 years (Descheemaeker *et al.*, 2006). A few studies reported that flow reduction due to afforestation varied with the age of the trees. For example, after clear-felling and then replanting, pine trees in Jonkershoek, South Africa, flows increased after deforestation and returned to preclearing levels within 12 years, with the peak increase after 20 years and thereafter the reduction was less, (Scott *et al.*, 2000). In other studies reductions continued for 35 years (Scott *et al.,* 2000). One case study, of unspecified tree species, reported an increase in surface water quantity with afforestation (Akele *et al.*, 2019), whilst two, a non-native case in Malawi (Mbano *et al.*, 2009) and an unspecified case in Ethiopia (Tesfaye *et al.*, 2017), reported no hydrological change.

Deforestation was reported to increase downstream surface water resource quantity in over half (35 of 59) of case studies. Of these 35, 15 case studies concerned native species, 11 non-native, 3 mixed and 6 unspecified. However, almost one third (19 of 60) of case studies countered this trend reporting that deforestation decreases surface water quantity. Of the 19, 8 were native species studies, 1 non-native, 5 mixed and 5 unspecified. The strongest evidence for an increase in water resource quantity with deforestation is for annual flow metrics, with 26 case studies, as opposed to 10 showing a decrease. For dry season flows, the evidence is mixed with a shade more deforestation case studies showing a decrease (7) compared to an increase (6). For native forests, which are likely to be the focus of nature-based solutions, 10 case studies report an increase in annual flow volume following deforestation, whilst 3 report a decrease. There is equal evidence for an increase (4) or a decrease (4) in dry season flows after native forest removal.

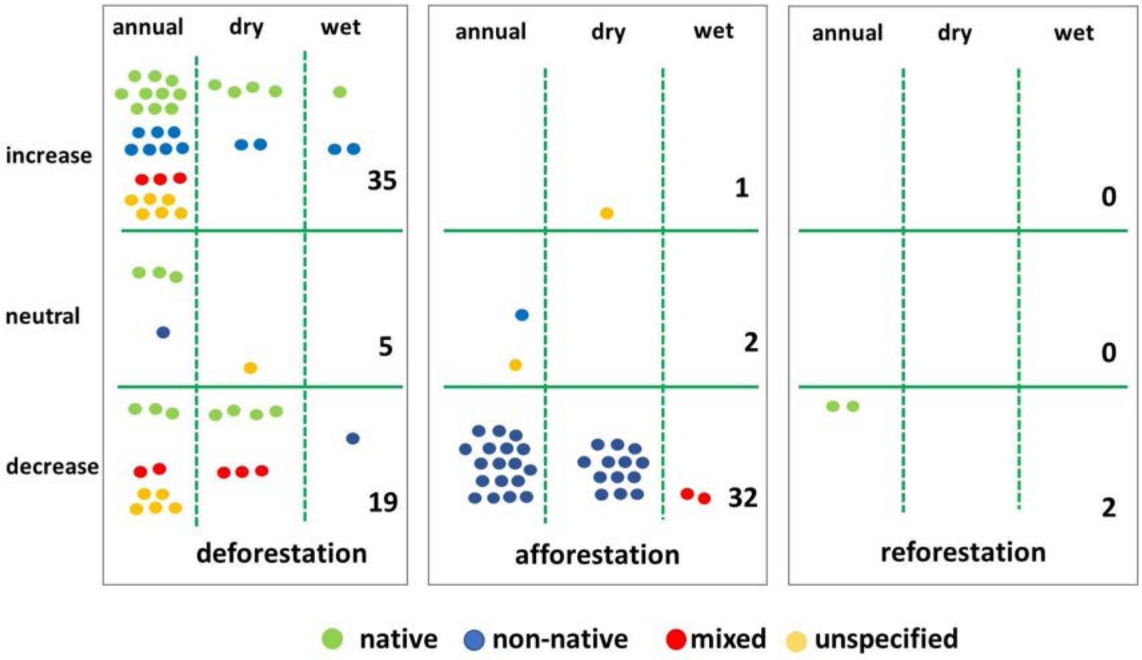

Figure 1. Changes in downstream surface water resource quantity under deforestation (left) and afforestation (centre) and reforestation (right). Case studies of native forest studies are shown in green, non-native forest studies in blue, mixed forest studies in red and unspecified forest studies in orange.

No studies reported a specific location of the forest, they simply reported percentage forest cover within the catchment. Therefore, it was not possible to assess the differing impacts of forests in different locations, such as headwaters or along the main channel. All case studies reported at a single measuring point, none reported changes in water resources at different distances downstream so it was not possible to determine how an effect might propagate downstream.

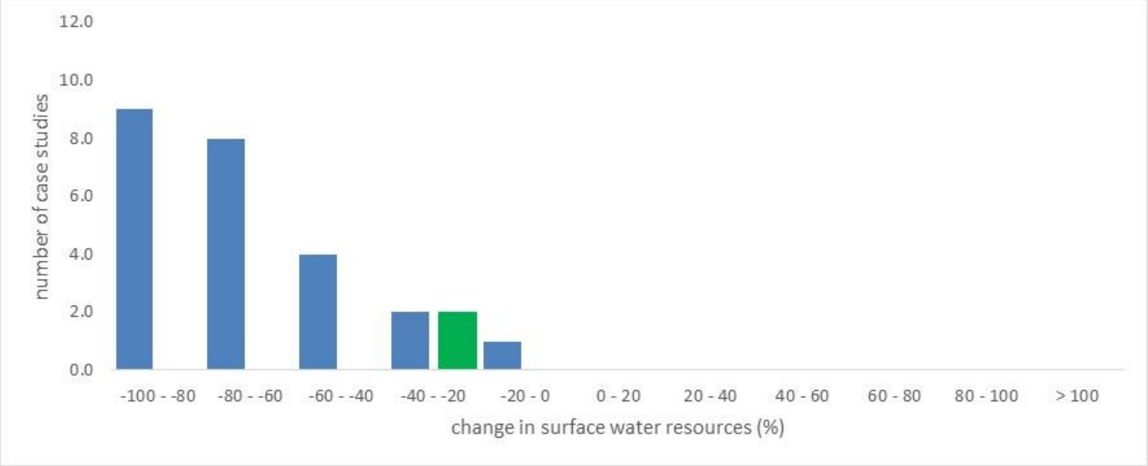

Figure 2. Number of studies of reforestation (green) and afforestation (blue) showing different changes in surface water resource quantity downstream.

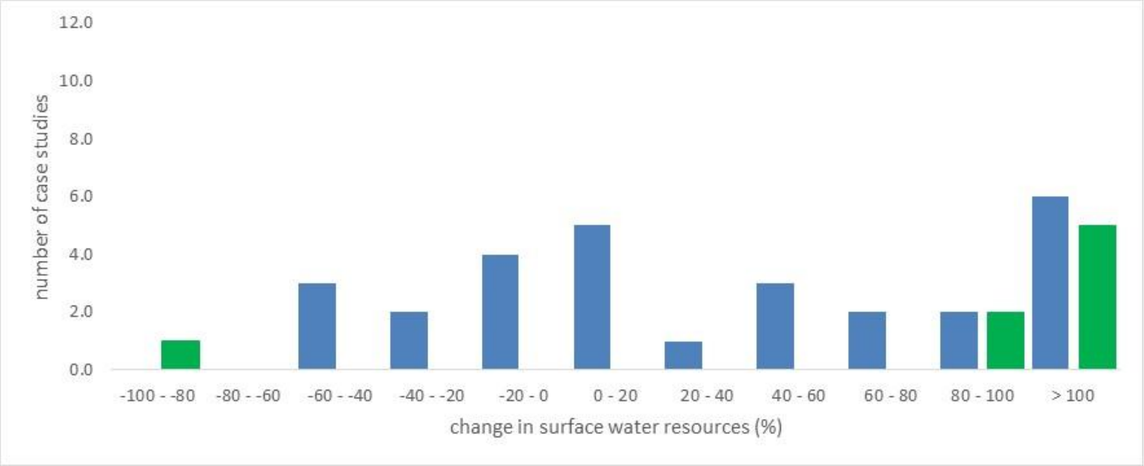

Figure 3. Number of studies of deforestation of native (green) and non-native (blue) trees showing different changes in surface water resource quantity downstream.

Figure 2 shows that both case studies of reforestation report decreases in surface water resource quantity greater than 20% (34.7% & 21.4%), whilst two-thirds (17 of 24) of the case studies of afforestation show decreases in surface water resource quantity of greater than 60%. Figure 3 shows that surface water resource quantity changes are less consistent for deforestation. Most (7 of 8) case studies of native tree deforestation report 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 show increases in water quantity of greater than 40%, whereas one third (9 of 28) show decreases *i.e.* less than zero %.

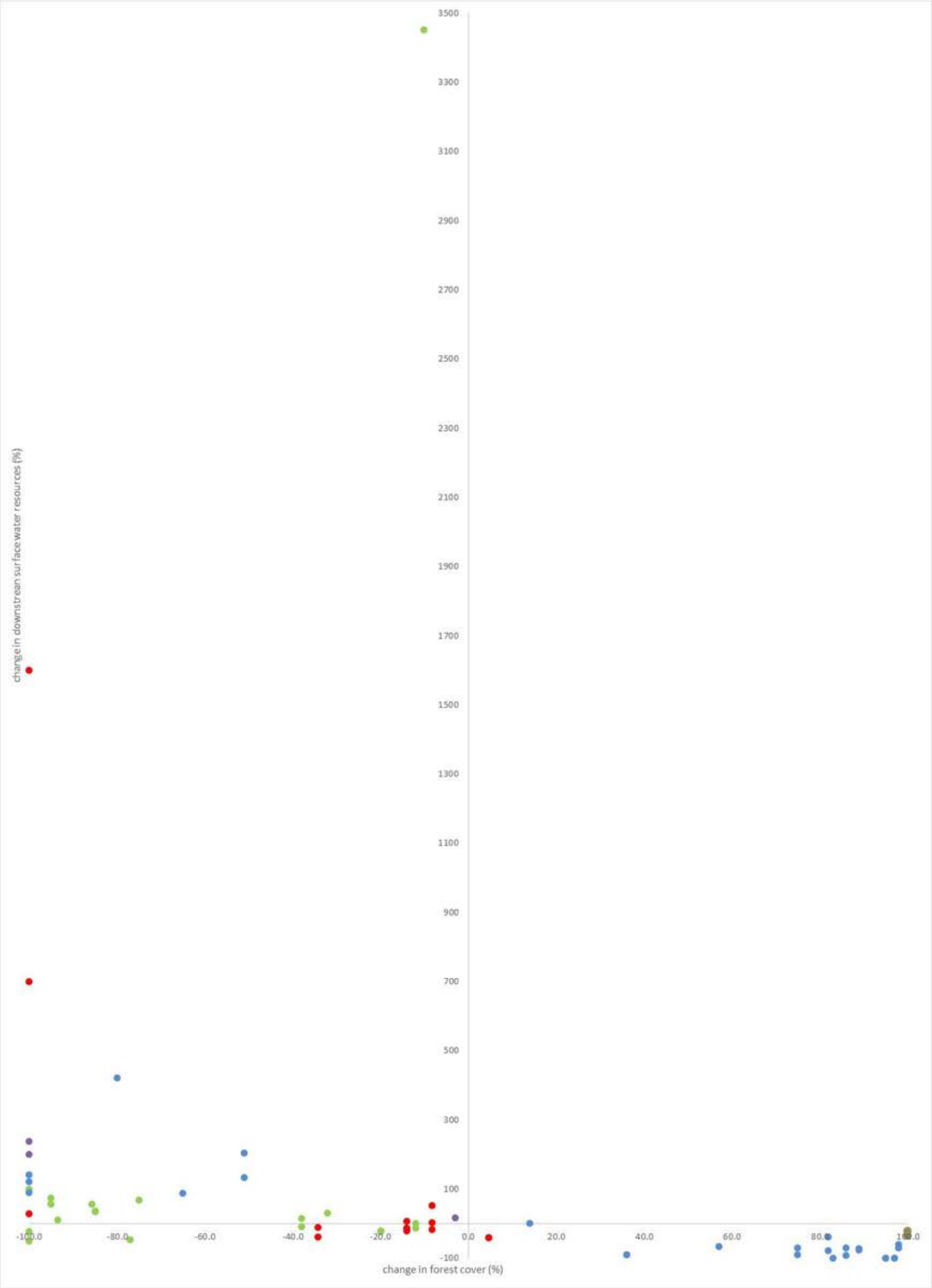

Figure 4. Relationship between change in forest cover (%) and change in downstream surface water resource quantity (%). Case studies of native deforestation are shown in green, studies of native reforestation are shown in brown, non-native forest studies in blue, mixed forest studies in red and unspecified forest studies in orange. On the horizontal axis deforestation is shown as negative values, whilst afforestation and reforestation are shown as positive values.

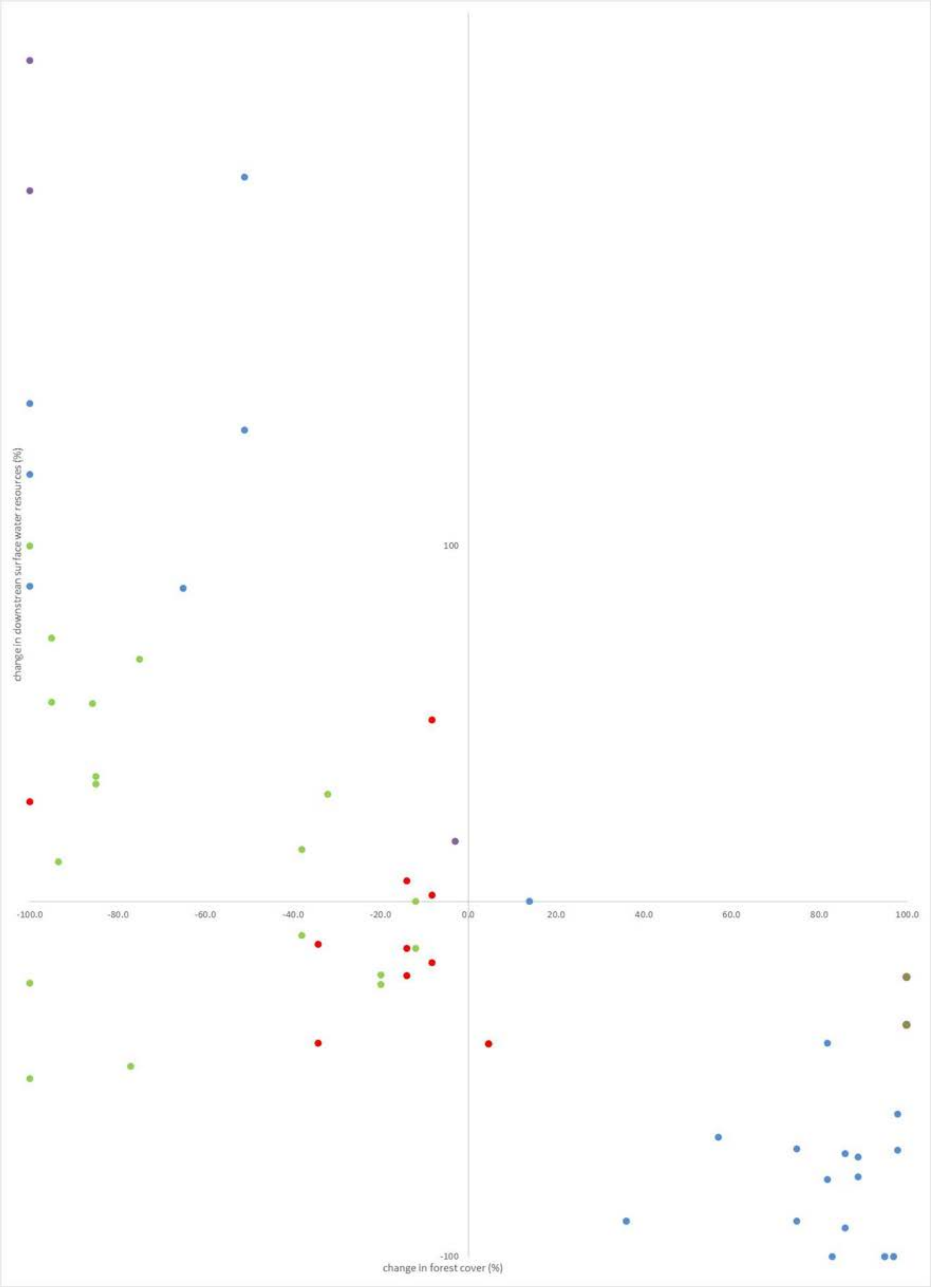

Figure 5. Relationship between change in forest cover (%) and change in downstream surface water resource quantity (%). Case studies of native deforestation are shown in green, studies of native reforestation are shown in brown, non-native forest studies in blue, mixed forest studies in red and unspecified forest studies in orange. The vertical axis is truncated at 250% to aid visualisation of lower values.

Figure 4 shows percentage change in surface water resource quantity (vertical axis) for a given change in percentage of the catchment forested (the horizontal axis shows negative value for deforestation and positive for afforestation) for the subset of the case studies that reported both values. One native forest and two unspecified case studies reported some very high increases in quantity: a 36 fold increase from removal of native forest from 10% of the catchment in Zambia (McCartney *et al.*, 2013), for which the without-forest flow data are from a hydrological model, and a 7 fold increase in Nigeria (Lal, 1997) and 16 fold increase in Ethiopia (Girmay *et al.*, 2009), both from 100% removal of mixed forests.

Figure 5 shows the same graph as Figure 4 with the vertical axis truncated at 250% to aid visualisation of lower values. The two reforestation case studies show decreases in annual flow volume of 34.7% and 21.4% (Descheemaeker *et al.*, 2006). The maximum decrease in surface water quantity from deforestation is 50% from clear-felling native trees in Tanzania (Lundgren, 1980) whilst several studies report 100% decrease (drying of the river) from afforestation. The general trend is 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 increases. Changes in water resource quantity are generally greater for non-native than for native species. Case studies covered a range of forest types found in Africa, but notable exceptions were tropical rainforests and cloud forests. There was no clear pattern of the direction of change in water resource quantity with forest type (Table 15). The two case studies of reforestation were of Ethiopian montane woodland. These trends have not been tested for statistical significance. Nevertheless, there is good evidence that removal of non-native forests increases downstream surface water resource quantity, though the evidence for native and mixed forests is less clear, with 12 cases in which deforestation reduced water resource quantity compared to 18 where it led to an increase.

Table 15. Type of native forests (ecoregion from Olsen *et al.*, 2001) in case studies of deforestation impacts on water resource quantity

	country	**forest type**
annual flow volume		
increase in water availability	Tanzania	Montane evergreen forest
	Malawi	Montane forest
	Kenya	Montane forest
	Benin	Forest-savannah mosaic
	Tanzania	Miombo woodland
	Zambia	Miombo woodland
	Kenya	Forest-savannah mosaic
neutral	Ethiopia	Montane forest
decrease in water availability	Tanzania	Eastern arc forests
dry season flow volume		
increase in water availability	Tanzania	Acacia woodlands
	Tanzania	Montane woodland
	Malawi	Miombo woodland
	Zambia	Miombo woodland
decrease in water availability	Ethiopia	Montane forest
	Zambia	Miombo woodland
wet season flow volume		
increase in water availability	Ethiopia	Montane forest

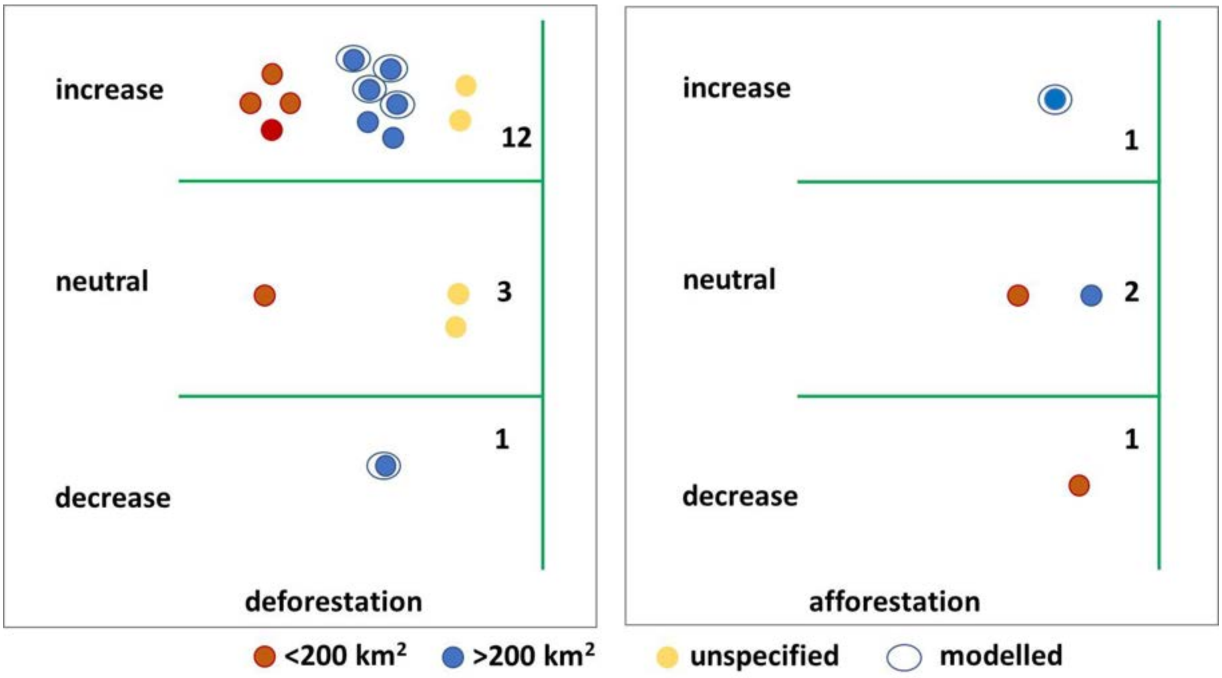

Figure 6. Changes in downstream flood magnitude under deforestation (left) and afforestation, and reforestation (right). Case studies of catchments smaller than 200 km2 are show in red, studies of catchments larger than 200 km2 are shown in blue, studies where the catchment area is not specified are shown in orange. Modelling studies have surrounding circles.

The 20 case studies of flood response to changes in forest cover (Figure 6) were from a range of catchment sizes from > 17000 km² to < 1 km² and show a diverse pattern. Three quarters (12 of 16) of deforestation case studies reported an increase in downstream flood magnitude, whilst three showed no effect. 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. Most of the large catchment studies used models. The one example showing a decrease in flood magnitude following deforestation comes from the Rivi Rivi River in Malawi (McCartney *et al.*, 2013), for which the without-forest flood data were from a hydrological model. The one example showing an increase in flood magnitude following afforestation came from a broad-scale statistical study of data from across Africa (Li *et al.*, 2016). It is possible that this resulted not from the increase in afforestation but due to other land cover changes in the catchment that happened at the same time. All case studies reported at a single measuring point, none reported changes in floods at different distances downstream so it was not possible to determine how an effect might propagate downstream.

The 10 case studies providing numerical values for percentage change in flood magnitude and percentage in catchment area forested are shown in Figure 7 (horizontal axis with negative value for deforestation and positive for afforestation); there were no studies providing quantitative results of afforestation effects on floods. Although there are limited data, they suggest that greater deforestation causes increased flood magnitude. This trend has not been tested for statistical significance. Nevertheless, there is good evidence that preventing deforestation can avoid increases in flood risk. There is insufficient evidence to draw conclusions about the effect of afforestation on floods.

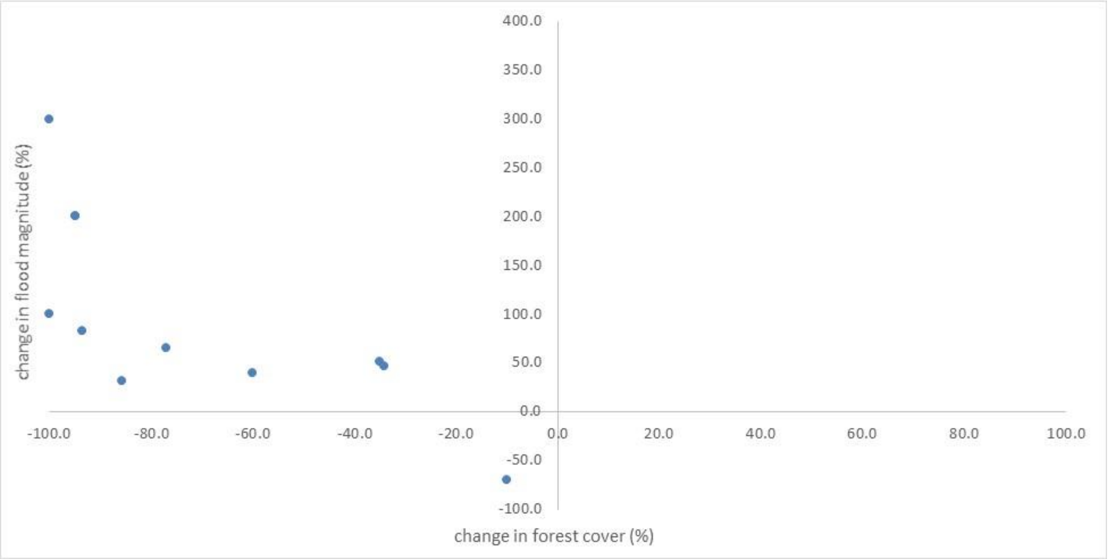

Figure 7. Relationship between change in forest cover (%) and change in flood magnitude (%). The horizontal axis shows negative value for deforestation and positive for afforestation.

Most 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 about half of the total observed increases in discharge in relation to rainfall (Recha *et al.*, 2012).

The 11 case studies of change to sediment yield in response to changes in forest cover are shown in Figure 8. Most (9 of 11) case studies indicate that deforestation increases sediment yield downstream and one shows decreasing sediment yield with afforestation. One study in the Congo (Coynel *et al.*, 2005) does not conform to this trend, but sediment concentrations from the forested catchments and savannah catchments were both very low so the difference may not be very significant. There is strong evidence that afforestation or reforestation provides a good nature-based solution for reducing sediment yields.

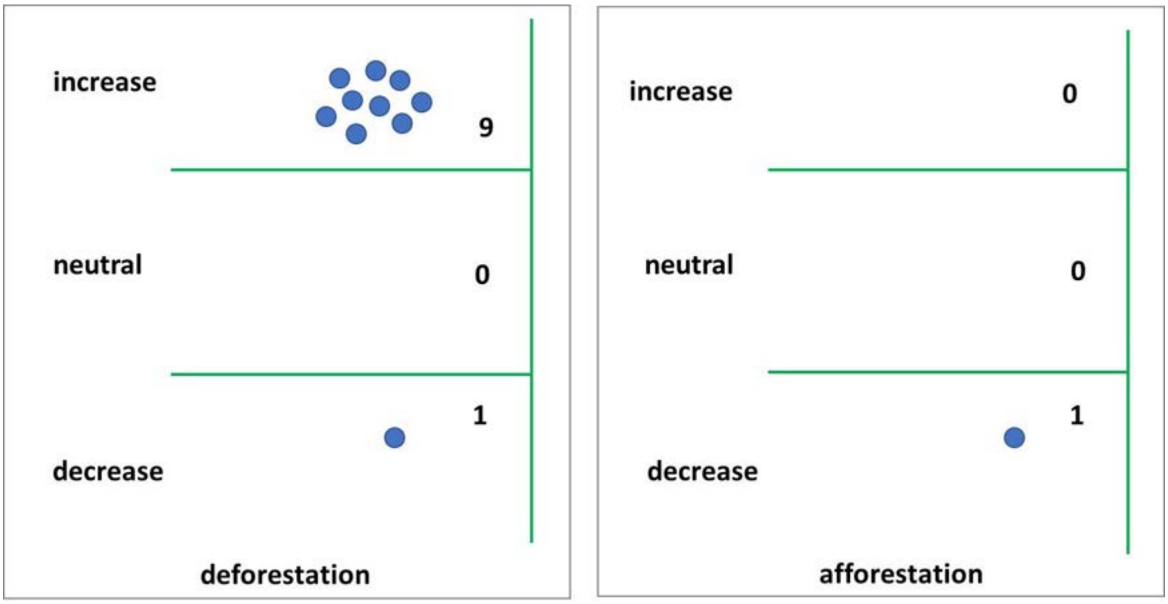

Figure 8. Changes in sediment load downstream under deforestation (left) and afforestation, including reforestation (right) for all types of forest combined.

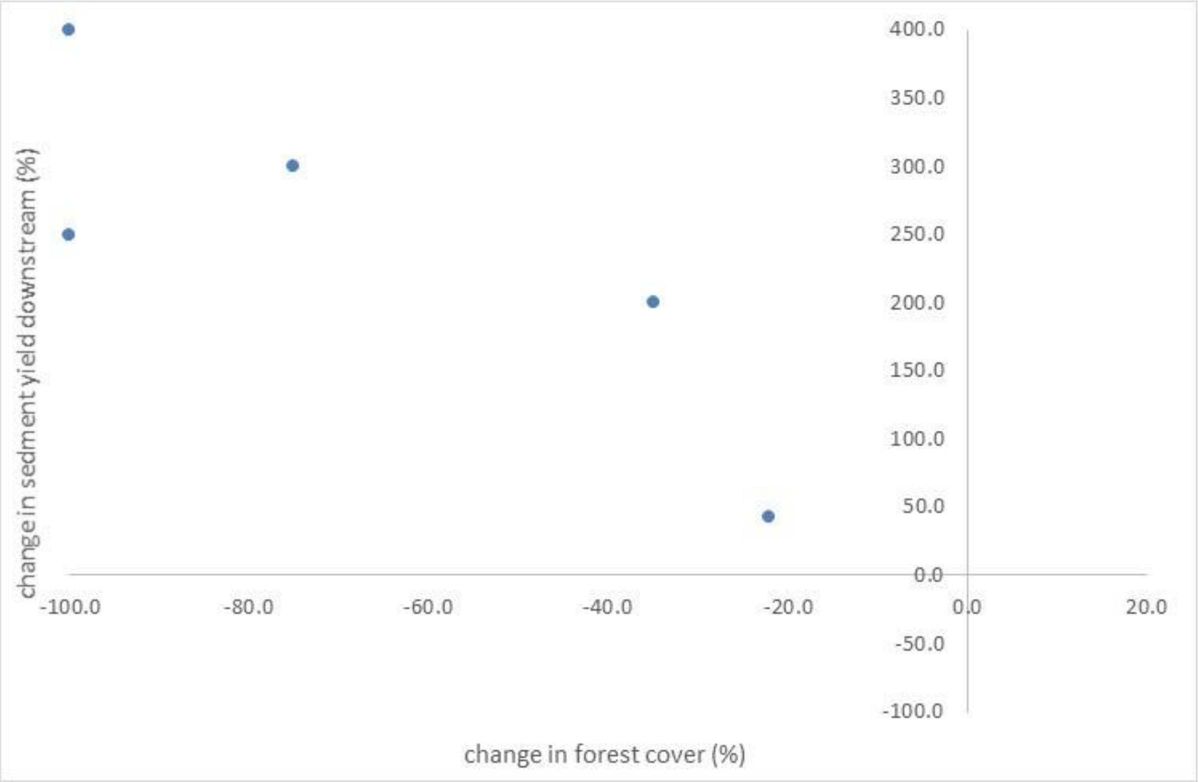

Figure 9. Relationship between change in forest cover (%) and sediment yield (%). The horizontal axis shows negative value for deforestation and positive for afforestation.

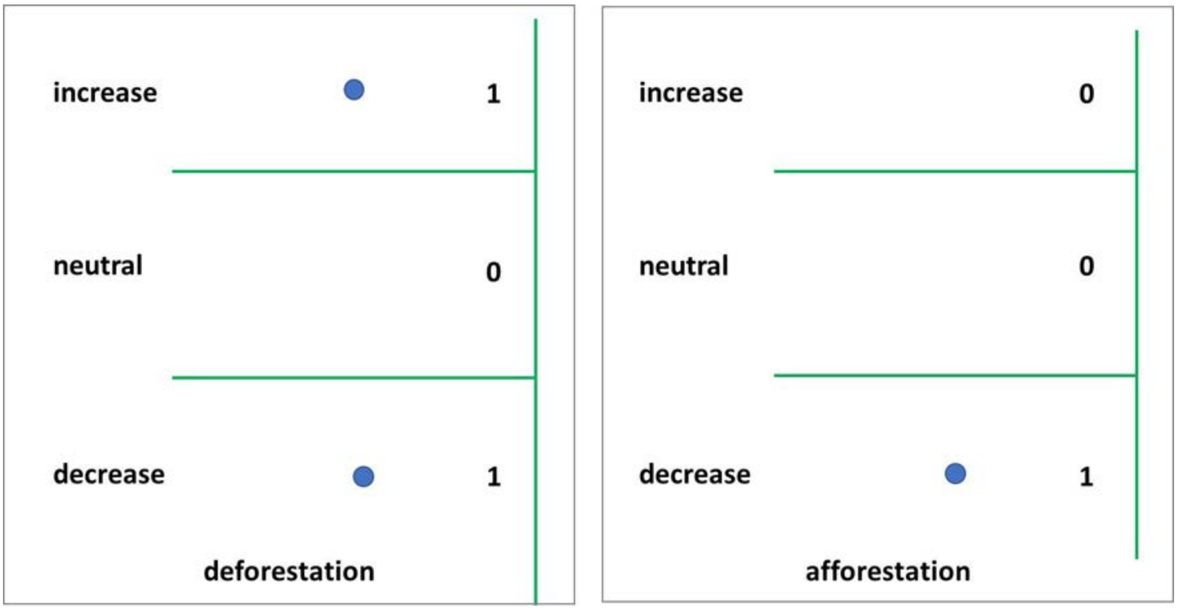

Figure 10. Changes in groundwater resource quantity under deforestation (left) and afforestation, including reforestation (right) for all types of forest combined.

Only 5 of the 11 case studies reporting changes in sediment contained data for percentage change in sediment yield and percentage in catchment area forested (Figure 9). These data suggest a strong trend of increasing sediment yield with decreasing forest cover, with up to a 4-fold increase in sediment with clear-felling. The trend has not been tested for statistical significance. Afforestation or reforestation would appear to be a good nature-based solution for reducing sediment loads. All case studies reported at a single measuring point, none reported changes in sediment at different distances downstream so it was not possible to determine how an effect might propagate downstream. No case studies reported how change in sediment might vary over time, such as with tree growth under afforestation.

Only 3 case studies reported change in groundwater resource quantity in response to changes in forest cover (Figure 10), and these do not show any trend. There is little evidence that afforestation provides a good nature-based solution for increasing groundwater resource quantity.

4.2 Natural wetlands

The evidence search produced 144 case studies reporting changes to water metrics associated with the presence of natural wetlands within catchments ranging in size from > 300 000 km^2 to < 1 km^2. Although a range of wetland types was represented (characterised by different vegetation and soils), the vast majority were referred to by the authors as either dambos (all in headwater areas) or floodplains (downstream). Catchment location is a long-standing simple method of classifying wetlands for functional assessment (Novitski, 1978; Adamus & Stockwell, 1983; Bullock & Acreman, 2003). Three case studies involved a statistical analysis of a large number of wetlands of various types, but the remaining 141 were divided into two broad categories: headwater wetlands including dambos and headwater peat swamps, and floodplains that included lowland papyrus wetlands, inland deltas and lowland valley swamps.

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 might vary over time such as with wetland management.

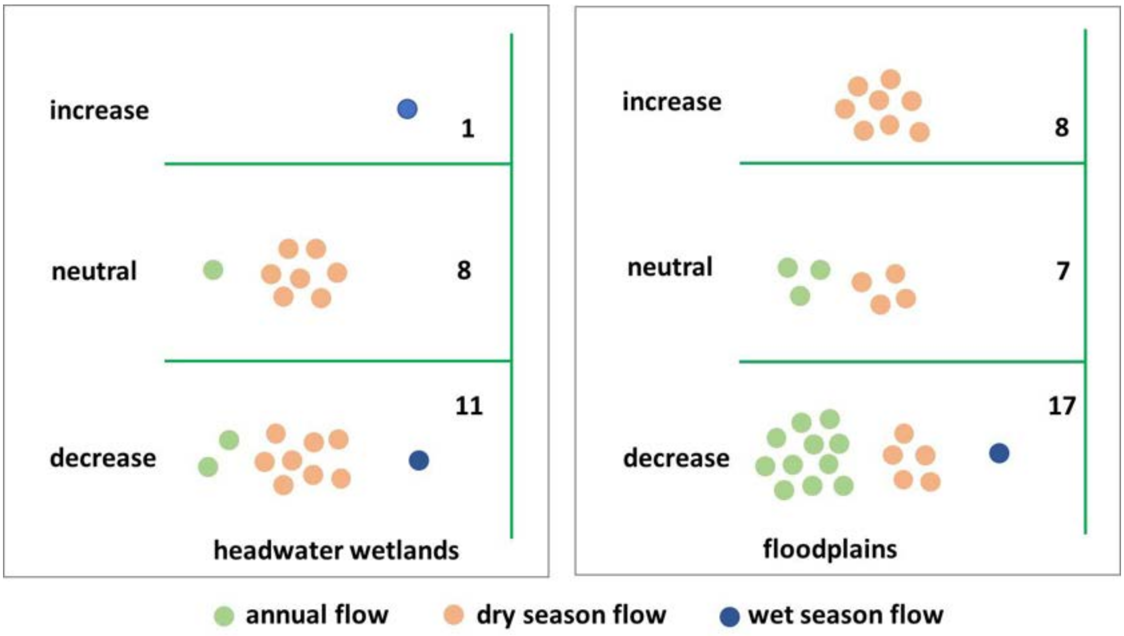

Figure 11. Changes in surface water resource quantity associated with the presence of natural headwater wetlands and floodplains for different flow metrics.

The 53 case studies reported surface water resource quantity metrics. The 52 that could be classified as headwater or floodplain are shown in Figure 11 (one was of multiple wetland types). Most (32) reported dry season flows, some (17) reported annual total flows and a few (3) reported wet season flows. Just over half of the studies (28 of 52) reported that wetlands (of both types) are associated with reduced surface water resources downstream, with less than a fifth (9 of 52) reporting an increase in surface water resources of which most (8 of 9) were floodplains. In detailed studies of dambo headwater wetlands in Zimbabwe, it was found that dry season depletion of dambos in dambos is dominated by high evaporation from open water and emergent vegetation rather than by contributing to downstream river flow (McCartney & Neal, 1999). Similarly, the water balance of large floodplains (Senegal, Sudd, Niger and Okavango) are dominated by high evaporation (Sutcliffe & 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 & Perry, 1973).

The case studies providing numerical values for percentage change in surface water resource quantity and percentage of the catchment area covered by wetlands are shown in Figure 12. The outlier on the graph is the case study of the Inner Niger delta in Mali (Sutcliffe & Parks, 1989), which reports a 5-fold increase in dry season flows downstream of the wetland compared to upstream. This inland delta is very large (30 000 km^2) and holds water for many months such that released water increases flows downstream during the dry season. The data points are more widely spread for small wetlands, but there are few for large wetlands. Since all the case studies compare the presence of a wetland with no wetland, the horizontal axis in Figure 12 can equally be called ‘change in area of wetland (as a proportion of catchment size)’.

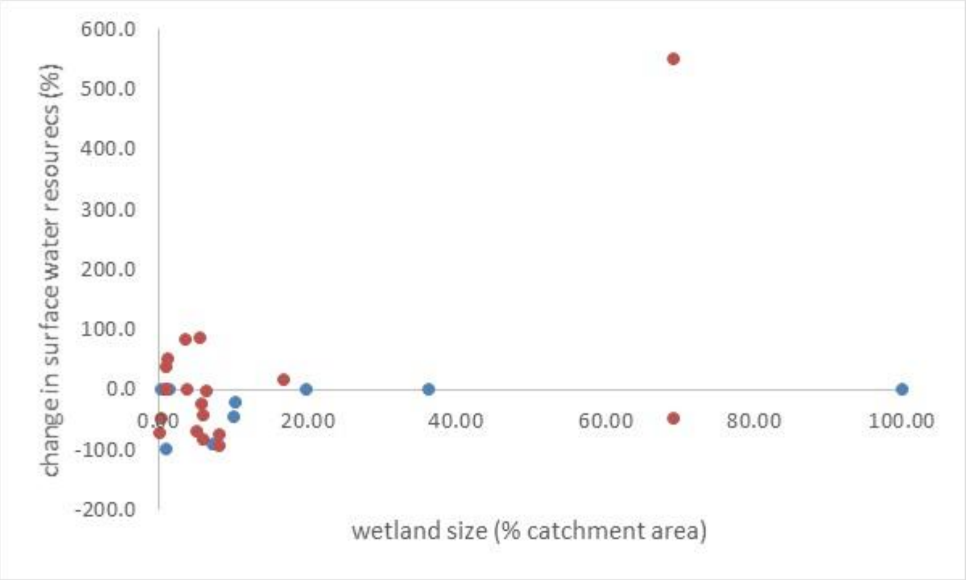

Figure 12. Relationship between (change in) wetland size (% catchment area) and surface water resource quantity (%) for headwater wetlands (blue) and floodplains (red).

The 38 natural wetland case studies reported flood metrics. Two general wetland studies report increases in small floods in the presence of wetlands. The other 36 are shown in Figure 13. Of these, 14 are studies of headwater wetlands and 22 are of floodplains. Almost all (20 of 22) of the floodplain studies reported a decrease in flood magnitude, whilst the other two reported no effect. In contrast most (11 of 14) studies of headwater wetlands showed increased floods associated with their presence. The only case study reporting a decrease in flood magnitude with a headwater wetland present is of a dambo in Malawi (Smith-Carrington, 1983). Detailed studies of dambos were undertaken in Zimbabwe

(McCartney *et al.,* 1998a, 1998b, McCartney, 2000) and combined water balance studies, comparisons of catchments with and without dambos and water tracer experiments. These studies concluded that the dambos had a small capacity to absorb rainfall at the start of the wetland season, when water table levels were low, but soon became saturated and contributed to flood runoff thereafter. This is consistent with basic hydrological knowledge stretching back to the classic studies (Hewlett and Hibbert, 1967 repeated by Nippgen *et al.,* 2015), who recognised that headwater river margins are normally saturated, have no available water storage and act as variable source areas for flood generating and called them 'contributing' areas, which generate large quantities of flood runoff (Burt, 1995). These areas are called wetlands by hydrologists. In contrast floodplains are normally dry and provide large volumes of flood water storage that reduce floods downstream (NERC, 1975).

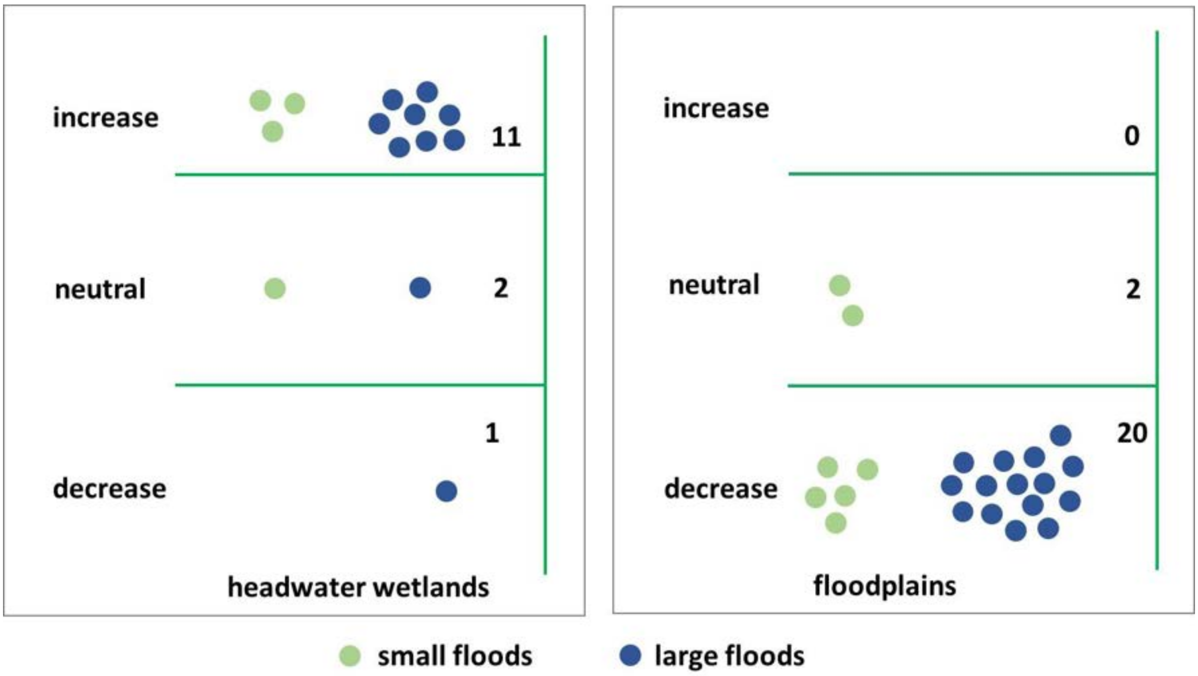

Figure 13. Changes in flood magnitude resulting from the presence of natural headwater wetlands and floodplains.

The phrase 'associated with' is used above when discussing the relationship between headwater wetlands and floods as the presence of wetlands can be seen as an indicator of flood generating processes *i.e.* rainfall, topography and soil properties simultaneously create saturated conditions that we call wetlands and which generate flood runoff.

The 26 case studies providing values for percentage change in flood magnitude and percentage in catchment area covered by wetlands are shown in Figure 14, divided into studies of large rarer floods and small more frequent floods. There is a slight tendency for larger headwater wetlands to increase floods to a greater extent and to increase larger floods. The data also suggest that flood reduction increases with growing floodplain size up until 20% of the catchment is covered; above this coverage flood reduction remains at 80%. This trend has not been tested for statistical significance. The evidence suggests that restoring floodplains could be a nature-based solution for reducing floods but the presence of headwater wetlands would increase flood risk and would not be a solution.

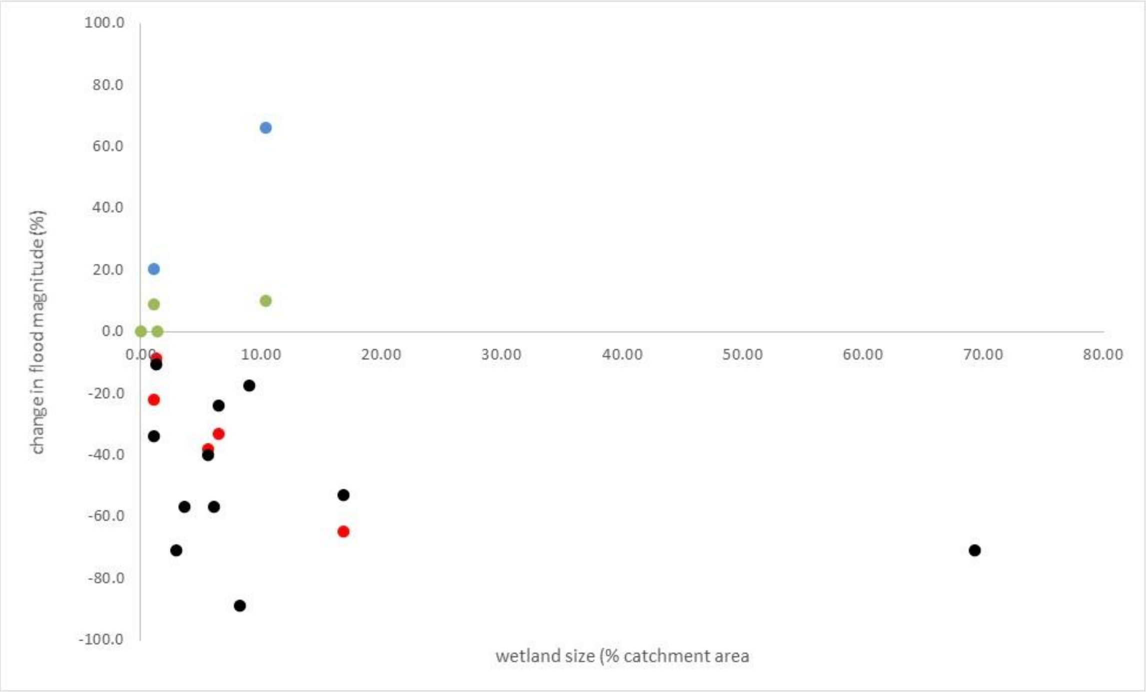

Figure 14. Changes in flood magnitude % as a function of natural wetland size (% catchment area) headwater wetlands: large floods (blue) small floods (green) and floodplains: large floods (red) small floods (black).

Twenty case studies reported interactions between natural wetlands and underlying aquifers. Of these, 13 assessed whether wetlands affected groundwater recharge, with eight simply stating recharge occurs, three reporting recharge did not occur, one reported the wetland increased recharge, whilst one reported the wetland decreased recharge. 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 is site specific and no generalisations can be made from the evidence reported in the case studies found. Furthermore, although, for example, floodplain inundation was found to recharge aquifers underlying the Senegal River floodplain (Hollis, 1996) and Hadejia-Nguru floodplain, Nigeria (Goes, 1999), the results could not be formulated as simple rules.

Only three case studies of natural wetlands reported changes to sediment in downstream water courses. All three 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 metal (cadmium, copper, iron, lead, manganese, uranium and zinc) in downstream water courses; all were decreases ranging from -61% to full removal (-100%). There is strong evidence that all wetlands provide nature-based solutions for reducing sediment, nutrients and heavy metals. One case study reported that phosphorous can build-up in sediment to the extent that the wetland becomes a source rather than a sink it which case management action is required (Kanyiginya *et al.,* 2010).

4.3 Constructed wetlands

The evidence search produced 202 case studies reporting changes to water metrics resulting from the construction of wetlands. These studies report a wide range of water quality metrics including sediment, ammonia, nutrients (nitrogen and phosphorus), biological oxygen demand (BOD), chemical oxygen demand (COD), heavy metals (e.g. cadmium, lead, zinc, copper, iron, manganese, mercury), oil and grease, E. coli, parasite eggs, Salmonellae and faecal coliforms. All case studies report reductions in these metrics (Figures 15, 16, 17). Many case studies were concerned with the relative removal rates of pollutants from different designs of constructed wetlands or types of vegetation employed.

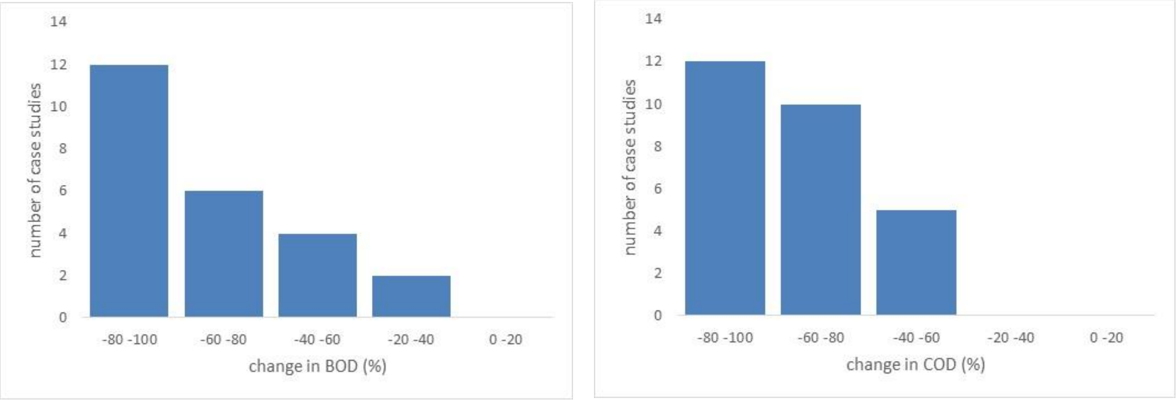

Figure 15. Number of studies of constructed wetlands showing changes in BOD and COD.

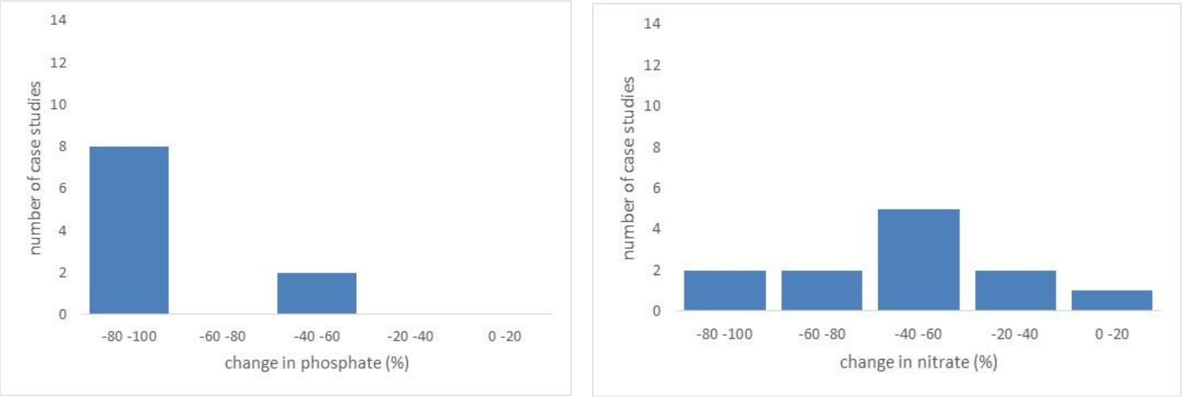

Figure 16. Number of studies of constructed wetlands showing changes in phosphate and nitrate.

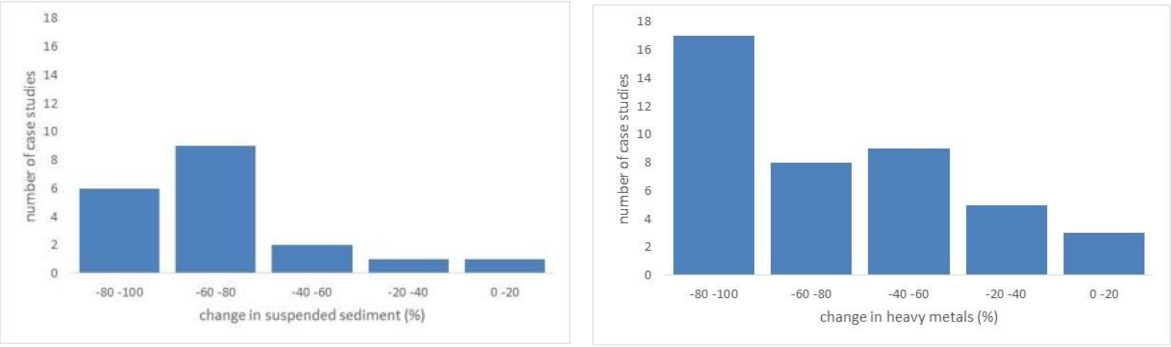

Figure 17. Number of studies of constructed wetlands showing changes in suspended sediments and heavy metals.

Figures 18 and 19 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 division by the input flow rate ($m^3 \ d^{-1}$). There is a tendency towards improved pollutant removal with larger wetlands. The relationships have not been tested for statistical significance.

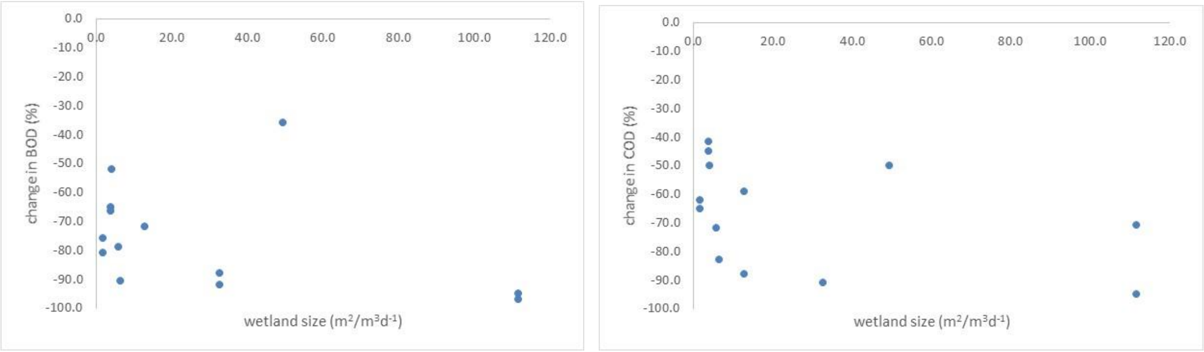

Figure 18. Changes in BOD and COD with wetland size (as a function of input flow rate).

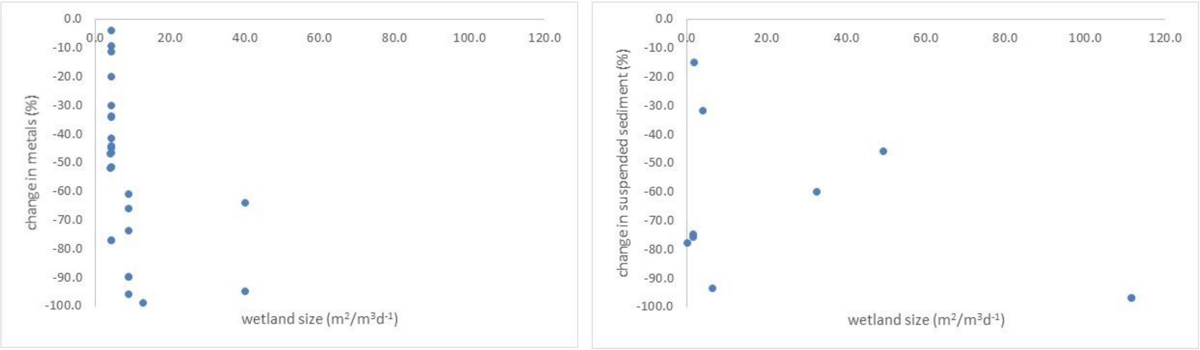

Figure 19. Changes in heavy metals and suspended sediment with wetland size (as a function of input flow rate).

4.4 Other nature-based interventions

The searches returned 1218 publications referring to nature-based solutions (other than wetlands and forests), such as 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 9 publications provided quantitative results of impacts on downstream floods, water resource quantity or water pollution, yielding 13 case studies. These included rainwater harvesting, aquifer recharge and sustainable urban drainage.

Three case studies of greenways linking cities and forests reported reduced runoff coefficients, potentially reducing flood risk and increasing 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 chemical oxygen demand (Fitchett, 2017).

5. Discussion

5.1 Utility of the database

Most studies of nature-based solutions involve case studies in north America or Europe (e.g. Kabisch *et al.*, 2017) and reviews have found only a few studies in Africa (Hanson *et al.,* 2017). However, the current review has revealed 494 case studies undertaken in African countries. This constitutes a strong database of evidence on which to base the spatial analysis of Africa to identify likely hotspots for nature-based solutions to climate-water risks (Task 2) and to identify overlaps between nature-based solution hotspots and biodiversity hotspots, with particular reference to freshwater biodiversity (Task 3). A notable limitation was the lack of studies of tropical rain forests, particularly cloud forests. Much of the evidence is consistent and lends itself to spatial analysis, such as the increased reduction in flood risk and sediment as forest area increases. Some evidence is inconsistent, for example floodplains can in some cases increase downstream surface water resource quantity, but in other cases decrease them. However, further analysis of the source publications might clarify the reason for differences. Additionally, the contextual information concerning these case studies, such as eco-climatic zone (Olsen *et al.*, 2001; Abel *et al.,* 2008), can support identification of donor case studies for specific locations of potential nature-based solutions.
Deforestation and forestation involve different processes and thus may not be entirely reversible. Furthermore, there were few cases of native forest restoration (reforestation) found on which to base the likely effectiveness of reforestation for water risks. However, if the goal of the nature-based solution is to restore natural forests, results of studies of deforestation of native trees can be used in reverse to assess the potential for reforestation.

Nature-based solutions are unlikely to involve the creation of floodplains, so the literature showing the hydrological implications of floodplain presence might seem of limited practical importance. However, many floodplains have effectively been lost by building of embankments that separate floodplains from their rivers. The results of case studies can be used to assess flood risk reduction from reconnecting floodplains with their rivers (*e.g.* Acreman *et al.*, 2003). Such reconnection and resultant floodplain inundation may also augment aquifer recharged as reported for the Senegal River floodplain (Hollis, 1996) and Hadejia-Nguru floodplain, Nigeria (Goes, 1999).

5.2 Comparison of results with other reviews and studies out with Africa

The evidence found from the searches is consistent with previous reviews. Nature-based solutions are featuring in many African countries including within national climate change adaptation policies (Seddon *et al.*, 2019.

The subject of the interaction between forests and water is plagued by myths, misinterpretations and too hasty generalisations (Andréssian, 2004; Chappell, 2005; Tognetti *et al.*, 2005). An early review of basin studies within the tropics found that forests generally reduced river low-flows and thereby have a negative impact on the provisioning ecosystem service of water supply (Bruijnzeel, 1990) due to high evaporation. To observe increases in low-flows following tree planting, the increase in evaporation must be a smaller than the increase in infiltration (the so called 'infiltration trade-off hypothesis') but evidence to support this hypothesis has not yet been produced (Bruijnzeel, 2004).

The systematic review of impacts of forest restoration on water yield (Filoso *et al.* 2017) found that most studies reported a decrease in water yields resulting from an increase in forest area. In a general global assessment (Farley *et al.*, 2005) annual runoff was found to be reduced on average by 44% (±3%) and 31% (±2%) when grasslands and shrublands were afforested, respectively. Many of these studies are of planting of non-native forests, such as eucalyptus and pines. Eucalyptus tree are known to be high water users in other continents especially India. They have deep roots that can continue to take up water as they lower the water table, though water use tends to diminish over time if the water table becomes very low (Calder *et al.*, 1993).

A systematic review by Smith *et al.* (2017) noted particularly that fast-growing commercial plantations of non-native species, such as pine and eucalyptus, reduced water supply in arid regions, while native forests could enhance water supply through improving infiltration or (in cloud forests) capturing atmospheric moisture (though the studies supporting this latter conclusion were not from Africa).

In the absence of direct measurements of the effects of deforestation and afforestation, particularly at large scale, researchers have turned to use of mathematical computer models. Sáenz *et al.* (2014) modelled water balances in Colombia and predicted that if cloud forests are restored to 36% of the catchment, the water inflow to the dam downstream increases by 5.9%. Modelling of catchments in Indonesia, Sri Lanka, Brazil and Tanzania (miombo woodland) found that the impacts of forest removal is 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 20% and 40% within the Xingu River basin, Brazil, increased discharge by 4-8% and 10-12%, but deforestation of the Amazon region more generally could reduce discharge by 6-36% (Strickler *et al*, 2013). None of these model predictions were tested with observed data.

The high water use of trees has been incorporated within water policy in South Africa, where forestry 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 & Roberts, 2006). However, some organisation promote trees as a solution to drought (TreeAid, 2019).

Previous reviews have found that at small spatial scales (< 20 km^2) forests can reduce flood flows, but not for the most extreme floods, and measured data for impacts in larger catchments (> 100 km^2) are lacking (Dadson *et al.* 2017). Stratford *et al.* (2017) also found that studies of large catchments were limited to modelling due to lack of empirical data. However, this review was limited to biogeographical regions similar to the UK, and thus excluded empirical catchment studies in North America where large-scale deforestation has been associated with significant increases in peak flow (Smith *et al.*, 2017). In the current evidence review for Africa, many (6 of 9) of the large (>200 km^2) catchment studies used models. Some authors have examined the hydrological processes involved in flooding and concluded that infiltration-excess overland flow, when floods are caused by water not being able to infiltrate into the soil, produces very little river flow in most vegetated areas (Dubreuil, 1985), so planting trees cannot significantly reduce peak flows generated by this mechanism (Chappell *et al.*, 2006. Only in localised areas of very slowly permeable topsoil (e.g. FAO Gleysol, FAO Vertisol) that coincide with areas dominated by intense rainfall (e.g. areas below the tracks of tropical cyclones or extreme rainfall events in other areas of the globe), might the effect of trees on infiltration capacity affect floods, but evidence is lacking (Zimmerman *et al.*, 2012).

A review of evidence of the role of wetlands in hydrological cycles (Bullock & Acreman, 2003) and follow-up research (Acreman & Holden, 2013) concluded that the relationship between wetlands and floods depends largely on available water storage. Upstream wetlands, such as dambos in Africa, predominantly generate or enhance floods (compared to catchments without these headwater wetlands) because they quickly become saturated at the start of the wet season and then generate rapid runoff. In contrast, downstream floodplains reduce floods as they tend to be dry before floods and have large storage volumes. These reviews also conclude that in most cases, wetlands reduce downstream water resource quantity due to high evaporation, which can be extremely high in hot climates (Hollis, 1992).

The conclusions that some wetlands generate floods and most reduce water resource quantity seems at odds with the widely held perception that wetlands "act like a sponge", soaking-up water during wet periods and releasing it during dry periods (*e.g.* Bucher et al, 1993). This concept has been promoted by many organisations, such as IUCN-The World Conservation Union (Dugan, 1990), Wetlands International (Davis and Claridge, 1993) and the Ramsar Convention on Wetlands of International Importance (Davis, 1993). They have influenced international wetland policy (OECD, 1996) and its uptake at the national (*e.g.* Zimbabwe and Uganda), and continental levels e.g. Europe (CEC, 1995) and Asia (Howe *et al*, 1992). A major cause of inconsistency between science and policy stems from the general use of the term 'wetland' with the implications that all wetlands perform all services equally. This review has reconfirmed the finding that different wetlands act hydrologically in different ways, reinforcing the need to use more specific terminology, such as floodplain or dambo.

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.

5.3 Comparison with Oxford University database

The Oxford University Nature-based Solutions Initiative evidence platform (http://www.nature-basedsolutionsevidence.info) was examined in particular to assess evidence for forest types not found in African case studies, such as tropical rainforests and cloud forests (Table 15). This database contained 10 references to studies of forest restoration and protection outside of Africa labelled as positive for water availability. Oxford database entries were collated using different selection criteria than used for this Task 1 study. Some of the entries were reviews, so to avoid reviewer interpretations and double-counting, these publications were not used directly, but their citations and reference lists were scanned for studies with primary data. Other references considered single hydrological parameters such as interception, evapotranspiration and infiltration; these could not be included in the Task 1 study, as they did not assess directly downstream water resource quantity or quality or floods. It is important to note that entries to the database labelled as negative for water availability were not assessed.

Benegas *et al.* (2024) studied tropical savannahs in Costa Rica, comparing infiltration in coffee growing areas under trees with areas without trees. Trees were found to improve infiltrability. Brauman *et al.* (2010) explored rainfall and cloud interception in two native rainforest sites on leeward Hawaii island. Throughfall in one forest was nearly double that in the other due to increased cloud interception in the denser forest resulting from cattle exclusion and limited grazing.
Brauman *et al.* (2012) measured evapotranspiration from trees and grasses at Kona, Hawaii. They found that while evapotranspiration is very low in all of these forest and pasture ecosystems, modelled values from pasture were higher than from forests. In a review Hamilton (1995) reported net precipitation is significantly enhanced by direct canopy interception of cloud water in rainforests of Hawaii; he quoted Stadtmüller (1987), who quoted results of studies indicating cloud water capture values as a percent of normal precipitation ranging from 7 percent (Baynton, 1969) to 158 percent (Juvik & Ekern, 1978). Gomez-Peralta *et al* (2008) evaluated the importance of cloud/fog water to montane forests in two forests in the eastern Andes of central Peru. Annual net precipitation was 92.4% and

70.4% of rainfall at the upper and lower sites respectively due to differences in interception and interception losses. Ilstedt *et al.* (2007) reviewed four papers containing 14 studies of the effects of afforestation on infiltrability in the tropics. They found that infiltration capacity increased on average approximately three-fold after planting trees in agricultural fields. Kagawa *et al.* (2009) measured sap flow in native *Metrosideros polymorpha* forest and adjacent alien timber plantations on the island of Hawaii and estimated total stand transpiration. *Metrosideros polymorpha* had the lower sap flux and water use than timber species *Eucalyptus saligna* or *Fraxinus uhdei*. Sáenz, & Mulligan (2013) reported that whilst cloud affected forests (CAFs) cover only 4.4% of the extent of dam watersheds in tropical regions, they receive and filter 21% of the surface water balance. High cloud water interception and reduced actual evapo-transpiration mean cloud affected forests are likely to be wetter than their lowland counterparts. They modelled water balances of catchments containing cloud forests across the tropics that contain important dams, but they state that they "did not explore the impact of CAFs loss in the delivery of this water". None of these studies referred to in this paragraph included measurements of downstream water resource quantity, so there is no direct evidence and impacts would need to be inferred.

In a review, Bruijnzeel (2001) reported that due to added moisture inputs from cloud water interception and relatively low water use, water yields for a given amount of rainfall from cloud forested headwater areas tend to be higher than streamflow volumes emanating from montane forests not affected by fog and low cloud. In other reviews the same author states that "conversion of tropical forests of any kind to annual cropping or grazing is almost inevitably followed by increases in amounts of surface runoff during the wet season" (Bruijnzeel, 1990), "with diminished streamflow during the dry season" (Bruijnzeel, 1989; 2000). These review conclusions seem to be based on one study in Java (RIN, 1985) which reports a decline in river flows by 20% in the Kali Konto river in east Java from 1915-1942 (when the catchment was largely forests) to 1951-1972 (by which time a 'fair proportion' of the forest had been converted to shrubland, dryland agriculture and urban areas). The likely different impacts of forest removal and urbanisation are not separated. In another review, Bruijnzeel (2000) concluded that total annual water yield appears to increase with the percentage of forest biomass removed, but actual amounts differ between sites and years due to differences in rainfall and degree of surface disturbance. If surface disturbance remains limited, most of the water yield increase occurs as baseflow (low flows), but rainfall infiltration is often reduced to the extent that insufficient rainy season replenishment of groundwater reserves results in strong declines in dry season flows. However, in later research, Bruijnzeel *et al.* (2010) found that conversion of cloud forest to pasture in northern Costa Rica did *not* produce the expected decreases in annual or even seasonal water yield; rather the effect on streamflow was more or less neutral. Furthermore, Bruijnzeel *et al.* (2011) reported that conversion of lower montane rain forest or tall lower montane cloud forest to pasture in Mexico likely results in substantial increases in water yield because of low cloud water interception by the local lower montane cloud forest and a much higher water consumption by the cloud forest than by pasture. They concluded that changes in water yield after upper montane cloud forest conversion are probably modest due to trade-offs between concurrent changes in evapotranspiration and 'cloud-water' interception.

Bruijnzeel *et al.* (2010) undertook comparisons of rain forest type and reported that catchment water yields typically increase from lower montane rain forest to tall lower montane cloud forest sub-alpine cloud forest reflecting concurrent increases in incident precipitation and decreases in evaporative losses. Singh & Mishra (2012) compared three types of tropical forest in the western Ghats of India (1) primary forest (with no or inconsequential human disturbance), (2) mature secondary forests (regenerating largely through natural processes after significant human and/or natural disturbance) and (3) disturbed forests (that have been exploited on moderate to large scale for timber, fuel wood, fodder, shifting cultivation. They found that the old forests were observed to positively and highly significantly influence runoff coefficient (a measure of water yield). This study provides evidence about forest management, but not about the impact on water resource quantity of deforestation or afforestation.

From the publications in the Oxford database, three are transferable to Africa using the criteria in this evidence review. (1) removing tropical forests in Java reduced dry-season water availability downstream, though this could be the result of urban developments that replaced the forest (2) cloud forest conversion in Mexico would lead to a major local increase in water availability; and (3) conversion of cloud forest to pasture in Costa Rica had no effect on water yield. These results do not provide sufficiently consistent evidence to produce relationships between changes in forest cover and water resource quantity in Africa.

5.4 Management associated with interventions

The case studies found for Africa were almost entirely concerned with the presence or absence of features or interventions that can be termed nature-based solutions, e.g. forests v. grassland, wetland v. no wetland. However, associated management, such as pre-afforestation ploughing, thinning of trees or removal of undergrowth and draining or grazing vegetation of natural wetlands, was rarely mentioned, so their hydrological implications could not be assessed.

Nature-based solutions are actions taken to protect, restore, create or sustainably manage ecosystems. In practice it is not easy to create headwater wetlands or floodplains (although constructed urban water balancing ponds might be considered as floodplains). The flood reduction function of a floodplain can be eliminated by separating it from its river by embankments. A nature-based solution might be to remove the embankment and restore the service of flood reduction. For example, embanking the River Cherwell, UK, to isolate the floodplain from the river increased flood peaks by 50-150% (Acreman *et al.*, 2003). The physical hydraulics of rivers and floodplains are fairly universal, so such findings could be relevant to Africa. For headwater wetlands, a management action might be to drain water to prevent saturation or flooding (e.g. to improve agriculture), but this would not be classed as a nature-based solution as it would work against, not with, the natural ecosystem of the wetland and would have negative impacts on biodiversity. A nature-based action might be to block the drains to re-establish wet conditions. No publications were found that discussed this issue in Africa. Studies in Europe and North America have found that blocking drains can sometimes increase floods and sometimes decrease floods depending on many factors including drainage network configuration, vegetation and soil type (Acreman & Holden, 2013), but the relevance of these findings to African wetlands is uncertain because these factors are likely to differ.

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 *Phragmities 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 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 periodically removing sediment mechanically from the wetland.

There is also evidence around the world that restoration of river channel morphology and floodplain woodlands with associated large wood logjams may reduce flood risk (Sear *et al.* 2010). Flood peak attenuation by floodplains is sensitive to surface roughness, such as the presence of trees or shrubs (Hall *et al.*, 2005. Nature-based solutions may be enhanced by engineering nature. For example, flood attenuation at Holnicote, UK, was achieved predominantly by building artificial deflectors on the floodplains rather than the presence of the floodplain itself (National Trust, 2015). Constructed wetlands are also good examples of engineering nature to enhance ecosystem functions. No evidence was found for similar activities in Africa.

Many nature-based solutions are forms of naturalising engineering (rather than engineering nature) including green roofs, sustainable urban drainage and environmental flow releases from dams. Only a few examples were found for Africa that assessed impacts on downstream water metrics.

5.5 Location of intervention with the catchment

In some case studies of small catchments or plots, forest covered all or most of the catchment area. For larger catchments, the area covered by forests was usually reported in the case studies and occasionally the publication included a map showing many forest patches spread across the catchment. Hence it was not possible to identify the location of the forest (e.g. headwaters) or to calculate an index of fragmentation. Furthermore, hydrological metrics were reported at a single measuring point, none reported changes at different distances downstream. In the case of natural wetlands, the hydrological assessment point was normally immediately downstream, so effectively the wetland was located at the downstream extreme. For constructed wetlands, the hydrological measures were inputs to and outputs from the systems, so effectively upstream and downstream of the wetland.

The potential for different hydrological impacts resulting from interventions in different parts of a catchment has been discussed theoretically (e.g. Ramsbottom, 1993) and used for the design of urban flood management schemes (Strandskov, 2014). For example, a floodplain wetland on a tributary may reduce flood flows immediately downstream, but this may also delay the peak such that it coincides with the flood peak coming down the main river, which can increase the peak flow downstream of the confluence. A rare study in Scotland (Acreman, 1985) found that afforestation of the lower catchment resulted in reduced flood peaks, whilst similar practices upstream increased peak flows. The searches did not reveal evidence on the issues of synchronisation and de-synchronisation in Africa.

5.6 Temporal aspects

Most studies reported downstream hydrological changes for specific single periods. However, a few studies reported several periods that showed how flow reductions resulting from afforestation varied with the age of the trees. For example, during clear-felling and replanting pine trees in Jonkershoek, South Africa, flows increased after deforestation and returned to preclearing levels within 12 years; reductions increased to a peak after 20 years and thereafter reductions declined in magnitude (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 5 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).

5.7 Inter-catchment and regional scale impacts of nature-based solutions

The classical view of the hydrological cycle, a single loop, implies that rainfall is largely driven by evaporation from sea and that most precipitation finds its way back to the sea through the land. Embedded within this concept is a notion that evaporation from land is a loss and not a significant input to the cycle (many studies use the term 'evaporation loss'. However, it is now widely accepted that different hydrological cycles operate at different scales and that there are linkages between catchments at regional, continental and global scales and within catchments at local scale. This perspective is also important as it replaces the idea of evaporation as a loss with the understanding that it may become a gain elsewhere.

Hydro-meteorological models have been employed to study water circulation at regional and global scale. Deforestation of tropical regions has been found to significantly affect precipitation at mid- and high latitudes (Avissar & Worth, 2005). Ellison *et al.* 2012 argue that whilst trees can reduce runoff at the small catchment scale – at larger scales, trees are more clearly linked to increased precipitation and water availability. In computer simulated deforestation, Strickler *et al.* (2013) found that whilst deforestation within the Xingu River basin increased discharge locally, deforestation of the Amazon region reduced rainfall decreasing discharge within the basin. It has similarly been suggested that evaporation from the Sudd wetlands 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) and that there would be negligible impact if Sudd evaporation declined or ceased due to building the Jonglei canal (Mohammed *et al.,* 2005).

Whilst it is recognised that, for example, reduced river flows downstream of a new forest may mean greater flows in a neighbouring catchment, generated by evaporation from the forest, this review focuses only on the direct downstream hydrological implications of water-related nature-based solutions.

5.8 Benefits, synergies and trades-off

The results of the evidence review are presented in terms of changes in water metrics (floods, water quality, water quantity). These changes need to be analysed to determine the impacts on people and wildlife. Reductions in pollutants in rivers are normally positive for everyone. Reductions in flooding are positive for people and infrastructure (e.g. roads, hospitals, factories and housing) at risk of flooding, but the same reductions may be negative for flood-dependent ecosystems, such as floodplain wetlands. The human impact of changes in river flow volume depends on how water resources are managed. Increases in wet season flows are beneficial for reservoirs that support irrigation, public supply or hydropower generation, whereas increases in dry season flows are beneficial where abstractions are made directly from flowing rivers.

The aim of this review was to assess the evidence for changes to water-climate risks resulting from nature-based solutions, such as reducing floods or improving water quality in a cost-effective, sustainable manner. However, the wider literature promotes nature-based solutions as typically delivering multiple benefits for both nature and people, such as carbon sequestration, local micro-climate amelioration and biodiversity enhancement as well as water management (Ellison et al., 2017; Abell *et al.* 2017; WWAP, 2018; Chausson *et al.,* in press). Even constructed wetlands, which focus on pollutant removal and may involve monocultures of reeds, potentially offer multiple benefits compared to the 'grey infrastructure' equivalent of a purely engineered water treatment plant, including aesthetic value, carbon sequestration and potentially some biodiversity benefit. In a similar way, restoring river channel geometry and reinstating woody debris is primarily a hydraulic device for reducing floods, but it normally increases habitat diversity. However, protection and restoration of native ecosystems (including grassland and savannahs) is more likely to deliver benefits for biodiversity as well as multiple benefits for people, compared to actions such as constructed wetlands or afforestation with non-native species.

Whilst well-designed nature-based solutions offer multiple benefits, there may also be significant trade-offs (Raymond *et al.* 2017). Hydrological restoration of peat wetlands may reduce carbon dioxide emissions but can also increase methane emissions (Acreman *et al.*, 2011). Trade-offs can also arise if climate mitigation policy encourages nature-based solutions with low biodiversity value, such as afforestation with non-native monocultures (Seddon *et al.,* 2020). Few such trade-offs are empirically documented (Frantzeskaki *et al.* 2019), but major reviews *e.g.* by Smith *et al.* (2017) and Chausson *et al.* (in press) found that the main trade-off is the potential for afforestation (particularly with non-native species) to reduce downstream water resource quantity, even though it may provide other benefits such as reducing soil erosion and river sedimentation. In these situations, removing non-native plantations and restoring native grassland or savannah could be a nature-based solution if the main objective is to increase downstream water resource quantity, and this would also bring biodiversity benefits. However, deforestation of native woodlands would not be consistent with most definitions of nature-based solutions 'to protect, sustainably manage, and restore natural or modified ecosystems'. This review has also highlighted further potential trade-offs between wetland restoration and flood risk or water supply, although again drainage of a natural wetland in order to attempt to mitigate these issues would meet not the other objectives in definitions of nature-based solutions described above.

Furthermore, different groups of people may benefit or suffer from nature-based interventions depending on their livelihoods and location within a catchment. Many mechanisms have been proposed to deal with trade-offs, such as economic valuation of, or payments for, ecosystem services, in which those who may lose from an intervention are compensated by those who gain, but further analysis of this is beyond the scope of this report. A coherent framework for river management research, policy and planning should focuses on (a) the ways in which political economy, institutions and infrastructure mediate access and entitlements to benefits derived from ecosystem services, and (b) the feedbacks and trade-offs between investments in physical and social structures and processes (Tickner *et al.*, 2017).

5.9 Gaps

This review found 10 633 publications related to nature-based solutions in Africa, of which 150 held new empirical data, so few are contributing to new knowledge. 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.*, 2016). Most studies of changes in forest cover 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 drainage of wetlands. More work is also needed on effects of the siting of nature-based interventions within catchments and whether their location in upstream areas has a different impact than putting them downstream or on a tributary.

Many nature-based solutions are forms of naturalising engineering (rather than engineering nature) including green roofs, sustainable urban drainage and environmental flow releases from dams. Only a few examples were found for Africa that assessed impacts on downstream water metrics.

Key research topics are:

- Hydrological effects of native forest reforestation
- Effects of management such as grazing, drainage, tree thinning, undergrowth removal
- Effects of the location of nature-based solutions with a catchment
- Monitoring downstream at various locations to assess propagation of effects
- Long term monitoring to assess changes over time following interventions
- 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

6. Conclusions

This evidence review found 10 633 publications related to nature-based solutions in Africa. Of these 150 reported new 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 to floods, and sediment generation, whilst constructed wetlands reduce water pollution. Generally, headwater wetlands and non-native forests tend to reduce water resource quantity downstream, so are not useful solutions to water problems, whilst the evidence is inconsistent for native forests. Although there is a need for more studies, this database of the results from these publications provides a basis for Task 2: spatial analysis of Africa to identify likely hotspots for nature-based solutions to climate-water risks and Task 3: spatial analysis to identify overlaps between nature-based solution hotspots and biodiversity hotspots, with particular reference to freshwater biodiversity. Information provided by the case studies allows relationships between interventions and impacts to be estimated. The potential exists to resolve some inconsistent results by examining contextual information.

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