International Water Management Institute

176

Research Report

Underground Transfer of Floods for Irrigation (UTFI): Exploring Potential at the Global Scale

Mohammad Faiz Alam and Paul Pavelic

Research Reports

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

The International Water Management Institute (IWMI) is an international, research-for-development organization that works with governments, civil society and the private sector to solve water problems in developing countries and scale up solutions. Through partnership, IWMI combines research on the sustainable use of water and land resources, knowledge services and products with capacity strengthening, dialogue and policy analysis to support implementation of water management solutions for agriculture, ecosystems, climate change and inclusive economic growth. Headquartered in Colombo, Sri Lanka, IWMI is a CGIAR Research Center and leads the CGIAR Research Program on Water, Land and Ecosystems (WLE). www.iwmi.org

IWMI Research Report 176

Underground Transfer of Floods for Irrigation (UTFI): Exploring Potential at the Global Scale

Mohammad Faiz Alam and Paul Pavelic

International Water Management Institute (IWMI)
P. O. Box 2075, Colombo, Sri Lanka

The authors: Mohammad Faiz Alam is Researcher - Water Resources/Agricultural Water Management at the International Water Management Institute (IWMI), New Delhi, India (m.alam@cgiar.org); and Paul Pavelic is Senior Researcher - Hydrogeology at IWMI, Vientiane, Lao PDR (p.pavelic@cgiar.org).

Alam, M. F.; Pavelic, P. 2020. *Underground Transfer of Floods for Irrigation (UTFI): exploring potential at the global scale*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 58p. (IWMI Research Report 176).
doi: https://doi.org/10.5337/2020.204

/ flood irrigation / river basins / groundwater recharge / aquifers / water storage / water supply / water demand / drought / economic analysis / cost benefit analysis / benefit-cost ratio / flood control / disaster risk reduction / mitigation / ecosystem services / watershed management / water resources / water management / surface water / water availability / climate change / water security / food security / policies / stakeholders / groundwater irrigation / infrastructure / wells / pumps / crop production / land use / rain / monsoon climate / socioeconomic environment / urban areas / rural areas / models / South Asia / South East Asia / Central Asia / South America / North America / Central America / Europe / Africa South of Sahara / North Africa / India / Ethiopia / Thailand /

ISSN 1026-0862
ISBN 978-92-9090-899-9

Please send inquiries and comments to IWMI-Publications@cgiar.org

A free copy of this publication can be downloaded at www.iwmi.org/publications/iwmi-research-reports/

Acknowledgements

The authors are grateful to Dr. Alok Sikka (Country Representative - India, International Water Management Institute [IWMI]) and Dr. Prasun Gangopadhyay (Scientist [Climate Change], Borlaug Institute for South Asia [BISA], India [formerly IWMI]) for the assistance provided in conducting the spatial analyses, and to Dr. Amare Haileslassie (Principal Researcher, IWMI, Ethiopia) for providing information on the Awash River Basin. The valuable comments and feedback provided by Dr. Karen G. Villholth (Principal Researcher and Coordinator - Groundwater, IWMI, South Africa), Dr. Andrew Ross (Research Fellow, Australian National University), Dr. Mark Smith (Director General, IWMI, Sri Lanka), and Dr. Ted Horbulyk (Associate Professor Emeritus of Economics, University of Calgary, Canada [formerly IWMI]) helped to improve the content of this report.

Donors

This research was carried out as part of the CGIAR Research Program on Water, Land and Ecosystems (WLE) and supported by Funders contributing to the CGIAR Trust Fund (https://www.cgiar.org/funders/).

This work was implemented as part of the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which is carried out with support from the CGIAR Trust Fund and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors. The views expressed in this document cannot be taken to reflect the official opinions of these organizations.

Contents

Acronyms and Abbreviations vi

Summary vii

Introduction 1
- Problem Statement 1
- Underground Transfer of Floods for Irrigation (UTFI): Overview 2
- Objectives of the Study 7

Spatial Analysis 8
- Overview of Spatial Suitability Assessment Methods 8
- Data for the Spatial Analysis 8
- Methods Applied for the Spatial Analysis 9
- Limitations in the Spatial Analysis 10
- UTFI Suitability Results 13

Economic Analysis 18
- Characteristics of the Selected River Basins 18
- Model Framework 20
- Economic Feasibility Results 23

Discussion 26
- Distribution of UTFI Potential 26
- The Economics of UTFI 27
- Selected Regional Priorities and Entry Points for UTFI 28
- Approach to UTFI Implementation and Management 29

Conclusions 30

References 31

Appendix 1. List of Countries and their Associated Subregions as Defined by the United Nations 38

Appendix 2. UTFI Suitability Maps for Each of the Three Thematic Groups 41

Appendix 3. The 100 Most Populous River Basins with Mean UTFI Score and Suitability 43

Appendix 4. Data Used in the Economic Analysis 45

Acronyms and Abbreviations

BCR	Benefit-cost Ratio
CIESIN	Center for International Earth Science Information Network
DFO	Dartmouth Flood Observatory
DRV	Design Recharge Volume
EM-DAT	Emergency Events Database
ETB	Ethiopian Birr
GDP	Gross Domestic Product
HydroSHEDS	Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales
INR	Indian Rupee
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
IWMI	International Water Management Institute
MAR	Managed Aquifer Recharge
MENA	Middle East and North Africa
NERC	Natural Environmental Research Council
NPV	Net Present Value
O&M	Operation and Maintenance
SEDAC	Socioeconomic Data and Applications Center
S	Surface (recharge methods)
SS	Subsurface (recharge methods)
SSA	Sub-Saharan Africa
SWAT	Soil and Water Assessment Tool
THB	Thai Baht
UTFI	Underground Transfer of Floods for Irrigation
UN	United Nations
USA	United States of America
USD	United States Dollar
WASP	Weighted Anomaly of Standardized Precipitation
WHYMAP	World-wide Hydrogeological Mapping and Assessment Programme
WRI	World Resources Institute

Summary

Underground Transfer of Floods for Irrigation (UTFI) is an approach to co-manage floods and droughts at the river basin scale. It involves targeted recharge of aquifers using seasonal excess surface water flows that potentially pose a flood risk, with the aim of mitigating downstream flooding and increasing groundwater storage. Increased groundwater storage provides the opportunity to increase agricultural production during the dry season and enhance resilience to droughts. Identifying suitable areas for UTFI is a vital first step towards successful implementation outcomes. In this study, an analysis was carried out at the global scale – with a spatial resolution of 30 arc-minutes, translating to approximately 55 km^2 pixels at the equator – to map and classify areas suitable for implementation of the UTFI approach. Lessons learned from initial UTFI conceptualization in Thailand and pilot implementation of the approach in the Ganges River Basin were also taken into consideration. Datasets on flood and drought hazard frequency, mortality, economic losses, groundwater depth, aquifer type and groundwater salinity were arranged into three broad thematic groups that cover water supply, water demand and water storage. Each data layer in the three thematic groups was assigned a weight based on its relative importance in the theme, and the features within each data layer were given a reclassified value based on their likely correlation with UTFI potential. The results of the analysis highlight that, at the global scale, areas with high to very high UTFI suitability account for a population of approximately 3.8 billion people and a crop area of 622 million hectares. South Asia, East Asia, Southeast Asia and sub-Saharan Africa (SSA) are regions with the highest UTFI potential. Aggregation of UTFI suitability levels at the river basin scale reveals high suitability across some of the major river basins in Asia (Ganges, Chao Phraya, Mekong), SSA (Volta, Awash, Tana, Save, Shebelle), Latin America (Rio Balsas, Magdalena, Rio Parnaiba) and North America (Sacramento, Brazos). An economic analysis was undertaken in three selected river basins in different regions: Awash Basin in Ethiopia, Ramganga Basin (part of the Ganges River Basin) in India and Chao Phraya Basin in Thailand. These basins show high economic viability for UTFI implementation with internal rate of return values ranging from 20% to 122% for the base case scenario. Analysis of different scenarios of economic viability reveals the importance of recharge rates and crop prices in particular. The major benefits associated with UTFI implementation vary across the three basins and contrasting regional contexts. Enhanced crop production is the predominant benefit arising from UTFI implementation in the Awash and Ramganga basins, while it is flood damage mitigation in the Chao Phraya Basin. Results show that areas with high UTFI suitability emerge in diverse contexts, including the more disaster-prone areas of Asia and Africa. The maps and data from this study provide an early identification of the likely potential for UTFI implementation. They also provide the basis for more detailed investigations at country and basin scales to ascertain UTFI potential with higher confidence. The broad prerequisites and steps needed to implement UTFI in practice and potential areas for further research are also highlighted in this report.

Underground Transfer of Floods for Irrigation (UTFI): Exploring Potential at the Global Scale

Mohammad Faiz Alam and Paul Pavelic

Introduction

Problem Statement

Variable and unpredictable availability of freshwater resources represents a considerable challenge to water security globally with profound ramifications for the domestic, industrial and food production sectors in particular (Hall et al. 2014; Hoekstra et al. 2012; Smakhtin et al. 2015). Water variability manifests in recurrent flood and drought events, causing negative environmental impacts and associated losses in human life, agricultural output, livestock and livelihoods, with ripple effects throughout the economy (Hall et al. 2014; Smakhtin et al. 2015). Water variability is anticipated to increase with climate change. According to the Intergovernmental Panel on Climate Change (IPCC), water-related hazards will increase in both frequency and severity, raising the risk of disasters and outstripping the capacity of societies to adapt (IPCC 2012; Smakhtin et al. 2015). Further, increased competition for water among sectors to sustain the demand for water and food of increasing populations, supply industries, and fulfil urban and rural populations will likely compound the impacts from these hazards (Hoekstra et al. 2012).

Flooding accounted for 47% of all weather-related disasters between 1995 and 2015, as documented by the Emergency Events Database (EM-DAT). These events affected 2.3 billion people, the majority of whom (95%) live in Asia (CRED and UNISDR 2015). Over the same time period, droughts only accounted for approximately 5% of all weather-related disasters, but affected 1.1 billion people (or more than a quarter of all people affected by weather-related disasters worldwide) (CRED and UNISDR 2015). Two stark examples that demonstrate the vulnerability of society to extreme weather events are: (i) the flooding in Thailand in 2011, which caused economic losses amounting to USD 46.5 billion (Poapongsakorn and Meethom 2012); and (ii) the drought in Kenya during the period 2008-2011, which caused damage and losses amounting to USD 9 billion (FAO 2015a). The agriculture sector, which is strongly dependent on climate, is thus highly vulnerable to weather-related disasters (Turrall et al. 2011). This has strong implications for developing countries aiming to achieve food security and reduce poverty (Mendelsohn 2008). Floods and droughts accounted for 83% of total crop and livestock production losses. This was clear from an analysis of 67 countries which incurred similar losses amounting to USD 80 billion due to 140 medium- to large-scale natural disasters (including non-water-related events) assessed between 2003 and 2013 (FAO 2015a).

Most river basins face contrasting situations of water shortage and abundance separated by time and/or space. Hoekstra et al. (2012) analyzed 405 river basins for the period 1996-2005 and found that 201 of these basins, supporting 2.67 billion inhabitants, faced severe water scarcity during at least one month of the year. Thus, there is a clear need to develop better policies and plans to enhance resilience by addressing water variability to reduce societal vulnerability to floods and droughts.

Various types and scales of water storage infrastructure play an important role in adapting to the spatial and temporal imbalance and uncertainty in water resources. Therefore, investments in such infrastructure could enhance water security, strengthen global food security and spur economic growth (Hall et al. 2014; Smakhtin et al. 2015). Surface and subsurface water storage options include dams (large and small), natural wetlands, local farm reservoirs, soil moisture, rainwater harvesting ponds and recharge of groundwater aquifers (McCartney and Smakhtin 2010).

Groundwater, with its high buffer capacity due to relatively large storage, is generally more reliable and less susceptible to evaporation than surface water resources (van der Gun 2012), thus providing a potentially attractive option for managed water storage. Developing groundwater storage also has the advantage of causing little or no harm to the environment when compared to large dams (Bouwer 2000). Similar to dams, this storage option could be used to capture excess flows in the wet season and make it available during dry periods, thus mitigating the impacts of floods and droughts (Pavelic et al. 2015). The use of groundwater for irrigation has increased in recent decades due to reliability and accessibility of the resource to small farmers, and the lower capital requirement in comparison to surface water systems (GWP 2012). This has consequently created latent opportunities to harness the occasionally depleted groundwater storage and use it to store excess surface flows. Thus, groundwater storage, with its intrinsic benefits, provides an opportunity to resolve temporal and spatial imbalances in water availability, if effective forms of intervention and management measures are put in place (Villholth et al. 2018). The opportunities and associated potential benefits of utilizing groundwater storage could be tapped by operationalizing integrated management of surface water and groundwater. This has been found to be more effective for adapting to water variability than focusing on surface water or groundwater in isolation (Evans et al. 2012; Ross 2012).

Underground Transfer of Floods for Irrigation (UTFI): Overview

One novel way of applying integrated water management in practice involves targeted recharging of excess wet season flows in aquifers through an approach known as '*Underground Transfer of Floods for Irrigation*' (UTFI). UTFI is a form of managed aquifer recharge (MAR) that involves interventions at the basin scale through the installation of groundwater recharge infrastructure at strategic sites distributed across a basin. The approach involves recharging aquifers that have depleted groundwater storage capacity with excess wet season flows, which pose potential flood risks downstream, to protect lives and assets, and to boost agricultural productivity within the targeted basin by increasing water availability during dry periods (Figure 1) (Pavelic et al. 2015). The stored recharge water can be recovered later for use in irrigated agriculture and for other purposes. Thus, by enhancing the provision of ecosystem services, such as flood control, groundwater recharge and water availability in the dry season, UTFI can transfer the impacts felt in one part of a basin to opportunities elsewhere in the same basin. The approach adds new value to often isolated MAR efforts and puts it into a larger-scale perspective that offers a wider range of benefits to both upstream and downstream areas. It also provides a direct way of linking MAR to flood and drought mitigation (Pavelic et al. 2012, 2015).

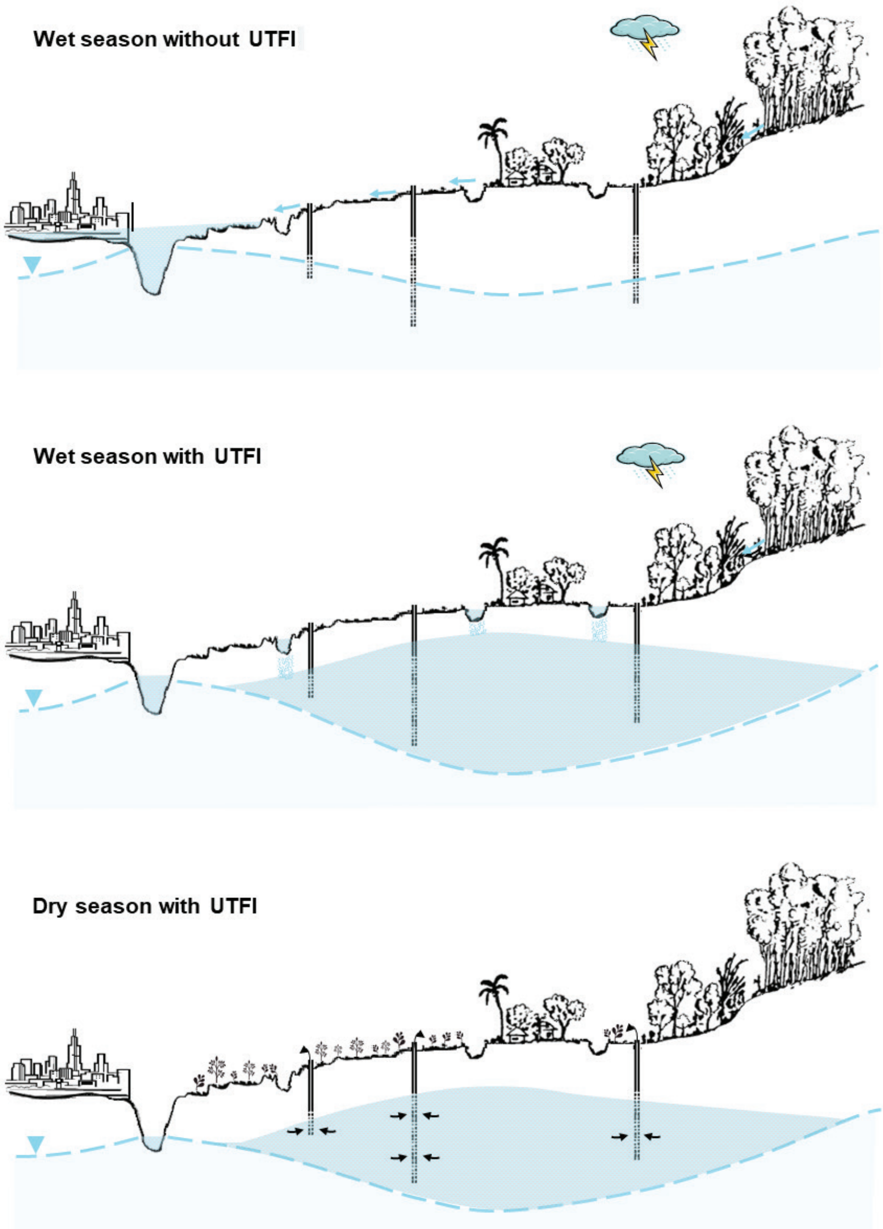


Figure 1. Schematic representations of a flood-prone landscape with and without UTFI. The figure illustrates that strategic capture and storage of water underground can offset downstream flooding that would otherwise occur while also boosting groundwater reserves and agricultural production.

Key Conditions for UTFI Implementation

The three primary conditions that underpin the suitability of UTFI in any given area include the following:

- *Supply* – relates to flooding and flood impacts.
- *Demand* – water use linked to drought events/ impacts and groundwater availability.
- *Storage* – UTFI interventions appropriate to the landscape and subsurface conditions to create additional water storage.

From a *supply* perspective, UTFI focuses on and addresses seasonal floods of longer duration that build up over weeks and months and take place on a recurring basis during the predominant wet season. The approach does not address short-duration and extreme flood events that occur as a result of cyclones, dam breakage and flash floods, due to limitations in recharge rates. Under flood conditions, natural rates of groundwater recharge may be high in inundated areas. Thus, the augmentation of groundwater recharge through UTFI should be distinctly different and provide additional benefits compared to recharge that naturally occurs during a flood event.

There must also be a *demand* for the existing or induced stored water to enable its productive use and ensure that adequate storage capacity is created for subsequent recharge seasons. This groundwater recovery component of the UTFI approach fills a demand gap for irrigation and other forms of water use to alleviate the impacts of drought or high groundwater demand or limited water availability during dry seasons.

Finally, in terms of aquifer *storage*, UTFI is an approach that relies on identifying suitable hydrogeological conditions and implementing designs that are appropriate to the setting. Aquifers targeted for storage would typically be unconfined or semi-confined formations to depths of up to approximately 50 meters (m). Avoiding saline groundwater eliminates constraints associated with the mixing of brackish or saline aquifers. In specific cases, depleted deeper aquifers may be preferentially targeted. The use of surface recharge structures such as infiltration basins are preferable if land is available as they are simplest to construct and maintain. In settings with low permeability soil layers or poor shallow aquifers, subsurface recharge methods involving the use of wells are preferable to surface methods. The main conditions that are conducive to UTFI implementation are summarized in Table 1.

Table 1. Enabling conditions for UTFI implementation.

Supply	Flood frequency	Regular seasonal floods of longer duration and its impact
	Operational management of recharge infrastructure	Intended to capture excess flows, not necessarily in equal proportion in all years
Demand	Droughts, dry periods	Regular drought occurrence and impacts or intra-year water variability due to short wet season
	Irrigation	Groundwater irrigation is practiced or there is potential for its development
Storage	Target aquifer	Transmissive aquifers under unconfined or semi-confined conditions, typically at depths less than 50 m; available storage capacity; good groundwater quality
	Recharge infrastructure	Simple, low-cost technologies with adequate pretreatment of source water, ideally manageable by local communities; surface methods (basins, ponds, etc.) for areas with permeable soils and unconfined areas or subsurface methods (wells) for other areas

Origin of UTFI and Current Status in India

UTFI was first identified as a result of desktop studies and fieldwork conducted in the Chao Phraya River Basin in Thailand (Pavelic et al. 2012). It was widely believed that opportunities for new large-scale water infrastructure projects within this river basin were limited, as the basin was essentially '*closed*' (Molle 2002); yet, periodic large-scale flooding and the overexploitation of groundwater for agriculture within the plains created scope for UTFI implementation. Despite a favorable initial assessment, the UTFI approach was not taken forward in the basin. Instead, efforts were diverted to the Ganges River Basin, where a UTFI trial was conducted to assess actual performance, benefits, costs and trade-offs (Pavelic et al. 2015).

Pilot-scale demonstration and testing of UTFI started in 2015 in Jiwai Jadid village of Milak block, Rampur district, Uttar Pradesh, India (Figure 2). Jiwai Jadid village is situated in Ramganga River Basin on the Upper Gangetic Plains in India. Selection of the pilot study site at Jiwai Jadid village followed three broad steps: (i) suitable watersheds were narrowed down from the regional-scale UTFI suitability assessment carried out by Brindha and Pavelic (2016); (ii) extensive fieldwork was carried out within a limited number of watersheds to identify potential sites; and (iii) a suitable site was selected based on local conditions and the degree of anticipated support from stakeholders, including the local community.

The case study area receives monsoonal rainfall only during a few months of the year (June to September), leading to a large deficit between water demand and surface water availability in non-monsoon months. Floods are an annual occurrence in the Ramganga Basin, with major flooding in 2003, 2005, 2008 and 2010, and an average inundation extent of approximately 800 to 1,000 km^2 (Pavelic et al. 2015). In contrast, groundwater is the main source of water for domestic use and irrigation in the area, and there is therefore an increasing risk of resource depletion. In Rampur district, where the pilot site is located, groundwater was classified as overexploited in only one of six administrative units in 2004, but in four of the six in the more recent assessment in 2013 (CGWB 2017; Tripathi 2009).

The infrastructure for UTFI was sited in an unused village pond for the pilot study, as land availability is a serious constraint throughout most of the basin owing to high population density and intensive year-round cultivation. The pond was dewatered, cleaned and excavated up to a depth of 2 m and reshaped to an area of 2,625 m^2 (75 m x 35 m). In total, 10 recharge wells were installed at the base of the pond (Figure 3). The source water was siphoned into the pond from an adjacent irrigation canal. Recharge was only performed during the monsoon season when the water level in the canal was sufficiently high.

Over 3 years, the average volume of water recharged during the 62 to 85 days of the recharge season was ~44,000 m^3 (values ranged from 26,000 m^3 to 62,000 m^3) (Alam et al. 2020). The inter-annual variation in recharge rates appeared to be due to a range of variables: the amount and intensity of rainfall, quality of recharged water, extent of de-clogging operations and local hydraulic gradients. The recharged water from the pilot system would be sufficient to irrigate ~13 ha of cropland (*Rabi* wheat with an irrigation requirement of ~350 mm). The UTFI system with recharge wells increased overall groundwater recharge by a factor of ~3-7 compared to recharge from infiltration alone from the base of the pond.

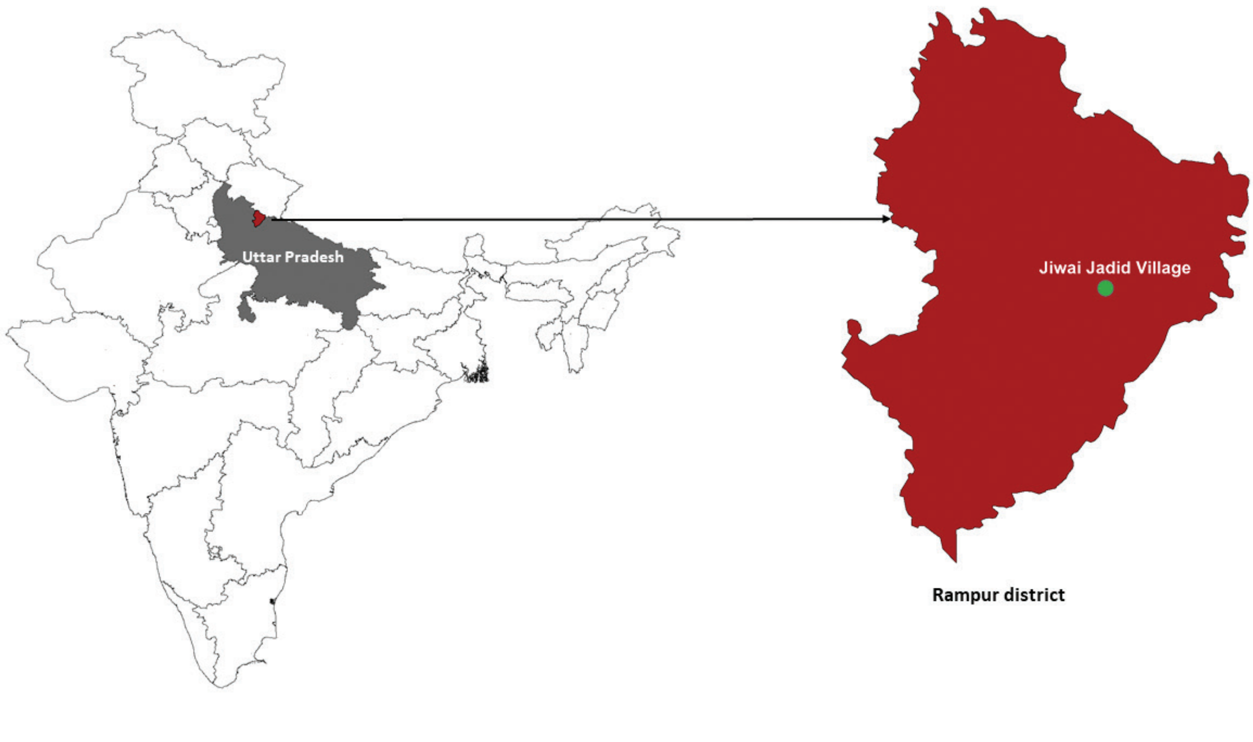


Figure 2. Location of the UTFI pilot study site at Jiwai Jadid village, Rampur district, Uttar Pradesh, India.

Figure 3. Infrastructure for UTFI in place at Jiwai Jadid village, Rampur district, Uttar Pradesh, India (*photo:* Prashanth Vishwanathan/IWMI).

Overall, recharged water from the pilot UTFI system represented approximately 1.3-3.6% of total natural recharge in the village. Groundwater mounding due to recharge was limited and was most clearly evident when recharge rates were highest at the beginning of the season. The low contribution from UTFI to overall recharge and limited mounding reflects the limited scale of the pilot intervention. This is because the contribution of one pilot to the overall groundwater balance is expected to be small, especially in high-storage, alluvial aquifer settings characteristic of the area. If the UTFI approach is scaled up across the Ramganga Basin, this could result in more substantial impacts. This was demonstrated by Chinnasamy et al. (2018), who used integrated surface water and groundwater modelling methods to show that recharging 50% of excess river flow from the basin could reduce the ratio of groundwater discharge to recharge from 168% to 103% at basin scale and mitigate declining groundwater levels, with an increase in levels by ~3.5 m relative to the baseline scenario.

Given the small scale nature of the pilot trial, studying the potential for mitigating downstream floods was not appropriate. However, the basin-scale modelling study for the Ramganga (Chinnasamy et al. 2018) also showed that, under different scenarios, capturing between 10% and 50% of excess flow can reduce the flood inundation area with a return period of 5 years by 5.1% to 27.1%. The potential for upstream water resources development (e.g., through rainwater harvesting, enhanced recharge, irrigation intensification) to significantly reduce downstream flows has been reported in India in multiple studies (Bouma et al. 2011; Calder et al. 2008; Nune et al. 2014).

Other potential benefits of the UTFI approach were either not applicable or not evaluated due to the limited scale of the pilot study. However, these benefits could include enhanced groundwater-dependent ecosystem services, increased resilience to climate change, land subsidence control and prevention of saline water intrusion, increased dry-season baseflows to rivers, streams and wetlands, and reduced pumping costs and associated carbon emissions. However, there is a strong body of evidence from research on MAR to show that such benefits may eventuate if MAR is planned and evaluated rigorously (Dillon et al. 2014; Maliva 2014; Vanderzalm et al. 2015). These benefits would, in turn, give rise to secondary benefits, including reduced public/private spending on flood/drought damage and relief efforts, and increased food security, agricultural production, employment and farmer incomes (Prathapar et al. 2015).

UTFI Policy Landscape

UTFI provides a management solution to address fundamental development issues such as food and water security, as well as a broader suite of issues related to climate change adaptation and disaster risk reduction that are among the highest policy priorities of most countries and regions, globally (Figure 4). UTFI is a crosscutting approach. Therefore, the policies that can shape and influence UTFI are distributed across various thematic areas or sectors associated with climate change, water resources and agriculture. Alignment of the UTFI approach with other relevant policy domains, such as land use planning and urban/rural development, would also be beneficial. However, working across sectors, where necessary, would also need to overcome entrenched barriers given that government institutions commonly work in isolation from one another (Azhoni et al. 2017).

Depending on the local context and priorities, countries may consider all or a few of the issues and underlying drivers shown in Figure 4 as the basic 'value proposition' for UTFI. They all reflect key opportunities from which tangible socioeconomic benefits may emerge, if the UTFI approach is applied successfully. Under existing government programs in many countries, substantial public and donor funds are spent on flood relief and restoration efforts (van Aalst et al. 2013), as well as through the provision of subsidies to farmers for groundwater extraction (Mukherjee and Biswas 2016). This approach seldom creates permanent assets or solutions to deal with the interrelated root causes of problems pertaining to water variability.

Regulatory and governance arrangements that have been developed for MAR offer useful insights for UTFI. MAR is specifically considered in policies and regulatory frameworks in countries such as the Netherlands, Germany, Finland, Spain, United States of America (USA), South Africa and Australia, where planning and practice have been underway for up to six decades (Dillon et al. 2019). Regulatory frameworks account for both quantity and quality issues, with the most stringent controls generally given to cases where the source of recharged water derives from some form of recycled water, such as treated wastewater. In a developing country context, India stands out strongly, because the additional groundwater storage capacity created through MAR under the auspices of watershed management programs (Khalid et al. 2004) administered by the government across many states exceeds that of all other developing countries, including China. Watershed management programs in India commonly include the implementation of various improved land and water management practices, including groundwater recharge, with stakeholder involvement (Reddy et al. 2018). Generally, these programs are implemented in the most drought-prone areas of the country. Existing regulatory and governance arrangements provide a foundation for UTFI that could be adapted accordingly without the need to create alternative plans.

In a complex institutional environment with multiple entry points for UTFI across several sectors, a thorough understanding of the local context is needed, through detailed multi-level and multi-sector stakeholder engagement, to establish clear objectives and pathways for UTFI implementation. Pavelic et al. (2015) and Reddy et al. (2017, 2018) provided examples of how this has been achieved in the Gangetic Plains.

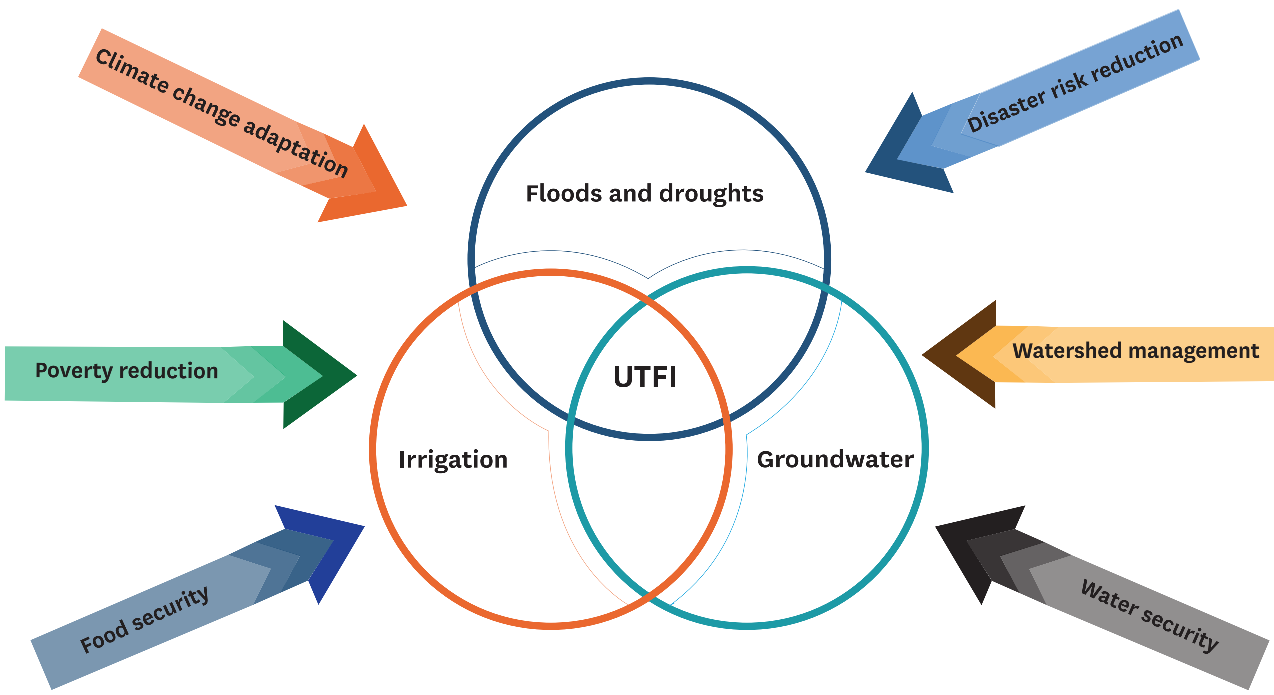


Figure 4. Key aspects and priorities of the water sector that closely intersect with the UTFI approach.

Synergies with UTFI at the Global Scale

In addition to the studies conducted in Thailand and India mentioned above, the idea of using large floods to recharge groundwater has independently been evaluated elsewhere. Several notable examples come from Nebraska (Gibson and Brozović 2018) and California (California Department of Water Resources 2018) in the USA, Namoi Valley in Australia (Rawluk et al. 2013), Madhya Ganga Canal in the Upper Ganga Basin, India (IWMI-Tata Water Policy Program 2002), Hinds pilot trial in New Zealand (Golder Associates 2017) and the lower Cornia valley aquifer system in Tuscany, Italy (LIFE-REWAT 2018).

The California Department of Water Resources is actively pursuing opportunities to use floodwater for groundwater recharge as a water resources management strategy through an approach known as 'Flood-MAR' (California Department of Water Resources 2018). Flood-MAR is a response to the occurrence of extreme periods of drought and flood in California, which will also lead to the need to rehabilitate and modernize water and flood infrastructure. It is envisaged that Flood-MAR can significantly help to improve water resources sustainability and climate resilience throughout the state. Using data on soils, topography and crop type, O'Geen et al. (2015) identified that there is good to excellent potential for floodwater recharge on 1.45 million hectares (Mha) (~20% of agricultural land in California).

In the case of the Madhya Ganga Canal situated in the state of Uttar Pradesh in India, surplus water in the Ganges River (234 m^3/s during high flows) was diverted to canals to irrigate wet season crops. Resulting seepage from the earthen canals and irrigated fields led to the reversal of declining water tables (average depth to groundwater decreased from an average of 12 m below ground level in 1988 to an average of 6.5 m in 1998), reduced pumping costs for irrigation (cost savings of INR 180 million or ~USD 3.7 million), and increased overall agricultural productivity (26% increase in average net income per hectare) (IWMI-Tata Water Policy Program 2002). In New Zealand, a pilot project in the Hind catchment involved diverting a total of ~2.44 million cubic meters (Mm^3) of river water for improving both the quantity and quality of water in the aquifer (Golder Associates 2017). In Australia, Rawluk et al. (2013) explored the scope for MAR using river water during floods in the Namoi Valley of the Murray-Darling Basin. The study suggested that there is scope for significant environmental, social and economic benefits, but also identified challenges related to institutional arrangements as well as environmental and ecological concerns. In addition, Pavelic et al. (2015) also provided an overview of case studies from Australia, Iran and Uzbekistan of MAR reliant on the harvesting of surface water runoff for groundwater recharge. While these cases did not directly aim to use MAR for flood mitigation, the existence of large schemes tapping surface water for groundwater recharge reinforces the technical feasibility and utility of the UTFI approach.

Objectives of the Study

The UTFI approach could be a potentially innovative solution that can contribute positively towards improved flood, drought and groundwater management with far-reaching co-benefits for communities in both rural and urban areas. With similar concepts and ideas discussed and explored independently in other parts of the world, the UTFI approach may have widespread potential to augment more conventional water resources management.

Consideration of the UTFI approach, as with any form of water management intervention, would be preceded by rigorous evaluation and planning at the local level. However, local-level planning and evaluation requires considerable time and financial resources to address wide-ranging technical, socioeconomic, institutional and environmental issues. Therefore, a pre-feasibility study assesses suitable locations for UTFI implementation, and an overall economic feasibility study is necessary to determine whether or not to proceed with more detailed analyses at more localized scales. Such decision-making is necessary before investment decisions and practical steps can be taken. In line with this approach, the objectives of this report are as follows:

1. *A broad global-scale assessment of the potential for UTFI*. Locating suitable areas for UTFI is a vital first step towards successful implementation and outcomes. This would support the identification of regions and basins where there is potential for UTFI implementation based on disaster risk (floods and droughts) and groundwater conditions. To date, the assessment of UTFI potential has been limited to small-scale analyses in the Ganges River Basin (Brindha and Pavelic 2016) and in Sri Lanka (Eriyagama et al. 2014). However, an assessment of wider applicability and the relative potential for UTFI across the world would give a broader understanding of the scope for this approach.

2. *An assessment of the economic viability of UTFI in selected river basins*. This is essential to indicate whether the benefits of flood damage mitigation and enhanced water availability to the local agricultural economy and wider public justify capital investment, and operation and maintenance (O&M) costs for UTFI implementation.

Who Should Read this Report?

Given that UTFI is a crosscutting management approach that covers multiple sectors and physical scales (local through to basin), this report is intended for multi-level and multi-sector stakeholders including the following:

- Policy makers and decision-makers working on challenges that intersect with UTFI (Figure 4).
- Government agencies with mandates covering floods, groundwater, agriculture, irrigation, watershed management and more.
- Researchers working on relevant problems and disciplinary areas.
- Development organizations looking to invest in the implementation of potential solutions to challenges related to water variability.

Spatial Analysis

Overview of Spatial Suitability Assessment Methods

Spatial mapping has previously been used to identify suitable sites for MAR at various scales across the world (INOWAS 2018; Russo et al. 2015; Yeh et al. 2009). It primarily involves: (i) selection of different data layers/ variables relevant for suitability mapping; (ii) assignment of weights to layers and reclassifying their data into a small number of discrete categories (from low to high) in terms of significance for UTFI suitability; (iii) overlaying for composite spatial analysis; and (iv) sensitivity analysis (Rahman et al. 2012). While following similar general principles, studies differ in terms of the number and types of variables selected, spatial scale of mapping, and approach used to assign weights to different variables and layers. They also differ in terms of the types of recharge methods and sources of water considered. The majority of studies that aim to determine the potential for groundwater recharge, storage and recovery through MAR use variables such as geology, slope, soil, groundwater level, aquifer permeability/transmissivity, groundwater quality, lithology, aquifer type, aquifer storage capacity, land cover and lineaments (Chenini and Mammou 2010; Yeh et al. 2009). In the majority of cases, the availabilty of water for groundwater recharge and demand for recharged water for irrigation or other uses are not explicit criteria included in the analysis (e.g., Bonilla Valverde et al. 2016; Russo et al. 2015). On the other hand, in addition to hydrogeological variables, UTFI also uses the quantity of floodwater and demand for recharged water as key factors in suitability mapping, as done in previous studies conducted in South Asia (Brindha and Pavelic 2016; Eriyagama et al. 2014).

Data for the Spatial Analysis

The potential for UTFI in a given location depends critically on the degree of inter- and intra-annual water variability and vulnerability of the area to impacts arising from this variability. High recurrence of large floods and droughts that impact agriculture and human settlements is a key feature of areas where there is high potential for UTFI. While flood and drought impacts provide an indication of the benefits of UTFI, suitable hydrogeological characteristics of a given location are central to realizing those benefits as they reflect the scope for implementing UTFI.

Therefore, for purposes of this assessment of UTFI suitability, data reflecting these hydrogeological characteristics were arranged into three broad thematic groups: water supply, water demand and water storage (Table 2). Variables related to supply account for the physical availability and socioeconomic impacts of floods that could be harvested and stored in aquifers via UTFI. Variables related to demand account for the frequency and impacts of drought. Variables related to storage account for hydrogeological conditions that determine the suitability of groundwater recharge structures. Table 2 summarizes the data used in the analysis. The analysis was carried out at the global scale with a spatial resolution of 30 arc-minutes, translating to approximately 55 km^2 pixels at the equator.

Data on the frequency and impacts of floods and droughts in terms of economic and mortality losses were taken from the Socioeconomic Data and Applications Center (SEDAC), hosted by the Center for International Earth Science Information Network (CIESIN) at Columbia University (CHRR and CIESIN 2005a; CHRR, CIESIN and IBRD 2005b, 2005c, 2005d, 2005e; CHRR, CIESIN and IRI 2005f; Dilley et al. 2005). Spatial data from CIESIN are at a resolution of 2.5 arc-minutes[1] with grid cells classified on a relative frequency score from 1 to 10 (higher frequency scores reflect higher frequency/ impact of drought or flood). Flood frequency is based on a global listing of significant flood events as compiled by the Dartmouth Flood Observatory (DFO), while drought frequency is calculated using the Weighted Anomaly of

[1] All datasets, if not already at a resolution of 30 arc-minutes, were resampled (using the average of grids) to a resolution of 30 arc-minutes (resolution of analysis) in ArcGIS software.

Standardized Precipitation (WASP) (Dilley et al. 2005). Data on economic and mortality losses from CIESIN are a function of hazard frequency data and expected losses per hazard event as obtained from historical losses reported in the international disaster database, EM-DAT, together with spatially gridded data on population, gross domestic product (GDP), agricultural GDP and infrastructure (road density) (Guha-Sapir et al. 2015).

Factors related to storage included aquifer type, and groundwater depth and salinity. Ideally, data on aquifer depth and storage capacity would have been included, but these details were not readily available at global scale. Aquifer type, taken from the World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP) (Richts et al. 2011), provides a broad indication of geology, aquifer permeability, storage and productivity. Groundwater depth strongly influences recharge operations: (i) very shallow groundwater levels are unsuitable for UTFI due to the risk of waterlogging, and (ii) deep levels are unsuitable due to high installation costs or limited benefits gained from recharge. Data on groundwater table depth were taken from Fan et al. (2013), which provides depths below ground surface at a resolution of 30 arc-minutes under modelled steady-state conditions. This level does not capture seasonal fluctuations or the response to groundwater pumping, but it gives a basic indication of the long-term storage capacity. Data on groundwater salinity were taken from WHYMAP, which delineates areas where salinity, measured in terms of total dissolved solids content, is above or below 5,000 mg/l (Richts et al. 2011). This value is, therefore, taken as a cutoff limit on the use of the aquifer for recharge and recovery of sufficiently fresh groundwater for productive purposes. Soil type and depth were not considered, as the design of the recharge structure may be adapted based on soil permeability. Broadly, surface recharge methods such as infiltration ponds/basins can be used wherever permeable soils overlay aquifers. In places where aquifers are overlain by impermeable soils or the aquifer is somewhat deep or confined, subsurface recharge methods such as injection or infiltration wells can be used. Agriculture and population data were not considered separately in relation to storage-related factors, for example, to illustrate the demand for storage. This is because these details are already indirectly incorporated in CIESIN datasets to determine the economic and mortality losses of floods and drought (Dilley et al. 2005).

Methods Applied for the Spatial Analysis

The framework developed for the spatial analysis is shown in Figure 5. Each data layer in the three thematic groups was assigned a weight (W_{DL}) based on its relative importance in the theme, and the features within each data layer were given a reclassified value (R_{FL}) based on their likely correlation with UTFI potential. Table 3 summarizes the weights assigned to each layer and the reclassified values for features within each layer, with reasons for choosing the weights and reclassification. Individual layers were combined into thematic groups through an overlay analysis to derive a composite suitability score for each thematic group (T_i). Thematic groups were subsequently combined, with each group given an equal weight to obtain the final UTFI suitability score ($UTFI_{SC}$) (Equations [1] and [2]). Additive aggregation was selected as it provides an easy and intuitive way to identify the relative contribution made by the factor(s) to determining the final score. The final suitability score was then normalized on a zero to 100 scale and divided into four equally distributed suitability classes: very low (0-25), moderate (> 25-50), high (> 50-75) and very high (> 75-100). As evidence of floods (representing supply) and droughts (representing demand) is an essential prerequisite for UTFI, areas with no significant floods or droughts were omitted from the analysis.

Table 2. Summary of the data used for the spatial analysis at the global scale, arranged according to the three thematic groups.

Thematic group	Layer	Source	Resolution
Supply	Flood hazard frequency Flood mortality Flood economic losses	SEDAC[a] CHRR and CIESIN 2005a; CHRR, CIESIN and IBRD 2005b, 2005c	2.5 arc-minutes (aggregated to 30 arc-minutes)
Demand	Drought hazard frequency Drought mortality Drought economic losses	SEDAC[a] CHRR, CIESIN and IBRD 2005d, 2005e; CHRR, CIESIN and IRI 2005f	2.5 arc-minutes (aggregated to 30 arc-minutes)
Storage	Groundwater depth	Fan et al. 2013	30 arc-minutes
	Aquifer type	WHYMAP[b] (Richts et al. 2011)	30 arc-minutes
	Groundwater salinity	WHYMAP[b] (BGR and UNESCO 2006)	30 arc-minutes

Notes:
[a] http://sedac.ciesin.columbia.edu/
[b] https://www.whymap.org/

$$UTFI_{SC} = T_{supply} + T_{demand} + T_{storage} \quad \text{.......} (1)$$

Where:

$UTFI_{SC}$ = Final suitability score

$$T_G = \sum_{i=1}^{n} (W_{DL} * R_{FL})_i \quad \text{.......} (2)$$

Where:

T_G = Thematic group score (where G is supply, demand and storage)

$W_{DL(i)}$= Weight assigned to i^{th} data layer of thematic group G (given in Table 3)

$R_{FL(i)}$= Reclassified value for feature in the i^{th} data layer of thematic group G (given in Table 3)

n = Layers in the thematic group

$UTFI_{SC}$ = Final suitability score

Sensitivity Analysis

When spatial suitability assessment methods are applied, criteria weights are often the main contributor to uncertainty due to the inherent subjectivity involved (Chen et al. 2010). Therefore, it is common for studies to carry out a sensitivity analysis to establish the level of uncertainty in the results (Bonilla Valverde et al. 2016; Delgado and Sendra 2004). In this study, the UTFI suitability map was checked by varying the weights assigned to layers in each thematic group. The main purpose of doing so was to check the robustness of the UTFI suitability score to changes in the underlying weights, and to determine the variables that are most critical in the assessment. The weights of all the layers (W_{DL} in Table 3) in a thematic group were varied over the range of ±20%; similar to the range chosen in other similar studies (Chen et al. 2009; Jeong and Ramírez-Gómez 2017). For each thematic group, by setting the weight of each of the three layers to their minimum (-20%) as well as maximum (+20%) values, a total of eight scenarios (i.e., 2^3) were obtained, thus giving a total of 24 scenarios. Sensitivity of the UTFI suitability map to the given weights was then assessed by determining the absolute and percentage changes for different suitability classes.

UTFI Suitability at Regional and Basin Scales

Final gridded UTFI suitability scores were analyzed further according to regions defined by the United Nations (UN) geographical convention (United Nations 2017). A list of countries and their associated UN subregions, including population and crop area with high UTFI suitability, is given in Appendix 1. In each region or subregion, the aggregated human populations, number of cities (population 0.5-10 million and > 10 million) and crop areas with high UTFI suitability were determined. To achieve this, gridded data on human population (CIESIN 2016), number of cities (ESRI 2017) and crop area (Ramankutty et al. 2008) were used.

UTFI suitability was further considered at the river basin level by averaging gridded score data to derive an overall basin suitability score. For this, the 100 most populous river basins according to the World Resources Institute (WRI) (Gassert et al. 2013a) were delineated using HydroSHEDS – Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales – at a resolution of 30 arc-seconds (Lehner et al. 2011). These 100 basins are home to approximately 60% of the world's population.

Limitations in the Spatial Analysis

Any spatial analysis is only as good as the underlying datasets. In the case of global datasets, they are often particularly limited by data constraints and poor resolution, as well as inherent uncertainties and assumptions (Margat and van der Gun 2013). For example, data on groundwater depth do not capture the local hydrogeological complexities, which could lead to an overestimation or underestimation of suitability of the aquifer for UTFI. There could also be inherent biases due to differences in monitoring/data access and availability for different countries/regions. For example, data on flood events collected by DFO could be biased towards media coverage of such events that cause large losses and thus ignore small-scale floods with relatively smaller losses (Sadoff et al. 2015). Similarly, data on drought events calculated using the WASP methodology does not take into account other drought indicators, related more clearly to water resources and agricultural impacts, which could give a better picture of how water scarcity is felt in any given region. Modelled groundwater depth data do not explicitly take into account the impacts of abstraction on groundwater levels (Fan et al. 2013). This could have an impact on the suitability of regions where over-abstraction has led to depleted aquifers, given that low rank is assigned to areas with shallow groundwater levels. In reality, shallow groundwater levels would be deeper and more suitable, but this could also make some areas less suitable if over-abstraction has caused these levels to be too deep.

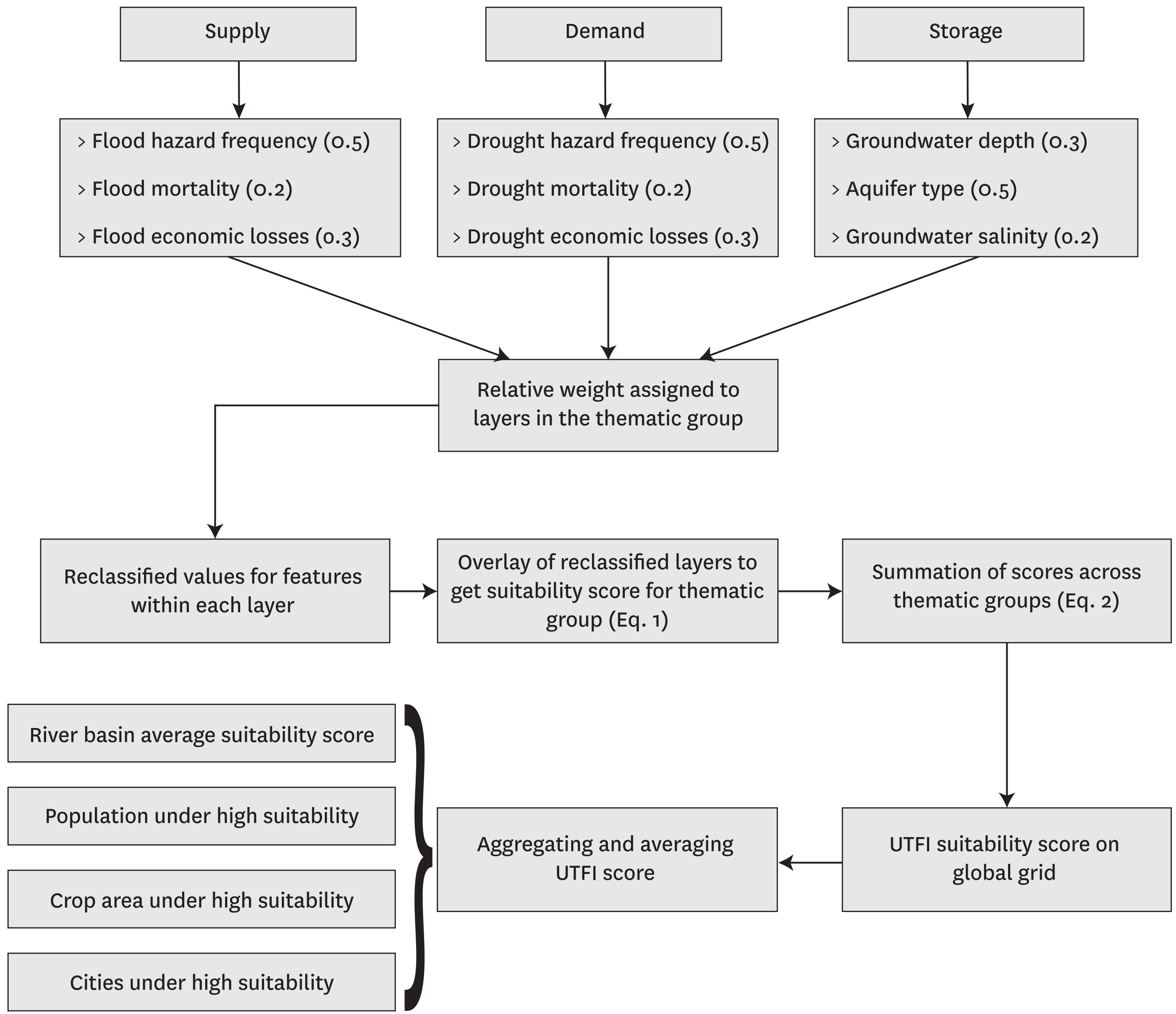


Figure 5. Framework used for the global UTFI suitability assessment.

Notes:
Weight (W_{DL}) assigned to each data layer, under the three thematic groups, is included within brackets.
Eq. - Equation.

Table 3. Weights assigned to each data layer in the three thematic groups and the reclassified values for features within each layer.

Thematic group (T)	Layer (D_L)	Weight (W_{DL})	Features (F_L)	Reclassified values for features within a layer (R_{FL})[a]
Supply[b]	Flood hazard frequency	0.5	Frequency score < 4	1
			Frequency score 4-6	2
			Frequency score 6-7	3
			Frequency score 8-10	4
	Flood mortality	0.2	Frequency score < 4	1
			Frequency score 4-6	2
			Frequency score 6-7	3
			Frequency score 8-10	4
	Flood economic losses	0.3	Frequency score < 4	1
			Frequency score 4-6	2
			Frequency score 6-7	3
			Frequency score 8-10	4
Demand[c]	Drought hazard frequency	0.5	Frequency score < 4	1
			Frequency score 4-6	2
			Frequency score 6-7	3
			Frequency score 8-10	4
	Drought mortality	0.2	Frequency score < 4	1
			Frequency score 4-6	2
			Frequency score 6-7	3
			Frequency score 8-10	4
	Drought economic losses	0.3	Frequency score < 4	1
			Frequency score 4-6	2
			Frequency score 6-7	3
			Frequency score 8-10	4
Storage[d]	Groundwater depth (m)[i]	0.3	< 3 m	0
			3 to 30 m	7
			> 30 m	3
	Aquifer type[ii]	0.5	Aquifers in fluvial deposits	3
			Major groundwater aquifers	3
			Aquifers in complex hydrogeological structures	2
			Aquifers in carbonate rocks	1
			Local and shallow aquifers	1
			Non-renewable aquifers	0
	Groundwater salinity (mg/l)[iii]	0.2	≤ 5,000 mg/l	7
			> 5,000 mg/l	3

Notes:

[a] Features within each data layer were given a reclassified value based on their likely correlation with UTFI potential.

[b] Higher the flood frequency score, the higher the hazard/impact and hence the assignment of a higher reclassified value. Economic losses are given a weight higher than mortality losses to acknowledge that measures to mitigate flood damage are more established in developed countries and this would reduce mortality losses in comparison to developing countries. This would also reduce economic losses, but any reduction in such losses would be offset by the high economic value of infrastructure in developed countries. Thus, to remove this bias to some extent, a lower weight is given to flood mortality.

[c] Higher the drought frequency score, the higher the hazard/impact and hence the assignment of a higher reclassified value. Similar to the rationale for flood economic losses, drought economic losses are also given a weight higher than mortality losses.

[d] i. Very shallow and deep groundwater depths are unsuitable for recharge operations.

ii. Fluvial deposits and major groundwater aquifers have high storage capacity, permeability and predictability, and are thus given high reclassified values. Lower reclassified values are given to complex aquifers with significant potential but added unpredictability in hard-rock areas, and to shallow and local aquifers which are likely to have low storage capacity and yield.

iii. High levels of salinity would make groundwater unsuitable for domestic and agricultural purposes. Although freshwater can be stored in saline aquifers, in general, saltier the groundwater, lesser the amount that can be recovered for productive use. Thus, recharge in saline systems requires better management, which may not be available universally, and hence highly saline groundwater is given a low reclassified value, but not zero.

Data on some important variables that could potentially impact UTFI feasibility, such as source water quality and types of flooding, are not considered due to lack of consistent data at this scale. For example, high silt loads, as is the case in the Yellow River (Chengrui and Dregne 2001; Yu 2002), is not considered in the analysis, and could add to O&M costs due to clogging. Similarly, UTFI is more suited for seasonal floods of longer duration rather than flash floods or coastal flooding, due to the physical limits on recharge capacity and potential added costs associated with the required interim detention storage (Pavelic et al. 2015). The type of flood could not be differentiated from flood occurrence and impact data, which combine all types of flooding. A critical limitation of the present analysis is that the impact of climate change is not considered, which will affect the spatial and temporal distribution of flood and drought risks. While there is a clear need for further research in this area, understanding UTFI feasibility under recorded levels of climate variability is an important first step.

UTFI Suitability Results

Spatial Analysis

The global-level UTFI suitability map, based on the analysis carried out, is presented in Figure 6. In total, approximately 26% of global land area is classified as having varying degrees of UTFI suitability, but the remaining 74% (shaded in yellow) is unclassified due to an absence of floods or droughts or both. Areas with high suitability (score > 50 – areas highlighted in light and dark green in Figure 6), representing about 11% of global land area (1,580 Mha), are seen to be distributed worldwide. Countries with a large proportion of land area (> 40% of country's land area) with high UTFI suitability are mainly located in South Asia (India, Bangladesh, Sri Lanka and Pakistan); Southeast Asia (Thailand, Philippines, Cambodia and Vietnam); East Africa (Ethiopia, Kenya, Tanzania, Sudan, Somalia and Zimbabwe); West Africa (Nigeria, Benin and Togo); and Central America (Costa Rica and Nicargua). Other larger areas with high UTFI suitability are concentrated in specific regions such as the North China Plain, High Plains in the USA, western parts of Iran, and eastern and southeastern Brazil.

In comparison, countries in Europe, West Asia, North Africa, Russia and Central Asia have relatively limited areas with high UTFI suitability (< 40% of the country's land area). However, there is a high degree of variability within these vast regions, with a high level of suitability apparent in some specific countries or smaller areas within countries. This applies, for example, to Lebanon (West Asia), Uruguay (South America), and the Netherlands and Belgium (Europe), which show good potential in regions with overall limited UTFI potential. The maps in Appendix 2 show the suitability scores given to each thematic group (supply, demand and storage) and also show their relative contribution to overall UTFI suitability. Overall, 41 countries distributed across five continents (all except for Australia and Antarctica) have more than 40% of their territory classified as high to very high UTFI suitability.

Areas identified with groundwater depletion were overlain on the UTFI suitability map to pinpoint where depletion and high suitability coincide, and therefore where UTFI may have a potential role in offsetting declining trends in groundwater level. Data on global groundwater depletion[2] were taken from Döll et al. (2014) and the areas with highest depletion rates were converted to polygons. This reveals that almost 90% of groundwater depletion occurs in areas with high UTFI suitability (Figure 6). These overlapping areas are mostly concentrated in the depleted aquifers of northwest India (Rodell et al. 2009), North China Plain (Changming et al. 2001), parts of the High Plains aquifer in the USA (Scanlon et al. 2012), northeastern Pakistan (Qureshi et al. 2010) and western Iran (Joodaki et al. 2014). On the other hand, depleted aquifers in the Middle East and North Africa (MENA) region (including the Arabian Peninsula, Nubian Sandstone aquifer in Northwestern Africa) are unsuitable for UTFI, as limited surface water availability from flooding reduces the supply-related component of the overall score (Appendix 1). To what extent UTFI could actually help to mitigate groundwater depletion in suitable areas remains an open question, as it would depend on multiple factors including the existing demand-supply gap, overall demand management, and the policy and regulatory frameworks in place.

Sensitivity Analysis: UTFI Suitability Classes

An analysis was carried out to identify the sensitivity of the UTFI suitability classes (low, moderate, high, very high) to weights assigned to layers, according to the maximum and minimum changes in global land area for the 24 scenarios considered (see section *Sensitivity Analysis*) (Table 4). A small change in either direction relative to the base case (UTFI suitability score with weights given in Table 3) is the desirable condition which shows high robustness of the results. Results indicate that the most sensitive class to the underlying weights given to layers is the low UTFI suitability class, varying from -17.4% to +21.8% relative to the base case. Other suitability classes show much lower levels of sensitivity. When areas with high suitability (score > 50) are considered together (adding areas under high and very high suitability classes), the sensitivity varies from -5.9% to +7.0%. This implies that the two favorable UTFI suitability classes (high and very high), which are of central interest, are robust to the underlying weights assigned. Further, the general trends across suitability classes are captured for the range of weights assigned.

UTFI Suitability: Regional Analysis

Spatial gridded UTFI suitability results were aggregated to derive estimates of the total human population, number of cities and crop area with high UTFI suitability. Analysis of data on human population and crop area in a

[2] Döll et al. (2014) estimated groundwater depletion (in mm/year) as the difference between groundwater abstraction and recharge, computed using the global hydrological model 'WaterGAP' at a spatial resolution of 30 arc-minutes (0.5°). Groundwater recharge is estimated as a long-term average (1980-2009) and takes into account diffuse groundwater recharge and recharge from surface water bodies. Groundwater abstraction includes sectoral water uses for irrigation, livestock, households, manufacturing and cooling of thermal power plants.

region with high UTFI suitability (score > 50) provides an indication of whether suitable areas cover predominantly human settlements or crop area or both. Table 5 summarizes the results for all geographical regions. At the global level, areas with high to very high UTFI suitability account for a population of approximately 3.8 billion people and a crop area of 622 Mha. This represents approximately 50% and 40% of the global population and crop area, respectively. The 40% of global crop area (excluding pastureland) is included in the 11% of global land area that is highly or very highly suitable for UTFI. This indicates that significant areas of cropland could benefit from additional water availability to expand irrigation and increase cropping intensities in areas already irrigated. Also, a total of 197 cities with populations greater than 500,000 people are located in areas with highly suitability.

South Asia (and Iran), East Asia and sub-Saharan Africa (SSA) top the list of regions with human populations and crop areas having high to very high UTFI suitability. In absolute terms, the much higher values of human population and crop area with high UTFI suitability in South Asia (in comparison to other regions) are due to high population density and cropping instensity across India, Pakistan and Bangladesh. This is followed by Southeast Asia, which shows a much higher human population with high suitability in comparison to crop area. South and Central America also have a good proportion (> 45%) of both human population and crop area with high suitability, although absolute numbers are much less in comparison to South, East and Southeast Asia. North America has a low proportion (< 30%) but a high absolute value for crop area (62 Mha) with high UTFI suitability, which reflects

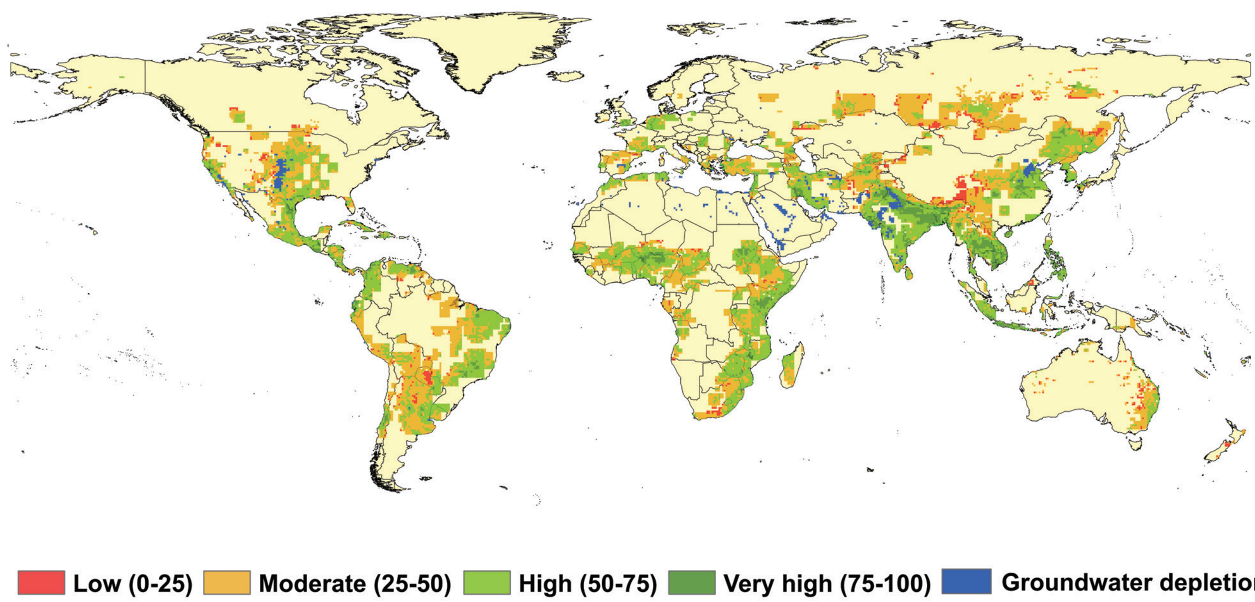


Figure 6. Global map of UTFI suitability on a spatial grid resolution of 30 arc-minutes.
Notes: Areas with highest groundwater depletion rates are shown in blue. Areas shaded in yellow over much of the global landmass respresent an absence of floods or droughts or both, and have therefore been omitted from the suitability analysis.

Table 4. Sensitivity of the UTFI suitability classes to weights assigned to layers, according to minimum and maximum changes in global land area for the 24 scenarios considered.

UTFI suitability class	Global land area (Mha) under different UTFI suitability classes		
	Base case[a]	Minimum	Maximum
Low	272	224 (-17.4%)	331 (+21.8%)
Moderate	1,699	1,620 (-4.3%)	1,730 (+2.2%)
High	1,352	1,280 (-5.5%)	1,440 (+6.6%)
Very high	228	207 (-9.3%)	251 (+9.9%)

Notes:
[a] Base case is the default UTFI score/map obtained with weights given in Table 3.
Percentage change in area relative to the base case is shown in brackets alongside the land area.

extensive cultivation in the High Plains of USA where it is mostly concentrated. There is limited potential for UTFI in the West Asia, North Africa, Europe, Russia and Central Asia regions. Similar trends are evident from data on the number of cities. Overall, South Asia has the most cities (39), including two megacities with populations greater than 10 million (Delhi and Dhaka), with high UTFI suitability.

High UTFI suitability scores in South Asia and East Asia are driven by vulnerability to frequent floods (Kale 2003; National Disaster Management Authority 2008; Yin and Li 2001; Yu 2002) and droughts (CRED and UNISDR 2015; Gassert et al. 2013b; Miyan 2015). In addition, these regions have extensive alluvial aquifer systems with the Indus-Ganges-Brahmaputra (IGB) Basin spread across North India, Northeast Pakistan and Bangladesh (MacDonald et al. 2015; Mukherjee et al. 2015), and the North China Plain aquifer (Changming et al. 2001). This coincides with extensive agricultural systems that are highly dependent on groundwater for irrigation (Siebert et al. 2010), which has led to overexploitation in many areas (Changming et al. 2001; Rodell et al. 2009). Thus, in these regions, UTFI might also offer the possibility of capturing floodwater in latent aquifer storage that could help to sustain groundwater development by increasing water availability for dry seasons and mitigating the damage caused by floods in large rivers such as the Ganges, Indus, Yellow, Yangtze and others. The potential of using aquifer storage to recharge monsoonal flow and its impact on flood reduction and increasing groundwater levels in the Ganges Basin have been studied by Chinnasamy et al. (2018) and Khan at al. (2014). Both studies suggested the effectiveness of this approach in mitigating the negative impacts of floods and increasing groundwater levels. However, for sustainable groundwater development, UTFI interventions would need to be considered along with proper management, including appropriate policies and regulatory frameworks. At the same time, there are significant intra-regional disparities which are important to consider when planning and implementing UTFI, as in the Ganges Basin, where groundwater is overexploited in the northwestern states and underdeveloped in the eastern states of India (CGWB 2014).

Droughts and floods are also quite prevalent in SSA, accounting for 80% of mortality losses and 70% of economic losses linked to natural hazards (Bhavnani et al. 2008). Drought is much more widespread (CRED and UNISDR 2015), whereas floods occur frequently along the major river systems and in many urban areas (Dingel and Tiwari 2010). This is reflected in the high supply and demand suitability scores as shown in the maps in Appendix 2. Demand-based suitability is much higher and more widespread than supply-based suitability, which is limited and restricted to areas in and around major river basins such as the Awash, Volta and Tana. SSA is also somewhat different from South and East Asia in terms of aquifer potential. Aquifers in SSA are generally not as productive due to limited well yields and storage capacity (MacDonald et al. 2012; Richts et al. 2011). Also, groundwater use in SSA is limited (Siebert et al. 2010) and negligible in comparison to South and East Asia, where groundwater is overexploited in many areas leading to depletion (Changming et al. 2001; Rodell et al. 2009). However, despite generally low well yields in basement aquifers, SSA has abundant groundwater resources and many studies have acknowledged the high potential and need for shallow groundwater development in the region, especially for irrigated agriculture (Altchenko and Villholth 2015; Xie et al. 2014). Thus, limitations of aquifer productivity and storage capacity along with limited groundwater use could have implications for UTFI in terms of implementation and costs. However, UTFI could provide a complementary way to co-manage floods and droughts in a number of river basins, while making agriculture more resilient to drought events through enhanced groundwater storage in conjunction with the development of groundwater irrigation.

In Southeast Asia, a large human population with high UTFI suitability relative to crop area is a result of high population density. This is mirrored by the large number of cities identified in the region. The region is characterized by a high frequency of flooding (Gupta 2010; Loo et al. 2015) and severe droughts are a recurring feature (Miyan 2015) due to intra-annual variability of the major monsoon season. Both hydrological extremes cause high economic, agricultural and mortality losses with low coping capacity for the three least developed countries in the region (Lao PDR, Cambodia and Myanmar), as well as for other more developed countries (Miyan 2015). In Vietnam, for example, during the drought from February to May 2016, 2 million people did not have access to water for drinking and domestic use, 1.1 million were food insecure and more than 2 million lost incomes due to damaged or lost livelihoods (World Bank and GFDRR 2017). Thus, the feasibility analysis shows that UTFI could potentially be a valuable and new approach for disaster risk reduction in Southeast Asia with significant benefits, given the region's vulnerability to extreme weather events and limited coping capacities. Actual implementation and success of UTFI would depend on a range of parameters, including technical, institutional, financial and social, which require detailed regional analyses that are not covered in this study.

The limited potential for UTFI in some areas reflects the lack of excess water availability: flooding and low cropping intensity in the Middle East and North Africa (Droogers et al. 2012); low vulnerability to drought in Europe (Carrão et al. 2016); and low cropping intensity and population density in Russia and Central Asia (CIESIN 2016; Ramankutty et al. 2008), which is reflected in the low demand suitability score. However, spatial heterogeneity within these areas could provide the opportunity to consider and implement UTFI at more localized scales.

UTFI Suitability: River Basin Analysis

The spatial analysis identified 16 basins (out of the 100 most populous river basins according to WRI) with high UTFI suitability (score > 50) (Figure 7). Table 6 provides details of these 16 river basins, including their human populations and crop areas (data for all 100 basins are given in Appendix 3). In terms of number, SSA has the highest number of basins (5 of 16), but most of the human population (77%) and crop area (62%) are concentrated in South Asia. This is mainly due to the relatively large size and high population density of the Ganges-Brahmaputra Basin.

The 100 most populous basins included here are not exhaustive but serve to indicate and identify UTFI suitability in some of the important basins at the global scale. There could be other basins that have high suitability but are not included in this study. The case of spatial heterogeneity in suitability, if sub-basins within these major basins are considered, was highlighted in the UTFI suitability assessment of the Ganges Basin (Brindha and Pavelic 2016). This would be important when planning UTFI interventions at the basin scale. This is evident in Figures 6 and 7, where some of the larger basins with overall scores less than 50 (not shown in Figure 7) have areas of high suitability but overall UTFI suitability remains low (e.g., Krishna, Godavari, Yangtze, Zambezi and Indus river basins).

Table 5. Total human population, number of cities and crop area with high to very high UTFI suitability (score > 50) for different regions of the world.

Region	Human population		Number of cities		Crop area	
	Millions	Percentage[a]	Small[b]	Large[c]	Mha	Percentage[d]
South Asia	1,496	87	37	2	179	78
East Asia	696	46	23	1	79	52
Sub-Saharan Africa[e]	462	51	28	0	88	47
Southeast Asia	385	72	12	0	60	55
South America	209	61	24	1	49	45
Central America	119	74	15	1	28	62
Europe[f]	118	21	13	0	25	14
North America	104	30	13	0	62	27
West Asia	73	31	9	0	12	30
North Africa	65	33	7	0	18	56
Central Asia + Russia	40	19	7	0	15	9
Other[g]	26	42	4	0	7	27
Total	3,793		192	5	622	

Notes:
[a] Proportion of population of a region with high UTFI suitability relative to the total population.
[b] City population of 0.5 to 10 million.
[c] City population greater than 10 million.
[d] Proportion of crop area of a region with high UTFI suitability relative to the total crop area.
[e] Includes subregions according to UN: Central Africa, East Africa, Southern Africa and West Africa.
[f] Includes subregions according to UN: Eastern Europe (excluding Russia), Northern Europe, Southern Europe and Western Europe.
[g] Includes subregions according to UN: Australia and New Zealand, Caribbean, Melanesia, Micronesia and Polynesia.

Figure 7. Distribution of the 16 river basins with high UTFI suitability (score > 50) based on an examination of the 100 most populous basins according to the World Resources Institute (WRI).

Table 6. List of the 16 river basins (out of the 100 most populous basins) including human populations and crop areas with high UTFI suitability (score > 50) in different regions of the world.

Region	Basin	Human population (millions)	Crop area (Mha)
Sub-Saharan Africa	Volta	29	9
	Shebelle	25	4
	Awash	12	2
	Tana	7	1
	Save	3	1
South Asia	Ganges-Brahmaputra	674	62
	Godavari	75	17
	Mahanadi	36	7
Southeast Asia	Mekong	55	14
	Chao Phraya	20	4
South America	Magdalena	36	3
	Rio Parnaiba	4	2
North America	Sacramento	7	2
	Brazos	3	4
Central America	Rio Balsas	12	2
	Grisalva	9	4

Economic Analysis

An economic analysis is carried out to assess the merits of UTFI implementation in economic terms. As UTFI planning is best carried out at the river basin scale, and given that it also represents a distinct hydrological unit, the economic feasibility analysis was also carried out at the basin scale. Three basins with high UTFI suitability were selected from different regions. This rationale recognizes that the costs and benefits of UTFI implementation would be expected to vary spatially due to differences in climatic, hydrologic, hydrogeological and socioeconomic variables (Arshad et al. 2013).

Characteristics of the Selected River Basins

The three river basins selected for this study are the Awash Basin in Ethiopia, Ramganga Basin (part of the Ganges Basin) in India and Chao Phraya Basin in Thailand (Figure 8). These basins have high aggregated UTFI suitability scores (Table 6) and are located in regions with significant UTFI potential, i.e., East Africa, South Asia and Southeast Asia (Figure 6; Table 5). Previous basin-level hydrologic studies conducted for the three selected basins reaffirmed the prevalence of flooding (Getahun and Gebre 2015; Mirza et al. 2001; Poapongsakorn and Meethom 2012), issues related to drought/water scarcity (Edossa et al. 2010; Khan et al. 2014; Molle 2002), and seasonal imbalances between water supply and demand (Adeba et al. 2015; Amarasinghe et al. 2016; Pavelic et al. 2012). The Ramganga is distinguishable as the location of a UTFI pilot study (Pavelic et al. 2015), and a basin-level modelling analysis indicates high potential for UTFI in this basin (Chinnasamy et al. 2018). Table 7 summarizes the key characteristics of the three basins. All three basins face common issues of floods and droughts due to high intra- and inter-annual water availability impacting agriculture, society and the economy. While the broad issues are similar, there are considerable contrasts in biophysical and socioeconomic characteristics among the basins.

The Awash Basin is located in the arid lowlands in Northeastern Ethiopia and is the most intensively utilized river basin in the country (Adeba et al. 2015). This is due to the availability of land and water resources, good transport infrastructure and siting of the national capital (Addis Ababa) within the basin (Taddesse et al. 2004). The Awash River flows west to east ending at Lake Abbe, the international border with Djibouti, with the majority of the basin (~99%) lying within Ethiopia (FAO 1997). The Awash Basin is divided into three agroclimatic zones (Upper, Middle and Lower Awash) with rainfall decreasing from the western highlands (~1,700 mm/year) to the eastern arid lowlands (~200 mm/year) (Desalegn et al. 2006). Most of the rainfall (60-80%) is received from July to August, leading to water shortages over the extended dry season (Desalegn et al. 2006; Edossa et al. 2010; Vivid Economics 2016). High intra- and inter-annual rainfall variability within the basin results in severe droughts and floods (Desalegn et al. 2006). Drought is a recurring natural hazard, whereas floods are limited to the lowland areas with intense seasonal rainfall, causing flooding of settlements close to rivers (Achamyeleh 2003; Taddesse et al. 2004). Agriculture is primarily rain-fed, with less than 2% of the cultivated area under irrigation. The basin is highly vulnerable to weather-related shocks (Vivid Economics 2016). The main cropping season (*Meher*) coincides with the main rainy season from June to September. Cropping without irrigation is not an option in the middle and lower valleys, as the annual potential evapotranspiration exceeds the annual rainfall by up to an order of magnitude (Berhe et al. 2013). According to Adeba et al. (2015), storing available surface water during the rainy season can greatly help to alleviate water scarcity within the basin.

The Ramganga Basin is one of the major tributaries of the Ganges River Basin, one of the world's largest (1.2 million km^2) and most heavily populated (655 million people) transboundary river basins extending over four countries (India, China, Nepal and Bangladesh) (cGanga and NMCG 2017; IIT 2012). The average annual precipitation in the Ramganga Basin is about 900 mm, of which 90% occurs during the monsoon period from June to September (Rajmohan and Amarasinghe 2016), with only 10% distributed over the remaining 8 months of the year. This brings about regular flooding during the monsoon season (Kale 2003; National Disaster Management Authority 2008) and water scarcity during the dry season, impacting domestic and agricultural water supplies. Over a 12-year record, major floods have been reported in 4 years, with an average inundation extent of approximately 800 to 1,000 km^2 (Pavelic et al. 2015). Crops are cultivated predominantly during the *Kharif* season coinciding with the monsoon season (June to October) and *Rabi* season (November to March), with limited cultivation during the summer (*Zaid*) season (April to May). The main crops cultivated are rice (*Kharif*), wheat (*Rabi*) and sugarcane (annual) (Department of Land Development and Water Resources 2009). Monsoon rainfall generally meets crop water requirements during the *Kharif* season, whereas irrigation is critical at other times, especially during the *Zaid* (summer) season, which limits cultivation. Despite the lack of water availability during the dry season, the region is dominated by large-scale groundwater irrigation due to the regionally extensive and highly productive Indo-Gangetic aquifers (Mukherjee et al. 2015), the development of which has helped boost production and moderate the impacts of drought. This has, however, led to groundwater overexploitation and associated water quality issues, threatening the sustainability of future development in the region (MacDonald et al. 2015).

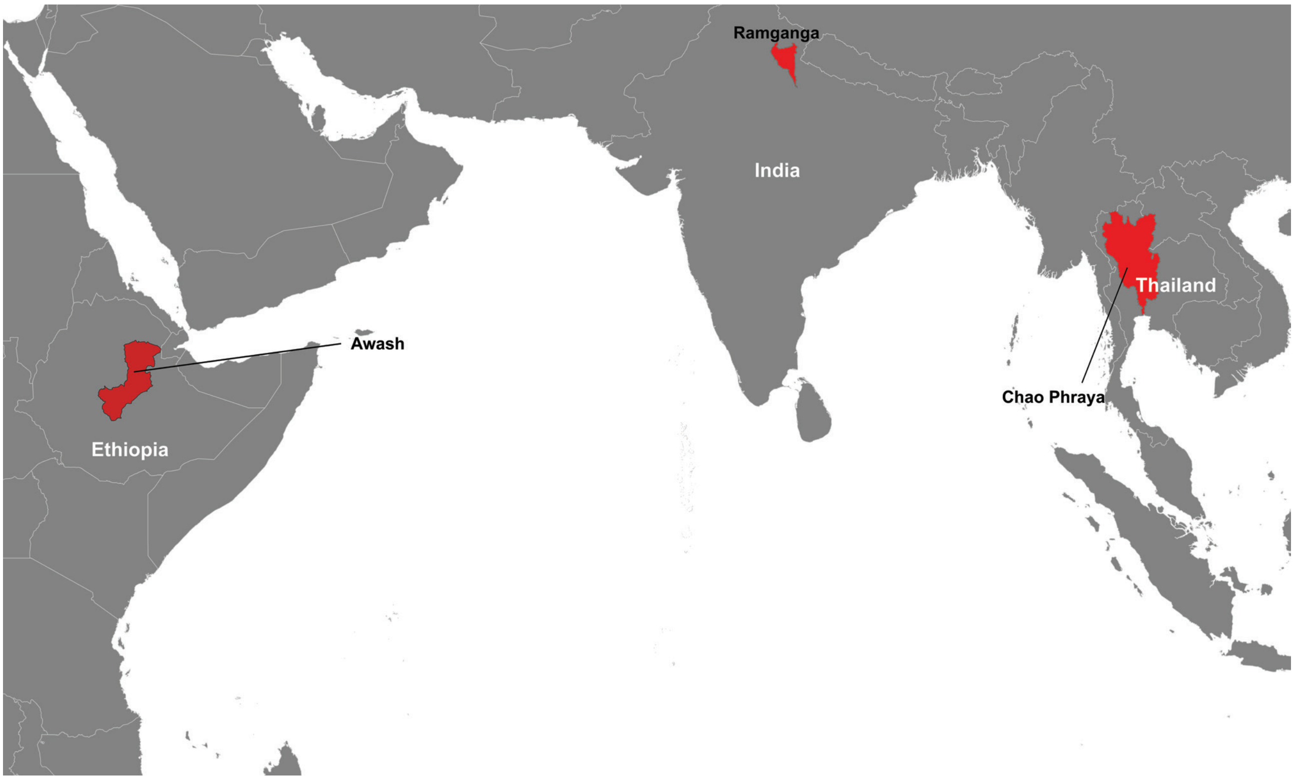


Figure 8. Locations of the Awash, Ramganga and Chao Phraya basins selected for the economic analysis.

Table 7. Summary of the key biophysical and socioeconomic characteristics of the Awash, Ramganga and Chao Phraya basins.

		Awash	Ramganga	Chao Phraya
General	Overall UTFI score	61	83	73
	Country	Ethiopia	India	Thailand
	Area (km²)	112,030	30,115	159,000
	Economic status[a]	Low income	Lower middle-income	Upper middle-income
	Population (millions)[b]	13.8	31.1	28.5
Climate	Wet season	June-September	June-September	May-October
	Dry season	October-February	November-May	November-April
	Annual rainfall	200-1,700	900-1,000 mm	1,000-1,500 mm
	Wet season rainfall	60-80%	> 80%	> 80%
	Flood frequency[c]	2-3 years	3-4 years	3-4 years
	Drought frequency[c]	2-4 years	4-5 years	2-4 years
	Climate change vulnerability[d]	Extreme risk	Extreme risk	Extreme risk
Agriculture and irrigation	Crop area (% of area)[e]	24	83	29
	Cropping intensity (%)[f]	99	188	163
	Irrigation (% of crop area)[g]	5	71	65
	Main crops	Teff, maize, sugarcane, cotton	Rice, wheat, sugarcane, maize	Rice, sugarcane, maize
Surface water	River length (km)	1,250	595	866
	Basin yield (km³/year)[h]	4.6	6.7	22.6
	Transboundary river basin[i]	Yes	Yes	No
Groundwater	Aquifer type	Igneous volcanic and part alluvial sediments	Alluvial (unconfined)	Multiple (un)confined coarse sand/gravel aquifers
	Groundwater irrigation (% of total irrigation)[g]	1	69	13

Notes:
[a] According to the income classification of the World Bank (World Bank 2018).
[b] Aggregated using gridded population of the world, version 4 (GPW 4) (CIESIN 2016).
[c] Approximate classification from the EM-DAT database (http://www.emdat.be/).
[d] Maplecroft climate change vulnerability index, 2011 (https://maplecroft.com/about/news/ccvi.html): Based on a country's capacity to mitigate risk to society and the business environment as a result of changing patterns in natural hazards such as drought, floods, storms, etc.
[e] Aggregated using crop data from Ramankutty et al. 2008.
[f] Awash: Ray and Foley 2013 (based on crop harvest frequency of Ethiopia); Ramganga: Pavelic et al. 2015; Chao Phraya: Molle et al. 2001.
[g] Aggregated using percentage of crop area under irrigation (Siebert et al. 2010).
[h] Awash: Adeba et al. 2015; Ramganga: Chinnasamy et al. 2018; Chao Phraya: the value is based on average flow at Nakhon Sawan located in the downstream part of the basin (DHI 2016).
[i] Defined as a transboundary river basin, if territory is shared by two or more countries. Awash Basin predominantly lies in Ethiopia (111,030 km²) with a minor part in Djibouti (1,000 km²) (FAO 1997); Ramganga (part of the Ganges Basin): India, Bangladesh, China and Nepal (cGanga and NMCG 2017).

The Chao Phraya Basin, situated entirely within Thailand, accounts for 30% of the country's land area, 40% of the population, 78% of the workforce and 66% of GDP (ONWRC 2003). The climate of the basin is tropical monsoon with annual rainfall ranging between 1,000 and 1,500 mm, of which about 90% is concentrated from May to October (Kure and Tebakari 2012). This gives rise to typical seasonal water imbalance problems: floods during the wet season and water shortfalls in the dry season. Floods are a regular phenomenon in the basin, causing significant economic losses (ONWRC 2003), and this is also the case with drought (Gupta 2001). Agricultural areas are mainly concentrated in the middle and lower parts of the basin, with rice and sugarcane being the major crops cultivated. Irrigation is mostly from surface water, with the dry season irrigated area limited by surface water availability (Molle 2002). Within formal irrigated areas and beyond, groundwater is an alternative source of water for irrigation (Molle 2002; ONWRC 2003). Droughts are a common occurrence, and this is exacerbated by rapid urbanization and industrialization in the Greater Bangkok Metropolitan Area situated downstream, and also by increasing dry season cultivation (Gupta 2001; Molle 2002). Thus, opportunities to capture floodwater to ease seasonal water deficits would have significant benefits for agriculture, industry, urban water demand and sustainable groundwater management in the basin.

Model Framework

The framework for the economic analysis developed and applied at the basin scale is shown in Figure 9. Table 8 provides an overview of the cost and benefit components considered in the analysis. To keep the framework simple and replicable, only costs and benefits that could be easily derived were considered. Therefore, due to the difficulty in converting the in situ benefits of groundwater to monetary values, these were not considered. Such benefits include enhancement of groundwater-dependent ecosystems (assuming not all recharged water is pumped out), increased resilience to climate change, land subsidence control and prevention of saline water intrusion (Dillon et al. 2014; Maliva 2014; Vanderzalm et al. 2015). Similary, the opportunity cost of recharged water (which includes downstream uses), which would require detailed accounting and modelling of the hydrological system, is not considered in this analysis. Also, the pretreatment cost of recharged water, which would vary depending on surface water quality, is only indirectly accounted for in the maintenance cost.

The three indicators used to identify economic feasibility are the Benefit-cost Ratio (BCR), Internal Rate of Return (IRR) and Net Present Value (NPV). In an attempt to account for inherent parameter uncertainty, a scenario analysis was carried out by considering a range of values as critical variables in the model (see section *Scenario Analysis*). The structure of the model offers a consistent framework to collect and use local data to measure economic feasibility that could be compared across the three river basins. Over the lifetime of a modelled UTFI project, the annual costs and benefits (cash flows) used to calculate these indicators are based on a set of variables and assumptions discussed below. Table 9 summarizes the main assumptions made in the modelling framework. Appendix 4 provides a more detailed description of the modelling approach and data used.

Total costs and benefits are driven by the 'design recharge volume' (DRV), a term used here to define the excess surface water flows during the wet season, after human and environmental requirements have been taken into consideration, that pose potential flood risk downstream and could be captured and used for groundwater recharge through UTFI. DRV is determined from existing studies on hydrological modelling (Awash and Ramganga) or flow observations (Chao Phraya), and takes into account water supply and demand in the basin. DRV for the Ramganga Basin is taken as 3.25 km^3, annually (Chinnasamy et al. 2018). Recharging this quantity of water would reduce the area inundated by floodwater with a 15-year return period by 24%. For the Awash Basin, DRV is taken as 2.41 km^3, annually (Adeba et al. 2015). This is based on an average imbalance between supply and demand during the wet season (June to September), as determined using the Soil and Water Assessment Tool (SWAT) after taking into account water required for domestic use, industry, agriculture and environmental flows. For the Chao Phraya Basin, DRV is taken as 3.36 km^3, which is only available in one out of every 4 years, on average (Pavelic et al. 2012). DRV in this basin is based on the frequency of floods, which is determined by comparing observed monthly flows against a threshold value (5 km^3/month). If this value is exceeded in any month of a year then that year is classified as a flood year. Based on this criterion, 11 out of 46 years were classified as flood years, translating to approximately once every 4 years. Therefore, although the DRV is available every year in the Awash and Ramganga basins, it is only available in one out of four years in the Chao Phraya Basin.

It is assumed that out of the total DRV recharged to the aquifer, only 75% could be utilized through groundwater pumping for consumptive purposes, while the remaining 25% would flow out and contribute to surface water flows as baseflow. The assumption about baseflow contributions is applicable to all three basins and is based on the baseflow value derived from integrated hydrologic modelling which took into account UTFI for the Ramganga Basin (Chinnasamy et al. 2018). While this baseflow provides benefits for ecosystem services and a proportion of it could potentially be captured downstream for consumptive use, we conservatively calculate benefits only from the recovered volume.

UTFI cuts across multiple issues, sectors and stakeholders, and hence the analysis of total costs and benefits is carried out at the aggregated basin scale without specific reference to any particular stakeholder group (farmers, water resources managers, urban planners, etc.). While some of the benefits (and costs) of UTFI could be mapped to particular stakeholders, to be consistent, costs and benefits in Table 8 are first estimated individually and then aggregated at the basin scale. Mapping costs and benefits to particular stakeholders would become important when UTFI is considered from more specific viewpoints, such as financing and institutional analysis, which is not the aim of this study. Rather, the 'most likely' investment costs and benefits are derived to provide an indication of the cost-effectiveness of UTFI. This would provide a rationale for taking up more detailed and rigorous assessments in areas with high UTFI potential.

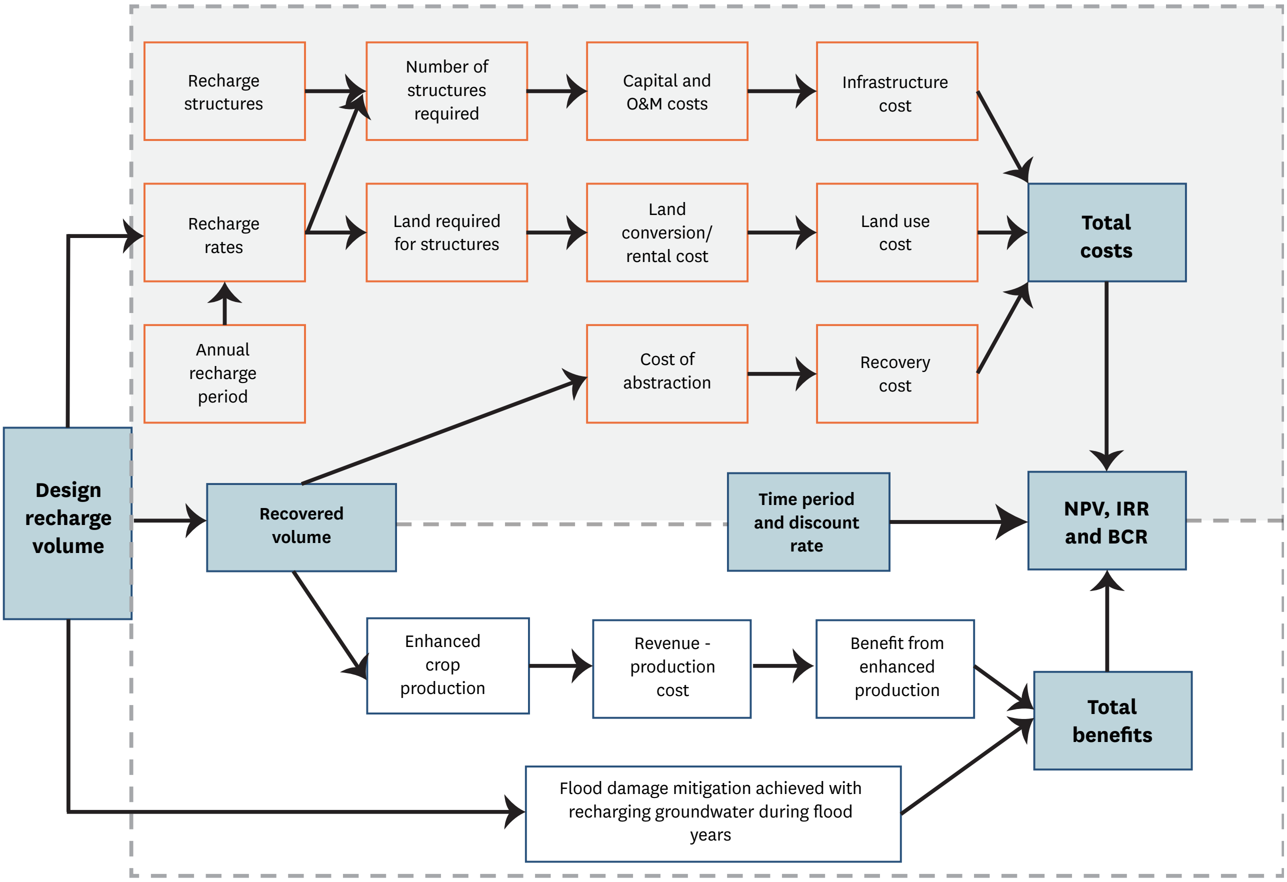


Figure 9. Framework for the economic analysis indicating the main streams of costs and benefits.

Notes: NPV - Net Present Value; IRR - Internal Rate of Return; BCR - Benefit-cost Ratio

Table 8. Costs and benefits considered in the economic analysis.

Costs	
Component	Description
Infrastructure	Capital required to construct recharge structures, and the annual O&M costs.
Land use	Acquiring the land required for constructing recharge structures.
Groundwater recovery	Cost of pumping recharged groundwater for irrigation. This includes the capital cost of constructing irrigation infrastructure, requiring a borehole and pump installation, and the annual O&M costs (including fuel).
Benefits	
Flood damage mitigation	By transferring surface water during high flows to groundwater storage, UTFI regulates and attenuates flood peaks, thus mitigating the damage caused to crops and infrastructure, and loss of livelihoods.
Enhanced crop production	The additional recharged groundwater would increase the amount of water available for irrigation. This water could be used for increasing crop production on fallow land or for cultivation during the dry season. The monetary value of these benefits can be obtained by taking into account crop price and production costs.

Determination of Costs

The total costs of UTFI were divided into three parts: infrastructure costs, land use costs and groundwater recovery costs. All input values, variables and equations associated with cost calculation are given in Appendix 4. Infrastructure costs include the capital cost of constructing recharge structures, and the annual O&M costs. Two distinct types of recharge structures were considered: surface recharge through infiltration ponds and basins, and subsurface recharge through recharge wells (Dillon 2005). Infiltration ponds are used to recharge surface water wherever permeable soils and subsoils overlay aquifers. In places where the aquifer is overlain with impermeable soils or the target aquifer is deep or confined, recharge wells are used. Subsurface recharge methods are generally more expensive than surface methods. Cost estimates are derived for both surface (S) and subsurface (SS) methods. However, it was recognized that, in practice, it is likely that a mix of both methods would be used depending on the conditions present in the basin.

The number of recharge wells and land required for infiltration ponds/basins is a function of DRV, the annual period of recharge and the recharge rates. The annual recharge period is the duration of the wet season during which excess surface water is available and recharge operations take place. This is assumed to be 100 days (Table 9). The recharge rate determines the volume of water that could be effectively recharged via these structures, and is based on the average soil infiltration rate in the case of surface methods and well yields for subsurface methods. The cost of acquiring the land needed for constructing recharge structures is determined using land rental rates as taken from the literature. Land requirement for the surface recharge method is a function of infiltration rate. For the subsurface method, land requirement is calculated by assuming that wells are distributed across sites with a well density of 20 wells/ha (Appendix 4, Table A4.4).

Groundwater recovery cost refers to the cost of pumping groundwater for irrigation, including the capital cost of constructing irrigation infrastructure, requiring a borehole and pump installation, and the annual O&M costs (including fuel). For calculating the capital cost, the depth of each groundwater pumping well is assumed to be 40 m in each basin (Appendix 4, Table A4.13). For operating costs, local fuel costs and well yields determine the cost of pumping. To simplify the analysis, we assume that only diesel pumps are used and no additional irrigation infrastructure is required for pumping, if existing groundwater irrigation accounts for 50% or more of total irrigation. If this is not the case, groundwater irrigation infrastructure is developed to recover the recharged water.

Determination of Benefits

The total benefits of UTFI were divided into two parts: flood damage mitigation, and enhanced crop production through an increase in the water available for irrigation. All input values, variables and equations associated with this component of the model are given in Appendix 4. Flood damage mitigation – limiting the damage caused to infrastructure, agriculture and livelihoods – by recharging the DRV that would reduce peak flood flows. This information was taken from relevant literature, which is based on either reported past flood damage in each region or modelled losses (Getahun and Gebre 2015; Pavelic et al. 2015; World Bank 2012). Supplementary groundwater recharge would increase water availability for irrigation and could enable the cultivation of an additional crop. In the given analysis, we do not explicitly include the timing of recharge and abstraction of recharged water for irrigation, but simply assume that recharge would create local storage that enables the additional water to be used for crop water requirements, most likely in the same hydrologic year for dry season cultivation. This would increase crop production, which is then converted into monetary terms using crop price and production costs. Benefits from enhanced crop production are calculated at the same frequency as the availability of DRV (annually for the Awash and Ramganga basins; every fourth year for the Chao Phraya Basin). Enhanced crop production is based on the assumption that farmers who are restricted by water availability during the dry season would use the recharged water to cultivate an additional crop, thus increasing cropping intensity. This is a critical assumption (Table 9) as water availability might not be the only factor constraining the use of groundwater for irrigation, especially in Ethiopia, where the development and use of groundwater are quite low. Development of groundwater infrastructure and use are important precursors to UTFI implementation. By including the capital and O&M costs of groundwater development in assessing UTFI cost, the lack of groundwater development and costs associated with it are accounted for. However, we also acknowledge that capital investment alone would not necessarily lead to groundwater development, which requires effective policies and institutions to remove existing barriers (Villholth 2013). Existing cropping intensity values are below 200% (Table 7) and indicate that there is sufficient scope to increase the intensity in all three basins.

For all the cases, an economic analysis was carried out over a period of 20 years, which is the typical lifetime of pumps with an assumed discount rate of 10% (Table 9). The selected discount rate of 10% is similar to discount rates used by multilateral development banks for their cost-benefit analyses in developing countries (Gunatilake 2013; Tsunokawa 2010).

Table 9. Assumptions associated with variables of the model.

Variables	Assumptions
Design recharge volume (DRV)	• DRV is available and could be recharged without impacting downstream users • Awash: 2.41 km^3 (annual) • Ramganga: 3.25 km^3 (annual) • Chao Phraya: 3.36 km^3 (every fourth year)
Baseflow	• Of the DRV, 25% is not recovered due to the proportion of baseflow transferred to surface water • Benefits gained from the non-recovered proportion are not considered
Recharge structures (subsurface)	• Recharge wells have a density of 20 wells/ha
Annual recharge period	• 100 days annually in the wet season
Pump	• Diesel pumps are used • There is no need for new infrastructure (for recovery of recharged water), if groundwater irrigation exceeds 50%
Enhanced crop production	• Water scarcity restricts crop production during the dry season/drought • Farmers invest in groundwater infrastructure for pumping
Flood damage mitigation	• Recharge of water leads to a reduction in peak flood flows, thereby decreasing the area inundated and the damage caused
Time period	• 20 years
Discount rate	• 10%

Scenario Analysis

Cost-benefit indicators were determined for a so-called 'base case scenario' that represents the most likely estimates for key variables for the major crop grown in the basin, according to details given in the section *Model Framework*. This base case scenario was determined for each river basin separately for the surface (S) and subsurface (SS) recharge methods. The sensitivity of both BCR and IRR values is assessed by altering critical variables: DRV (which affects both costs and benefits), recharge performance (affects costs) and crop prices (affects benefits). Each critical variable was checked for a lower bound (i.e., 20% reduction) and upper bound (i.e., 20% increase) relative to the base case giving eight scenarios (i.e., 2^3) for each S and SS recharge method. Flood damage mitigation is assumed to be directly and linearly correlated with DRV, and in scenarios, changed in the same direction and proportion (20% increase or 20% decrease) as DRV. Table 10 summarizes the base case scenario, and the lower and upper bound values for the critical parameters.

Economic Feasibility Results

Costs

Table 11 provides a breakdown of the costs (NPV in USD millions) for surface and subsurface recharge methods for the base case scenario, and the amortized cost of recharge structures (without groundwater recovery cost) per cubic meter of recharged water in the three basins. The cost of recharging groundwater (USD/m^3) is an order of magnitude lower than the cost of the 13 MAR schemes (where the water source is natural, not recycled water) assessed by Ross and Hasnain (2018) from developed countries (USA, Europe and Australia). However, despite the low cost per unit of recharged water, economic analysis points to high upfront capital costs associated with setting up UTFI infrastructure for the Awash and Chao Phraya basins, and additional investment in groundwater irrigation infrastructure as part of the groundwater recovery costs. This reflects the large scale of UTFI implementation, with DRVs many orders of magnitude higher than that seen in individual MAR schemes.

For all three basins, subsurface recharge methods cost more than surface recharge methods due to the additional cost of drilling and installing wells. The Awash Basin has the highest costs for the subsurface recharge method (Table 11), despite having the lowest DRV (Table 9) overall due to the presence of relatively low-yielding volcanic fractured aquifers (Table 8) combined with the high cost of drilling in SSA (Xenarios and Pavelic 2013).

Capital costs for recovering the recharged water comprise the highest component in the Awash Basin. This is because of the high number of pumping wells needed given the lower yield in the basin and negligible levels of existing groundwater irrigation (Table 7), and the requirement for new investment in groundwater infrastructure. The total capital cost for setting up groundwater recharge and pumping infrastructure in the Awash Basin would be USD 647 million for subsurface and USD 380 million for surface recharge methods. Capital costs for groundwater recovery are also significant in the Chao Phraya Basin, but not as high as the Awash Basin due to relatively higher yield (i.e., less wells needed) and lower drilling costs. For the Ramganga Basin, the capital costs for groundwater recovery are zero for both surface and subsurface recharge methods, because there is sufficient infrastructure for groundwater irrigation (Department of Land Development and Water Resources 2009). In all three basins, the O&M cost for groundwater recovery is quite significant, which is important to note from a planning perspective. This depends on well yields and the price of diesel in the regions. Land use costs are relatively small compared to other costs.

Benefits

Table 12 provides the contribution of different benefit streams (NPV in USD millions) for the base case scenario in the three basins. As the benefits are driven by the recovered volume of groundwater, they are the same for both methods of recharge (surface and subsurface). There are stark differences in the value of the benefit streams with the Chao Phraya Basin dominated by flood damage mitigation, whereas enhanced crop production plays a major role in the Awash and Ramganga basins. The value of flood damage mitigation is high in the Chao Phraya Basin due to highly developed urban and industrial downstream areas. However, most of the land in downstream areas of the Awash and Ramganga basins is used for agricultural production with low infrastructure value. This contrast also brings in the implicit difference and importance of the frequency of DRV considered in the model, where the recharge once every 4 years in the Chao Phraya Basin is distinct from the annual recharge in the Awash and Ramganga basins. Benefits (additional crop) calculated with the same frequency as the frequency of DRV lead to less NPV over the lifetime of the system. This shows that without the benefit of flood damage mitigation, the reduced frequency of DRV would diminish the benefits. This is evident from the fact that the benefit from the cultivation of an additional crop alone for the Chao Phraya Basin is lowest overall (Table 12).

In terms of crop production, the Awash Basin shows a relatively high value for teff. This difference in crop production value could be traced back to the relatively high price for teff (Table 10), leading to higher economic crop water productivity values in the model. The economic water productivity[3] for teff (0.35 USD/m^3 in Awash) is high in comparison to rice (0.06 USD/m^3 in Ramganga and 0.19 USD/m^3 in Chao Phraya). This is driven by the high market price and hence the higher profitability of teff, given that the physical water productivity[4] of teff (0.53 kg/m^3) is in the same range as rice (0.36 kg/m^3 in Ramganga and 0.56 kg/m^3 in Chao Phraya). The economic water productivity value for teff determined in the analysis is similar to the values reported in the literature (Araya et al. 2011; Yihun 2015). The lowest water productivity value in Ramganga is due to both relatively low price of rice (Table 10) and low rice yields (Sharma et al. 2009).

Benefit-Cost Ratio and Internal Rate of Return

Combining costs and benefits (Appendix 4), Table 13 shows the IRR and BCR values for the base case, and the worst and best case scenarios for the three river basins. An IRR value above the discount rate (10%) and BCR value above the threshold value of 1 indicate economic feasibility for UTFI implementation (IFAD 2015; Palenberg 2011).

The base case scenarios in the three river basins show high economic feasibility for UTFI implementation with high IRR and BCR values. The highest values, overall, are for the Chao Phraya Basin, which can be easily explained by the high flood damage mitigation value (Table 12) given that downstream parts include urban and industrial areas potentially facing huge losses (Poapongsakorn and Meethom 2012). Also, as expected, BCR and IRR values for subsurface recharge methods are consistently lower than surface methods, as previously explained (Table 11).

The worst and best case scenarios for IRR and BCR show a high range, implying significant sensitivity to the underlying parameters. For the Awash and Chao Phraya basins, the lower and upper case value ranges remain above the viable thresholds. However, this is not the case in the Ramganga Basin, where the lower case value for both surface and subsurface recharge methods falls well below the threshold. As BCR and IRR values for the base case scenario in Ramganga are lower than Awash and Chao Phraya, there is a higher likelihood of these values falling below the thresholds when crop prices and recharge rates are low. For both the Awash and Ramganga, the worst case scenarios correspond to the lower crop prices and recharge rates, and vice versa; the best case scenario corresponds to the higher prices and recharge rates. This shows that both the costs and benefits are driven largely by both crop prices and recharge rates, whereas the DRV plays a minor role. This can be explained by the fact that any change in DRV has similar impacts on both costs and benefits. The worst and best case scenarios correspond to low and high recharge rates, respectively, in the Chao Phraya Basin. In contrast to the Awash and Ramganga basins, there is no influence of crop price in the Chao Phraya basin. This is because the benefits from enhanced crop production in Chao Phraya only play a minor role, with higher benefits gained from flood damage mitigation (Table 12).

[3] Economic water productivity = (total crop production * price) / water consumption (per unit area).
[4] Physical water productivity = Total crop production / water consumption (per unit area).

Table 10. Critical parameter values used in the scenario analysis in the Awash, Ramganga and Chao Phraya basins.

Variable	Awash		Ramganga		Chao Phraya	
Recharge method	S	SS	S	SS	S	SS
DRV (km^3)[a]	2.41 (1.93 - 2.90)		3.25 (2.60 - 4.32)		3.36 (2.69 - 4.03)	
Crop	Teff[b]		Rice		Rice	
Crop price (USD/ton)[c]	668 (534 - 801)		207 (165 - 248)		336 (269 - 403)	
Recharge rate[d]	0.48 m/day (0.38 - 0.58)	173 m^3/day (138 - 207)	0.48 m/day (0.38 - 0.58)	259 m^3/day (207 - 311)	0.48 m/day (0.38 - 0.58)	259 m^3/day (207 - 311)

Notes:
Values in brackets are the lower and upper bound values used.
Exchange rates considered (as in 2017): Ethiopia: USD 1 = ETB 23.9; India: USD 1 = INR 65; Thailand: USD 1 = THB 32.3.
[a] Awash and Ramganga: km^3/year; Chao Phraya: km^3/fourth year.
[b] Teff is a staple food crop of Ethiopia and Eritrea (FAO 2017).
[c] Awash: Ethiopian Grain Trade Enterprise 2018; Ramganga: Commission for Agricultural Costs and Prices 2015; Chao Phraya: Office of Agricultural Economics 2018.
[d] Infiltration rate is taken as 0.48 m/day for all three basins, and is based on the average infiltration rate of sandy loam soils, which are appropriate for the surface recharge method (Brouwer et al. 1985). Recharge rate for the SS recharge method for Awash: taken as 173 m^3/day (MacDonald et al. 2012); Ramganga: taken as 259 m^3/day from the average value measured during the pilot UTFI trial; and Chao Phraya: taken as being equal to Ramganga (259 m^3/day), given that aquifers in both regions are of similar productivity.

Table 11. Costs for surface (S) and subsurface (SS) recharge methods for the base case scenario in the Awash, Ramganga and Chao Phraya basins.

		Awash		Ramganga (NPV in USD millions)		Chao Phraya	
Recharge method		SS	S	SS	S	SS	S
Infrastructure cost	Capital	332	65	196	143	284	178
	O&M	120	25	77	56	29	19
Groundwater recovery cost	Capital	315	315	-	-	85	85
	O&M	273	273	122	122	63	63
Land use cost		0.46	0.33	14	15	17	18
Total		1,041	683	409	336	479	364
USD/m^3 [a]		0.022	0.017	0.010	0.007	0.058	0.037

Notes:
[a] Amortized cost of recharge structures (without groundwater recovery cost) per cubic meter of recharged water. Capital cost is amortized annually using the capital recovery factor specified by Ross and Hasnain (2018) and added to annual O&M costs and divided by annual DRV (m^3).

Table 12. Benefits of enhanced crop production and flood damage mitigation for the base case scenario (NPV in USD millions) in the Awash, Ramganga and Chao Phraya basins.

	Awash	Ramganga (NPV in USD millions)	Chao Phraya
Enhanced crop production	3,263	545	300
Flood damage mitigation	4	21	7,962
Total	3,267	566	8,262

Table 13. IRR and BCR values for the base case, and worst and best case scenarios in the Awash, Ramganga and Chao Phraya basins.

Scenario	Surface (S)		Subsurface (SS)	
	Awash			
	IRR	BCR	IRR	BCR
Base case	72%	3.93	41%	2.50
Worst case	33%	2.03	15%	1.20
Best case	112%	5.89	69%	3.95
	Ramganga			
	IRR	BCR	IRR	BCR
Base case	30%	1.68	20%	1.38
Worst case	-10%	0.57	-22%	0.46
Best case	70%	3.03	50%	2.52
	Chao Phraya			
	IRR	BCR	IRR	BCR
Base case	122%	22.69	102%	17.24
Worst case	112%	19.56	93%	14.59
Best case	129%	25.40	110%	19.60

Discussion

Distribution of UTFI Potential

Spatial multi-criteria mapping indicates that areas with high to very high UTFI suitability are spread across ~11% of the global landmass. These areas account for approximately 50% and 40% of the global population and crop area, respectively. A large proportion (~49%) of the world's most suitable areas are concentrated in four key regions: South Asia, Southeast Asia, East Asia and SSA. Within other regions with sparser UTFI suitability, there is considerable spatial heterogeneity. This widely distributed suitability is in line with emerging trends across the globe to consider harvesting floodwater for underground storage in aquifers from the perspectives of managing variability in water availability, disaster risk reduction and climate change adaptation. Strategic recharge of river water during long-duration floods to achieve these objectives is in contrast to other forms of MAR where flood/surface runoff is used. Examples of river water recharge include spate irrigation in arid and semi-arid regions with unpredictable floods (van Steenbergen et al. 2010) or recharge of short-duration flash floods in arid regions of Iran (Hashemi et al. 2015) and Jordan (Steinel 2012).

Figure 10 presents the eight areas and regions where the potential for using river water or floodwater for groundwater recharge are known to have been studied (as described previously in the section *Synergies with UTFI at the Global Scale*). The majority of the areas/regions show a good degree of alignment with UTFI suitability. In the lower Cornia valley (Italy) and Namoi Valley (Australia), these sites are situated on the margins of areas that are suitable for UTFI. We recognize that a global analysis, as carried out here, cannot capture the level of detail that would be possible in local studies. However, the correspondence between suitable areas in the world and floodwater recharge studies shows that the global assessment carried out here may help form the basis for further studies in other areas and regions with high UTFI suitability. The absence of studies in Central and South America, Africa and East Asia also present new research opportunities.

Further, results of the suitability analysis show that 16 of the 100 most populous river basins have high UTFI suitability. A high degree of intra-basin heterogeneity is apparent, especially for the larger river basins, which necessitates analysis at the sub-basin scale to better establish the UTFI potential at more localized scales.

While the spatial mapping indicates a high potential for UTFI in many parts of the world, it is perhaps useful to reiterate that this is only a first step towards ascertaining the actual potential for UTFI. The results of this study should be used only to assess regional- and basin-scale potential on a broad scale. Further steps are necessary that would entail more detailed studies involving more localized ground-truthing and investigations (Pavelic et al. 2015). Assessment of UTFI potential in the Ganges River Basin followed by fieldwork in specific hot spots is a good example of how broadscale assessments of this kind can be carried out. In the spatial assessment carried out in the Ganges River Basin (Brindha and Pavelic 2016), the authors used detailed datasets capturing spatial variability, including groundwater depth, transmissivity (instead of aquifer type used in this analysis) and extreme rainfall events (to disregard extreme flood events).

This was followed by field surveys to ground-truth the suitability map in selected watersheds of the Ramganga Basin. This highlights the value of carrying out sufficient basin-scale and more localized analyses to site and design UTFI accordingly, while taking account of the wider basin conditions.

The Economics of UTFI

Cost-benefit analyses from the three river basins suggest a generally high economic feasibility, if investments in UTFI are directed towards geographic areas of high suitability. The economic feasibility is spatially variable since the costs and benefits associated with UTFI vary considerably due to the diversity of hydro-climatic, agricultural and socioeconomic conditions across river basins, as well as differences in downstream urban development. This emphasizes the importance of the many factors that govern the economics of UTFI and are highly site specific. In some cases, these are associated with high levels of uncertainty, which were explored through the sensitivity analysis. IRR and BCR are highly sensitive to both the performance of groundwater recharge structures (recharge rates) and crop prices (and hence crop selection). DRV governs the number of recharge structures required and, therefore, the capital investment needed. Deriving an optimum DRV is thus essential to ensure not to overdesign the UTFI structures, which would otherwise negatively impact economic viability.

Results show that significant costs may be incurred to set up infrastructure for recharge and to recover the recharged water in areas where groundwater development is limited. Total costs become significant (USD 336-1,041 million) when UTFI implementation is considered over the vast scales of the river basins examined. High investment costs of projects such as UTFI, where capital is required at the start but benefits accrue in the future, represent a potential limitation that is particularly acute in developing countries where financial resources are highly constrained (Maliva 2014). This could be minimized by the incremental staging of projects in sub-catchments, with lessons learned from earlier phases taken into account in later phases. It would appear unlikely that investments in UTFI would be rolled out across vast tracts of land. Instead, inherent spatial variability in flood frequency, groundwater stress and drought risk at more localized levels would necessitate more focused investments where local needs and opportunities are highest as per the procedures for implementation outlined below. Land availability for UTFI structures is another critical aspect that could be a potential bottleneck. Addressing land-related issues requires detailed planning, especially in densely populated and intensively cropped basins. Using community owned lands/ponds that were formerly defunct as done for a pilot project in the Ramganga Basin in India is one possible means of dealing with this issue (Pavelic et al. 2015).

The proposition to put in place UTFI systems with the aim of providing water mainly for lower valued rural water supplies (primarily for agriculture and domestic use) as opposed to higher value urban or industrial water supply necessitates minimizing capital and O&M costs without unacceptably compromising the system performance or project goals. Maximizing the economic viability of UTFI, therefore, requires close and careful attention to project design and implementation. Sites should be selected where all the technical and non-technical prerequisite conditions are met. Without profitable and sustainable farming systems, farmers will be reluctant to engage in the collective strategies needed for UTFI implementation

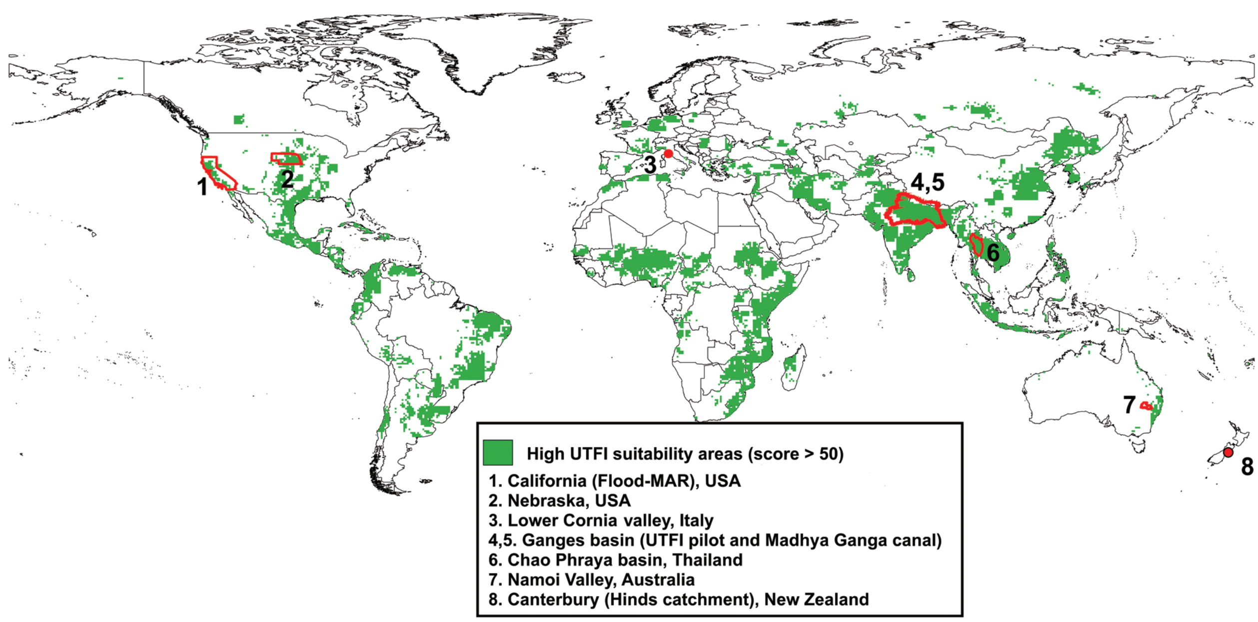


Figure 10. Locations of the eight areas/regions where the potential for using river water or floodwater for groundwater recharge has previously been studied.

Note: Areas with high UTFI suitability (score > 50) are also indicated.

and sustainable operations (Reddy et al. 2017). Farmers need to be provided with incentives, knowledge and support to pursue market-oriented, high-value irrigated cropping choices that maximize their incomes and thereby enhance project viability (Kahan 2013).

Financing UTFI projects could follow a market-based ‘beneficiary pays’ approach, whereby all the beneficiaries of improved water resources management, namely the water users and others who directly or indirectly benefit from flood and drought mitigation, contribute towards the costs of UTFI implementation (Reddy et al. 2017). This is along the principle of payments for ecosystem services (PES), where the services here encompass the disaster risk reduction associated with flood and drought mitigation through UTFI implementation (Dillaha et al. 2007; Fripp and Shantiko 2014). In developed countries, funding for water infrastructure projects is generated internally by governments and the private sector, through general revenue or by charges imposed on water users and water service providers (Maliva 2014). However, developing countries constantly struggle with limited financial resources to invest in infrastructure development projects (Gurara et al. 2017). External support to governments from international donor agencies would be vital in such cases, though not feasible or required in all countries. Financing options for project development are highly case specific and may include funding allocated to climate investments, green growth, implementation plans for the United Nations Sustainable Development Goals (SDGs) and private sector corporate social responsibility (CSR) efforts, among others.

Selected Regional Priorities and Entry Points for UTFI

There is high potential for raising agricultural production in SSA by closing yield gaps and increasing the land area under cultivation (Houmy et al. 2013; Kariuki 2011). The largely rain-fed production systems are limited by access to water during dry seasons and periods of recurrent droughts (Xie et al. 2014). High climatic variability has led to significant impacts on the region’s food and livelihood security (Sadoff et al. 2015). Groundwater irrigation in SSA covers only 1% of the cultivated area, whereas it covers 14% of the cultivated area in Asia (Siebert et al. 2010). This highlights the vast potential to expand irrigation further in SSA, especially since the region is blessed with abundant groundwater resources, which is the major source of water for domestic use (DFID, ESRC and NERC 2017; Pavelic et al. 2013). Multiple studies have acknowledged the high potential of shallow groundwater development for irrigation across SSA (Altchenko and Villholth 2015; Xie et al. 2014). Flood recession farming is already practiced throughout the region’s river floodplains and surrounding areas of wetlands and lakes to expand dry season agriculture (Everard 2016; Sidibe et al. 2016). Therefore, UTFI offers the opportunity to integrate ongoing programs on groundwater development with strategic flood mitigation, thereby enhancing agricultural production while simultaneously providing flood damage mitigation in frequently flooded major river systems (Niger, Volta and Awash). In these areas, this study presents an alternative option to dams and other infrastucture-based measures to mitigate floods and enhance water availability that could be considered. The much higher and widespread demand-based suitability (Appendix 1) relative to UTFI suitability (Figure 6) in SSA implies the need for a wider suite of measures to mitigate floods and its impacts. As groundwater irrigation development in SSA is limited, any implementation of UTFI would need to be preceded by, or carried out in parallel with, groundwater development. If this was done, it could have positive implications for food security (through increased crop production) and poverty alleviation (through disaster risk reduction), which are critical issues for SSA (Boussard et al. 2006).

The situation in the South Asia region is largely the opposite of that in SSA: high population densities, poverty and food insecurity, on the one hand, and high rates of economic growth and intensive farming, on the other (FAO 2015b; IFAD 2011; World Bank 2006). South Asia is synonymous with the most pronounced concentration of water-related risks and is also one of the most water-stressed regions of the world (Sadoff et al. 2015). Farmers rely heavily on groundwater resources from the highly productive, alluvial aquifers of the Indo-Gangetic Plains and hard-rock aquifers that underlie much of peninsular India and other areas, with a total abstraction of 253 km^3 per year (CGWB 2017) - the highest in the world. Year-round reliance on groundwater for agricultural production has led to significant levels of overexploitation (CGWB 2017; Rodell et al. 2009). In overexploited areas of India, UTFI could play a critical role in national-level programs that aim to increase water availability for irrigation, decrease overexploitation and increase resilience to climate change, e.g., National Action Plan on Climate Change (Prime Minister’s Council on Climate Change 2008); National Water Mission (Ministry of Water Resources 2011); and *Pradhan Mantri Krishi Sinchaayee Yojana* (PMKSY), which incorporates watershed management programs (Ministry of Agriculture and Farmers’ Welfare 2017). In the case of the Ganges River Basin, capturing excess water during the monsoons within the upper and middle parts of the basin (e.g., in the Indian states of Uttar Pradesh and Haryana), which are intensively irrigated with groundwater, would also help mitigate annual floods in the lower parts of the basin (e.g., in states such as Bihar and Jharkhand) (Amarasinghe et al. 2016). There is already a sufficiently strong case for UTFI in India with the government identifying UTFI as a strategic approach and envisaging investments in one – and potentially more – district-level irrigation plans over the current 5-year planning cycle (Gangopadhyay et al. 2018). As the evidence base is strengthened, it is expected that policy makers and investors in other countries and regions will request an in-depth, localized feasibility assessment of UTFI as a potential intervention when planning for climate change adaption/mitigation and disaster risk reduction.

In Southeast Asia, a vigorous monsoon often followed by an extended dry season creates the precursor for high exposure to the effects of floods and droughts. In Thailand, where extensive flood damage occurs in downstream areas of the Chao Phraya River, with water availability being limited in central areas during the dry season (Gupta 2001; Poapongsakorn and Meethom 2012), UTFI could help moderate and provide an alternative to conventional infrastructure solutions (dikes, dams, barrages) to manage floods. The average quantity of water that could be recharged to groundwater via UTFI (0.84 km^3/year) would represent the third highest storage within the basin, below only the Bhumibol and Sirikit dams (Pavelic et al. 2012).

Approach to UTFI Implementation and Management

Along with a range of benefits, implementation and management of extensive decentralized structures also bring with it new challenges and risks in the areas of land availability, financing, and O&M costs. Therefore, UTFI implementation at local scale would require further analysis not restricted to spatial and economic feasibility. This would include technical, socioeconomic, institutional and related issues, which are briefly introduced in this report but not analyzed. At the local scale, potential risks arise from the operation of individual sites. Such risks may include deterioration in groundwater quality due to poor quality recharge water, waterlogging of nearby areas, poor recharge performance due to clogging and other phenomena, and inequity in access to recharged water (Pavelic et al. 2015). Risks at the basin scale are dependent on how the positive and negative impacts associated with UTFI play out at the local level. Recharging groundwater upstream could have positive implications for flood mitigation downstream and/or negatively impact the ecosystem services provided by floods. Downstream impacts on users and opportunity costs could be an important area of contention, especially when implementing UTFI in transboundary river basins, thus necessitating the need to consider UTFI as part of overall effective transboundary water management.

Implementation of UTFI would require careful planning and staged development to overcome risks and challenges. This would, in turn, help to ensure that implementation is adaptive and responsive to local as well as basin-wide conditions and constraints, so that satisfactory outcomes are attainable. UTFI offers a larger, basin-level perspective to MAR by providing a range of benefits to upstream and downstream areas. Thus, despite the decades of experience gained from MAR implementation in countries such as India, USA, Netherlands, Australia, South Africa (CGWB 2013; Dillon et al. 2014), challenges and opportunities in relation to floodwater recharge are still clearly apparent and these may be addressed through UTFI.

In regions, countries or areas where UTFI is deemed to be potentially viable, a number of considerations and actions are needed to promote the advancement of the approach as suggested below:

- Mapping of potential for UTFI within the particular focal priority area at the finest scale based on available data and information. Suggested criteria for conducting such mapping are provided by Brindha and Pavelic (2016) and in this report.

- Identification of potentially suitable sites for UTFI implementation through local site suitability assessments. Guidance on this step was provided by Pavelic et al. (2015).

- Planning for UTFI that makes use of the most appropriate and acceptable technologies. Examples of different designs for groundwater recharge infrastructure are found in existing national guidelines for MAR referred to above.

- More detailed and rigorous assessments of economic feasibility using stochastic methods, for example, to analyze how probabilistic distributions of floods and droughts affect BCR and IRR, which would be required to support detailed designs of UTFI infrastructure with investment costs.

- Pilot-scale field testing and evaluation to establish a sound proof of concept and to demonstrate that key risks can be satisfactorily addressed. Stakeholders are critical to the success of pilots, and piloting should only proceed with the participation and support of key stakeholders. During the piloting stage, stakeholder appraisal should identify institutions that are mandated to take on field-level responsibilities pertaining to O&M, and others that may be linked and have higher levels of responsibility pertaining to regulation, licensing and monitoring.

- Capacity building of stakeholders involved in UTFI planning and management is a critical element in the proper functioning of these institutions. Building awareness of the positive benefits that emerge from UTFI is central to ensuring endorsement and support for local and high-level institutions.

- Informing and influencing policy makers and other key stakeholder groups to enable scaling up of the UTFI approach. Establishing clear guidance on how and where to implement UTFI based on adequate operational experience and tools. Handbooks and manuals that outline the minimum standards of good practice would be of value.

Conclusions

A global spatial analysis was conducted to identify areas with high suitability for UTFI implementation based on data related to three categories: water supply, water demand and water storage. Results show that areas suitable for UTFI extend across all inhabitated regions of the world. At the global level, areas with high to very high UTFI suitability cover a total land area of 1,580 Mha, and account for a population of approximately 3.8 billion people and 622 Mha of crop area, which is equivalent to approximately 50% and 40% of the global population and crop area, respectively.

Aggregating suitability scores on a basin scale shows that 16 of the 100 most populous river basins in the world have high UTFI suitability. Among the basins with high suitability, the Awash in Ethiopia, Ramganga in India (one of the major tributaries of the Ganges River Basin) and the Chao Phraya in Thailand were selected for the economic analysis in this study. Results indicate that UTFI is economically viable in all three basins, although to differing degrees with IRR values ranging from 20% to 122% for the base case scenario. Economic viability is highly sensitive to some of the underlying parameters, particularly recharge rates and crop prices. The highest economic viability was for the Chao Phraya Basin, with IRR values ranging from 93% to 129% for different scenarios of water available for recharge, recharge perfomance and crop prices. The benefits of UTFI are primarily associated with flood damage mitigation in the Chao Phraya Basin. However, in the Ramganga and Awash basins, the main benefits are derived from enhanced crop production. As UTFI benefits would be distributed spatially and across many stakeholders within any given basin, it will be critical that more detailed basin-level assessments are carried out as part of any future investment planning and feasiblity analysis, including allocation of benefits to different stakeholder groups.

UTFI cuts across a number of priority areas and sectors, including irrigation, food and water security, and disaster risk reduction, that provide multiple entry points and synergies that may aid with implemenation and in achieving greater beneficial impacts. However, working across sectors would also require overcoming existing institutional barriers with many of them working in silos.

Country-specific contexts and priorties would dictate scaling up of the UTFI approach and the purpose(s) for which it is carried out. For example, in the less-developed SSA region, UTFI could present a means to co-manage both floods and droughts together synergizing disaster risk reduction activities, while developing groundwater for irrigation to enhance crop production could drive the scaling up of UTFI in South Asia.

This study has clear limitations associated with the degree of certainty involved in the global datasets used and some of the assumptions made. The lack of independent datasets at the global level limits the opportunity for rigorous validation. However, sensitivity analysis carried out for both the spatial and economic analyses suggests that the findings are sufficiently robust and reliable to draw general conclusions about the potential for UTFI at the broadest level. This potential does not take account of future climate, urbanization and water demand, which are anticipated to have a significant impact on water-related risks and disasters in the coming decades and beyond.

The results from this study are intended to provide a first step towards identifying the broad areas (at the basin or country scale) where more detailed investigation would be worthwhile to ascertain the technical and economic feasibility of UTFI, with greater confidence. The case of the Ramganga Basin in India, where the suitability analysis was followed by ground-truthing of the results and selection of a pilot site, provides a concrete example of how this may be achieved in practice. Similar detailed studies could be carried out in other river basins identified with high UTFI suitability. Further, it is worthwhile to note that successful implementation of UTFI relies on going beyond just the technical and economic dimensions considered here. Implementation and management of UTFI are also contingent upon fully taking into account a host of social, legal, policy, institutional and environmental factors. Thus, more localized assessments would benefit greatly from the inclusion of multidisciplinary perspectives to ensure that key risks are clearly identified and addressed as these lie at the heart of successful UTFI implementation.

References

Achamyeleh, K. 2003. *Ethiopia: Integrated flood management*. WMO/GWP Associated Programme on Flood Management (APFM). Geneva, Switzerland: World Meteorological Organization (WMO).

Adeba, D.; Kansal, M.L.; Sen, S. 2015. Assessment of water scarcity and its impacts on sustainable development in Awash basin, Ethiopia. *Sustainable Water Resources Management* 1: 71-87. https://doi.org/10.1007/s40899-015-0006-7

Alam, M.F.; Pavelic, P.; Sharma, N.; Sikka, A. 2020. Managed aquifer recharge of monsoon runoff using village ponds: Performance assessment of a pilot trial in the Ramganga Basin, India. *Water* 12(4): 1028. https://doi.org/10.3390/w12041028

Altchenko, Y.; Villholth, K.G. 2015. Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. *Hydrology and Earth System Sciences* 19: 1055-1067. https://doi.org/10.5194/hess-19-1055-2015

Amarasinghe, U.A.; Muthuwatta, L.; Smakhtin, V.; Surinaidu, L.; Natarajan, R.; Chinnasamy, P.; Kakumanu, K.R.; Prathapar, S.A.; Jain, S.K.; Ghosh, N.C.; Singh, S.; Sharma, A.; Jain, S.K.; Kumar, S.; Goel, M.K. 2016. *Reviving the Ganges water machine: Potential and challenges to meet increasing water demand in the Ganges River Basin*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 42p. (IWMI Research Report 167). Available at https://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub167/rr167.pdf (accessed on March 03, 2020).

Araya, A.; Stroosnijder, L.; Girmay, G.; Keesstra, S.D. 2011. Crop coefficient, yield response to water stress and water productivity of teff (*Eragrostis tef* (Zucc.)). *Agricultural Water Management* 98 (5): 775-783. https://doi.org/10.1016/j.agwat.2010.12.001

Arshad, M.; Qureshi, M.E.; Jakeman, A.J. 2013. *Cost-benefit analysis of farm water storage: Surface storage versus managed aquifer storage*. Paper presented at the 20th International Congress on Modelling and Simulation. Adelaide, Australia, December 1-6, 2013.

Azhoni, A.; Holman, I.; Jude, S. 2017. Adapting water management to climate change: Institutional involvement, inter-institutional networks and barriers in India. *Global Environmental Change* 44: 144-157. https://doi.org/10.1016/j.gloenvcha.2017.04.005

Berhe, F.T.; Melesse, A.M.; Hailu, D.; Sileshi, Y. 2013. MODSIM-based water allocation modeling of Awash River Basin, Ethiopia. *Catena* 109: 118-128. https://doi.org/10.1016/j.catena.2013.04.007

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe); UNESCO (United Nations Educational Scientific and Cultural Organization). 2006. Groundwater resources of the world - Transboundary aquifer systems. Hannover, Germany: Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources); Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO). Available at https://www.whymap.org/whymap/EN/Maps_Data/Additional_maps/whymap_ed2006_map.pdf;jsessionid=3090598202E00DC29B145E9607B76067.2_cid292?__blob=publicationFile&v=4 (accessed June 12, 2017).

Bhavnani, R.; Vordzorgbe, S.; Owor, M.; Bousquet, F. 2008. *Report on the status of disaster risk reduction in the Sub-Saharan Africa region: January 2008*. Addis Ababa, Ethiopia: Commission of the African Union; Nairobi, Kenya: United Nations International Strategy for Disaster Reduction (UNISDR); Washington, DC, USA: The World Bank.

Bonilla Valverde, J.P.; Blank, C.; Roidt, M.; Schneider, L.; Stefan, C. 2016. Application of a GIS multi-criteria decision analysis for the identification of intrinsic suitable sites in Costa Rica for the application of managed aquifer recharge (MAR) through spreading methods. *Water* 8(9): 391. https://doi.org/10.3390/w8090391

Bouma, J.A.; Biggs, T.W.; Bouwer, L.M. 2011. The downstream externalities of harvesting rainwater in semi-arid watersheds: An Indian case study. *Agricultural Water Management* 98(7): 1162-1170. https://doi.org/10.1016/j.agwat.2011.02.010

Boussard, J.-M.; Daviron, B.; Gérard, F.; Voituriez, T. 2006. *Food security and agricultural development in sub-Saharan Africa: Building a case for more public support*. Working Paper No. 01/E. Rome, Italy: International Cooperation Centre of Agricultural Research and Development (CIRAD).

Bouwer, H. 2000. Integrated water management: Emerging issues and challenges. *Agricultural Water Management* 45(3): 217-228. https://doi.org/10.1016/S0378-3774(00)00092-5

Brindha, K.; Pavelic, P. 2016. Identifying priority watersheds to mitigate flood and drought impacts by novel conjunctive water use management. *Environmental Earth Sciences* 40(5): 407-431. https://doi.org/10.1007/s12665-015-4989-z

Brouwer, C.; Prins, K.; Kay, M.; Heibloem, M. 1985. *Irrigation water management: Irrigation methods*. Training manual no. 5. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO), Land and Water Development Division.

Calder, I.; Gosain, A.; Rao, M.S.R.M.; Batchelor, C.; Snehalatha, M.; Bishop, E. 2008. Watershed development in India. 1. Biophysical and societal impacts. *Environment, Development and Sustainability* 10: 537-557. https://doi.org/10.1007/s10668-006-9079-7

California Department of Water Resources. 2018. *Flood-MAR: Using flood water for managed aquifer recharge to support sustainable water resources*. White Paper. California, USA: California Department of Water Resources.

Carrão, H.; Naumann, G.; Barbosa, P. 2016. Mapping global patterns of drought risk: An empirical framework based on sub-national estimates of hazard, exposure and vulnerability. *Global Environmental Change* 39: 108-124. https://doi.org/10.1016/j.gloenvcha.2016.04.012

cGanga (Centre for Ganga River Basin Management and Studies); NMCG (National Mission for Clean Ganga). 2017. *Vision Ganga*. Uttar Pradesh, India: Centre for Ganga River Basin Management and Studies (cGanga), Indian Institute of Technology Kanpur; New Delhi, India: National Mission for Clean Ganga (NMCG).

CGWB (Central Ground Water Board). 2013. *Master plan for artificial recharge to ground water in India*. New Delhi, India: Central Ground Water Board (CGWB), Ministry of Water Resources, Government of India.

CGWB. 2014. *Ground water year book – India, 2013-14*. Haryana, India: Central Ground Water Board (CGWB), Ministry of Water Resources, Government of India.

CGWB. 2017. *Dynamic groundwater resources of India (as on 31st March, 2013)*. Haryana, India: Central Ground Water Board (CGWB), Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India.

Changming, L.; Jingjie, Y.; Kendy, E. 2001. Groundwater exploitation and its impact on the environment in the North China Plain. *Water International* 26(2): 265-272. https://doi.org/10.1080/02508060108686913

Chen, Y.; Yu, J.; Shahbaz, K.; Xevi, E. 2009. *A GIS-based sensitivity analysis of multi-criteria weights*. Paper presented at the 18th World IMACS / MODSIM Congress, July 13-17, 2009, Cairns, Australia.

Chen, Y.; Yu, J.; Khan, S. 2010. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. *Environmental Modelling & Software* 25(12): 1582-1591. https://doi.org/10.1016/j.envsoft.2010.06.001

Chengrui, M.; Dregne, H.E. 2001. Review article: Silt and the future development of China's Yellow River. *The Geographical Journal* 167(1): 7-22. https://doi.org/10.1111/1475-4959.00002

Chenini, I.; Mammou, A.B. 2010. Groundwater recharge study in arid region: An approach using GIS techniques and numerical modeling. *Computers & Geosciences* 36(6): 801-817. https://doi.org/10.1016/j.cageo.2009.06.014

Chinnasamy, P.; Muthuwatta, L.; Eriyagama, N.; Pavelic, P.; Lagudu, S. 2018. Modeling the potential for floodwater recharge to offset groundwater depletion: A case study from the Ramganga basin, India. *Sustainable Water Resources Management* 4(2): 331-344. https://doi.org/10.1007/s40899-017-0168-6

CHRR (Center for Hazards and Risk Research, Columbia University); CIESIN (Center for International Earth Science Information Network, Columbia University). 2005a. *Global flood hazard frequency and distribution*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4668B3D (accessed October 10, 2016).

CHRR; CIESIN; IBRD (International Bank for Reconstruction and Development, The World Bank). 2005b. *Global flood total economic loss risk deciles*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4T151KP (accessed October 10, 2016).

CHRR; CIESIN; IBRD. 2005c. *Global flood mortality risks and distribution*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H42F7KCP (accessed October 10, 2016).

CHRR; CIESIN; IBRD. 2005d. *Global drought total economic loss risk deciles*. Palisades, NY: NASA Socioeconomic Data and Applications Center SEDAC). http://dx.doi.org/10.7927/H4GQ6VP4 (accessed October 10, 2016).

CHRR; CIESIN; IBRD. 2005e. *Global drought mortality risks and distribution*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4R49NQV (accessed October 10, 2016).

CHRR; CIESIN; IRI (International Research Institute for Climate and Society, Columbia University). 2005f. *Global drought hazard frequency and distribution*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4VX0DFT (accessed October 10, 2016).

CIESIN (Center for International Earth Science Information Network, Columbia University). 2016. *Gridded population of the world, version 4 (GPWv4): Population density*. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H4NP22DQ (accessed May 23, 2017).

Commission for Agricultural Costs and Prices. 2015. *Price policy for Kharif crops: The marketing season 2015-16*. New Delhi, India: Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India.

CRED (Centre for Research on the Epidemiology of Disasters); UNISDR (United Nations Office for Disaster Risk Reduction). 2015. *The human cost of weather related disasters: 1995-2015*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNISDR); Brussels, Belgium: Centre for Research on the Epidemiology of Disasters (CRED).

Delgado, M.G.; Sendra, J.B. 2004. Sensitivity analysis in multicriteria spatial decision-making: A review. *Human and Ecological Risk Assessment: An International Journal* 10(6): 1173-1187. https://doi.org/10.1080/10807030490887221

Department of Land Development and Water Resources. 2009. *Integrated watershed management programme (I.W.M.P.) in Uttar Pradesh: Perspective and strategic plan 2009-2027*. India: Department of Land ic and Social Research Council); NERC (Natural Environment Research Council). 2017. UPGro – Unlocking the Potential of Groundwater for the Poor. Website. Available at https://upgro.org/ (accessed on July 18, 2017).

DHI. 2016. *Flood and drought management tools: Chao Phraya basin*. Factsheet. Global Environment Facility (GEF); United Nations Environment Programme (UNEP); International Water Association (IWA); DHI.

Dillaha, T.; Ferraro, P.; Huang, M.; Southgate, D.; Upadhyaya, S.; Wunder, S. 2007. *Payments for watershed services regional syntheses*. USAID PES Brief No. 7. Blacksburg, Virginia, USA: Office of International Research, Education, and Development (OIRED). 18p.

Dilley, M.; Chen, R.S.; Deichmann, U.; Lerner-Lam, A.L.; Arnold, M.; Agwe, J.; Buys, P.; Kjevstad, O.; Lyon, B.; Yetman, G. 2005. *Natural disaster hotspots: A global risk analysis*. Disaster Risk Management Series No. 5. Washington, DC: The World Bank.

Dillon, P.J. 2005. Future management of aquifer recharge. *Hydrogeology Journal* 13(1): 313-316. https://doi.org/10.1007/s10040-004-0413-6

Dillon, P.; Page, D.; Dandy, G.; Leonard, R.; Tjandraatmadja, G.; Vanderzalm, J.; Rouse, K.; Barry, K.; Gonzalez, D.; Myers, B. 2014. *Managed aquifer recharge and urban stormwater use options: Summary of research findings*. Technical Report Series No. 14/13. Adelaide, Australia: Goyder Institute for Water Research. 42p.

Dillon, P.; Stuyfzand, P.; Grischek, T.; Lluria, M.; Pyne, R.D.G.; Jain, R.C.; Bear, J.; Schwarz, J.; Wang, W.; Fernandez, E.; Stefan, C.; Pettenati, M.; van der Gun, J.; Sprenger, C.; Massmann, G.; Scanlon, B.R.; Xanke, J.; Jokela, P.; Zheng, Y.; Rossetto, R.; Shamrukh, M.; Pavelic, P.; Murray, E.; Ross, A.; Bonilla Valverde, J.P.; Palma Nava, A.; Ansems, N.; Posavec, K.; Ha, K.; Martin, R.; Sapiano, M. 2019. Sixty years of global progress in managed aquifer recharge. *Hydrogeology Journal* 27: 1-30. https://doi.org/10.1007/s10040-018-1841-z

Dingel, C.C.; Tiwari, A. 2010. *Report on the status of disaster risk reduction in sub-Saharan Africa*. Washington, DC, USA: The World Bank/Global Facility for Disaster Reduction and Recovery (GFDRR).

Döll, P.; Schmied, H.M.; Schuh, C.; Portmann, F.T.; Eicker, A. 2014. Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. *Water Resources Research* 50(7): 5698-5720. https://doi.org/10.1002/2014WR015595

Droogers, P.; Immerzeel, W.W.; Terink, W.; Hoogeveen, J.; Bierkens, M.F.P.; van Beek, L.P.H.; Debele, B. 2012. Water resources trends in Middle East and North Africa towards 2050. *Hydrology and Earth System Sciences* 16: 3101-3114. https://doi.org/10.5194/hess-16-3101-2012

Edossa, D.C.; Babel, M.S.; Das Gupta, A. 2010. Drought analysis in the Awash River Basin, Ethiopia. *Water Resources Management* 24: 1441-1460. https://doi.org/10.1007/s11269-009-9508-0

Eriyagama, N.; Muthuwatta, L.; Thilakarathne, M. 2014. Minimizing flood damage and augmenting dry season water availability: Prospects for floodwater harvesting and underground storage in Sri Lanka. In: *Proceedings of the Disaster Management Conference: The Future We Want - Safer Sri Lanka, Colombo, Sri Lanka, September 24-26, 2014*. Colombo, Sri Lanka: Ministry of Disaster Management. pp. 379-381.

ESRI (Environmental Systems Research Institute). 2017. World cities. Available at https://hub.arcgis.com/datasets/6996f03a1b364dbab4008d99380370ed_0?geometry=-472.723%2C-66.873%2C475.793%2C82.375 (accessed October 27, 2018).

Ethiopian Grain Trade Enterprise. 2018. Commodity statistics for free. Website. Available at https://www.egte-ethiopia.com/en/in-t-market/commodity-statistics.html (accessed on May 7, 2020).

Ethiopian Investment Agency. 2012. *Factor costs*. Available at http://ethemb.se/wp-content/uploads/2013/07/FACTOR_COSTS.pdf (accessed on March 29, 2020).

Evans, W.R.; Evans, R.S.; Holland, G. 2012. *Conjunctive use and management of groundwater and surface water within existing irrigation commands: The need for a new focus on an old paradigm*. Groundwater Governance - A Global Framework for Action. Thematic Paper No. 2.

Everard, M. 2016. Flood recession agriculture: Case studies. *In: The wetland book*, (eds.) Finlayson, C.M.; Everard, M.; Irvine, K.; McInnes, R.J.; Middleton, B.A; van Dam, A.A.; Davidson, N.C. Dordrecht: Springer. pp. 1-4.

Fan, Y.; Li, H.; Miguez-Macho, G. 2013. Global patterns of groundwater table depth. *Science* 339(6122): 940-943. https://doi.org/10.1126/science.1229881

FAO (Food and Agriculture Organization of the United Nations). 1997. *Irrigation potential in Africa: A basin approach*. FAO Land and Water Bulletin 4. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

FAO. 2015a. *The impact of natural hazards and disasters on agriculture, food security and nutrition*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

FAO. 2015b. *FAO statistical pocketbook 2015*. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO). 236p.

FAO. 2017. Traditional crops: Teff. Web page. Rome, Italy: Food and Agriculture Organization of United Nations (FAO). Available at http://www.fao.org/traditional-crops/teff/en/ (accessed on May 22, 2017).

Fripp, E.; Shantiko, B. 2014. *Payment for Ecosystem Services (PES): Assessment of PES potential in Kapuas Hulu*. CIFOR Working Paper 165. Bogor, Indonesia: Center for International Forestry Research (CIFOR).

Gangopadhyay, P.K.; Sharma, B.R.; Pavelic, P. 2018. Co-solving groundwater depletion and seasonal flooding through an innovative managed aquifer recharge approach: Converting pilot to a regional solution in the Ram Ganga Sub-basin. In: *Clean and sustainable groundwater in India*, (eds.) Saha, D.; Marwaha, S.; Mukherjee, A. Springer Hydrogeology. Singapore: Springer. pp. 173-189. https://doi.org/10.1007/978-981-10-4552-3_12

Gassert, F.; Reig, P.; Luo, T.; Maddocks, A. 2013a. *Aqueduct country and river basin rankings: A weighted aggregation of spatially distinct hydrological indicators*. Working Paper. Washington, DC: World Resources Institute (WRI).

Gassert, F.; Luo, T.; Shiao, T.; Luck, M. 2013b. *Yellow river basin study*. Working Paper. Washington, DC: World Resources Institute (WRI).

Gebregziabher, G.; Hagos, F.; Haileslassie, A.; Getnet, K.; Hoekstra, D.; Gebremedhin, B.; Bogale, A.; Getahun, Y. 2016. *Does investment in motor pump-based smallholder irrigation lead to financially viable input intensification and production? An economic assessment*. Livestock and Irrigation Value Chains for Ethiopian Smallholders (LIVES) Working Paper 13. Nairobi, Kenya: International Livestock Research Institute (ILRI). 28p.

Getahun, Y.S.; Gebre, S.L. 2015. Flood hazard assessment and mapping of flood inundation area of the Awash River Basin in Ethiopia using GIS and HEC-GeoRAS/HEC-RAS model. *Journal of Civil and Environmental Engineering* 5(4): 179. https://dx.doi.org/10.4172/2165-784X.1000179

Gheewala, S.H.; Silalertruksa, T.; Nilsalab, P.; Mungkung, R.; Perret, S.R.; Chaiyawannakarn, N. 2014. Water footprint and impact of water consumption for food, feed, fuel crops production in Thailand. *Water* 6(6): 1698-1718. https://doi.org/10.3390/w6061698

Gibson, K.; Brozović, N. 2018. *Managed aquifer recharge (MAR) in Nebraska: Using flood river flows to recharge groundwater for irrigation and enhance aquatic habitats*. Case study on Groundwater-based Natural Infrastructure for the Groundwater Solutions Initiative for Policy and Practice (GRIPP). Available at http://gripp.iwmi.org/natural-infrastructure/water-storage/managed-aquifer-recharge-mar-in-nebraska/ (accessed on February 26, 2020).

Golder Associates. 2017. *Hinds managed aquifer recharge pilot trial: Phase 1 report*. Report number: 1538632-7410-024-R-Rev2. Auckland, New Zealand: Golder Associates.

Guha-Sapir, D.; Below, R.; Hoyois, P. 2015. EM-DAT: The CRED/OFDA International Disaster Database. Brussels, Belgium: Université Catholique de Louvain.

Gunatilake, H.M. 2013. *Cost-benefit analysis for development: A practical guide*. Mandaluyong City, Metro Manila, Philippines: Asian Development Bank (ADB).

Gupta, A.D. 2001. Challenges and opportunities for water resources management in Southeast Asia. *Hydrological Sciences Journal* 46(6): 923-935. https://doi.org/10.1080/02626660109492886

Gupta, S. 2010. *Synthesis report on ten ASEAN countries disaster risks assessment*. ASEAN Disaster Risk Management Initiative. Geneva, Switzerland: United Nations International Strategy for Disaster Reduction (UNISDR)/Washington, DC, USA: World Bank.

Gurara, D.; Klyuev, V.; Mwase, N.; Presbitero, A.F.; Xu, X.C.; Bannister, G.J. 2017. *Trends and challenges in infrastructure investment in low-income developing countries*. IMF Working Paper No. 17/233. Washington, DC, USA: International Monetary Fund (IMF).

GWP (Global Water Partnership). 2012. *Groundwater resources and irrigated agriculture - Making a beneficial relation more sustainable*. GWP Perspectives Paper. Stockholm, Sweden: Global Water Partnership (GWP).

Hall, J.W.; Grey, D.; Garrick, D.; Fung, F.; Brown, C.; Dadson, S.J.; Sadoff, C.W. 2014. Coping with the curse of freshwater variability. *Science* 346(6208): 429-430. http://dx.doi.org/10.1126/science.1257890

Hashemi, H.; Berndtsson, R.; Persson, M. 2015. Artificial recharge by floodwater spreading estimated by water balances and groundwater modelling in arid Iran. *Hydrological Sciences Journal* 60(2): 336-350. https://doi.org/10.1080/02626667.2014.881485

Hoekstra, A.Y.; Mekonnen, M.M.; Chapagain, A.K.; Mathews, R.E.; Richter, B.D. 2012. Global monthly water scarcity: Blue water footprints versus blue water. *PLoS ONE* 7(2): e32688. https://doi.org/10.1371/journal.pone.0032688

Houmy, K.; Clarke, L.J.; Ashburner, J.E.; Kienzle, J. 2013. *Agricultural mechanization in sub-Saharan Africa: Guidelines for preparing a strategy.* Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

IFAD (International Fund for Agricultural Development). 2011. *Agriculture - Pathways to prosperity in Asia and the Pacific*. Rome, Italy: Asia and the Pacific Division, International Fund for Agricultural Development (IFAD).

IFAD. 2015. *Economic and financial analysis of rural investment projects: Basic concepts and rationale*. IFAD'S Internal Guidelines. Rome, Italy: International Fund for Agricultural Development (IFAD).

IIT (Indian Institutes of Technology). 2012. *Floral and faunal diversity of River Ramganga*. GRBMP: Ganga River Basin Management Plan. Indian Institutes of Technology.

INOWAS (Innovative Web-based Decision Support System for Water Sustainability Under a Changing Climate). 2018. Database for GIS-based suitability mapping – INOWAS. Available at https://inowas.com/tools/t04-database-for-gis-mcda/ (accessed on February 27, 2020).

IPCC (Intergovernmental Panel on Climate Change). 2012. *Managing the risk of extreme events and disasters to advance climate change adaptation*, (eds.) Field, C.B.; Barros, V.; Stocker, T.F.; Qin, D.; Dokken, D.J.; Ebi, K.L.; Mastrandrea, M.D.; Mach, K.J.; Plattner, G.-K.; Allen, S.K.; Tignor, M.; Midgley, P.M. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY, USA: Cambridge University Press. 582p.

IWMI (International Water Management Institute)-Tata Water Policy Program. 2002. *Innovations in groundwater recharge*. Vallabh Vidyanagar, Gujarat, India: International Water Management Institute (IWMI). 8p. (IWMI Water Policy Briefing 001). Available at http://www.iwmi.cgiar.org/Publications/Water_Policy_Briefs/PDF/wpb01.pdf (accessed on February 26, 2020).

Jeong, J.S.; Ramírez-Gómez, Á. 2017. A multicriteria GIS-based assessment to optimize biomass facility sites with parallel environment—A Case Study in Spain. *Energies* 10(12): 2095. https://doi.org/10.3390/en10122095

Joodaki, G.; Wahr, J.; Swenson, S. 2014. Estimating the human contribution to groundwater depletion in the Middle East, from GRACE data, land surface models, and well observations. *Water Resources Research* 50(3): 2679-2692. https://doi.org/10.1002/2013WR014633

Kahan, D. 2013. *Market-oriented farming: An overview*. Farm Management Extension Guide Series. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Kale, V.S. 2003. Geomorphic effects of monsoon floods on Indian rivers. In: *Flood problem and management in South Asia*, (eds.) Mirza, M.M.Q.; Dixit, A.; Nishat, A. Dordrecht, The Netherlands: Springer. pp. 65-84.

Kariuki, J.G. 2011. *The future of agriculture in Africa.* Boston, Massachusetts, USA: Boston University.

Khalid, M.A.; Mehar, M.; Nair, P. 2004. *Impact assessment study of the watershed development programme: A compendium*. New Delhi, India: The Energy and Resources Institute.

Khan, R.M.; Voss, C.I.; Yu, W.; Michael, H.A. 2014. Water resources management in the Ganges Basin: A comparison of three strategies for conjunctive use of groundwater and surface water. *Water Resources Management* 28(5): 1235-1250. https://doi.org/10.1007/s11269-014-0537-y

Kure, S.; Tebakari, T. 2012. Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand. *Hydrological Research Letters* 6: 53-58. https://doi.org/10.3178/hrl.6.53

Kwanyuen, B.; Mainuddin, M.; Cherdchanpipat, N. 2003. Socio-ecology of groundwater irrigation in Thailand. In: *KU-IWMI Seminar on Scientific Cooperation, Kamphol Adulavidhaya Conference Room, Kasetsart University, Bangkok, Thailand, March 26, 2003*. pp. 23-41.

Langdon & Seah (Thailand) Ltd. 2013. *Construction cost handbook Thailand 2013*. Bangkok, Thailand: Langdon & Seah (Thailand) Ltd.; and LECE (Thailand) Co., Ltd.

Lehner, B.; Verdin, K.; Jarvis, A. 2011. New global hydrography derived from spaceborne elevation data. *Eos, Transactions, American Geophysical Union* 89(10): 93-94. https://doi.org/10.1029/2008EO100001

LIFE-REWAT (Sustainable water management in the lower Cornia valley). 2018. Actions and result. Available at http://www.liferewat.eu/en/download.html (accessed on August 21, 2018).

Loo, Y.Y.; Billa, L.; Singh, A. 2015. Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia. *Geoscience Frontiers* 6(6): 817-823. https://doi.org/10.1016/j.gsf.2014.02.009

MacDonald, A.M.; Bonsor, H.C.; Dochartaigh, B.É.Ó; Taylor, R.G. 2012. Quantitative maps of groundwater resources in Africa. *Environmental Research Letters* 7(2). https://doi.org/10.1088/1748-9326/7/2/024009

MacDonald, A.M.; Bonsor, H.C.; Taylor, R.; Shamsudduha, M.; Burgess, W.G.; Ahmed, K.M.; Mukherjee, A.; Zahid, A.; Lapworth, D.; Gopal, K.; Rao, M.S.; Moench, M.; Bricker, S.H.; Yadav, S.K.; Satyal, Y.; Smith, L.; Dixit, A.; Bell, R.; van Steenbergen, F.; Basharat, M.; Gohar, M.S.; Tucker, J.; Calow, R.C.; Maurice L. 2015. *Groundwater resources in the Indo-Gangetic Basin: Resilience to climate change and abstraction*. British Geological Survey Open Report, OR/15/047. Nottinghamshire, UK: British Geological Survey (BGS), Natural Environment Research Council (NERC).

Maliva, R.G. 2014. Economics of managed aquifer recharge. *Water* 6(5): 1257-1279. https://doi.org/10.3390/w6051257

Margat, J.; van der Gun, J. 2013. *Groundwater around the World: A geographic synopsis*. Leiden, The Netherlands: CRC Press. 376p.

McCartney, M.; Smakhtin, V. 2010. *Water storage in an era of climate change: Addressing the challenge of increasing rainfall variability*. Blue paper. Colombo, Sri Lanka: International Water Management Institute (IWMI). Available at http://www.iwmi.cgiar.org/Publications/Blue_Papers/PDF/Blue_Paper_2010-final.pdf (accessed on May 7, 2020).

Mendelsohn, R. 2008. The impact of climate change on agriculture in developing countries. *Journal of Natural Resources Policy Research* 1(1): 5-19. https://doi.org/10.1080/19390450802495882

Ministry of Agriculture and Farmers' Welfare. 2017. Pradhan Mantri Krishi Sinchayee Yojana. Website. Available at http://pmksy.gov.in/ (accessed on April 26, 2017).

Ministry of Water Resources. 2011. *National Water Mission under National Action Plan on Climate Change*. Comprehensive Mission Document Volume - 1. New Delhi, India: Ministry of Water Resources. Available at http://nwm.gov.in/sites/default/files/nwm16606419934.pdf (accessed on April 26, 2017).

Mirza, M.M.Q.; Warrick, R.A.; Ericksen, N.J.; Kenny, G.J. 2001. Are floods getting worse in the Ganges, Brahmaputra and Meghna basins? *Global Environmental Change Part B: Environmental Hazards* 3(2): 37-48. https://doi.org/10.1016/S1464-2867(01)00019-5

Miyan, M.A. 2015. Droughts in Asian least developed countries: Vulnerability and sustainability. *Weather and Climate Extremes* 7: 8-23. https://doi.org/10.1016/j.wace.2014.06.003

Molle, F. 2002. *The closure of the Chao Phraya River Basin in Thailand: Its causes, consequences and policy implications.* Paper presented at the Conference on Asian Irrigation in Transition: Responding to the Challenges Ahead, Asian Institute of Technology, Bangkok, Thailand, April 22-23, 2002. 15p.

Molle, F.; Chompadist, C.; Srijantr, T.; Keawkulaya, J. 2001. *Dry-season water allocation and management in the Chao Phraya Delta*. Bangkok, Thailand: Kasetsart University, DORAS Center. DORAS-DELTA Research Report No. 8. 278p.

Mukherjee, A.; Saha, D.; Harvey, C.F.; Taylor, R.G.; Ahmed, K.M.; Bhanja, S.N. 2015. Groundwater systems of the Indian Sub-Continent. *Journal of Hydrology: Regional Studies* 4(Part A): 1-14. https://doi.org/10.1016/j.ejrh.2015.03.005

Mukherjee, S.; Biswas, D. 2016. An enquiry into equity impact of groundwater markets in the context of subsidised energy pricing: A case study. *IIM Kozhikode Society & Management Review* 5(1): 63-73. https://doi.org/10.1177/2277975215618329

National Disaster Management Authority. 2008. *National disaster management guidelines: Management of floods*. New Delhi, India: National Disaster Management Authority, Government of India.

Nune, R.; George, B.A.; Teluguntla, P.; Western, A.W. 2014. Relating trends in streamflow to anthropogenic influences: A case study of Himayat Sagar Catchment, India. *Water Resources Management* 28: 1579-1595. https://doi.org/10.1007/s11269-014-0567-5

O'Geen, A.T.; Saal, M.B.B.; Dahlke, H.E.; Doll, D.; Elkins, R.B.; Fulton, A.; Fogg, G.E.; Harter, T.; Hopmans, J.W.; Ingels, C.; Niederholzer, F.J.; Solis, S.S.; Verdegaal, P.S.; Walkinshaw, M. 2015. Soil suitability index identifies potential areas for groundwater banking on agricultural lands. *California Agriculture* 69(2): 75-84. https://doi.org/10.3733/ca.v069n02p75

Office of Agricultural Economics. 2018. Agricultural economic information: Agriculture product prices. Website. Bangkok, Thailand: Ministry of Agriculture and Cooperatives. Available at https://bit.ly/2KBJzb2 (accessed on May 7, 2020).

ONWRC (Office of National Water Resources Committee, Thailand). 2003. Pilot case studies: A focus on real-world examples: Chao Phraya River Basin, Thailand. Chapter 16 in *Water for people, water for life: The United Nations world water development report; a joint report by the twenty-three UN agencies concerned with freshwater.* Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO), World Water Assessment Programme (WWAP). pp. 387-400.

Palenberg, M. 2011. *Tools and methods for evaluating the efficiency of development interventions*. Bonn, Germany: Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (BMZ).

Pavelic, P.; Srisuk, K.; Saraphirom, P.; Nadee, S.; Pholkern, K.; Chusanathas, S.; Munyou, S.; Tangsutthinon, T.; Intarasut, T.; Smakhtin, V. 2012. Balancing-out floods and droughts: Opportunities to utilize floodwater harvesting and groundwater storage for agricultural development in Thailand. *Journal of Hydrology* 470-471: 55-64. https://doi.org/10.1016/j.jhydrol.2012.08.007

Pavelic, P.; Villholth, K.G.; Verma, S. 2013. Identifying the barriers and pathways forward for expanding the use of groundwater for irrigation in Sub-Saharan Africa. *Water International* 38(4): 363-368. https://doi.org/10.1080/02508060.2013.821643

Pavelic, P.; Brindha, K.; Amarnath, G.; Eriyagama, N.; Muthuwatta, L.; Smakhtin, V.; Gangopadhyay, P.K.; Malik, R.P.S.; Mishra, A.; Sharma, B.R.; Hanjra, M.A.; Reddy, R.V.; Mishra, V.K.; Verma, C.L.; Kant, L. 2015. *Controlling floods and droughts through underground storage: From concept to pilot implementation in the Ganges River Basin*. Colombo, Sri Lanka: International Water Management Institute (IWMI). 33p. (IWMI Research Report 165). Available at http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/pub165/rr165.pdf (accessed on February 13, 2020).

Poapongsakorn, N.; Meethom, P. 2012. Impact of the 2011 floods, and flood management in Thailand. In: *Economic and welfare impacts of disasters in East Asia and policy responses*, (eds.) Sawada, Y.; Oum, S. ERIA Research Project Report 2011, No. 8. Jakarta, Indonesia: Economic Research Institute for ASEAN and East Asia (ERIA). pp. 247-310.

Prathapar, S.; Dhar, S.; Rao, G.T.; Maheshwari, B. 2015. Performance and impacts of managed aquifer recharge interventions for agricultural water security: A framework for evaluation. *Agricultural Water Management* 159: 165-175. https://doi.org/10.1016/j.agwat.2015.06.009

Prime Minister's Council on Climate Change. 2008. *National action plan on climate change (NAPCC)*. New Delhi, India: Prime Minister's Council on Climate Change, Government of India. Available at http://www.nicra-icar.in/nicrarevised/images/Mission%20Documents/National-Action-Plan-on-Climate-Change.pdf (accessed on May 7, 2020).

Qureshi, A.S.; McCornick, P.G.; Sarwar, A.; Sharma, B.R. 2010. Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan. *Water Resources Management* 24(8): 1551-1569. https://doi.org/10.1007/s11269-009-9513-3

Rahman, M.A.; Rusteberg, B.; Gogu, R.C.; Lobo Ferreira, J.P.; Sauter, M. 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. *Journal of Environmental Management* 99: 61-75. https://doi.org/10.1016/j.jenvman.2012.01.003

Rajmohan, N.; Amarasinghe, U.A. 2016. Groundwater quality issues and management in Ramganga Sub-Basin. *Environmental Earth Sciences* 75(1030). https://doi.org/10.1007/s12665-016-5833-9

Ramankutty, N.; Evan, A.T.; Monfreda, C.; Foley, J.A. 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global Biogeochemical Cycles* 22(1): 19. https://doi.org/10.1029/2007GB002952

Rawluk, A.; Curtis, A.; Sharp, E.; Kelly, B.F.J.; Jakeman, A.J.; Ross, A.; Arshad, M.; Brodie, R.; Pollino, C.A.; Sinclair, D.; Croke, B.; Qureshi, M.E. 2013. Managed aquifer recharge in farming landscapes using large floods: An opportunity to improve outcomes for the Murray-Darling Basin? *Australasian Journal of Environmental Management* 20(1): 34-48. https://doi.org/10.1080/14486563.2012.724785

Ray, D.K.; Foley, J.A. 2013. Increasing global crop harvest frequency: Recent trends and future directions. *Environmental Research Letters* 8(4). https://dx.doi.org/10.1088/1748-9326/8/4/044041

Reddy, V.R.; Rout, S.K.; Pavelic, P. 2017. Underground taming of floods in the Ganges basin: technologies, institutions and policies. In: *Proceedings of the 10th World Congress on Water Resources and Environment, "Panta Rhei", Athens, Greece, July 5-9, 2017*, (eds.) Tsakiris, G.; Tsihrintzis, V.A.; Vangelis, H.; Tigkas, D. Athens, Greece: European Water Resource Association. pp. 2061-2067.

Reddy, V.R.; Pavelic, P.; Hanjra, M.A. 2018. Underground taming of floods for irrigation (UTFI) in the river basins of South Asia: Institutionalising approaches and policies for sustainable water management and livelihood enhancement. *Water Policy* 20(2): 369-387. https://doi.org/10.2166/wp.2017.150

Richts, A.; Struckmeier, W.F.; Zaepke, M. 2011. WHYMAP and the groundwater resources map of the world 1:25,000,000. In: *Sustaining groundwater resources: A critical element in the global water crisis*, (ed.) Jones, J.A. Dordrecht, Netherlands: Springer. pp. 159-173.

Rodell, M.; Velicogna, I.; Famiglietti, J.S. 2009. Satellite-based estimates of groundwater depletion in India. *Nature* 460(7258): 999-1002. https://doi.org/10.1038/nature08238.

Ross, A. 2012. Easy to say, hard to do: Integrated surface water and groundwater management in the Murray–Darling Basin. *Water Policy* 14(4): 709-724. https://doi.org/10.2166/wp.2012.129

Ross, A.; Hasnain, S. 2018. Factors affecting the cost of managed aquifer recharge (MAR) schemes. *Sustainable Water Resources Management* 4: 179-190. https://doi.org/10.1007/s40899-017-0210-8

Russo, T.A.; Fisher, A.T.; Lockwood, B.S. 2015. Assessment of managed aquifer recharge site suitability using a GIS and modeling. *Groundwater* 53(3): 389-400. https://doi.org/10.1111/gwat.12213

RWSN (Rural Water Supply Network). 2006. *Drilling for water in Ethiopia: A country case-study by the cost-effective boreholes flagship of the Rural Water Supply Network*. Volume 1: Main report. Switzerland: Rural Water Supply Network (RWSN), Skat Foundation.

Sadoff, C.W.; Hall, J.W.; Grey, D.; Aerts, J.C.J.H.; Ait-Kadi, M.; Brown, C.; Cox, A.; Dadson, S.; Garrick, D.; Kelman, J.; McCornick, P.; Ringler, C.; Rosegrant, M.; Whittington, D.; Wiberg, D. 2015. *Securing water, sustaining growth*. Report of the GWP/OECD Task Force on Water Security and Sustainable Growth. Oxford, UK: University of Oxford. 180p.

Scanlon, B.R.; Faunt, C.C.; Longuevergne, L.; Reedy, R.C.; Alley, W.M.; McGuire, V.L.; McMahon, P.B. 2012. Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *PNAS* 109(24): 9320-9325. https://doi.org/10.1073/pnas.1200311109

Sharma, B.R.; Amarasinghe, U.A.; Cai, X. 2009. *Assessing and improving water productivity in conservation agriculture systems in the Indus-Gangetic Basin*. Invited lead paper presented at the 4th World Congress on Conservation Agriculture Innovations for Improving Efficiency, Equity and Environment, Session 1.4, Irrigated systems, National Academy of Agricultural Sciences, NASC Complex, Pusa, New Delhi, India, February 4-7, 2009. 12p.

Sidibe, Y.; Williams, T.O.; Kolavalli, S. 2016. *Flood recession agriculture for food security in Northern Ghana: Literature review on extent, challenges, and opportunities*. GSSP Working Paper 42. Washington, DC, USA: International Food Policy Research Institute (IFPRI); Addis Ababa, Ethiopia: Ethiopian Development Research Institute (EDRI).

Siebert, S.; Burke, J.; Faures, J.M.; Frenken, K.; Hoogeveen, J.; Döll, P.; Portmann, F.T. 2010. Groundwater use for irrigation – a global inventory. *Hydrology and Earth System Sciences* 14: 1863-1880. https://doi.org/10.5194/hess-14-1863-2010

Smakhtin, V.; Pavelic, P.; Amarnath, G.; McCartney, M. 2015. *Managing water variability, from floods to droughts*. Brief for Global Sustainable Development Report (GSDR) 2015. New York, USA: United Nations Department of Economic and Social Affairs.

Steinel, A. 2012. *Guideline for assessment and implementation of Managed Aquifer Recharge (MAR) in (semi-)arid regions - Pre-feasibility study for infiltration of floodwater in the Amman-Zarqa and Azraq basins, Jordan*. Final report of GeoSFF study "MAR in Jordan" prepared by MWI & BGR. 220p. Hanover, Germany: Federal Institute for Geosciences and Natural Resources (BGR).

Taddesse, G.; McCornick, P.G.; Peden, D. 2004. Economic importance and environmental challenges of the Awash River Basin to Ethiopia. In: *Proceedings of Water Rights and Related Water Supply Issues, Water Management Conference, United States Committee on Irrigation and Drainage, Salt Lake City, Utah, USA, October 13-16, 2004*. pp. 257-268.

Tripathi, A.K. 2009. *District ground water brochure of Rampur district, U.P.* New Delhi, India: Central Ground Water Board (CGWB).

Tsunokawa, K. 2010. *Road projects cost benefit analysis: Scenario analysis of the effect of varying inputs*. Transport Research Support Program. Washington, DC, USA: World Bank.

Turral, H.; Burke, J.J.; Faurès, J.M. 2011. *Climate change, water and food security*. FAO Water Reports No. 36. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Tyagi, N.K.; Sharma, D.K.; Luthra, S.K. 2000. Determination of evapotranspiration and crop coefficients of rice and sunflower with lysimeter. *Agricultural Water Management* 45(1): 41-54. https://doi.org/10.1016/S0378-3774(99)00071-2

United Nations. 2017. Geographic regions. New York, USA: Statistics Division, United Nations Department of Economic and Social Affairs (UN DESA). Available at https://unstats.un.org/unsd/methodology/m49/ (accessed July 10, 2017).

van Aalst, M.; Kellett, J.; Pichon, F.; Mitchell, T. 2013. *Incentives in disaster risk management and humanitarian response.* Background note for World Development Report 2014. Washington, DC, USA: World Bank.

van der Gun, J. 2012. *Groundwater and global change: Trends, opportunities and challenges*. Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO).

van Steenbergen, F.; Lawrence, P.; Haile, A.M.; Salman, M.; Faurès, J.-M. 2010. *Guidelines on spate irrigation*. FAO Irrigation and Drainage Paper 65. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).

Vanderzalm, J.L.; Dillon, P.J.; Tapsuwan, S.; Pickering, P.; Arold, N.; Bekele, E.B.; Barry, K.E.; Donn, M.J.; McFarlane, D. 2015. *Economics and experiences of managed aquifer recharge (MAR) with recycled water in Australia*. Queensland, Australia: Australian Water Recycling Centre of Excellence.

Villholth, K.G. 2013. Groundwater irrigation for smallholders in Sub-Saharan Africa – a synthesis of current knowledge to guide sustainable outcomes. *Water International* 38(4): 369-391. https://doi.org/10.1080/02508060.2013.821644

Villholth, K.G.; López-Gunn, E.; Conti, K.I.; Garrido, A.; van der Gun, J. (Eds.) 2018. *Advances in groundwater governance*. Leiden, The Netherlands: CRC Press.

Vivid Economics. 2016. *Water resources and extreme events in the Awash basin: Economic effects and policy implications*. Report prepared for the Global Green Growth Institute.

World Bank. 2006. *South Asia - Growth integration and regional integration*. Washington, DC: World Bank. Available at http://documents.worldbank.org/curated/en/843381468334773128/South-Asia-growth-integration-and-regional-integration (accessed on March 29, 2020).

World Bank. 2012. *Thai flood 2011: Rapid assessment for resilient recovery and reconstruction planning: Overview*. Bangkok, Thailand: The World Bank.

World Bank. 2018. World Bank country and lending groups. World Bank data help desk. Available at https://datahelpdesk.worldbank.org/knowledgebase/articles/906519 (accessed January 10, 2018).

World Bank; GFDRR (Global Facility for Disaster Reduction and Recovery). 2017. *Toward integrated disaster risk management in Vietnam: Recommendations based on the drought and saltwater intrusion crisis and the case for investing in longer-term resilience*. Washington, DC, USA: The World Bank.

Xenarios, S.; Pavelic, P. 2013. Assessing and forecasting groundwater development costs in Sub-Saharan Africa. *Water SA* 39(4): 529-537. http://dx.doi.org/10.4314/wsa.v39i4.12

Xie, H.; You, L.; Wielgosz, B.; Ringler, C. 2014. Estimating the potential for expanding smallholder irrigation in Sub-Saharan Africa. *Agricultural Water Management* 131: 183-193. https://doi.org/10.1016/j.agwat.2013.08.011

Yeh, H.-F.; Lee, C.-H.; Hsu, K.-C.; Chang, P.-H. 2009. GIS for the assessment of the groundwater recharge potential zone. *Environmental Geology* 58(1): 185-195. https://doi.org/10.1007/s00254-008-1504-9

Yihun, Y.M. 2015. *Agricultural water productivity optimization for irrigated teff (Eragrostic tef) in a water scarce semi-arid region of Ethiopia*. Leiden, The Netherlands: CRC Press. 98p.

Yin, H.; Li, C. 2001. Human impact on floods and flood disasters on the Yangtze River. *Geomorphology* 41(2-3): 105-109. https://doi.org/10.1016/S0169-555X(01)00108-8

Yu, L. 2002. The Huanghe (Yellow) River: A review of its development, characteristics, and future management issues. *Continental Shelf Research* 22(3): 389-403. https://doi.org/10.1016/S0278-4343(01)00088-7

Appendix 1. List of Countries and their Associated Subregions as Defined by the United Nations.

Table A1 provides a list of countries and their associated United Nations (UN) subregions, including population and crop area with high UTFI suitability.

Table A1. Countries and their subregions (arranged alphabetically) according to the UN.

	Country	UN Subregion	Population (millions)	Crop area (Mha)
1	Australia	Australia and New Zealand	8.4	1.6
2	Cuba	Caribbean	5.3	3.3
3	Dominican Republic	Caribbean	5.2	0.9
4	Haiti	Caribbean	6.7	0.9
5	Jamaica	Caribbean	0.5	0.1
6	Costa Rica	Central America	2.3	0.3
7	El Salvador	Central America	0.3	0.1
8	Guatemala	Central America	12.9	1.4
9	Honduras	Central America	5.1	0.5
10	Mexico	Central America	93.1	23.9
11	Nicaragua	Central America	4.7	2.0
12	Panama	Central America	0.7	0.2
13	Kazakhstan	Central Asia	2.1	0.6
14	Kyrgyzstan	Central Asia	0.8	0.1
15	Tajikistan	Central Asia	6.1	0.7
16	Turkmenistan	Central Asia	0.2	0.1
17	Uzbekistan	Central Asia	15.7	2.3
18	Burundi	Eastern Africa	8.6	0.6
19	Eritrea	Eastern Africa	0.3	0.1
20	Ethiopia	Eastern Africa	49.8	6.1
21	Kenya	Eastern Africa	37.6	3.6
22	Madagascar	Eastern Africa	5.4	0.6
23	Mozambique	Eastern Africa	19.4	3.1
24	Malawi	Eastern Africa	15.3	1.6
25	Rwanda	Eastern Africa	1.7	0.1
26	Somalia	Eastern Africa	5.9	1.0
27	South Sudan	Eastern Africa	0.8	0.5
28	Uganda	Eastern Africa	9.5	2.4
29	United Republic of Tanzania	Eastern Africa	30.1	2.8
30	Zambia	Eastern Africa	2.0	0.4
31	Zimbabwe	Eastern Africa	12.2	3.0
32	China	Eastern Asia	637.3	75.8
33	Japan	Eastern Asia	7.9	0.2
34	North Korea	Eastern Asia	12.0	1.4
35	South Korea	Eastern Asia	38.6	1.7
36	Bulgaria	Eastern Europe	0.6	0.4
37	Hungary	Eastern Europe	1.7	1.4
38	Poland	Eastern Europe	3.7	1.3
39	Romania	Eastern Europe	4.2	3.2
40	Russia	Eastern Europe	15.6	10.9
41	Ukraine	Eastern Europe	0.4	0.4
42	Angola	Middle Africa	5.5	0.4
43	Central African Republic	Middle Africa	1.4	0.5
44	Cameroon	Middle Africa	8.5	1.3
45	Chad	Middle Africa	7.4	1.9
46	Democratic Republic of the Congo	Middle Africa	7.9	0.3
47	Republic of the Congo	Middle Africa	7.4	0.1
48	Algeria	Northern Africa	19.5	3.7
49	Morocco	Northern Africa	17.3	6.5
50	Sudan	Northern Africa	20.0	5.8

(Continued)

Table A1. Countries and their subregions (arranged alphabetically) according to the UN. (Continued)

	Country	UN Subregion	Population (millions)	Crop area (Mha)
51	Tunisia	Northern Africa	8.4	2.3
52	Canada	Northern America	2.4	2.9
53	United States of America	Northern America	102.0	58.6
54	United Kingdom	Northern Europe	21.8	1.8
55	Argentina	South America	30.0	14.5
56	Bolivia	South America	4.1	0.3
57	Brazil	South America	70.2	21.3
58	Chile	South America	12.5	1.6
59	Colombia	South America	48.8	2.9
60	Ecuador	South America	11.7	1.8
61	Paraguay	South America	4.8	2.2
62	Peru	South America	6.7	0.6
63	Uruguay	South America	2.4	0.9
64	Venezuela	South America	17.6	2.6
65	Cambodia	Southeastern Asia	15.2	3.6
66	East Timor	Southeastern Asia	0.6	0.3
67	Indonesia	Southeastern Asia	165.3	21.3
68	Laos	Southeastern Asia	3.7	0.5
69	Malaysia	Southeastern Asia	0.9	0.3
70	Myanmar	Southeastern Asia	24.0	5.7
71	Philippines	Southeastern Asia	62.3	7.6
72	Thailand	Southeastern Asia	62.4	15.8
73	Vietnam	Southeastern Asia	50.7	4.8
74	Botswana	Southern Africa	0.8	0.3
75	Lesotho	Southern Africa	1.3	0.3
76	South Africa	Southern Africa	18.7	4.2
77	Swaziland	Southern Africa	0.2	0.1
78	Afghanistan	Southern Asia	12.9	1.6
79	Bangladesh	Southern Asia	138.6	8.6
80	Bhutan	Southern Asia	0.6	0.1
81	India	Southern Asia	1,088.8	137.2
82	Iran	Southern Asia	53.6	9.9
83	Nepal	Southern Asia	32.3	2.5
84	Pakistan	Southern Asia	157.8	18.0
85	Sri Lanka	Southern Asia	11.4	1.4
86	Albania	Southern Europe	0.1	0.1
87	Greece	Southern Europe	3.6	0.7
88	Italy	Southern Europe	4.0	0.9
89	Portugal	Southern Europe	4.2	0.8
90	Republic of Serbia	Southern Europe	3.4	1.3
91	Spain	Southern Europe	5.8	2.6
92	Benin	Western Africa	7.4	2.4
93	Burkina Faso	Western Africa	12.3	2.6
94	Ghana	Western Africa	5.5	2.5
95	Ivory Coast	Western Africa	1.2	0.9
96	Mali	Western Africa	12.0	2.6
97	Mauritania	Western Africa	0.5	0.1
98	Niger	Western Africa	17.0	13.0
99	Nigeria	Western Africa	133.2	25.0
100	Senegal	Western Africa	9.3	1.7
101	Sierra Leone	Western Africa	2.5	0.2
102	Togo	Western Africa	3.0	1.7
103	Azerbaijan	Western Asia	0.8	0.3
104	Iraq	Western Asia	6.4	0.9
105	Israel	Western Asia	5.0	0.6
106	Jordan	Western Asia	4.0	0.3
107	Lebanon	Western Asia	5.9	0.3

(Continued)

Table A1. Countries and their subregions (arranged alphabetically) according to the UN. (Continued)

	Country	UN Subregion	Population (millions)	Crop area (Mha)
108	Palestine	Western Asia	3.7	0.2
109	Syria	Western Asia	13.0	2.0
110	Turkey	Western Asia	33.9	7.9
111	Belgium	Western Europe	4.5	0.4
112	France	Western Europe	12.8	4.2
113	Germany	Western Europe	39.6	4.9
114	Luxembourg	Western Europe	0.4	0.1
115	Netherlands	Western Europe	7.2	0.5
			3,793.3	**622.2**

Note: Mha – Million hectares.

Appendix 2. UTFI Suitability Maps for Each of the Three Thematic Groups.

Figures A2.1 to A2.3 show the suitability scores given to each thematic group (supply, demand and storage) and their relative contribution to overall UTFI suitability.

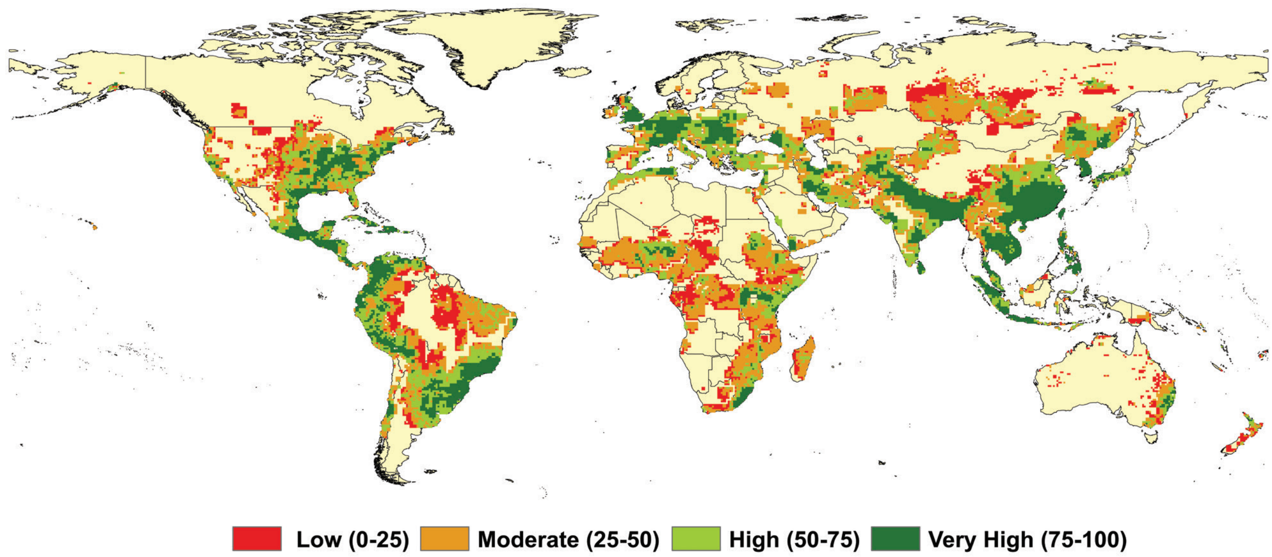


Figure A2.1. UTFI suitability map for the water supply thematic group.

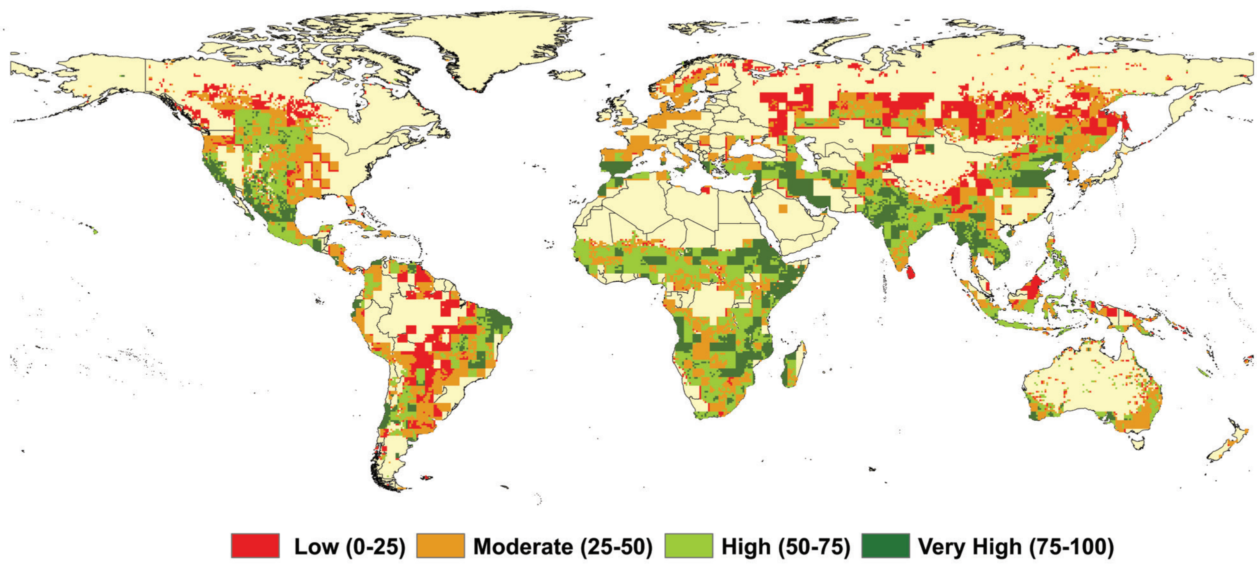


Figure A2.2. UTFI suitability map for the water demand thematic group.

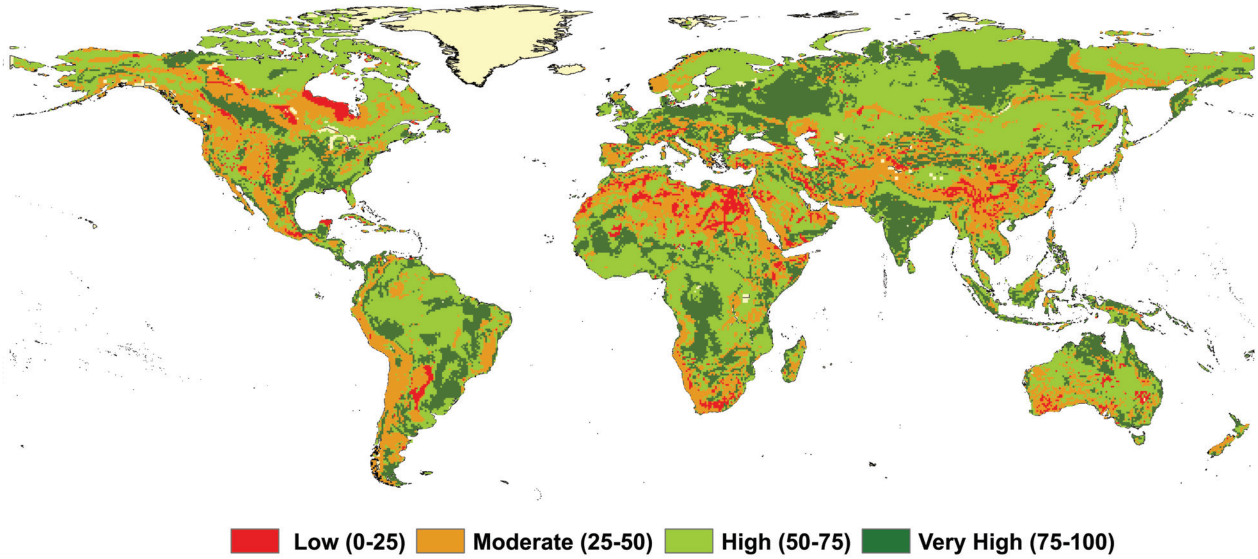


Figure A2.3. UTFI suitability map for the water storage thematic group.

Appendix 3. The 100 Most Populous River Basins with Mean UTFI Score and Suitability.

Table A3 lists the 100 most populous river basins according to the World Resources Institute (WRI), with their mean UTFI suitability score and class. The 16 basins identified with high UTFI suitability (score > 50) are shaded in gray.

Table A3. The 100 most populous river basins.

	Basin	Mean UTFI score	UTFI Suitability class
1	Tana	77.14	Very high
2	Chao Phraya	73.52	High
3	Magdalena	64.66	High
4	Save	61.00	High
5	Awash	60.86	High
6	Grisalva	58.67	High
7	Mahanadi	58.57	High
8	Godavari	57.58	High
9	Rio Balsas	55.88	High
10	Rio Parnaiba	55.66	High
11	Brazos	53.40	High
12	Ganges-Brahmaputra	52.14	High
13	Sacramento	51.91	High
14	Mekong	51.66	High
15	Shebelle	51.49	High
16	Volta	51.12	High
17	São Francisco	47.46	Moderate
18	Mar Chiquita Lake	47.04	Moderate
19	Rufiji	46.23	Moderate
20	Limpopo	44.55	Moderate
21	Liao He	44.40	Moderate
22	Lake Chad	44.37	Moderate
23	Rio Salado (Rio De La Plata)	44.36	Moderate
24	Irrawaddy	42.14	Moderate
25	Krishna	40.25	Moderate
26	Indus	39.54	Moderate
27	Santiago	38.24	Moderate
28	Yongding He	36.87	Moderate
29	Niger	36.85	Moderate
30	Hong (Red)	36.31	Moderate
31	Sanaga	35.82	Moderate
32	Paraná	35.75	Moderate
33	Huang He (Yellow)	35.03	Moderate
34	Rovuma	33.84	Moderate
35	Douro	33.51	Moderate
36	Rio Grande (Bravo)	32.85	Moderate
37	Lake Titicaca	32.56	Moderate
38	Narmada	32.28	Moderate
39	Yangtze River (Chang Jiang)	31.50	Moderate
40	Rhône	29.25	Moderate
41	Mississippi	28.96	Moderate
42	Amudaryo	28.24	Moderate
43	Salween	27.67	Moderate
44	Tocantins	27.65	Moderate
45	Lake Turkana	27.44	Moderate
46	Yenisei	26.63	Moderate
47	Amur	25.19	Moderate
48	Loire	25.01	Moderate
49	Kura	24.76	Low
50	Zambezi	23.35	Low

(Continued)

Table A3. The 100 most populous river basins. (Continued)

	Basin	Mean UTFI score	UTFI Suitability class
51	Sirdaryo	23.02	Low
52	Rhine	22.96	Low
53	Cuanza	22.19	Low
54	Uruguay	21.85	Low
55	Nile	21.72	Low
56	Tigris and Euphrates	21.12	Low
57	Murray	20.37	Low
58	Ob	20.06	Low
59	Helmand	19.62	Low
60	Orinoco	19.28	Low
61	Senegal	19.21	Low
62	Alabama River and Tombigbee	18.56	Low
63	Elbe	15.86	Low
64	Colorado (Argentina)	15.60	Low
65	Harirud	15.05	Low
66	Xi Jiang	13.78	Low
67	Cunene	12.96	Low
68	Ogooue	12.65	Low
69	Orange	12.53	Low
70	Nelson	11.41	Low
71	Ural	11.32	Low
72	Colorado (Pacific Ocean)	10.58	Low
73	Congo	10.11	Low
74	Essequibo River	9.96	Low
75	Amazonas	9.58	Low
76	Lena	9.54	Low
77	Danube	9.28	Low
78	Don	8.04	Low
79	Bandama	6.67	Low
80	Oder	6.32	Low
81	Columbia	5.96	Low
82	Okavango	5.49	Low
83	Negro (Argentina)	4.55	Low
84	Balkhash	3.68	Low
85	Volga	3.02	Low
86	Mackenzie	2.80	Low
87	Wisla	2.23	Low
88	Albany	1.39	Low
89	Severn (Hudson Bay)	0.50	Low
90	Churchill	0.49	Low
91	Saint Lawrence	0.30	Low
92	Churchill (Atlantic)	0.00	Low
93	Rivière Saguenay	0.00	Low
94	Dnieper	0.00	Low
95	Fraser	0.00	Low
96	Grande Riviere	0.00	Low
97	Hayes (Hudson Bay)	0.00	Low
98	Moose (Hudson Bay)	0.00	Low
99	Neman	0.00	Low
100	Rivière Koksoak	0.00	Low

Appendix 4. Data Used in the Economic Analysis.

Variables and Equations Used to Derive Costs and Benefits

Table A4.1 lists the common variables used for deriving costs and benefits.

Table A4.1. Variables common to the assessment of costs and benefits.

Parameter	Symbol	Unit	Explanation
Design recharge volume	DRV	m^3	Surface water volume available for aquifer recharge
Baseflow	b	Percentage	Proportion of the design recharge volume that contributes to baseflow
Recovered volume	R_v	m^3	Proportion of the design recharge volume that is available for recovery (i.e., R_v = DRV * (1 - (b/100)))
Discount rate	i	Percentage	Discount rate used to calculate discount cash flow and derive NPVs
Time period	T	Years	Time period over which the economic analysis is carried out

Variables and Equations Used to Derive Costs

Tables A4.2 to A4.7 show the variables and equations used to derive the different components of costs.

Table A4.2. Design, capital and O&M costs considered for surface recharge methods.

Cost component	Parameter	Symbol	Unit	Explanation
Design	Infiltration rate	I	mm/hour	Average rate of recharge beneath infiltration basins
	Annual recharge period	R_T	Days	Duration of recharge based on the wet season period
Capital	Excavation depth	D	m	Depth of excavation needed to construct infiltration basins
	Buffer (B)	B_S	Percentage	For miscellaneous tasks (percentage of total capital cost)
	Excavation cost	E_{CS}	Cost/m^3	Cost of excavation
O&M	Desilting cost	D_{CS}	Fraction	Cost of excavation (percentage of capital cost)
	Manpower	M_N	Integer	Total number of people needed to operate and manage structures
		M_C	Local currency	Annual salary (per year)

Table A4.3. Design, capital and O&M costs for subsurface recharge methods.

Cost component	Parameter	Symbol	Unit	Explanation
Design	Well recharge rate	R	Liters/second (l/s)	Average recharge rate of the recharge well
	Number of wells per hectare	W_N	Wells/ha	Well density to calculate land requirements
	Annual recharge period	R_T	Days	Duration of recharge based on the wet season period
Capital	Cost of recharge well	R_C	Local currency	Combined cost of drilling, well head, screen, casing, etc.
	Buffer (B)	B_{SS}	Percentage	For miscellaneous tasks such as gravel packs/filling, drain construction (as a percentage of the total capital cost)
	Effective excavation (EE)	EE	m^3	Depth of pit/well where well is installed * area for each well
	Excavation cost	E_{CSS}	Cost/m^3	Manual/machine excavation cost
O&M	Desilting cost	D_{CSS}	Fraction	Fraction of capital cost of excavation
	Unclogging of well	U_C	Fraction	Fraction of capital cost of recharge well
	Manpower	M_N	Integer	Total number of people needed to operate and manage structures
		M_C	Local currency	Annual salary (per year)

Table A4.4. Derived cost values based on parameters in Tables A4.2 and A4.3 and their associated equations for subsurface and surface recharge methods.

Cost component	Parameter	Symbol	Unit	Equation
Subsurface recharge method (recharge wells)	Total number of recharge wells	N_W	Wells	$DRV / (R * 3.6 * 24 * R_T)$
	Land required	L_{SS}	ha	N_W / W_N
	Total cost of recharge well	TR_C	Local currency	$N_W * R_C$
	Total excavation cost	TE_C	Local currency	$N_W * EE * E_{CSS}$
	Capital cost	C_{SS}	Local currency	$(TR_C + TE_C) * (1 + B_{SS})$
	O&M cost (annual)	OM_{SS}	Local currency	$D_{CSS} * TE_C + U_C * TR_C + M_N * M_C$
Surface recharge method (infiltration basins)	Land required	L_S	ha	$DRV / (I * 0.001 * 24 * R_T * 10{,}000)$
	Capital cost	C_S	Local currency	$(L_S * D * E_{CS}) * (1 + B_S)$
	O&M cost (annual)	OM_S	Local currency	$D_{CS} * L_S * D * E_{CS} + M_N * M_C$

Table A4.5. Design, capital and O&M costs used to calculate the groundwater recovery cost.

Cost component	Parameter	Symbol	Unit	Explanation
Design	Pump abstraction rate	Q	l/s	Average pump abstraction rate
	Groundwater level	H	m	Depth of groundwater table below ground surface
	Area irrigated using the well	W_A	ha	Area irrigated by each well
	New pumps	N_P	Percentage	If groundwater irrigation > 50%, N_p = 0% else N_p = 100%
Capital	Cost of the pump	P_C	Local currency	Combined cost of drilling and completing well (to a depth of 40 m)
O&M	Fuel cost	P_F	Local currency/liter	Cost of fuel (diesel)
	Pump efficiency	e	Fraction	Efficiency of groundwater pumps
	Maintenance cost	P_M	Fraction	Annual maintenance cost as a percentage of capital cost of the pump

Table A4.6. Derived outputs based on parameters in Table A4.5 and their associated equations to calculate groundwater recovery cost.

Parameter	Symbol	Unit	Equation
Total number of pumps	N_p	Integer	(A_I / W_A)[a]
Capital cost	C_P	Local currency	$N_p * P_C$
Total pumping hours	P_H	Hours	$R_V / (Q * 3.6)$
Total fuel cost for pumping	TP_F	Local currency	$(P_H * P_F * Q * H * 3.6) / (366 * e)$
O&M cost (annual)	OM_P	Local currency	$TP_F + (P_M * P_C)$

Note:

[a] A_I is the area that can be irrigated based on crop water requirements and recovered volume (R_V). It is calculated later in benefits parameters.

Table A4.7. Variables used to determine the land use cost.

Parameter	Symbol	Unit	Explanation
Land use (annual)	L_C	Local currency/hectare	Rental value of land

Land use cost = $C_L = L_C * L_{SS}$ or $L_C * L_S$ (based on subsurface or surface recharge method, L_{SS} and L_S from Table A4.4)

All the annual O&M costs are converted to NPV using time period (T) and discount rate (i).

Total cost = Capital (C_s or $C_{SS} + C_P$) + NPV of annual costs (OM_s or $OM_{SS} + OM_P + C_L$)

Variables and Equations Used to Derive Benefits

Tables A4.8 and A4.9 show the variables and equations used to derive the benefits.

Table A4.8. Variables used to determine the benefits from enhanced crop production.

Parameter	Symbol	Unit	Explanation
Yield	Y	Tons/ha	Yield of irrigated crop
Crop water requirement	C_W	mm	Crop water requirement is calculated as: ET_c / 0.7, where ET_c is potential crop evapotranspiration and 0.7 is taken as the efficiency of groundwater irrigation
Price	C_{PR}	Local currency/ton	Price of the crop in the local market
Production cost	C_{PC}	Local currency/ha	Cost of producing the crop

Potential area that could be irrigated (in hectares) using available water is calculated as follows:

$$A_I = (R_V / [C_W * 0.001]) / 10{,}000$$

Benefits = $B_E = A_I * (Y * [C_{PR} - C_{PC}])$

Flood damage mitigation is estimated using past flood loss data and frequency of losses. Input parameters are flood damage loss (F) and frequency of flood damage (F_q), and NPV of flood damage mitigation is calculated based on these parameters.

Table A4.9. Variables used to determine the benefits from flood damage mitigation.

Parameter	Symbol	Unit	Explanation
Flood damage loss	F	Local currency	Recorded economic loss from floods
Frequency	F_q	Year	Return period of flood expected to cause flood damage loss (F)

Flood damage mitigation = $F_R = F * (T/F_q)$

All benefits are converted to NPV using time period (T) and discount rate (i).

Total benefits = NPV of benefits ($B_E + F_R$)

To calculate IRR, the cash flow for each year is calculated as the difference between Costs (C_s or $C_{SS} + C_P$ + [OM_s or OM_{SS}] + $OM_P + C_L$) and Benefits ($B_E + F_R$).

BCR is calculated based on the ratio of NPV of total benefits and total costs.

Input Data Used to Derive Costs and Benefits

All the costs/prices are in the countries' local currencies (as in 2017):

- Ethiopia: ETB (USD 1 ~ ETB 23.9)
- India: INR (USD 1 ~ INR 65 INR)
- Thailand: THB (USD 1 ~ THB 32.3)

Table A4.10 shows the input data for the common variables defined in Table A4.1.

Table A4.10. Input data from common variables across costs and benefits.

Parameter	Symbol	Unit	Awash	Ramganga	Chao Phraya
Design recharge volume (km^3)	DRV	km^3	2.41	3.25	3.36
Baseflow	b	Percentage	25	25	25
Annual recharge period	R_T	Days	100	100	100
Discount rate	i	Percentage	10%	10%	10%
Time period	T	Years	20	20	20

Input Data Used to Derive Costs

Recharge Structures

Tables A4.11 and A4.12 show the input data for the variables defined in Tables A4.2 and A4.3.

Table A4.11. Input data for the surface recharge method.

Cost component	Parameter	Symbol	Unit	Awash	Ramganga	Chao Phraya
Design	Infiltration rate[a]	I	mm/hour	20	20	20
Capital	Excavation depth[b]	D	m	1	1	1
	Buffer (B)	B_S	Fraction	0.1	0.1	0.1
	Excavation cost[c]	E_{CSS}	Cost/m^3	ETB 30	INR 125	THB 75
O&M	Desilting cost[d]	D_{CS}	Fraction	0.05	0.05	0.05
	Number of people[e]	M_N	Integer	40	30	30
	Annual salary[f]	M_C	Local currency	ETB 8,400	INR 150,000	THB 240,000

Notes:

[a] Infiltration rates are set at 20 mm/hour (based on sandy loam to sand soils). It would be expected that infiltration basins would be set up where soils are permeable (Brouwer et al. 1985).
[b] Assumed to be 1 meter (effective) depth of infiltration basins.
[c] Awash: Ethiopian Investment Agency 2012; Ramganga: average cost from pilot trial (Pavelic et al. 2015); and Chao Phraya: Langdon & Seah (Thailand) Ltd. 2013.
[d] Assumed to be 0.05 (5%) of the excavation cost.
[e] Based on an average of two people per administrative area (*woreda* in Awash; block in Ramganga; and province in Chao Phraya). *Woreda* - the third-level administrative divisions of Ethiopia.
[f] Awash: http://www.wageindicator.org/main/salary/minimum-wage/ethiopia, in the range of level 1 and 2 clerks; Ramganga: average cost of skilled labor; and Chao Phraya: http://www.tradingeconomics.com/thailand/wages.

Table A4.12. Input data for the subsurface recharge method.

Cost component	Parameter	Symbol	Unit	Awash	Ramganga	Chao Phraya
Design	Well recharge rate[a]	R	l/s	2	3	3
	Number of wells per hectare[b]	W_N	Integer	20	20	20
Capital	Cost of recharge well[c]	R_C	Local currency	ETB 50,000	INR 85,000	THB 60,000
	Buffer (B)	B_{SS}	Fraction	0.1	0.1	0.1
	Effective excavation (EE)[d]	EE	m^3	60 m^3	60 m^3	60 m^3
	Excavation cost	E_{CS}	Local currency/m^3	ETB 30	INR 125	THB 75
O&M	Desilting cost	D_{CSS}	Fraction	0.05	0.05	0.05
	Unclogging of well[e]	U_C	Fraction	0.05	0.05	0.05
	Number of people	M_N	Integer	40	30	30
	Annual salary	M_C	Local currency	ETB 8,400	INR 150,000	THB 240,000

Notes:
[a] Awash: MacDonald et al. 2012, average of 1-5 l/s; Ramganga: average as observed in pilot field study; and Chao Phraya: taken as being equal to Ramganga, given that aquifers in both regions are of similar productivity.
[b] Density of recharge wells (similar to pilot site in Ramganga).
[c] Awash: RWSN 2006; Ramganga: average cost as reported from the field, 40 m depth; and Chao Phraya: cost is based on borehole cost (including drilling, screen and gravel pack) of THB 1,500/m for a well depth of 40 m.
[d] Assumed to be effective excavation for setting up a recharge well in a pit of radium ~ 3 m and depth 2 m.
[e] Assumed to be 5% of initial capital cost of recharge well.

Groundwater Recovery

Table A4.13 shows the input data for the variables defined in Table A4.5.

Table A4.13. Input data for calculating groundwater recovery cost.

	Parameter	Symbol	Unit	Awash	Ramganga	Chao Phraya
Design	Pump abstraction rate[a]	Q	l/s	3	5	5
	Water table depth[b]	H	m	30	10	17
	Hectares per well[c]	W_A	ha	2	2	2
Capital	New pumps[d]	N_P	Percentage	100	0	100
	Cost of pump[e]	P_C	Local currency	ETB 10,000	INR 20,000	THB 6,000
	Borehole cost[f]	P_B	Cost/m	ETB 800	INR 700	THB 500
O&M	Fuel cost[g]	P_F	Cost/liter (diesel)	ETB 16	INR 55	THB 25
	Pump efficiency	e	Fraction	0.6	0.6	0.6
	Maintenance cost[h]	P_M	Fraction	0.05	0.05	0.05

Notes:
[a] Awash: pump abstraction rate is limited by aquifer yield, the average of which is in the range of 1-5 l/s (MacDonald et al. 2012); Ramganga and Chao Phraya: aquifer yields are not a limiting factor (high-yield aquifers), so a pump with an abstraction rate of 5 l/s was selected. Pumps with flows of 5 l/s can provide a field of 2 ha with 1,800 mm of irrigation water annually, with 2,500 operating hours and an efficiency of 80%. This amount of water is sufficient to completely or partially irrigate a crop depending on rainfall, climate and crop water requirements. Thus, selecting pumps with a flow of 5 l/s is suitable for a small-scale irrigation system, which, at present, is the predominant way of carrying out agricultural activities.
[b] Awash: MacDonald et al. 2012, average of 10-50 m; Ramganga: CGWB 2014; and Chao Phraya: Kwanyuen et al. 2003.
[c] based on the assumption that water from each well can be used to irrigate an area of 2 ha.
[d] Awash and Chao Phraya: less than 20% of the cultivated area is irrigated using groundwater; and Ramganga: no cost because more than 50% of the cultivated area is already irrigated using groundwater.
[e] Awash: in the range as reported by Gebregziabher et al. 2016; Ramganga: average value reported by farmers in the area; and Chao Phraya: approximate price of a pump with maximum flow of 5 l/s (http://www.clinton-marketing.co.th/WATER-PUMPS/WATER-PUMP3).
[f] Awash: RWSN 2006; Ramganga: as reported from field studies conducted; and Chao Phraya: range as discussed in online forums (https://www.thaivisa.com/forum/topic/721109-cost-of-sinking-a-borehole-for-water/).
[g] Global petrol prices (http://www.globalpetrolprices.com).
[h] Assumed to be 5% of initial capital cost.

Land Use

Table A4.14 shows the input data for the variables defined in Table A4.7.

Table A4.14. Input data for calculating land use cost.

	Symbol	Awash	Ramganga	Chao Phraya
Rental cost/ha	L_c	ETB 200[a]	INR 17,500[b]	THB 11,331[c]

Notes:
[a] Rain-fed crop area in Amhara region (Ethiopian Investment Agency 2012).
[b] Pavelic et al. 2015.
[c] Based on rice production over 1 ha.

Input Data Used to Derive Benefits

Tables A4.15 and A4.16 show the input data for the variables defined in Tables A4.8 and A4.9.

Enhanced Crop Production

Table A4.15. Input data for calculating the benefits of enhanced crop production.

Name	Symbol	Awash	Ramganga	Chao Phraya
		Teff	Rice	Rice
Yield (tons/ha)[a]	Y	2.4	2.4	4.3
Water requirement (mm)[b]	C_w	453	670	731
Price (per ton)[c]	C_{PR}	ETB 16,000	INR 13,600	THB 10,512
Production cost (per hectare)[d]	C_{PC}	ETB 21,816	INR 2,345	THB 33,995

Notes:
[a] Awash: teff (average yield reported from field experiments in Yihun 2015 and Araya et al. 2011); Ramganga: rice (Department of Land Development and Water Resources 2009); and Chao Phraya: rice (Office of Agricultural Economics 2018).
[b] Awash: teff (Araya et al. 2011); Ramganga: rice (Tyagi et al. 2000, assuming 70% water-use efficiency and that 80% of crop evapotranspiration is met by groundwater irrigation); and Chao Phraya: rice (Gheewala et al. 2014, Table 2 - cubic meters per hectare (m^3/ha) is converted to millimeters taking into account a water-use efficiency of 0.7).
[c] Awash: teff (Ethiopian Grain Trade Enterprise 2018); Ramganga: rice (Commission for Agricultural Costs and Prices 2015); and Chao Phraya: rice (Office of Agricultural Economics 2018).
[d] Awash: taken as 75% of total revenue from one hectare; Ramganga: (Commission for Agricultural Costs and Prices 2015, pages 122 and 132). For production cost, 85% of the cost stated is taken since irrigation cost is considered separately; and Chao Phraya: taken as 75% of total revenue from one hectare.

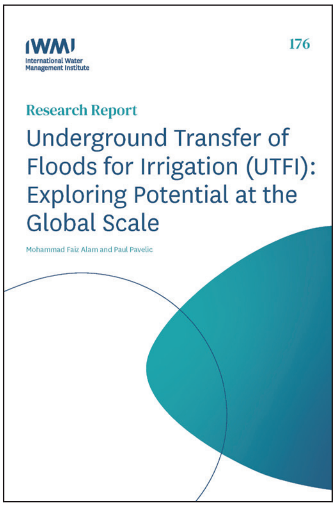
Flood Damage Mitigation

Table A4.16. Input data for calculating the benefits of flood damage mitigation.

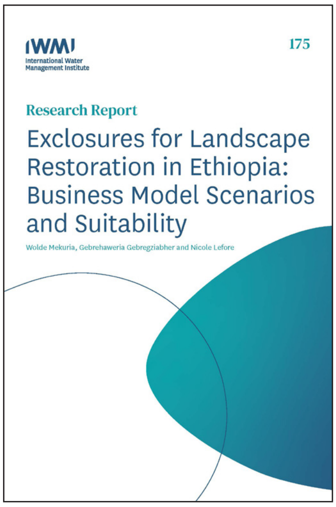
Parameter	Symbol	Awash[a]	Ramganga[b]	Chao Phraya[c]
Flood damage loss	F	ETB 76,000,000	INR 1,000,000,000	THB 164,500,000,000
Frequency	F_q	4	4	5

Notes:
[a] **Awash**
Given the lack of information on the damage caused by floods, the losses incurred as a result were estimated using the land inundation values for different return periods as determined by Getahun and Gebre (2015). The study used data from the most upstream gauging station at Melka Kuntrie. It was identified that a total area of 44 km^2 is flooded along the Awash Basin, and 27 km^2 of this flooding is in the lower basin and 17 km^2 in the upper basin (Getahun and Gebre 2015). Assuming that half of the flooded area along the Awash River (22 km^2 = 2,200 ha) is cropland (under teff and maize cultivation), the damage caused is calculated using the loss of production, which is estimated at ETB 76 million (~ USD 3.3 million) every fifth year. This is similar to the loss reported in the Wonji sugar plantation of ETB 47 million in 1996. Our estimate is conservative given that infrastructural losses are not considered.
[b] **Ramganga**
In Moradabad district (situated within the Ramganga Basin), the damage caused by floods in 2010 was INR 1 billion (~USD 15 million) (Pavelic et al. 2015). This value is considered as being applicable to the entire Ramganga Basin, due to the lack of basin-wide estimates. This is a conservative estimate given that the basin is five to six times the area of Moradabad district. It is assumed that such a flood will occur every fifth year based on flood frequency.
[c] **Chao Phraya**
Flood damage mitigation is calculated based on the damage reported during the 2011 floods in Thailand, which was estimated at USD 46.5 billion excluding additional funds needed for recovery and reconstruction (World Bank 2012). The majority of this loss (~70%) is estimated to have been shouldered by the manufacturing industry, due to the flooding of several industrial estates which are located mostly in the southern region (Nakhon Sawan Province and southern provinces, including Bangkok). Considering the total damage of USD 46.5 billion in Thailand and conservatively assuming that 50% of that damage occurred in the Chao Phraya Basin, which was severely affected and where most of the industries are located, leads to a value of USD 23.25 billion. Design recharge volume is ~40% of flood volume in the basin in 2011. Therefore, associated flood damage mitigation by recharging this volume is taken as being proportional to flood volume (i.e., 40%), giving a mitigation value of USD 9.4 billion in the Chao Phraya Basin. Now, we conservatively assume that capturing this excess flow through the UTFI approach would not reduce the entire flood damage in the basin but only 50%, giving a final mitigation value of USD 4.7 billion every fourth year.

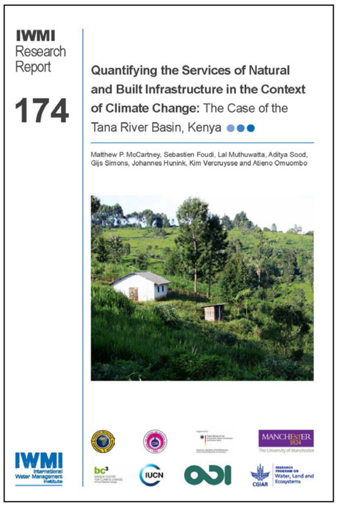
IWMI RESEARCH REPORT SERIES



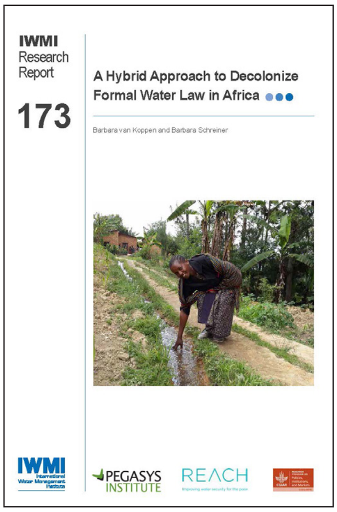
176 Underground Transfer of Floods for Irrigation (UTFI): Exploring Potential at the Global Scale
https://doi.org/10.5337/2020.204



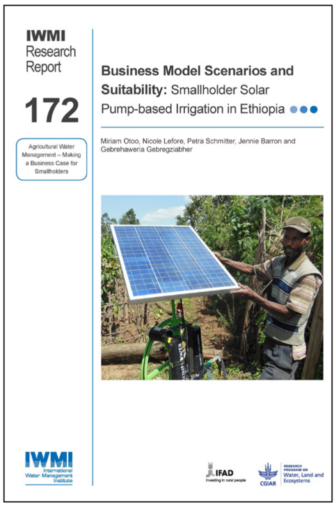
175 Exclosures for Landscape Restoration in Ethiopia: Business Model Scenarios and Suitability
https://doi.org/10.5337/2020.201



174 Quantifying the Services of Natural and Built Infrastructure in the Context of Climate Change: The Case of the Tana River Basin, Kenya
https://doi.org/10.5337/2019.200



173 A Hybrid Approach to Decolonize Formal Water Law in Africa
https://doi.org/10.5337/2018.219



172 Business Model Scenarios and Suitability: Smallholder Solar Pump-based Irrigation in Ethiopia
https://doi.org/10.5337/2018.207

171 Joint Ventures in the Flag Boshielo Irrigation Scheme, South Africa: A History of Smallholders, States and Business
https://doi.org/10.5337/2018.202

For access to all IWMI publications, visit www.iwmi.org/publications/

Headquarters
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Mailing address
P. O. Box 2075
Colombo
Sri Lanka

Telephone
+94 11 2880000

Fax
+94 11 2786854

Email
iwmi@cgiar.org

Website
www.iwmi.org

International Water Management Institute

IWMI is a CGIAR Research Center

ISSN 1026-0862
ISBN 978-92-9090-899-9