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

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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).
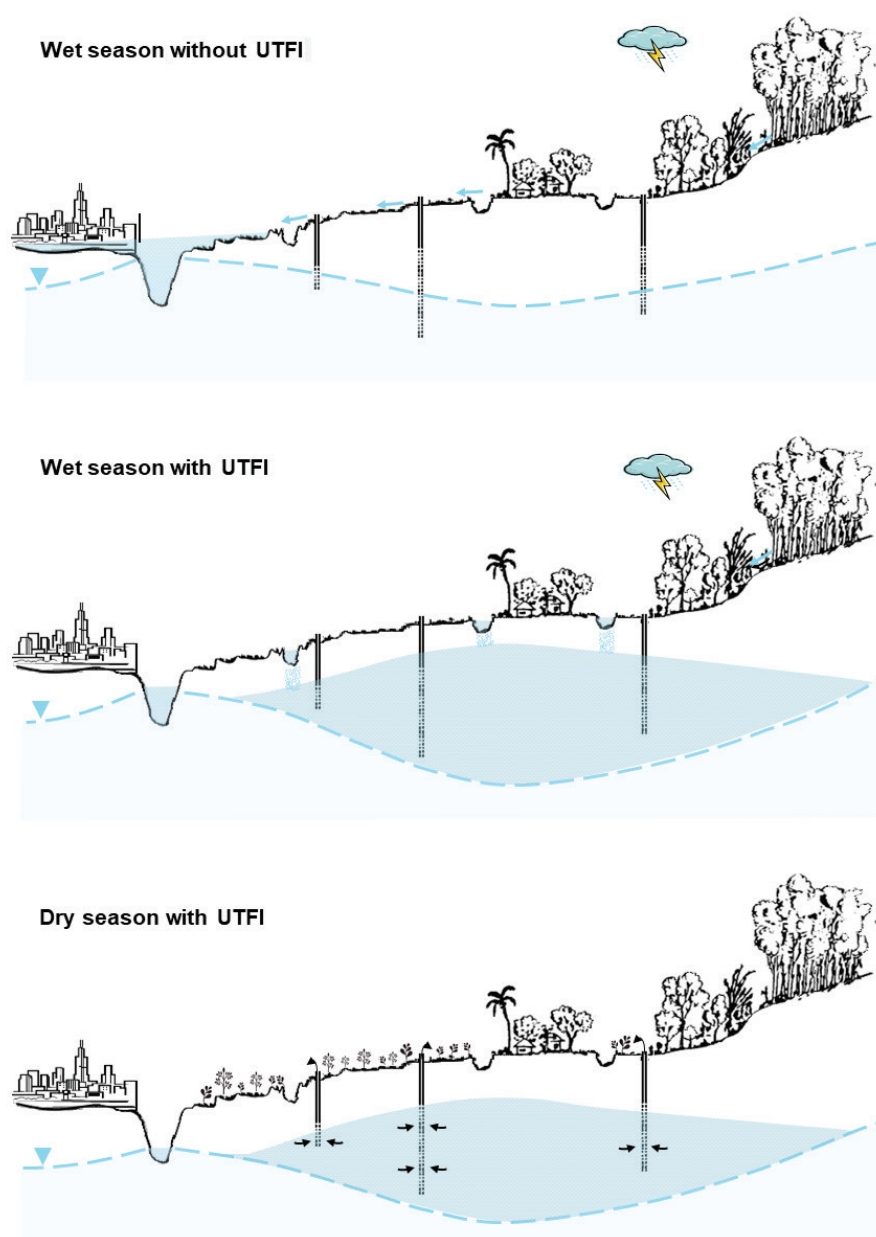

Figure 1. Schematic representations of a flood-prone landscape with and without UTFI. The figure illustrates that strategic capture and storage of water underground can offset downstream flooding that would otherwise occur while also boosting groundwater reserves and agricultural production.

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.
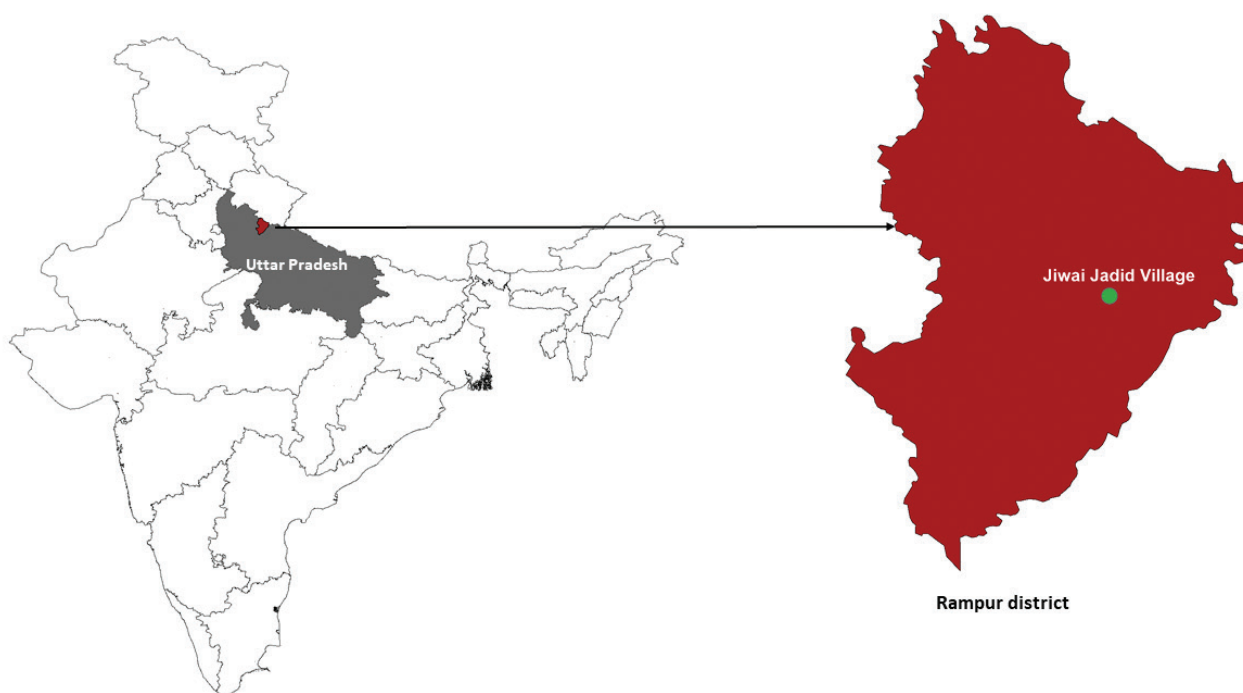

Figure 2. Location of the UTFI pilot study site at Jiwai Jadid village, Rampur district, Uttar Pradesh, India.

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.
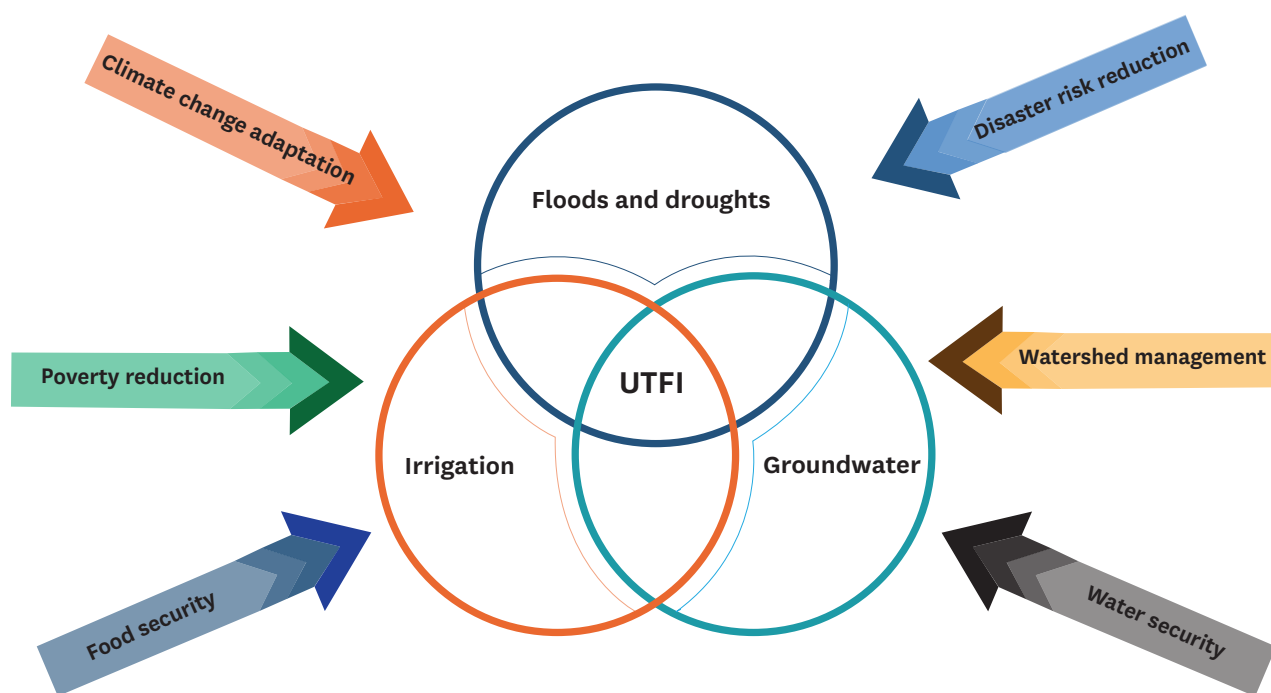

Figure 4. Key aspects and priorities of the water sector that closely intersect with the UTFI approach.

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 m³/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 (Mm³) 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

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[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 Aquifer type	Fan et al. 2013 WHYMAP[b] (Richts et al. 2011)	30 arc-minutes 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/

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

Where:

UTFI$_{SC}$ = Final suitability score

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

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 ith 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., 2³) 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.
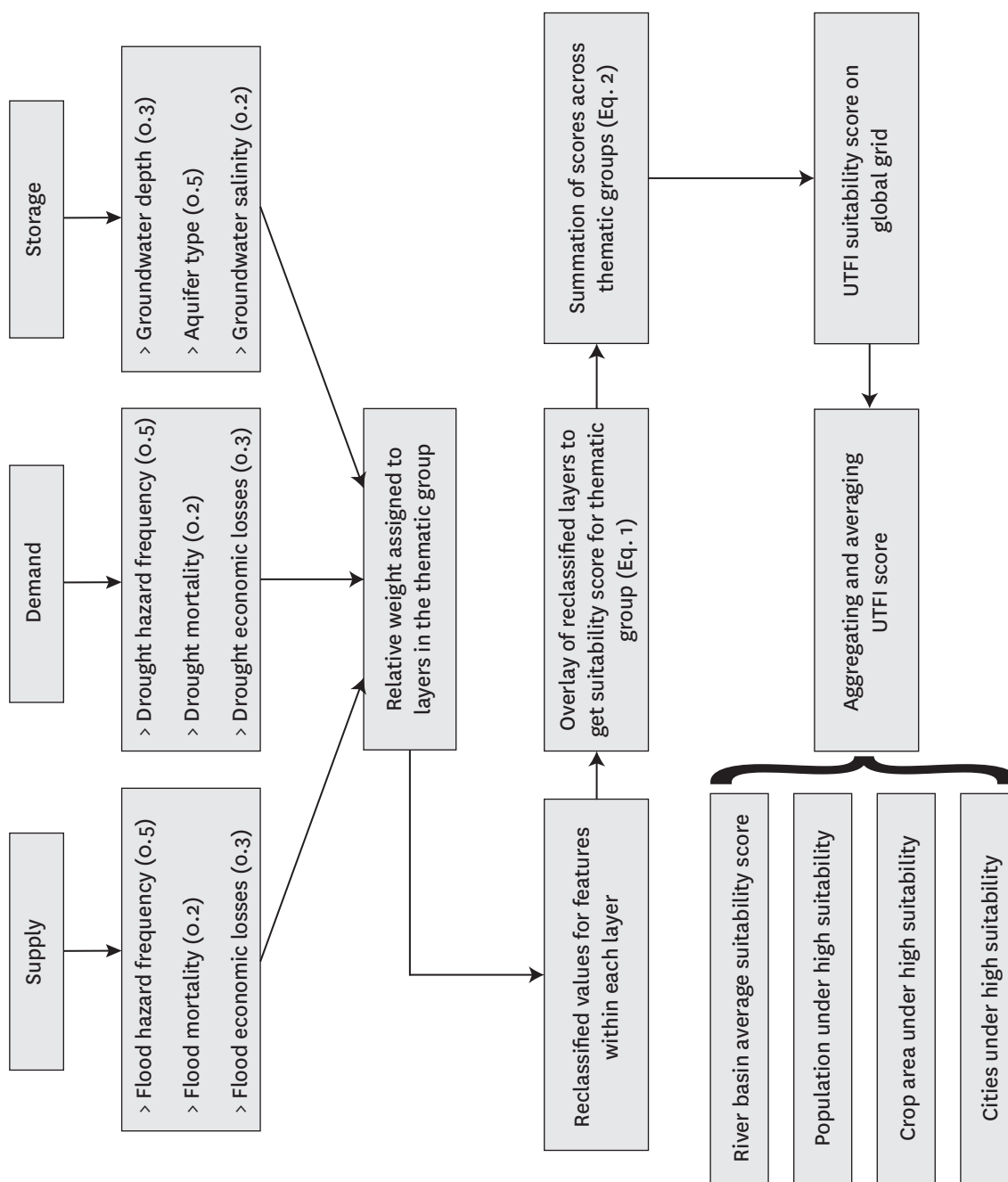
Figure 5. Framework used for the global UTFI suitability assessment.

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

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[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
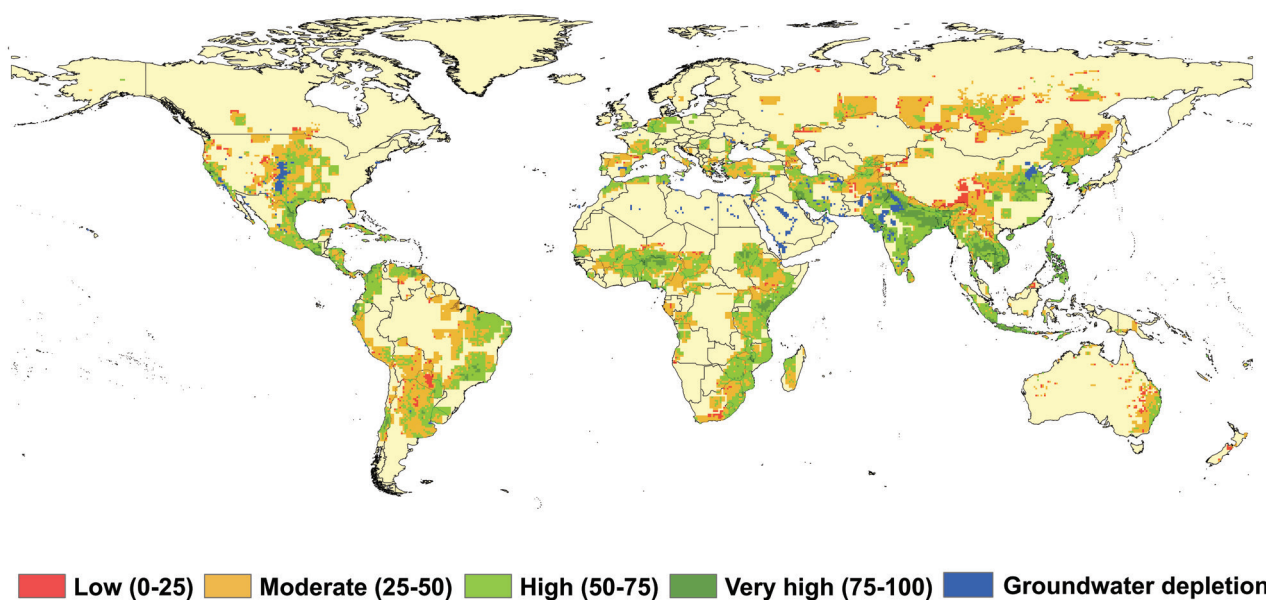

Figure 6. Global map of UTFI suitability on a spatial grid resolution of 30 arc-minutes.
Notes: Areas with highest groundwater depletion rates are shown in blue. Areas shaded in yellow over much of the global landmass respresent an absence of floods or droughts or both, and have therefore been omitted 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.
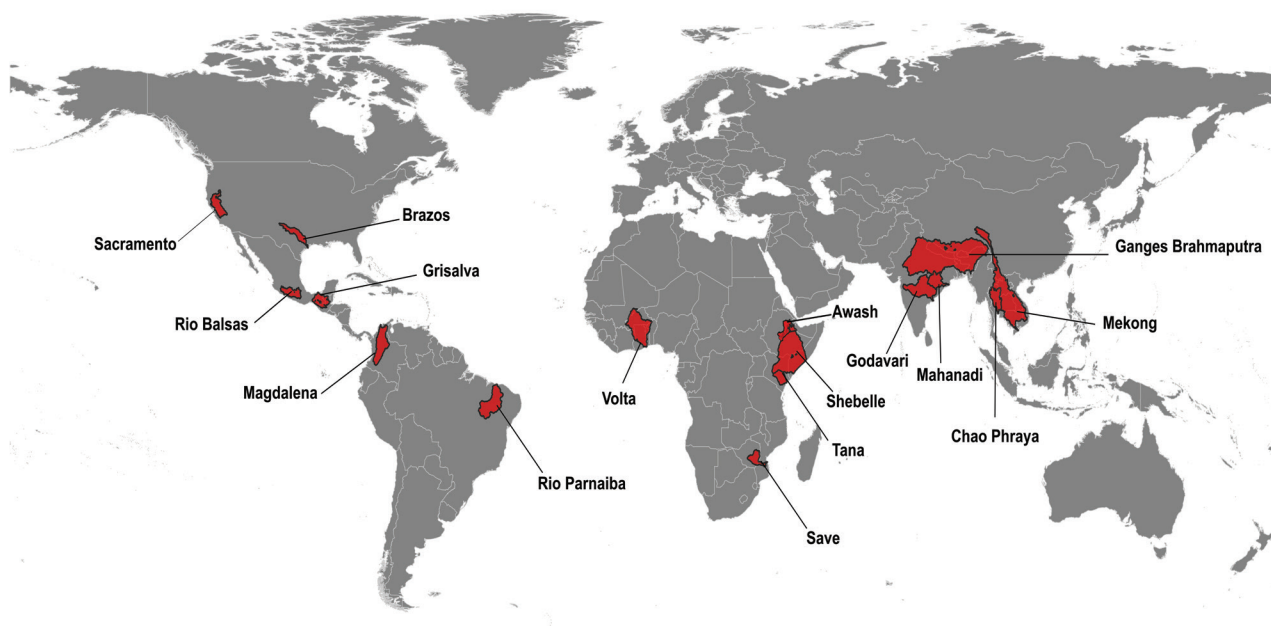
Figure 7. Distribution of the 16 river basins with high UTFI suitability (score > 50) based on an examination of the 100 most populous basins according to the World Resources Institute (WRI).

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). Similarly, 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.
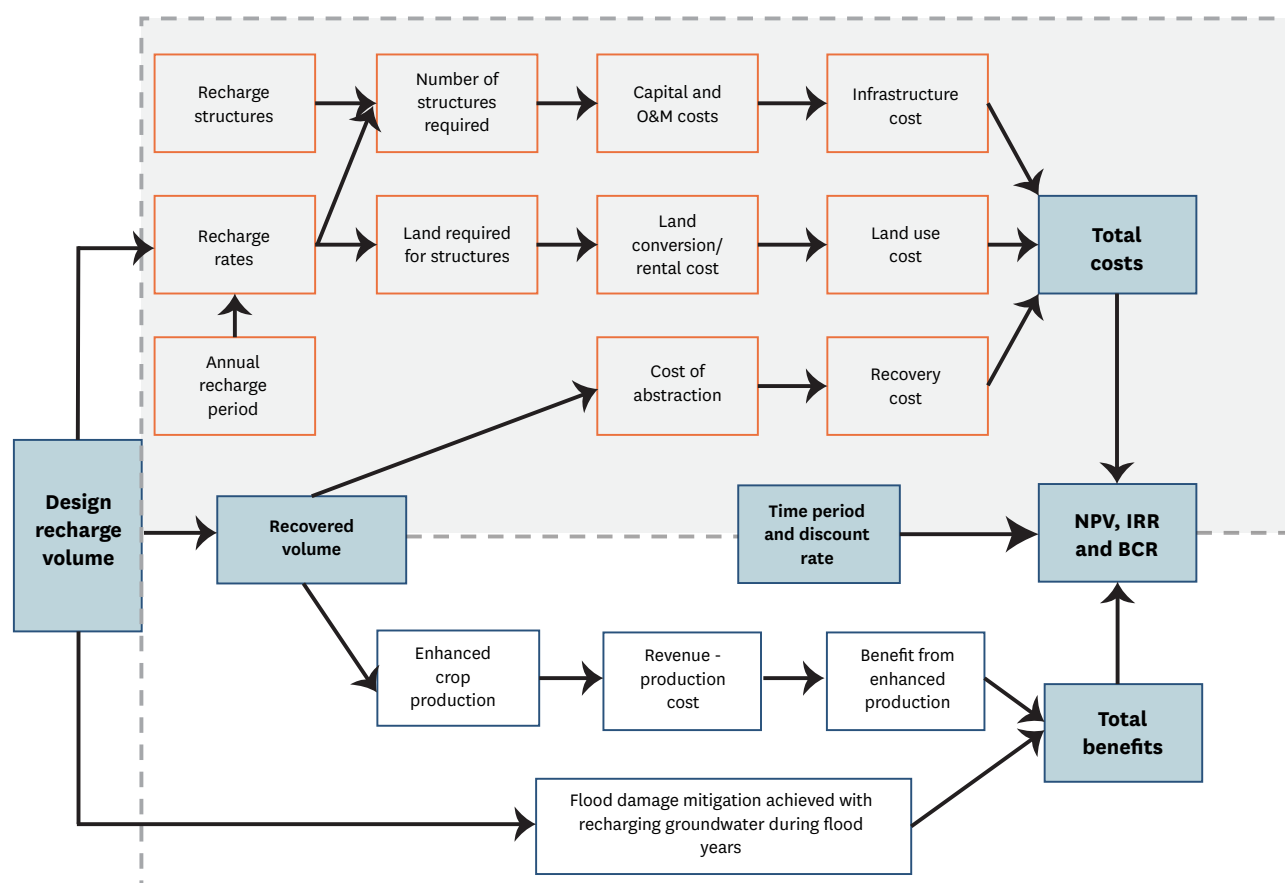

Figure 9. Framework for the economic analysis indicating the main streams of costs and benefits.

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 km³ (annual) • Ramganga: 3.25 km³ (annual) • Chao Phraya: 3.36 km³ (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/m³) 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).

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[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 (km³)[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 m³/day (138 - 207)	0.48 m/day (0.38 - 0.58)	259 m³/day (207 - 311)	0.48 m/day (0.38 - 0.58)	259 m³/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: km³/year; Chao Phraya: km³/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 m³/day (MacDonald et al. 2012); Ramganga: taken as 259 m³/day from the average value measured during the pilot UTFI trial; and Chao Phraya: taken as being equal to Ramganga (259 m³/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	Capital	315	315	-	-	85	85
recovery cost	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/m³ [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 (m³).

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
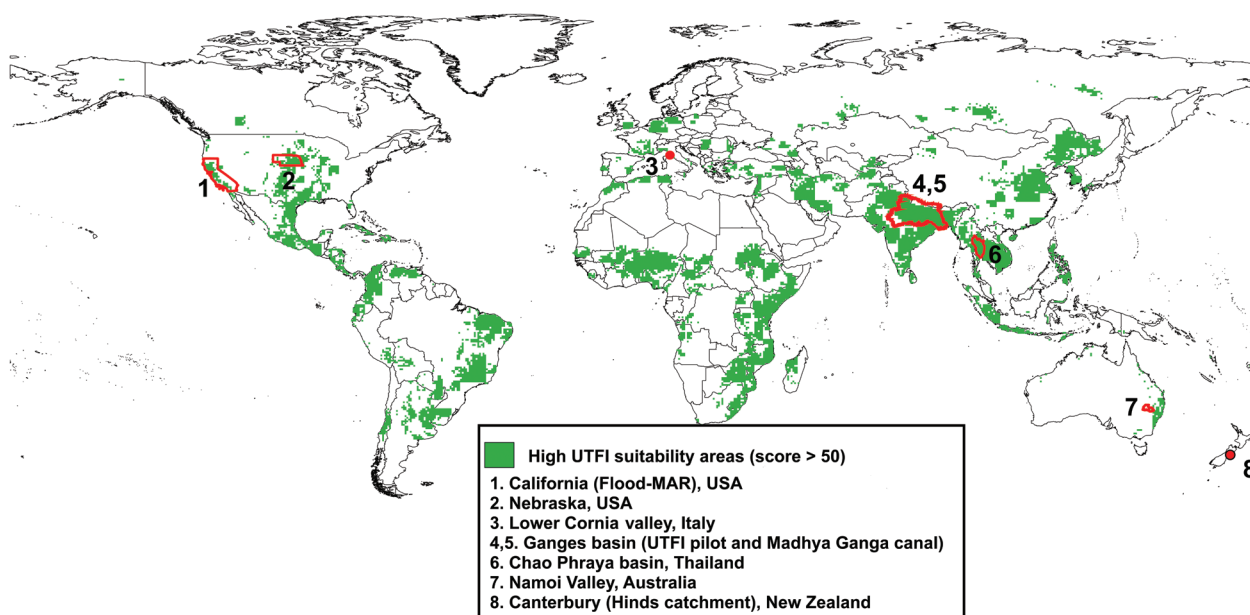

Figure 10. Locations of the eight areas/regions where the potential for using river water or floodwater for groundwater recharge has previously been studied.

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 infrastructure-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 inhabited 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.