IWMI Research Report 165

Controlling Floods and Droughts through Underground Storage: From Concept to Pilot Implementation in the Ganges River Basin

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Front cover photograph shows a scientist measuring the water collected in a pond created under the Underground Taming of Floods for irrigation (UTFI) approach in Jiwai Jadid village, Rampur District, Uttar Pradesh, India (*photo*: Prashanth Vishwanathan/IWMI).

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Contents

Acronyms

EVI	Enhanced Vegetation Index
GIS	Geographic Information System
INR	Indian Rupee
IRR	Internal Rate of Return
MAR	Managed Aquifer Recharge
MODIS	Moderate Resolution Imaging Spectroradiometer
NPV	Net Present Value
PES	Payments for Environmental Services
SI	Suitability Index
SWAT	Soil and Water Assessment Tool
USD	United States Dollar
UTFI	Underground Taming of Floods for Irrigation

Summary

Floods and droughts, along with over-exploitation of groundwater, are major issues of concern across much of the developed and developing world. This report presents an approach – referred to as ‘Underground Taming of Floods for Irrigation’ (UTFI) – for tackling these challenges in a novel and integrated manner. This approach involves interventions at the river basin scale to strategically recharge aquifers upstream during periods of high flow, thereby preventing local and downstream flooding and simultaneously providing additional groundwater for irrigation during the dry season for livelihood improvement. The three key stages and risks to be addressed in moving from the concept stage to mainstream implementation of UTFI are explained. An analysis of the Ganges River Basin indicates that the prospects for UTFI are high, with 68% of the inner region of the basin having high or very high suitability. Based on a hydrologic analysis of the Ramganga sub-basin, along with tentative estimates of recharge performance based on surface and subsurface recharge methods, the anticipated land area required to store and capture excess floodwater and reduce peak flows are defined. The economic benefits to local agriculture and the wider public benefits from flood reduction are substantial, and warrant the upfront investments and maintenance. After a detailed site selection and consultation process, a suitable site was selected in western Uttar Pradesh where a village pond was retrofitted with recharge wells and associated infrastructure to draw monsoon flows from a nearby flood-prone river. This pilot trial serves as both a scientific experiment and practical demonstration. If the trial and the UTFI approach, in general, can be technically, economically, socially and institutionally verified then there is enormous potential to apply the approach to help decision makers when planning investments in climate change adaption/mitigation and disaster risk reduction.

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Introduction

Water-related disasters have significant social, environmental and economic impacts at the global level, and there is mounting scientific evidence to suggest that their frequency and severity will continue to increase (IPCC 2012). This will place increasing pressure on developing countries already overwhelmed with efforts to boost their economies, enhance living standards and forge pathways for sustainable development (Agrawala and Fankhauser 2008; Patt et al. 2010; World Bank 2010). Floods and droughts account for 90% of the people affected by so-called 'natural' disasters. On average, over the period from 1980 to 2013, floods killed around 5,000 people, affected the lives of 52 million and cost USD 16 billion in damages each year (CRED 2014). The corresponding figures for droughts were 17,000 killed, 76 million people affected and USD 3.5 billion in damages each year. In geographic terms, Asia eclipses all other regions and accounts for about 95% of all people affected by both floods and droughts. Negative impacts of extreme climatic events are most severe for the poorest people within developing countries, who are the most vulnerable and suffer the most in terms of loss of lives and livelihoods (ADPC-UNDP 2005).

Approaches to flood and drought mitigation typically look at one or more structural measures to store and divert/transfer water, along with non-structural measures that seek to provide information-enhanced capacity to warn and respond to such events, and also building institutions and greater participation at the grassroots level (Jha et al. 2012). In recent years, greater emphasis has been given to integrated flood management, which combines both the hard and soft approaches. In the case of flooding, structural measures such as building dams, levees, dikes and diversions can also have negative effects, including the shifting of flood problems downstream, adverse ecological impacts, and high capital and maintenance costs. It is worthwhile noting that, in some instances, positive impacts on livelihoods can emerge from flooding that is periodic and at a manageable scale, through nutrient-laden silt deposition onto floodplains, salt flushing and biodiversity enhancement (Nguyen et al. 2007).

Enhancing water storage, both above and below ground, mitigates both types of hydrologic extremes: droughts and floods. Big dams are beneficial, but are also expensive and highly controversial from a variety of perspectives. Large dams create economic growth, but this growth may be highly inequitable and not necessarily trickle down to the poorest communities (Ansar et al. 2014). The flooding of valleys causes translocation of affected human settlements, and the modification of river flows can lead to negative impacts on river ecology. There is little doubt that dams can have a positive ameliorating effect on both floods and droughts. Juggling the multiple purposes that dams are expected to serve by prescribing suitable operating rules to achieve multiple sets of objectives is highly challenging. For example, dams constructed specifically for hydropower generation and/or irrigation tend to be operated from those perspectives and can perform poorly from the viewpoint of flood control (Goldsmith and Hildyard 1984).

One fact that is often overlooked is that the largest reservoirs lie below the ground in the form of aquifers, where the active aquifer storage potential is usually vast (Tuinhof et al. 2005). In times of drought, groundwater reserves, which are more highly buffered to rainfall variability than surface water, can provide emergency relief and ongoing water supplies for critical purposes (McCartney and Smakhtin 2010). Global groundwater use has intensified significantly, creating enormous socioeconomic benefits for public health, sanitation and food security (Giordano 2009). Undesirable impacts have also resulted from intensive pumping, notably groundwater depletion, water quality degradation, reduced inflows to streams and wetlands, and land subsidence. Many of these changes are irreversible over the short and medium term, and restoration of regional aquifer systems may take decades or centuries even if sustainable practices were implemented immediately.

The advantage of intensified groundwater use is that the capacity for aquifers to store surface water through infiltration and other recharge methods has increased, and so has the need for this to take place to offset unsustainable groundwater use in many areas. Thus, solutions to flooding issues can, if chosen wisely, create new opportunities during drier periods that can yield significant benefits for drought protection, agricultural production and ecosystem functioning. Enhancing water storage, particularly below the ground, offers an effective means of mitigating both flood and drought hazards.

River basins provide an ideal scale to address water resource problems. River basin management is universally faced with challenges associated with the mismatch between supply and demand brought about by variability in rainfall (Krysanova et al. 2008). In most river basins, situations of water shortage and abundance co-exist, although separated by time and/or space. Water scarcity in the dry season can emerge just a few months after heavy monsoonal flooding and, on occasion, flooding can emerge soon after a prolonged drought. While downstream locations experience flooding, upstream locations can face water shortages.

One of the major challenges for research on climate change adaptation is to provide the solutions needed by decision makers and practitioners that are affordable, implementable and sustainable (Moss et al. 2013). Ideally, solutions must work on a variety of levels. They must serve not only their most immediate goals, but also the poorest and most vulnerable members of the community who typically carry an unduly high burden.

We begin here with the premise that the existing portfolio of technologies and practices to address current and future problems associated with water-related disasters are inadequate and that alternatives are needed. This report describes the overarching idea for a new approach, and the generic steps required for its implementation and prospective areas for future research. The framework that has been developed is applied within the Ganges River Basin through a detailed program of analyses and engagements. This has enabled narrowing down from the broad scale prospects across the basin, through detailed analysis in a representative sub-basin, and finally selecting and setting up a pilot trial for implementation and testing.

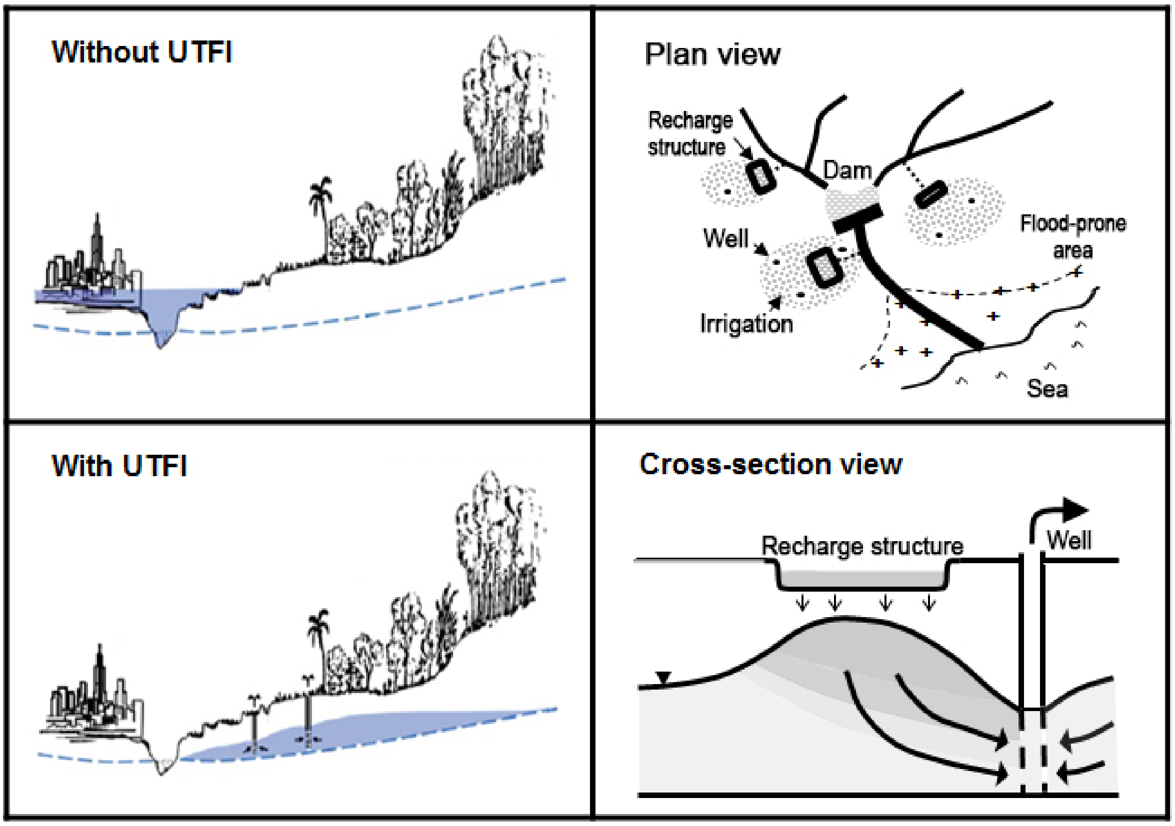
The Concept

Description and Biophysical Dimensions

For river basins that have a frequent occurrence of negatively-impacting floods during the wet season and water deficits in the dry season brought about by groundwater depletion or drought, the main question is how to intercept surplus surface water flows to minimize these impacts without unduly compromising existing downstream water users and environmental flow requirements in the dry season. A novel form of conjunctive water use management referred to herein as '*Underground Taming of Floods for Irrigation*' (UTFI) (pronounced 'utify') has been devised to address this issue. The concept is best reflected visually as illustrated in Figure 1. Capture and storage of high wet-season flows that potentially pose a flood risk take place through groundwater recharge structures (interventions) installed in upstream areas for the protection of highly valued assets (urban, industrial, cultural, etc.) locally and in downstream areas. This would then enable the recovery of water stored underground for productive use and livelihood enhancement. Therefore, in a sense, the impacts that would be felt across one part of the system could be offset to create opportunities in another part.

UTFI is a specific and unique application of managed aquifer recharge (MAR) (Table 1). UTFI adds new value to often ad hoc MAR efforts and puts it into a larger-scale perspective that offers a wider range of benefits to both upstream and downstream areas. Central to UTFI is distributing

FIGURE 1. Schematic illustrating the UTFI concept for harvesting, recharging and recovering floodwater in upstream areas to protect downstream communities.



recharge-enhancing interventions across strategic parts of the basin to provide supplies to meet additional demand during the dry season, and for this water to be recovered via agricultural wells rather than allowing surface water to concentrate and be problematic in the floodplain areas. The use of surface structures such as infiltration basins is preferable as they are simplest to construct and maintain. In some hydrogeological settings with low permeability surficial layers or poor surficial aquifers, deep infiltration systems such as recharge wells may be needed instead. All recharge systems are more prone to clogging impacts, and thus require higher levels of pre-treatment of recharge water and careful ongoing maintenance. Aquifers targeted for storage would typically be the upper unconfined or semi-confined formations with latent storage capacity and adequate aquifer productivity. Given the types of operational characteristics outlined, flooding events that are of a larger scale and longer duration in nature are more suited to UTFI than those that are localized or rapid.

Storing surface water from various sources (rooftops, drains, canals, rivers, lakes, wastewater treatment plants, etc.) in underground formations through different types of MAR has been implemented for decades (Dillon 2005). However, to our knowledge, the UTFI approach has not yet been put into practice and evaluated at scale. Some case study examples that have relevance to UTFI are presented in Table 2. They illustrate the diversity of settings and problems to which MAR has been applied. It demonstrates the clear preference towards surface-based recharge methods in alluvial settings and addresses issues related to water scarcity. Case studies 2 and 3 provide the closest comparison to UTFI, although the differences remain large. Case study 2 considers downstream capture of storm water runoff from a local peri-urban watershed in southern Australia and then pumping the water into a confined aquifer for irrigation of a park. Case study 3 is for an arid region in rural Iran, where infrequent runoff is collected and recharged for irrigation.

The origins of the UTFI approach emerged as a spin-off from a pilot-scale MAR trial conducted in a sub-basin of the Chao Phraya River Basin, Thailand (Pavelic et al. 2012). Water resources in the basin are heavily relied upon to support economic development, but severe problems associated with water surpluses and shortfalls are experienced on a regular basis. On average, 28% of the wet-season discharge into the Gulf of Thailand from the basin (3,370 million cubic meters [Mm^3] yr^{-1}) could be harvested without significantly impacting on water use associated with existing large to medium storages or the riverine ecosystem, in terms of preventing seawater ingress and pollution of marine ecosystems by maintaining nutrient and sediment loads to levels comparable to the period prior to major economic development.

TABLE 1. Generalized characteristics of UTFI.

Rationale	Mitigate seasonal flooding and improve groundwater storage.
Scale	Watershed through to river basin.
Target aquifer	Primarily medium-shallow, unconfined or semi-confined.
Site selection	Regular flood occurrence and impact, hydrogeological suitability, groundwater depletion.
Design	Targets simple, low-cost technologies that can be managed by local communities.
Frequency of operation	Intended to capture only excess flows, not necessarily in equal amounts in all the years.
Operation and maintenance	Local communities operating collectively in partnership with local authorities.
Benefits	Upstream and downstream benefits in terms of improved groundwater availability, flood mitigation and improved livelihoods.

TABLE 2. Case studies of MAR reliant on harvesting surface water runoff.

	Case studies						
Parameter	1	2	3	4	5	6	7
Region	Northern Australia	Southern Australia	Southwest Iran	Lower Northern Thailand	Western India	Uzbekistan	Eastern India
Recharge water type	River water	Storm water runoff	Floodwater	Canal water	Catchment runoff	River water	Runoff from fields
Recharge technology	Ponds and trenches	Injection well	Floodwater spreading system	Basins	Ponds, check dams	Infiltration basin	Aquifer storage and recovery (ASR) well
Volume recharged	100 x 10^6 m^3/year	0.25 x 10^6 m^3 over 4 years	<1 to >20 x 10^6 m^3/year	5,000 m^3 in 30 days	374 x 10^3 m^3/year	58,000 m^3 over 1.5 months (potentially 100 Mm^3/year at scale)	220 mm/year
Aquifer	Alluvial, unconfined	Limestone, confined	Alluvial, unconfined	Alluvial, unconfined	Fractured basalts	Coarse alluvium	Alluvial, semi-confined
Setting	River delta	Peri-urban	Arid plain	Alluvial plains, humid tropics	Semi-arid	Semi-arid valley	Hilly to gentle plains and coastal area
MAR objective	Scheme to reduce groundwater overuse/ seawater intrusion to sustain sugar production	Pilot to test creating new freshwater for landscape irrigation and reduce coastal discharge of runoff	Harvest floodwater to offset groundwater overuse	Pilot aimed to reverse groundwater depletion	Evaluation of recharge from micro-watersheds over several years	Pilot to enhance groundwater use sustainably for irrigation to overcome dry season water shortfalls downstream	Utilize excess monsoon runoff to meet irrigation demands
Problems experienced	Unlicensed groundwater abstraction	Well clogging	Decline in groundwater persists due to huge demand, sediment deposition and flood damage to system	Large area of land used as wetland for pre-treatment; long-term performance is unclear	None reported	None reported	Clogging of injection wells
Implementing agency	Water boards (regional government organization)	State government		Central government			
Source	Charlesworth et al. 2002	Pavelic et al. 2006	Hashemi et al. 2015	Pavelic et al. 2012	Sharda et al. 2006	Karimov et al. 2013	Holländer et al. 2009

These volumes, which create an enormous hazard when concentrated downstream in built-up floodplains, could be easily accommodated to refill the vast alluvial aquifers in the central plains which are extensively utilized for irrigation of rice and sugarcane. Results from pilot recharge trials reveal that this water could be readily recharged and accommodated within the vast shallow alluvial aquifers situated within and upstream of the flood-prone areas. Capturing peak flows would take place in wet years and requires dedicating around 200 km^2 of land for groundwater recharge within the basin. This would not only reduce the magnitude and costs of flooding, but also generate USD 140 million per year to boost the livelihoods of thousands of farming households, and thereby allow capital investments to be recouped over reasonably short time frames.

Financial and Economic Dimensions

The ‘value proposition’ for UTFI revolves around transferring investments from traditional watershed management approaches in downstream areas into alternative interventions upstream. UTFI requires upfront and ongoing costs that in turn provide benefits both in terms of flood mitigation and improved agricultural productivity, and generally increases socioeconomic well-being in addition to existing benefits.

It may be argued that UTFI is not a straightforward case of cost-benefit analysis, as the costs and benefits take place in different locations involving private as well as public goods and services. The public benefits as a result of UTFI are environmental services that go beyond flood mitigation, and include increased groundwater availability during the dry season and continuity of groundwater baseflows into surface water bodies, thereby enhancing environmental assets. Indirect services include sustainable drinking water provision, improved livelihood activities and enhanced economic well-being, including health and education. The distribution of these additional benefits horizontally (across space) and vertically (across socioeconomic groups) could potentially result in increased prosperity and more equitable societies, resilient communities, improved natural resource governance and protected ecosystems. UTFI places importance on the ecosystem services from watershed-level interventions. It is anticipated that the economic valuation of ecosystems will lead to their optimal use and preservation of their services.

Institutional and Policy Dimensions

UTFI cannot be undertaken by any single party alone. Close partnerships are required between different stakeholder groups in upstream and downstream areas, through institutional and broader governance arrangements that are inclusive and effective.

Farmers are a key beneficiary as well as strategic partners, and thus their participation and ownership is central to the operational success and sustainability of UTFI. Targeted operation of recharge structures to intercept excess flows, and flows in normal or dry years are perhaps permitted to bypass for use in downstream areas when and where necessary, is a crucial consideration. As important and perhaps more challenging, there is a high level of interdependence created between stakeholders situated in lowland flood-affected areas and runoff generating in upstream areas. How will upstream stakeholders be co-opted and encouraged to use land for dedicated recharge purposes, and manage this infrastructure on an ongoing basis for the benefit of downstream communities? In areas with intensive land use, this may require conversion of land use for recharge purposes. How will the number of stakeholders required to achieve positive impacts participate in this collective action? How will downstream stakeholders mobilize resources to support upstream actions? How to operationalize rules for when and how to harvest floodwater, and the minimum quantity of groundwater that needs to be withdrawn to achieve effective storage capacity?

The governance challenge is to identify institutional mechanisms for equitable distribution of the cost and benefit sharing necessary for ensuring the sustainability of these interventions and the follow-on benefits to farmers, urban areas and ecosystems. Financial or other incentives on a continuous basis are necessary to enable the effective and ongoing functioning of infrastructure over the long term. Since such incentives would need to be linked to flood events, there is also uncertainty in their use because such events can be irregular and difficult to forecast.

In terms of implementing UTFI, a number of models are possible:

- Linkages to existing government programs that address flood, groundwater and irrigation management.
- Market-based approaches such as Payment for Environmental Services (PES).
- Non-market-based (participatory) approaches.

Government agencies and programs with synergies to UTFI cut across numerous sectors that encompass the management of surface water resources, groundwater, irrigation, land-use planning, urban/agricultural development and others. This complex institutional environment can be simplified, if UTFI can be integrated into existing government development programs or strategies. In some cases, the integration needed exists in the form of river basin organizations, watershed improvement programs and others. To fully understand the context and entry points for UTFI in urban and rural planning, detailed multi-level/sector stakeholder engagement is vital from the very beginning.

PES is an institutional approach linking environmental service providers and users (i.e., beneficiaries) based on the principle that those who benefit from environmental services should pay, and those who provide these services should be compensated (Pagiola and Platais 2007). PES has been found to be a cost-effective means for a range of natural resource management issues. However, although attractive in theory, putting it into practice is far from being simple in most cases (Dillaha et al. 2007). PES can give rise to collective action dilemmas at the local level from political corruption, unequal power relationships and other processes. Given the nature and scale of UTFI, this needs to be managed within both upstream (seller) and downstream (buyer) locations by the community, private sector or the government itself acting in the public interest, or using a combination of these where parties work together covering the interests of both buyers and sellers.

Non-market (participatory) instruments are based on decentralized governance principles and are from a natural resource management perspective, which include approaches such as community participation and contribution, participatory learning and social regulation. Non-market approaches have been globally applied to various aspects, including groundwater, watersheds, irrigation systems, flood/drought risks, wetlands and others (Villarroya and Aldwell 1998; Shah 2009). Such approaches are applicable in arriving at agreements between communities that may have highly contrasting socioeconomic conditions and natural resource issues, especially when considered at a scale that is sufficiently large or rather complex. The success of informal participatory approaches is often attributable to strong local leadership or support from nongovernmental organizations (NGOs). Therefore, the sustainability and scalability of these initiatives is of major concern. It has generally been observed that, in the absence of regulatory controls, formal or informal, farmers have little incentive to follow specified practices in the given policy environment (Reddy 2012). Levels of trust between farmers and the public or government service delivery mechanisms are a key determinant. While continuity and up-scaling of these successful small-scale initiatives is not easy, the learnings that are derived could be integrated into formal institutions. A number of participatory institutions would need to be integrated in the context of UTFI. The feasibility of social regulation at scale and achieving equity in the UTFI context appear to be plausible in theory but needs to be investigated further.

Ultimately, it is difficult, if not impossible, to be prescriptive in advance of field testing, and operational experience of the actual merits and potential of these approaches.

From Concept to Mainstream Practice

New water management approaches will entail risks that must be identified and addressed. In this particular case, the following risks can be partitioned into four main types - technical (T), social and institutional (S&I), economic (EC) and environmental (EN):

- Poor site selection (T).
- Inappropriate system design leading to low performance (T, EN).
- Poorly targeted governance model (S&I).
- Lack of operating rules leading to ineffective flood mitigation (S&I).
- Large capital or operating costs relative to other approaches (EC).
- Waterlogging due to over-filling of aquifer (T, EN, S&I).
- Contamination of aquifer due to pollutants in recharge water (T, EN, S&I).
- Interception of downstream environmental flows (EN, S&I)

To address these risks, a staged and adaptive management approach is proposed to maximize the benefits of investments and to avert major failures. This is consistent with the messages reported by experienced practitioners of MAR (Bouwer 2002; Dillon 2005). It is also recognized that unless careful planning takes place, technical failures can occur which are rarely reported but can significantly set back advancements.

It is envisaged that the advancement of UTFI from inception to widespread implementation will involve a series of steps or stages that would collectively lead to advanced progress. For convenience, three main stages are defined here: i) broad-scale opportunity assessments, ii) pilot-scale testing and evaluation, and iii) scaling up.

Broad-scale Opportunity Assessments

The goal here is to develop an understanding of the likely scope for UTFI implementation within a broad region, such as a country or river basin. A disaggregated analysis across the region would serve to pinpoint the localities that are most favorable for its implementation; envisaged to be areas where suitable biophysical, socioeconomic and institutional characteristics converge.

Broad-scale assessments to examine the potential of MAR have been carried out in various regions (Smith and Pollock 2012; Alraggad and Jasem 2010; Chusanathas et al. 2010). The focus of these studies is twofold: i) nature of the subsurface, and its capacity to accept, store and recover water; and 2) availability of sufficient water to meet the project objectives. These are useful starting points, but do not necessarily include all the key elements needed for a UTFI opportunity assessment. A generalized methodology has been developed for UTFI, and applied to Sri Lanka, Myanmar and the Ganges River Basin. The results of the Ganges River Basin assessment is presented in the following section.

Pilot-scale Testing and Evaluation

The areas with the highest potential for UTFI implementation were identified from the opportunity assessment. A detailed proof of concept by field implementation on a pilot scale would follow.

The key biophysical measures of performance would be in terms of flood attenuation and risk reduction, along with enhanced groundwater storage and irrigation intensities. There is a need for demonstrated performance on a sustained basis that extends across multiple years to capture variability in rainfall and flood characteristics. Sustainable operations of groundwater recharge interventions are underpinned by effective participation from the relevant actors derived from local communities and local government. Research activities would cover site selection, biophysical and socioeconomic site characterization, pilot-scale design and implementation or storage/recharge interventions, baseline data, performance monitoring and testing, hydrologic modelling and forecasting, training and capacity building, social/institutional policy arrangements, and cost-benefit analyses. Pilots would need to be on a sufficiently representative yet achievable scale, and operational testing and evaluation should be carried out over extended periods to fine-tune operational systems and protocols.

Site selection is arguably the most critical step, since it provides the foundation for a successful pilot study. Cases of MAR failures being reported are rare. However, of the few exceptions that are reported, poor site characteristics have been a key attributing factor (Pavelic et al. 2010).

Scaling Up

It is expected that the direct benefits that can emerge from any individual pilot trial will be modest. How to best bring UTFI up to scale and the benefits of the approach are reliant on the use of decision support tools, such as hydrologic models, which offer predictions based on one or more implementation scenarios. Such tools/models also have value in designing the pilot trials in the second stage.

The evidence base generated, when disseminated in well-targeted ways, can lead to policy acceptance and the guidance needed to enable larger-scale rollout by governments and other investors, which may be linked to ongoing government programs that address flood/groundwater/irrigation management or crosscutting areas such as climate change adaptation and mitigation. Bringing on board key stakeholders from the development sector, including private enterprise and international financial institutions, can also help facilitate uptake of UTFI.

Finally, it is also recognized that development pathways are rarely as simple or straightforward as presented in the three-stage process defined here. Also, within and between each stage may lie a myriad of sub-steps and interactions that are highly case specific and difficult to identify a priori.

Potential for UTFI in the Ganges River Basin

This section is multi-faceted and describes assessments made at the basin, sub-basin, district and village scales. It applies a variety of methods and approaches to assess the feasibility of UTFI at these different scales. This finally leads to on-the-ground implementation of a UTFI pilot trial in one prospective village.

Basin-scale Opportunity Assessment

The Ganges River Basin in South Asia, where problems related to seasonal flooding, groundwater depletion and food security are particularly acute, was selected for development of the opportunity assessment. The basin is one of the world's largest (1.2 million km^2) and most heavily populated (655 million people) transboundary river basins that extends over four countries - Bangladesh (4%), China (3%), India (79%) and Nepal (14%) (JRCB 2011). Floods are an annual occurrence and the basin has a well-known history of devastating flooding events, and low-lying parts of the basin are regularly inundated by floodwaters. In fact, some of South Asia's largest and fastest-growing cities (e.g., Delhi, Kolkata, Lucknow, Dhaka) sit on low-lying floodplain and deltaic settings that are highly susceptible to natural disasters such as floods and sea-level rise. The economies of the major riparian countries of the basin are highly driven by agriculture, and many areas remain steeped in poverty (World Bank 2014). Rapid increases in population and economic growth have increased food demand in recent decades. The gross irrigated area in the Indian part of the basin is estimated at 23 million hectares (Mha). Pumping of groundwater to support irrigated agriculture is a major water source across the basin. This heavy reliance on groundwater has led to depletion across the northwestern Gangetic Plains, which includes much of Haryana, Delhi and western Uttar Pradesh.

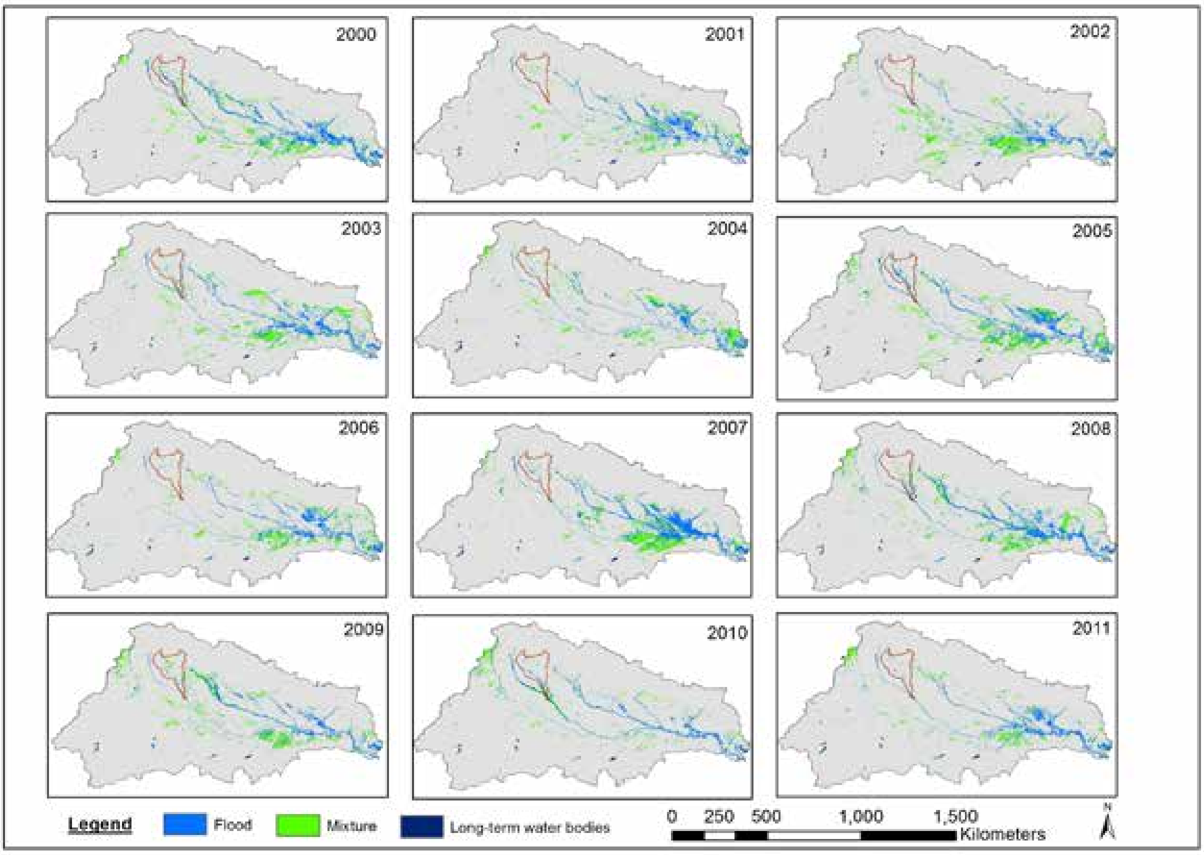
Identifying locations with characteristics suited for UTFI implementation using scientifically-based methods and tools is a necessary first step. UTFI interventions require an area-based approach, and must be implemented at a sufficient scale to be effective in dampening flooding impacts. While tools that indicate MAR site selection or climate vulnerability exist in different regions, the methodologies used for this purpose are not directly transferable to UTFI and hence a specific approach was developed. Only an overview of the assessment protocols and results are provided here, and more detailed information can be found in Brindha and Pavelic (Forthcoming).

Factors influencing the occurrence and impacts of floods in the Ganges were identified based on literature which focused on flood-risk mapping, groundwater development and mapping of groundwater potential zones. Nine surface characteristics of the basin (drainage density, population density, geology, flood frequency, flood mortality and distribution, extreme rainfall events in a year, land use, slope and soil type), two subsurface characteristics (groundwater level and transmissivity of the aquifer) and economic losses due to floods were included. Data related to these surface and subsurface characteristics of the area were collected from different sources. Processing of the layers was carried out through a multi-layer geographic information system (GIS) analysis, whereby a suitability index (SI) was determined. Each of the layers was sorted under three distinct groups representing different parts of the cycle of water flows: (i) flood occurrence and impacts; (ii) capture and recharge; and (iii) groundwater storage, use and demand. Only 43% of the basin encompassing the 'inner zone' was analyzed, because it was found that UTFI is not feasible in the 'outer zone' due to the risk of flooding, drought and human/economic losses. Data were available at a diverse range of scales, which were then aggregated and analyzed at the watershed level. Ranks were assigned for features within the thematic layers, and a weight given for each layer was then merged to arrive at a final SI map organized into four suitability classes: low, moderate, high and very high (Brindha and Pavelic Forthcoming).

Flood occurrence was drawn directly from the work of Amarnath et al. (2012), which established the maximum area inundated by flooding revealed from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data. These data consisted of 500-m resolution images of ground spectral reflectance at 8-day intervals over the period from 2000 to 2011, and was interpreted using flood detection mapping algorithms. Across the Ganges River Basin, the maximum inundation was highly variable with an area varying from 6,000 km^2 to 11,000 km^2. The longest inundation periods were in 2007 and 2010 (although not immediately evident from Figure 2).

Results show that 24% of the inner basin had very high suitability and a further 44% had high suitability for UTFI (Figure 3). The SI distribution reveals differentiation in suitability across the landscape – not all areas have the same potential to support UTFI implementation.

FIGURE 2. Annual maximum inundation maps of the Ganges River Basin showing the maximum area of flood inundation for each year between 2000 and 2011. *Flood* pixels have Enhanced Vegetation Indices (EVI) of ≤ 0.1; *Mixture* pixels include water, vegetation and soil coverage with EVI > 0.1 and ≤ 0.3; *Long-term water body* pixels have inundation periods > 120 days. The boundary of the Ramganga sub-basin is indicated by the red line.



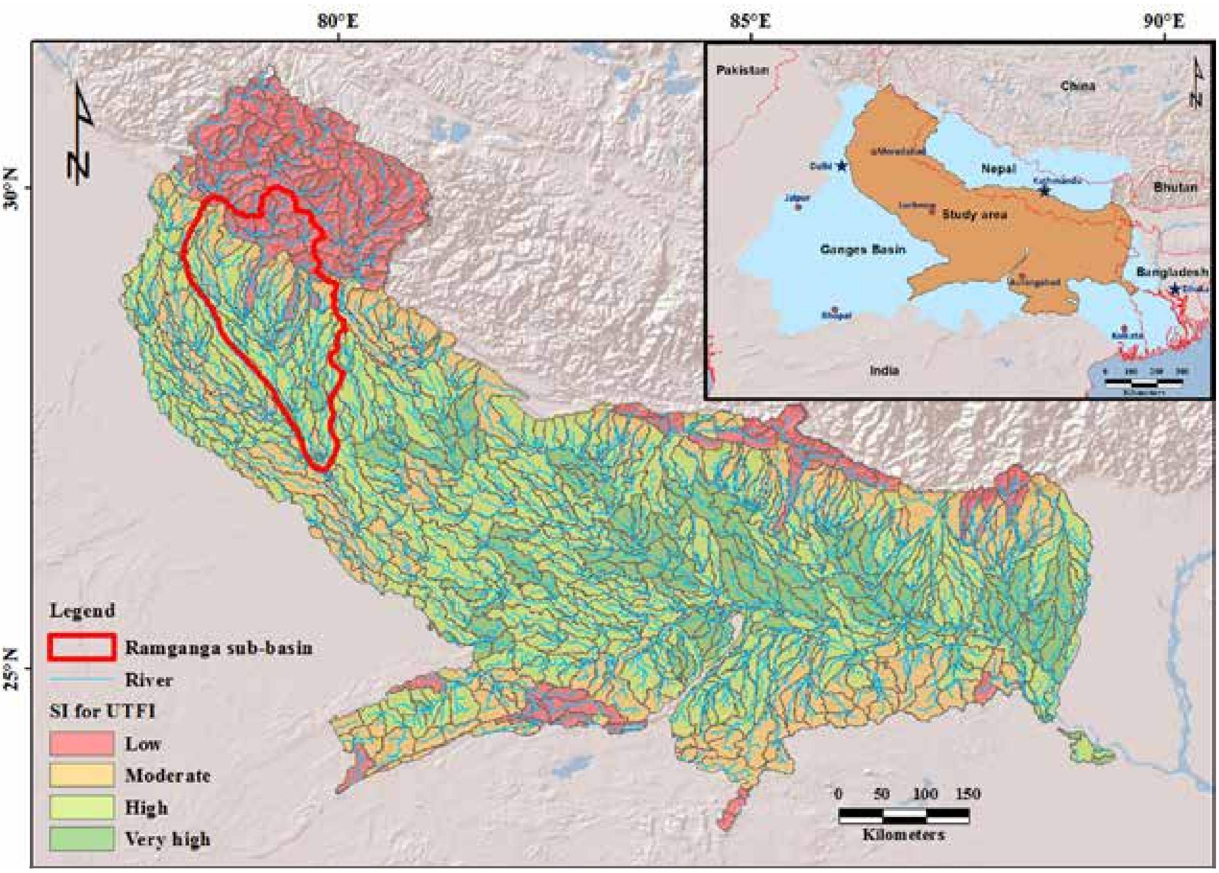
Source: After Amarnath et al. 2012.

There was a tendency for the watersheds at the periphery to have a low SI, a natural transition considering that the adjacent areas could be excluded from the analysis. These upland areas with low SI contribute runoff that can lead to flood inundation downstream (Sharma and de Condappa 2013). This highlights the scalar nature of the problem, and the dilemma in trying to find a balance between considering scales that are either too small or too large. A scale that is too small may disconnect the problem areas downstream from the areas where there are opportunities upstream. A scale that is too large creates excess aggregation and separation between the upstream and downstream areas.

Sub-basin Assessment

According to Figure 3, one of the areas with generally high potential for UTFI implementation is the Ramganga sub-basin. The Ramganga originates from the high altitude zone of 750-2,300 m before descending upon the Upper Gangetic plains. Its drainage area is 18,665 km^2 with an average annual discharge of about 200 m^3 s^{-1} (ignoring the drainage area of a tributary in the East, which flows separately into the Ganges but is commonly included in the sub-basin analysis of other studies). The largest storage, the Ramganga reservoir located near Kalagarh, provides for irrigation and hydroelectric generation.

FIGURE 3. Suitability index (SI) rankings across the inner Ganges River Basin determined at the watershed level.



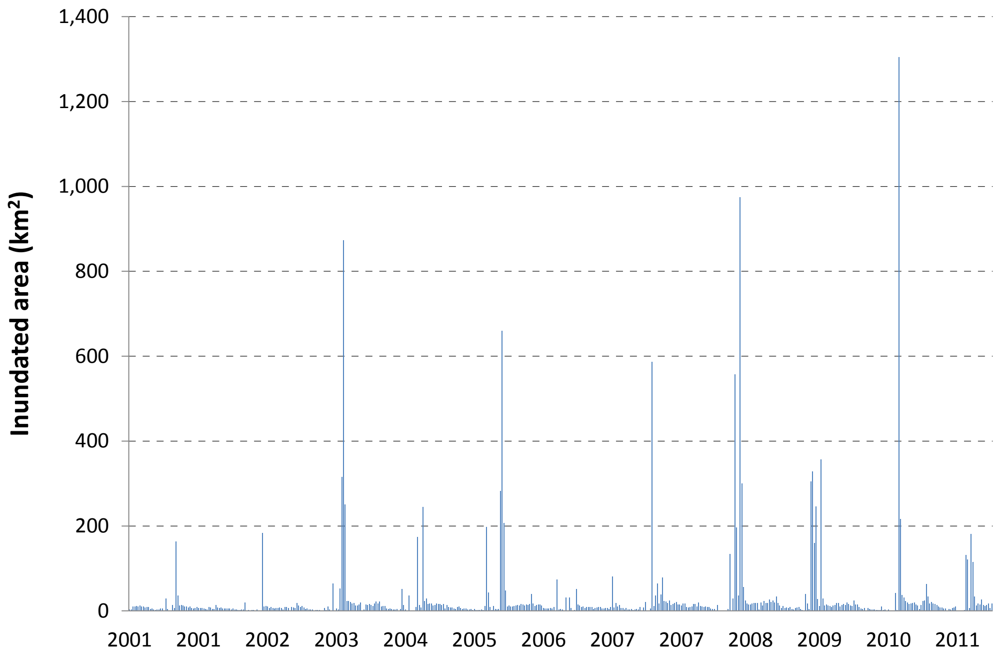
Source: Adapted from Brindha and Pavelic Forthcoming.

This sub-basin is the first major river joining the Ganges River, and the length of the river from the source to the confluence with the Ganges is 596 km. The sub-basin extends over two administrative states: Uttaranchal and Uttar Pradesh. The important tributaries that flow into the Ramganga River are the Kho, Gangan, Aril, Koshi and Gorra. There are about 20 million people living in the sub-basin. As in other parts of the Ganges River Basin, the most challenging water resources management issue in this sub-basin is the difference between water demand and seasonal availability. Average annual precipitation in the basin is about 900 mm, and ranges from 550 mm to 1,340 mm. The monsoon period is from June to September and about 85% of the precipitation occurs during these monsoon months. Also, more than 80% of the annual flow in the Ramganga River occurs during these months, resulting in widespread flooding. During the rest of the year, surface water flows are limited, and this has an impact on domestic and agricultural supplies, and ecosystems. Groundwater levels are dropping across the basin, especially in non-command areas where groundwater pumping is not being countered by seepage from canals and surface water return flows (CWC 2012).

Flow-flood Relationships

The Ramganga sub-basin has a high flood frequency with major flooding estimated for 2003, 2005, 2008 and 2010, with an average inundation extent of approximately 800 km^2 to 1,000 km^2 (Figure 4). In sub-basins of the Upper Ganges River Basin, such as Ramganga, flood events are most apparent in the period between late August and early October.

FIGURE 4. Temporal changes in the extent of estimated *flood* pixels within the Ramganga sub-basin.



Source: After Amarnath et al. 2012.

A flow analysis of the Ramganga sub-basin was carried out using the Soil and Water Assessment Tool (SWAT) model, calibrated with hydrograph records from several river monitoring stations over a 15-year period from 1996 to 2010, to better understand the volumes of problematic water flows and to design interventions accordingly. Due to the flow monitoring stations being located in the upper and middle parts of the basin, the model had to be used to simulate the total outflow from the sub-basin. It also served to better understand the hydrology of a basin, which will be useful for other facets of the study as described later.

The annual peak monthly flow simulated at the outlet station is strongly correlated (R^2 = 0.62) to the maximum area inundated by floods as revealed by the MODIS data. It verifies that reducing peak monthly flows will have a commensurate impact on reducing flood inundation. In theory, reducing peak monthly flows to around 500 m^3 s^{-1} or less is needed to eliminate major negative flooding, although smaller, more manageable floods would likely not be eliminated (Figure 5).

Interventions to Reduce Flows

The average runoff volumes for 100% flow, and the associated volumes that need to be recharged to achieve 25% and 50% reductions in flow are shown in Table 3. A 50% reduction would reduce flow of the highest magnitude in 2010 with a recurrence interval of 16 years down to 2 years. For the 50% target, across the entire sub-basin, about 1,741 m^3 ha^{-1} would need to be intercepted, stored and recharged, on average, or this could be up to 2,377 m^3 ha^{-1}, if the variability in flows are taken into account.

On the heterogeneous alluvial soils characteristic of the Ramganga floodplain, we consider two methods of recharge: (i) surface infiltration to account for areas where the unsaturated zones are permeable, and (ii) subsurface recharge for less permeable zones. The 50% reduction target is used here for demonstration purposes.

For the first method, it is assumed that a minimum infiltration rate of 10 m per wet season may be achieved in any area targeted for recharge (Bouwer 2002), which is a conservative

FIGURE 5. Relationship between annual maximum area inundated by floods determined from MODIS data and the maximum monthly flow simulated with SWAT over a 10-year period (2001-2010).

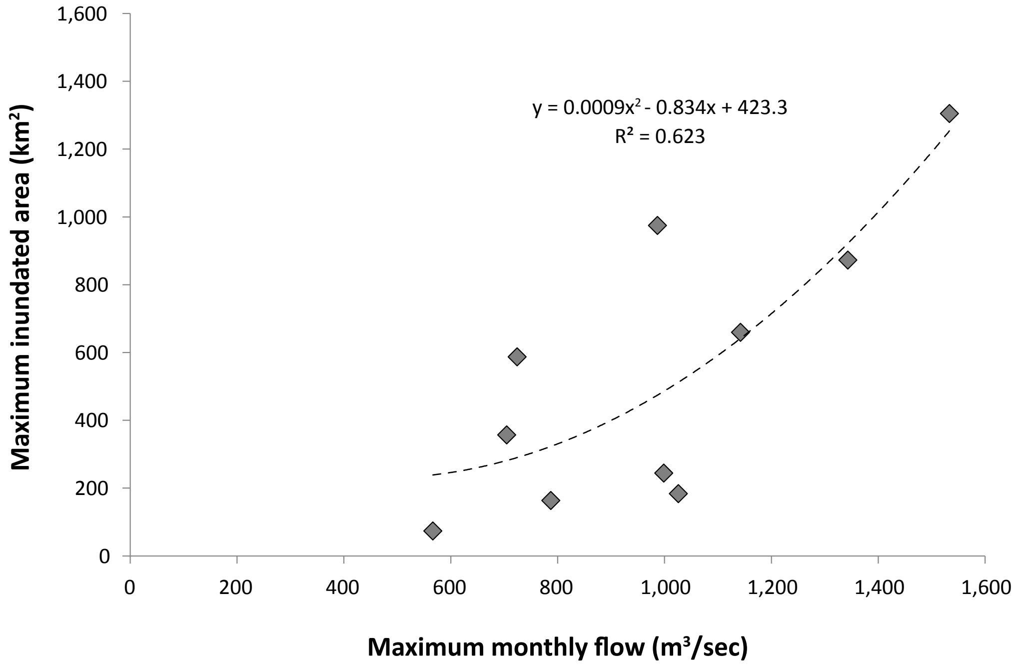


TABLE 3. Annual and standard deviation outflow volumes for 100, 75 and 50% flows and flow reductions, and the captured water needed to achieve each scenario.

Percentage of flows	Mean annual outflow ± Standard deviation (Mm^3)	Mean annual flow reduction (Mm^3)	Mean captured water yield ± Standard deviation (m^3 ha^{-1})
100	6,498± 2,375	0	0±1,272
75	4,873±1,782	1,624	870±955
50	3,249±1,188	3,249	1,741±636

estimate based on international experience in similar settings. In this case, where the recharge target is 1,741 m^3 ha^{-1}, less than 2% of the land area would need to be dedicated to recharge interventions across the entire Ramganga sub-basin. If areas with most permeable surface and subsurface strata are targeted then higher infiltration rates may be achieved and the dedicated area will reduce proportionately. For example, achieving 100 m of recharge per season would reduce the land area to around less than 0.2%, whereas if only 1 meter of recharge was achieved due to poor site selection or performance, the area required would be up to 20%.

For the second method, it is assumed that recharge wells are used. With high transmissivities in Uttar Pradesh in the order of 3,000 m^2/day (MacDonald et al. 2015), it is conservatively assumed that each well can recharge 100 m^3 day^{-1} (1.2 liters s^{-1}) and that recharge takes place during a 100-day period of the wet season.

Recharging floodwater to achieve the 50% reduction target can be reached with a well density of 0.17 wells per hectare. If 10 wells were installed in the base of a typical village pond then one pond installation would provide sufficient flood proofing for an area of 58 ha.

The values presented here for both methods provide preliminary estimates of what the possible performance could be in practice, accounting for some degree of uncertainty. Further data would be needed to establish actual recharge rates, supported by a more rigorous analysis that links the river flows to the recharge dynamics. Further, the high silt load of the Ganges floodwaters makes the recharge design challenging and necessitates the need to consider pre-treatment of source water. The implications are that periodic desilting of recharge structures would be needed to achieve effective ongoing performance.

Cost-benefit Analysis at District Level

Ex-ante costs and benefits from UTFI interventions are assessed for Moradabad District, which is situated within the middle reaches of the Ramganga sub-basin. The average population density is 745 persons per km^2, with 68% of the people living in rural areas. The district is intensively used for agriculture, with 83% of the area under irrigation, high cropping intensities and three major cropping seasons. Over 95% of irrigation draws on groundwater from open wells or tube wells. According to the district profile of the Central Ground Water Board (CGWB), over half of the assessment units have groundwater resources that are classified as ‘unsafe’ (i.e., semi-critically over-exploited) and, on average, groundwater draft has reached 95% of the recharge. Major crops include rice in the wet season, wheat in the winter season, and maize and menthol are sown during the summer. Sugarcane, grown year-round, is another major crop.

During the past 5 to 10 years, there were no declared droughts, although water stress due to increasing groundwater depletion is on the rise and causing productivity losses in some seasons. Moradabad District experiences frequent floods, with three flood events in the past 5 years, i.e., September 2010, August 2012 and July 2014. Both the 2010 and 2014 floods were severe and resulted in the loss of lives, and caused extensive damage to crops and property in rural as well as urban areas. A number of villages were submerged in Moradabad District, such that state flood relief agencies were overwhelmed and rescue operations through the military were needed.

Here we use the example of the extent and cost of damage caused by the floods in 2010. As per the official estimates in 2010, there were 28 lives lost and 412,000 people in 216 villages were affected, with flood damage totalling about INR 1,000 million (USD 17 million). This damage/ cost estimate does not include the loss of human life, losses due to transport delays, losses due to school days or workdays lost, and losses due to disease- and health-related problems.

The various cash flow measures using the data on flood damage, costs of UTFI investments and gains to farmers are estimated based on a set of assumptions, in order to arrive at a cost-benefit assessment over a 20-year time frame using 3% and 8% discount rates (Table 4). We assume that about 25% of the cultivable wasteland and fallow lands, and just 2% of the irrigated land need to be dedicated for capturing floodwaters under UTFI interventions. The captured water yield is sufficient to enable at least one additional irrigation application to support cropping during water-short periods. The assumed capital cost of establishing UTFI interventions (INR 36,000/ USD 600 per hectare) is set at three times the allocation made towards watershed management programs at the national level, due to the huge volume of floodwaters that would need to be arrested in the area. Rental value of irrigated land is used to estimate the opportunity cost of using this land for UTFI interventions. The additional cost of groundwater recovery for irrigation is assumed to be equivalent to the cost of renting pump sets (including diesel) by the farmers. Governance costs are assumed according to the annual salary of staff needed for the supervision of UTFI interventions. Gains in earnings to farmers through greater cropping intensity and crop diversification are estimated using prevailing market prices. The farm-gate prices are assumed to be 80% of the wholesale market prices.

Farmers use additional groundwater harnessed by the UTFI interventions to bring more land area under food security crops (rice is taken as the model crop), close the yield gap (model crop is sugarcane) and then diversify the cropping pattern (more potatoes, less sugarcane) to enhance revenues. Cropping intensity increases to 195% (up from 188%) with just one additional irrigation application, and could reach 250% with wider adoption and broad-scale implementation of UTFI. Preliminary estimates show that farmers benefit from gains in farm earnings through greater cropping intensity (INR 42/USD 0.7 million per year, on average), closing the yield gap and crop diversification (INR 812/USD 13.5 million per year, on average). Benefits from the flood damage prevented and savings to the government on emergency flood relief operations are substantial to justify the investments in UTFI interventions. The returns are quite high, even if only the benefits to farmers and the local agricultural economy are considered. It is also apparent that high NPV and IRR could be achieved, yet the numbers are indicative only and detailed field data are required for a more robust economic analysis of UTFI. Further, this analysis provides guidance on the viability of UTFI in Moradabad District in the absence of any comparative interventions such as medium- or large-sized dams.

TABLE 4. Cost-benefit analysis of UTFI implementation in Moradabad District, Uttar Pradesh, India.

Item	INR (millions)	USD[1] (millions)
Costs		
Total investment, establishing floodwater harvesting interventions	286.9	4.78
Total operation and maintenance (O&M) costs:	237.3	3.96
a. Average annual O&M cost for maintaining UTFI structures	28.7	0.48
b. Opportunity cost of land acquisition	91.2	1.52
c. Groundwater recovery for irrigation	117.3	1.96
d. Governance of UTFI (supervision)	0.2	0.003
Benefits		
Benefit of the damage prevented (per flood event)	953.0	15.9
Savings to the government in terms of flood rescue and relief operations (per flood event)	136.6	2.28
Gains in farm earnings, greater cropping intensity	42.3	0.71
Gains in farm earnings, closing the yield gap and crop diversification	812.2	13.5
Net present value (NPV) @3%	13,660.9	227.7
NPV @8%	7,930.3	132.2
Internal rate of return (IRR)	77%	
IRR with agricultural benefits only	42%	

Note: [1] It is assumed that USD 1 = INR 60.

Planning and Establishment of Pilot Trial

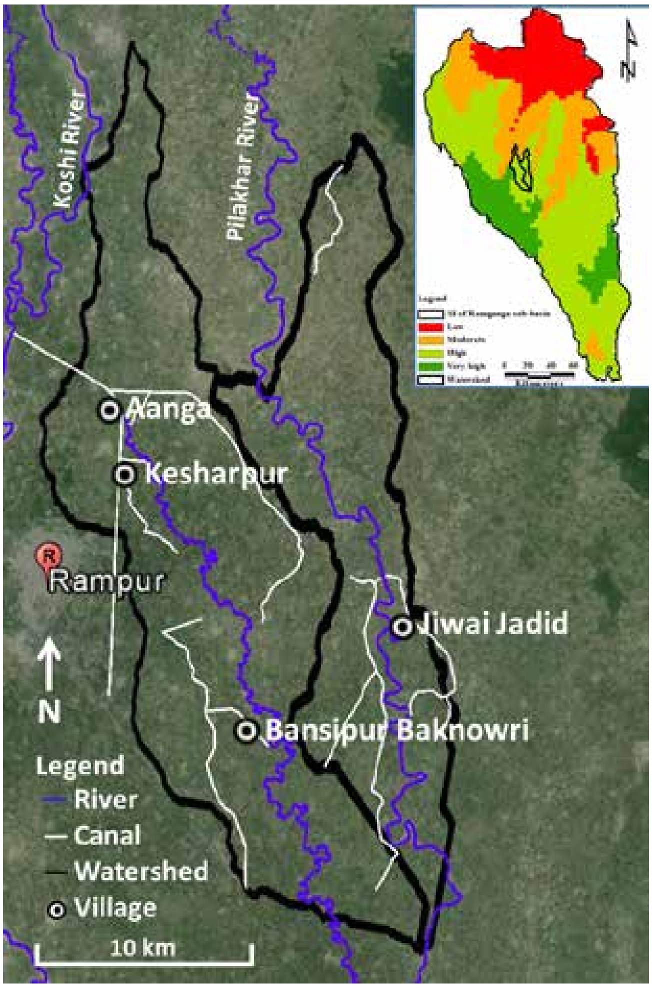
Site Selection Processes

The first major step for piloting involved selection of the most suitable site by narrowing down the area from the Ramganga sub-basin to the village scale. Two adjacent meso-scale watersheds, 248 and 295 km^2 in size, were selected in an area with a high SI according to the opportunity assessment map, where canals or rivers and ponds are present, and in close proximity to the administrative capital of the district (Rampur) (Figure 6).

Using the sub-basin-level datasets supplemented by available district-level information, such as the groundwater reports of CGWB and the agriculture contingency plan of the Uttar Pradesh Department of Agriculture and Cooperation (AGRICOOP), a set of local indicators were identified to assist in the process of selecting a suitable pilot site. These indicators included the following:

- Occurrence of flooding.
- Depth to the water table and long-term trends in groundwater levels (stable, rising, falling).
- Distance of proposed recharge structure (ponds) to nearest river or canal.
- Size and number of ponds in each village.
- Type of ownership of ponds (government/ community or privately owned).

FIGURE 6. Satellite map of the two focal watersheds and four short-listed villages in Rampur District. The village ultimately selected for piloting (Jiwai Jadid) is amongst those indicated in the map.



Maps for each indicator were prepared and villages within the watersheds were ranked against those indicators. Over the period from February to May 2015, visits were made to the ten highest ranking villages, which were ranked again after the visits. Of these, the top four villages were revisited and a detailed questionnaire was administered under several themes: general information, floods, groundwater, agriculture, socioeconomic and institutions. Team members from the Central Soil Salinity Research Institute (CSSRI), Krishi Vigyan Kendra and the International Water Management Institute (IWMI), with collective knowledge on biophysical as well as socioeconomic aspects, contributed to preparing and carrying out the questionnaire survey.

In the intensively cultivated plains of the lower Ramganga sub-basin, availability of land to implement UTFI is a major constraint. The ponds within the villages situated in local depressions, where there is scope to propose conversion of land for floodwater recharge, became the obvious focal point. There are two types of village ponds: (i) community ponds owned by the local government (*Gram Panchayat*), and (ii) private ponds owned by one or more community members. Community ponds, which were once heavily relied upon for domestic and agricultural water supplies, and for other purposes, have been replaced by private wells tapping groundwater, and these ponds now serve as repositories for domestic sewage within the villages. As national sanitation programs, such as the Clean India Mission, have been implemented, households have constructed toilets to replace open defecation practices. Due to this, pollutant loading has become most concentrated within the built-up village environment, and ultimately ends up in the community ponds. Most of these ponds are choked with water hyacinth due to high nutrient inputs. On the other hand, private ponds, which tend to lie in the fringes and rural parts of a village, collect runoff from local catchments and is sometimes supplemented by groundwater pumping rather than wastewater, and are thus visibly less polluted. Private ponds are typically used for growing water chestnut, raising ducks, fish farming and livestock watering/bathing. Thus, private and community owned ponds each have specific characteristics. The cleaner environment of private ponds must be weighed up against the need to fully understand the motivations and interests of their owners. Community ponds, which lie on common land as a public asset, offer long-term security and may be eligible to attract funding through government development schemes to support livelihood-related activities. For the purpose of site selection, neither option was explicitly ruled out, but rather left to the merits of each individual site and the views of the selection team members.

On the basis of the final ranking, site visits and detailed consultations (described in a later sub-section), Jiwai Jadid village, situated in Milak block, Rampur District, was selected for piloting. In particular, a community pond situated adjacent to a sealed road and a canal transporting water from the Pilakhar River (Pilakhar minor canal) were selected (Table 5). The site is conveniently accessed and prominently located on a transport corridor linking Milak with Bilaspur via Kemri.

Considering multiple watersheds provided benefits beyond simply site selection, namely: i) a greater understanding of the factors affecting site suitability at the local level, and ii) identifying multiple sites that could be setup during a subsequent expansion phase.

Pilot Trial: Design and Construction

When retrofitting village ponds for recharge purposes, surface infiltration methods are generally preferred as they are cheap, simple and easy to manage compared to other methods (CGWB 2007). However, as the top few meters of the soil profile in Jiwai Jadid village is composed of heavy clay topsoil, percolation rates can be expected to be negligible. A viable alternative is to use deep infiltration methods, which bypass upper layers that are resistive to flow, to transfer water directly under gravity to deeper more permeable layers. In this case, groundwater recharge was achieved through recharge wells that transfer excess canal water (filtered) under gravity through the well to subsurface permeable zones.

TABLE 5. Comparison of villages visited in May 2015 to identify suitability to implement UTFI.

Parameter[1]	Jiwai Jadid	Aanga	Kesharpur	Bansipur Baknowri (site 1)	Bansipur Baknowri (site 2)
Flooding[2]	X	X	X	-	X
Water table in decline	X	X	X	X	XX
Proximity to canal/river	XXX	XXX	XXX	X	XXX
Number of ponds	2	1	1	2	2
Ease of access[3]	XXX	XXX	XXX	XXX	XXX
Type of pond[4]	GP	P	GP	GP	P
Ranking	1[5]	2	3	5	4

[1] X = Low rating; XX = Medium rating; XXX = High rating.
[2] No loss of human lives reported.
[3] Distance from the nearest highway.
[4] Owned by the local government, i.e., *gram panchayat* (GP), or privately owned (P) by one or more community members.
[5] Aanga village was initially ranked ahead of Jiwai Jadid. However, as Aanga has a privately owned pond, the latter was most preferred by the team.

This approach has been practiced widely across the Ganges River Basin and considerable operational experience has emerged (e.g., Kaledhonkar et al. 2003; Kumari et al. 2014).

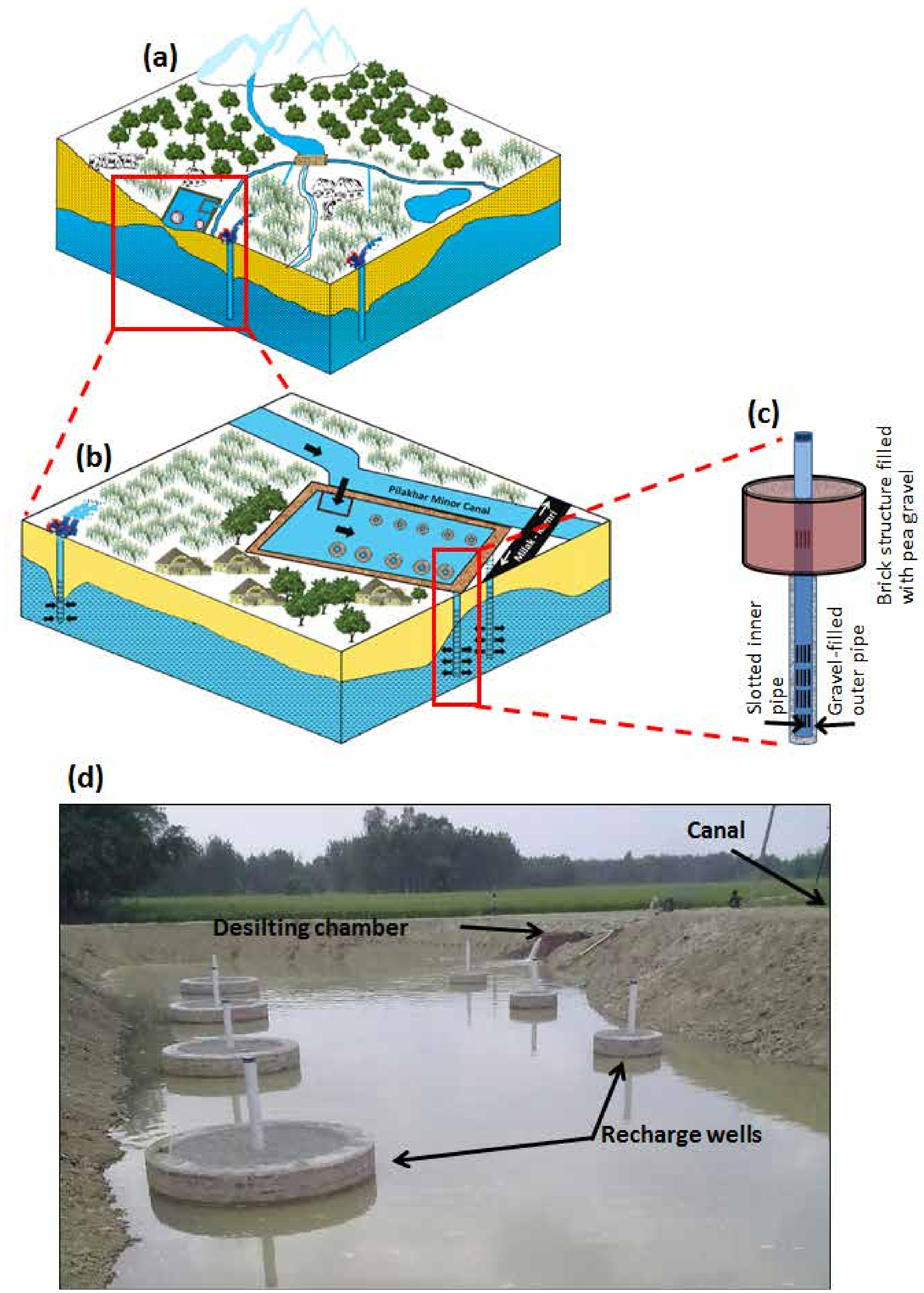
In an effort to establish the pilot site swiftly to maximize the opportunities presented by the 2015 monsoon season, the private sector was solicited to submit bids. Water Solutions, a company based in Delhi with extensive experience in MAR in the region, was selected to undertake the work. The pond was dewatered and excavated to a depth of 2 m, and the soil recovered was used for raising and strengthening the banks (Figure 7). A set of 10 gravity-fed recharge wells with six-inch inner diameter PVC pipes slotted at the base were sunk into the bottom of the pond. Around each pipe of the recharge well is a brick masonry chamber filled with pea gravels to filter out suspended silts and ensure higher rates of groundwater recharge. The wells are coupled to a recharge filter consisting of gravel in a small brick masonry chamber. Wastewater which previously flowed into the pond from around 12 households was diverted away from the pond. Water flows from the canal enters a stilling chamber within the pond via a pipe and recharge operates when water levels within the pond are from 1 to 2 m, thereby ensuring around 1 m of permanent water within the pond to serve other community purposes. Three monitoring wells were installed within close proximity of the pond to evaluate the impacts of recharge, and groundwater levels and quality.

The anticipated recharge rates could be as high as 432 m^3 day^{-1} $well^{-1}$ based on initial testing of the performance of the recharge well. The total volume of water to be recharged at the site each season will be dependent on the acceptance rate of the wells, taking into account the degree of filtering and well clogging experienced, and the duration of water availability in the canal. These characteristics will be revealed over the course of the monitoring process. Community members will be provided with training by the research team to desilt the filter chambers and wells, and to generally maintain the functionality of the site while also raising awareness of the direct benefits of doing so.

Consultative Processes

Over the course of site selection and establishment, meetings were held with government officials from the local level through to the national level in Delhi, Lucknow, Moradabad and Rampur, as well as in numerous villages within the targeted watersheds. These meetings served to inform people about the project, solicit their views and seek their support. The local knowledge provided at these meetings helped immensely to improve the site establishment process.

FIGURE 7. Schematic illustrations and photographs of the UTFI pilot site at Jiwai Jadid village. (a) Basin-scale, and (b) local-scale representations; (c) design of recharge wells; and (d) photograph of the retrofitted village pond.



The key stakeholders that the research team interacted with included the following:

- Department of Irrigation, including the Engineer of Rampur Canal Division.
- District Magistrate of Rampur District.
- Commissioner of Moradabad Division (covering Moradabad, Bijnor, Rampur, Amroha and Sambhal districts).

The acceptance of any UTFI trial by the local community emerged as an important issue. Prior to visiting each site, courtesy visits were made to the village head (*Pradhan*) and other village officials to appraise them of the concept and the planned trial, and to seek their views and support for the project. A brochure about the project in English and Hindi to cater for the local people was prepared. It is worthwhile to add that the ultimate selection of Jiwai Jadid village had a lot to do with community acceptance of the trial, as well as the biophysical suitability.

The project is harnessing the goodwill and support of the Jiwai Jadid community, and providing the capacity and linkages to broader institutions needed. This will enable the local community to ultimately manage the system over the longer term, with links to the government to provide the necessary support and services.

Prior to commencement of the field activities, a community meeting was held in the village on June 23, 2015, and a resolution prepared (in Hindi) was passed by the head and other members of the village committee (*Panchayat Samiti*) for implementation of the project. The resolution confirmed that the village head and its residents were pleased to welcome the research team, other development agencies and the district administration of Rampur to carry out the project, and agreed to extend their full cooperation to the project team members during the construction and evaluation phases, and in all other project-related activities. The project team were, in turn, committed to keeping the *Gram Pradhan* and other key members informed about their activities, and to work together in harmony and cooperation. A letter of notification was also prepared and provided to the Commissioner of Moradabad Division, District Magistrate (Rampur), Chief Development Officer (Rampur) and the Subdivisional Magistrate (Milak). The site was also visited by the *Lekhpal* (Administrative Clerk: Land Records), and checks were carried out on the site ownership and boundaries.

Next Steps

The pilot site in western Uttar Pradesh has been prepared and the trial is under way. The pilot site is intended to serve the dual purposes of a practical demonstration of UFTI at a local level as well as a scientific experiment. The major activities that are being conducted include the following:

- Performance monitoring and evaluation from biophysical, socioeconomic and institutional standpoints.
- Training and capacity building of the local institutions on UTFI operations.
- Baseline surveys of the biophysical and socioeconomic conditions in the focal village and wider watershed.
- Broad-scale and local hydro-dynamic modelling of surface water and groundwater systems to assess UTFI impacts and develop scaling-up scenarios.
- Social/institutional/policy arrangements and cost/benefit-sharing mechanisms that facilitate successful participation.
- Gender/equity impacts in upstream and downstream contexts.
- Costs and benefits of UTFI, and comparative analyses with traditional and contemporary water management technologies.

The analysis emerging from these data will reveal the degree of success of the demonstration/trial from technical, economic, social and institutional standpoints when considered over successive years.

Conclusions

UTFI has been presented here as a new approach for conjunctively managing water resource problems in a way that offers the dual advantages of enhancing irrigation potential and livelihoods in the upstream, and moderating the negative impacts of floods in the downstream. The approach uses components that are generally tested well individually, but in a combined manner and in settings that are novel, and are distinct from other modes of MAR. Opportunities for UTFI implementation are gradually becoming realized. A research and development framework is offered for piloting and upscaling UTFI, and for better understanding the risks involved and how they can be addressed and managed to achieve wider acceptance and implementation.

The Ganges River Basin case study demonstrates that the characteristics conducive to implementing UTFI are present over large tracts (68%) of the inner region of the basin. An analysis presented for the Ramganga sub-basin suggests that diverting and recharging around 1,741 m^3 ha^{-1} would reduce peak floods by 50%, and significantly diminish flood return periods. This is achieved through surface or subsurface recharge interventions, by dedicating a proportion of the land in low-lying areas that is hydraulically connected to rivers or canals.

A cost-benefit analysis for one midstream district (Moradabad) suggests that the economics are favorable for implementation, with agricultural production gains and public benefits greatly exceeding investments and ongoing costs. The hydrological and economic analyses reported here are largely indicative, and detailed field data are required for a more robust hydro-economic analysis of UTFI.

A detailed process has been followed to identify and set up a pilot trial in Rampur District in western Uttar Pradesh. The recharge interventions are low-tech, robust, make the best use of existing infrastructure, and aim to be managed by farmers. Performance evaluation is under way to determine the impact of UTFI interventions on surface water and groundwater hydrology, agricultural production and food/nutritional security, household incomes and gender/equity dimensions.

The piloting seeks to generate a sufficiently strong body of scientific evidence on the technical and non-technical performance to verify sustainable implementation, and to find workable policy instruments and institutional arrangements for UTFI to be implemented on a scale that achieves significant positive impacts. With flood and drought events still regularly inflicting enormous socioeconomic costs across South Asia, government agencies and other decision makers should consider UTFI amongst the portfolio of options when making investments in climate change adaptation/mitigation and disaster risk reduction. Scope also exists to consider UTFI beyond the areas where the idea emerged and where efforts are currently being focused to include other regions, and potentially in developed countries as well.

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