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Assessing the feasibility of climate change adaptation options in the water sector: examples from rural and urban landscapes

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Abstract

Water availability mediates rural and urban development through impacts on sectors such as agriculture and industry. Recognising that climatic risks attenuate this water availability, various adaptation options have been implemented in the water sector. To inform adaptation prioritisation, it is critical to assess the growing literature on adaptation options related to water management and synthesise lessons on which options are feasible and under what conditions. We assess the multidimensional feasibility of adaptation options in the water sector at the global scale using two examples: strategies to improve irrigation efficiency in rural areas (e.g. drip irrigation, watershed management), and sustainable water management in urban areas (e.g. flood management, upgrading sewage systems). To contextualise the assessment and showcase how adaptation feasibility is regionally differentiated, we present two case studies: flood management in Jakarta and Rotterdam; and community-based watershed management in India and the Dry Corridor of Central America, specifically Guatemala and Honduras. The assessment highlights that while improving irrigation efficiency is technically feasible and has economic benefits, it is constrained by issues of replicability and trade-offs across scale and institutional barriers. In urban areas, flood management measures are technologically and geophysically feasible but barriers such as inadequate institutional capacities constrain their feasibility. We also assess mitigation and sustainable development synergies and trade-offs for the two adaptation options. The findings on factors constraining adaptation feasibility in the water sector are useful for policymakers who are increasingly faced with a diverse suite of adaptation choices.

Keywords: climate change; adaptation; irrigation efficiency; sustainable urban water management; feasibility; sustainable development; synergies and trade-offs

1 Introduction

Anthropogenic climate change and water security are deeply linked: it is projected that by 2050, 0.5 to 3.9 billion people will be exposed to water scarcity globally due to climate change (Gosling and Arnell 2016). Further, climate change exacerbates the frequency and intensity of water-related hazards such as cyclones, sea level rise, drought, and floods (IPCC 2018). Climate-driven changes in temperature, precipitation, and extreme events also interact with non-climatic drivers such as urbanization, increasing consumption, population growth, and land use change to mediate water availability, demand, and use (Revi et al. 2014; IPCC 2019).

In rural areas, changing temperature profiles, increasing rainfall variability (Hoegh-Guldberg et al. 2019), and desertification (Mirzabaev et al. 2019) are driving water scarcity, shifting cropping patterns, and impacting natural resource-based livelihoods (Kilroy 2015). These climatic risks interact with non-climatic risks such as environmental degradation, changing cropping patterns, and groundwater over-extraction, necessitating better water management (Blakeslee et al. 2020; Singh et al. 2019).

In urban areas, climatic risks such as sea level rise and increasing extreme events such as cyclones, flooding, and heatwaves (Muis et al. 2017; Neumann et al. 2015; Revi et al. 2014) interact with urbanization trends such as changing land use (e.g. increasing built up area), densification, and infrastructure development to shape water availability and access. To adapt to these risks, cross-sectoral sustainable urban water management is essential (Hurlimann and Wilson 2018; de Coninck et al. 2018).

In the water sector across rural and urban areas, different regions, countries, and communities are adapting to deal with current impacts, prepare for projected water insecurity, and reduce risks from water-related hazards, (Jiménez Cisneros et al. 2014; Tilleard and Ford 2016; Araos et al. 2016). Several adaptation options have been proposed, implemented, and tested (Table 1). These include 'hard,' infrastructural options[1] such as building canals to improve water access and reduce seepage in rural areas (Aspe et al. 2016) or sea walls to reduce exposure to sea level rise in coastal cities (Siegel 2020). Other options are 'soft' adaptation strategies aimed at changing dominant practices to reduce climate impacts e.g. shifting crop sowing dates to adapt to changing precipitation patterns

[1] Adaptations options are often described as hard options, i.e. those that involve predominately human-built infrastructural interventions, or soft options that focus on empowering local communities, and building institutional capacity and community assets (Sovacool 2011; Hallegatte 2009; Boyd 2017). There is growing evidence that argues for reorienting the focus from infrastructure and technology-heavy interventions to soft options that build local capacities through behavioural and institutional change (Nightingale et al. 2019; Boyd 2017).

(Jain et al. 2015) or building risk awareness through early warning systems to reduce flood risk in cities (Pappenberger et al. 2015).[2]

Table 1 Indicative list of adaptation strategies in the water sector. Modified from (Noble et al. 2014)

Landscape	**Key risks**	**Adaptation strategies in the water sector**
Rural	• More erratic rainfall with longer dry spells, unprecedented hail or rain • Extreme rain related landslides, floods • Drought and water scarcity • Cyclones, storm surges, sea level rise • Temperature shifts (e.g. hotter summers and milder winters)	Improving irrigation efficiency through reduced loss by evaporation, seepage etc.
		Changes in irrigation practices (e.g. moving from flood to drip/sprinkler irrigation)
		Change in crops grown (e.g. shift from water-intensive to drought-tolerant crops)
		Changes in cropping practices (e.g. shifting sowing dates, mulching, zero-budget natural farming)
		Watershed management to capture and conserve rainwater, use natural cover to restore degraded lands
		Natural or ‘green’ barriers to control erosion, reduce flood risk
Urban	• More intense rainfall events leading to flooding, landslides • Changes in rainfall patterns leading to water scarcity and drought • Storms, cyclones • Coastal and inland flooding • Sea level rise and land subsidence • Temperature extremes and heatwaves	Water management through appropriate zoning policies, building codes
		Protection measures such as building seawalls, dams, dikes
		Flood management through infrastructural measures such as wet/dry-proofing houses and buildings.
		Flood/cyclone management through relocation, evacuation, early warnings etc.
		Reducing water use through smart meters, pricing policies, water taxes
		Increasing supply (e.g. rooftop rainwater harvesting, protecting urban wetlands)
		Ecosystem restoration
		Desalination in coastal areas

There is emerging evidence on the role of technological adaptation options such as changing from flood to drip irrigation (Frisvold and Deva 2013) or fitting household-level smart meters to regulate water use (Kim 2019). Finally, there is a growing literature on ecosystem-based adaptation (EbA). In rural areas, this can include watershed management (e.g. restoring green cover, building small check dams to build local adaptive capacity) (Singh 2018; Bhandari et al. 2007), while in cities, EbA measures include protecting and growing urban green cover to improve local climate and maintain ecosystem services such as water recharge and supply (Brink et al. 2016). EbA measures are considered useful for

[2] There are several categorisations of adaptation strategies based on focus, e.g. as infrastructural, ecosystem-based, institutional, and behavioural (Revi et al. 2014); extent, e.g. adaptation actions that are incremental versus transformational (de Coninck et al. 2018); and intent e.g. planned adaptation which is typically government- or donor-led, project-based adaptation versus autonomous adaptation that refers to ongoing strategies people undertake to manage risk proactively (Mersha and van Laerhoven 2018). In this paper, we focus on two adaptation options which can have infrastructural, institutional, ecosystem-based, and behavioural aspects.

achieving triple wins, i.e. meeting mitigation, adaptation, and sustainable development goals (Geneletti and Zardo 2016; Elmqvist et al. 2015).

While a vast and growing literature reports adaptation in different geographies (across the world), sectors (agriculture, energy, waste etc.), landscapes (rural, urban, peri-urban), and on different themes (e.g. gendered water access) (Bassett and Fogelman 2013), they tend to be at different scales, disparate, and difficult to synthesise from (Berrang-Ford et al. 2015). Moving from this large body of adaptation option- or sector-specific evidence to inform national and sub-national policy making and adaptation prioritisation is extremely challenging (Tilleard and Ford 2016; Berrang-Ford et al. 2019). To overcome this, it is critical to assess this growing literature on adaptation options in the water sector and synthesise lessons on which options are feasible and under what conditions.

In this paper, we develop and apply a methodology to assess the feasibility of adaptation options related to water security with examples from rural and urban areas. We focus on two adaptation options: (1) improving irrigation efficiency in the agriculture sector in rural areas, and (2) sustainable urban water management through flood management in cities. We also examine the synergies and trade-offs of these adaptation options with mitigation and sustainable development.

In Section 2, we describe the methodological framework used to assess adaptation feasibility. In Section 3, the results are reported on improving irrigation efficiency in rural areas and sustainable water management in urban areas. Two case studies are presented to showcase how adaptation feasibility and implementation are strongly mediated by local ecological, socio-economic, and institutional contexts. We conclude with a discussion on the contributions of the paper for adaptation in the water sector specifically, adaptation prioritisation in general, and avenues for future research (Section 4).

2 Methodology

2.1 Feasibility assessment framework

Prioritising adaptation options is key to informing adaptation planning, financing, and implementation (de Coninck et al. 2018; Klein et al. 2014). In the water sector especially, there are numerous adaptation options (Noble et al. 2014) and assessing adaptation feasibility can help prioritise interventions, inform national and sub-national plans, and enable integrated risk management (de Bruin et al. 2009). However, assessing the feasibility of highly contextual adaptation options based on discrete case-based evidence is often challenging and constrained by the low consensus on metrics to assess adaptation outcomes (Ford et al. 2013, 2015; Berrang-Ford et al. 2011).

We present a multidimensional feasibility assessment of two adaptation options within the water sector (detailed in Section 2.3) and draw on the IPCC's SR1.5 (Allen et al. 2018) to define feasibility as "the degree to which climate goals and response options are considered possible". We assess feasibility across six dimensions: economic, technological, institutional, socio-cultural, geophysical, and environmental, which are informed by developments in the climate change adaptation literature (Table 2). Underlying the six dimensions of feasibility are 19 indicators developed through expert elicitation and a literature review (detailed in Supplementary Material 1). This methodology was piloted in the IPCC Special Report on 1.5 degrees C (de Coninck et al. 2018) and has been reported in a companion methodological paper (Singh et al. 2020).

Table 2 Six dimensions of adaptation feasibility

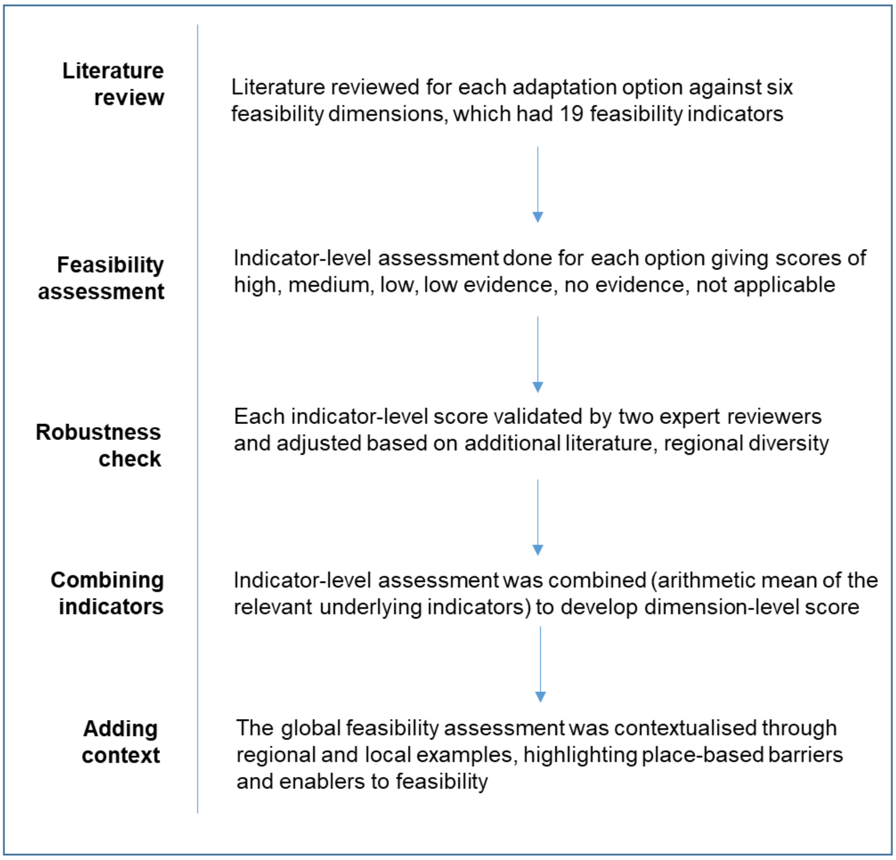
Feasibility dimension	**Explanation and supporting references**
Economic	Economic costs and benefits associated with an adaptation option including impacts on employment, productivity, income etc. (Fader et al. 2016; Fu and Song 2017; Hunt et al. 2017)
Technological	Technological know-how and associated human, financial, and administrative resources for a specific option (Alfieri et al. 2016; van Vliet et al. 2016)
Institutional	The institutional and legal capacity, and political acceptability of an option (Costa et al. 2016). Includes assessing the level of accountability and transparency (through monitoring and evaluation) related to an adaptation option (Ford and King 2015; Ford et al. 2015).
Socio-cultural	The social co-benefits of an adaptation option e.g. for health, nutrition or education, socio-cultural acceptability of an option (e.g. compared to local norms, beliefs), as well as equity concerns across regions and generations (Sovacool et al. 2015; Tschakert et al. 2017)(Sovacool et al. 2015; Ford et al. 2017; Tschakert et al. 2017; Pearce et al. 2015; Singh et al. 2018).
Environmental	Examines if the option enhances ecosystem services, builds adaptive capacities, and/or contributes to resilience (Berbés-Blázquez et al. 2017; Wamsler et al. 2016).
Geophysical	Assesses whether the option has any physical barriers (e.g. ecological limits) (Dow et al. 2013), and potential to reduce hazard risk (Thomalla et al. 2006) or enhance land use (Harvey et al. 2014).

The feasibility assessment draws on a 'barriers to adaptation' framework (Eisenack et al. 2014; Barnett et al. 2015) and the six dimensions identify the extent to which technological, institutional, socio-cultural, geophysical, and environmental factors constrain an adaptation option. Thus, the framework moves beyond cost-benefit or technical feasibility assessments (which are more common in the literature) to incorporate social and governance dimensions of adaptation feasibility (e.g. equity outcomes, institutional capacities). Each dimension is further broken down into indicators (Supplementary Material 1).

2.2 Methodological process

For the feasibility assessment, five steps were followed (Figure 1). First, for each adaptation option assessed, a literature review was conducted using Web of Science (WoS) and Google Scholar. WoS was selected because it is one of the most widely used, up-to-date, and comprehensive search engines, and is commonly used in adaptation research that draws on interdisciplinary, peer-reviewed literature (Berrang-Ford et al. 2011). Peer reviewed publications published after 31 August 2013[3] were included and a string of keywords were used to conduct searches that included [adaptation option] AND [feasibility dimension/indicator] AND [region, based on IPCC WGII regions]. The literature identification process was not a systematic review but was strengthened by (1) reference checking where additional literature was reviewed based on bibliographies of selected papers; (2) citation tracking where additional papers were found based on citations; and 3) iterative additions where the author team added to the literature based on their knowledge of the literature until saturation was reached.

Figure 1 Methodological process to assess feasibility of adaptation options



[3] The August 2013 cut-off date was chosen because papers before this date were assumed to be summarised in the IPCC Assessment Report 5.

Second, the feasibility assessment was carried out for each indicator. Through a review of adaptation scholarship and past IPCC reports, a set of guiding questions were developed for each indicator (see Supplementary Material 1). Based on these guiding questions, the literature was assessed, and for each option, the 19 indicators were populated as having high, medium, or low scores. These scores denoted whether an indicator blocks the feasibility of the option or not i.e. whether the indicator acts as a barrier to the adaptation option or not. A high score signifies the absence of barriers in the feasibility indicator, medium denotes that on average, the indicator has neither an enabling nor constraining impact on the option's feasibility, and low denotes the presence of barriers.

For example, for the technological feasibility of improved irrigation efficiency, we examined whether technical resource availability constrained the adaptation option or not. Since the literature reported growing technological advancement to improve irrigation efficiency but behavioural constraints in its adoption (based on farm size, technology availability, price, fit with local agricultural practices), this indicator was scored 'medium' reflecting that there were some barriers. The scoring was thus informed by the literature but required judgements by the research team on the relative blocking capacity of an indicator. In cases where literature was insufficient, the indicator was scored as having no evidence (NE) or limited evidence (LE) (where there were two papers or fewer). When an indicator was not applicable to a certain option, it was scored as NA.

The third step in the feasibility assessment ensured robustness. Here, after the initial assessor had reviewed the literature and given indicator-level scores, two other authors reviewed the scores and suggested changes based on new literature or regional differences. Where contradictions emerged, scores were changed in the light of new literature, literature from other geographies, and expert judgement. Thus, each option's indicator-level assessment was validated by at least three authors. Further, the scores were checked by two external reviewers familiar with agriculture and urban systems respectively.

Fourth, the indicator-level scores were combined by taking the arithmetic mean of the underlying indicator scores to develop a dimension level score. Indicators assessed as NA, LE or NE were not included in this overall assessment since the evidence was treated as either inadequate or not applicable in these cases. Based on the arithmetic mean of the indicators, each dimension was classified as having 'insignificant barriers' ($AVG > 2.5$), 'mixed or moderate barriers' ($1.5 < AVG \leq 2.5$), or 'significant barriers' ($AVG \leq 1.5$) to feasibility. The final feasibility assessment (Figure 2) reports findings based on these dimension-level scores.

In a fifth step, the global assessment was contextualised by providing place-based examples of barriers and enablers to adaptation feasibility. For example, under the adaptation option "improved irrigation efficiency", we discuss one *intervention* "community-based watershed management" drawing on evidence in India and Central America to demonstrate how feasibility can differ based on social-ecological and institutional contexts. For sustainable urban water management, examples of flood management in Jakarta and Rotterdam are used to showcase how differences in hazard exposure, financial capacity, and urban governance shape adaptation feasibility. The specific cases are used as illustrative devices to demonstrate how feasibility varies based on local contexts (e.g. coastal, high-income city of Rotterdam vs. medium-income Jakarta). Choice of case studies was based on presence of adaptation options and supporting literature in these locations, as well as differing socio-economic and ecological contexts.

In this paper, the multi-dimensional feasibility assessment is conducted at a global scale by assessing adaptation evidence across regions. In the description accompanying the feasibility assessment (Sections 3.1.1 and 3.1.2), examples of how feasibility is differentiated across different geographies is also reported. In an additional step, after the feasibility assessment, we assessed synergies and trade-offs with mitigation and sustainable development for each option (reported in Section 3.3). This additional step is given to showcase how even when feasible, some adaptation options can have significant synergies and trade-offs for GHG emissions and/or sustainable development.

2.3 Adaptation options assessed

This paper assesses the feasibility of two adaptation options in the water sector, one from rural and one from urban landscapes. These options were chosen because they are (1) important to water security in rural and urban areas, (2) have a strong climatic driver that is shaping current impacts and future risks, and (3) are directly linked to local livelihoods (e.g. irrigation efficiency directly impacts crop productivity and farm incomes).

(1) Improving irrigation efficiency in the agriculture sector in rural areas

Traditionally, irrigation efficiency in the agriculture sector has been defined as "the ratio of the irrigation water consumed by the crops of an irrigation farm… to the water diverted from a river or other natural water source into the farm" (Perry 2007, p. 371). Subsequent definitions take a systems approach (Grafton et al. 2018) and highlight that water considered 'wasted' either due to seepage or evaporation is not lost, and feeds back into the hydrological cycle through groundwater or air moisture. The agricultural adaptation literature has focussed on improving irrigation efficiency as a way to reduce water demand and augment water supply (Molden 2007) and thereby adapt to risks of reduced crop productivity due to climatic risks. For this paper, under 'improving irrigation efficiency', we include a range of plot-level and basin-scale interventions to reduce leakages (e.g. lining of water channels), reducing water consumption (e.g. through drip or sprinkler irrigation), and augmenting water supply (e.g. through watershed management). In the case study (Sec. 3.2.1) we focus on community-based watershed management.

(2) Sustainable urban water management (SUWM)

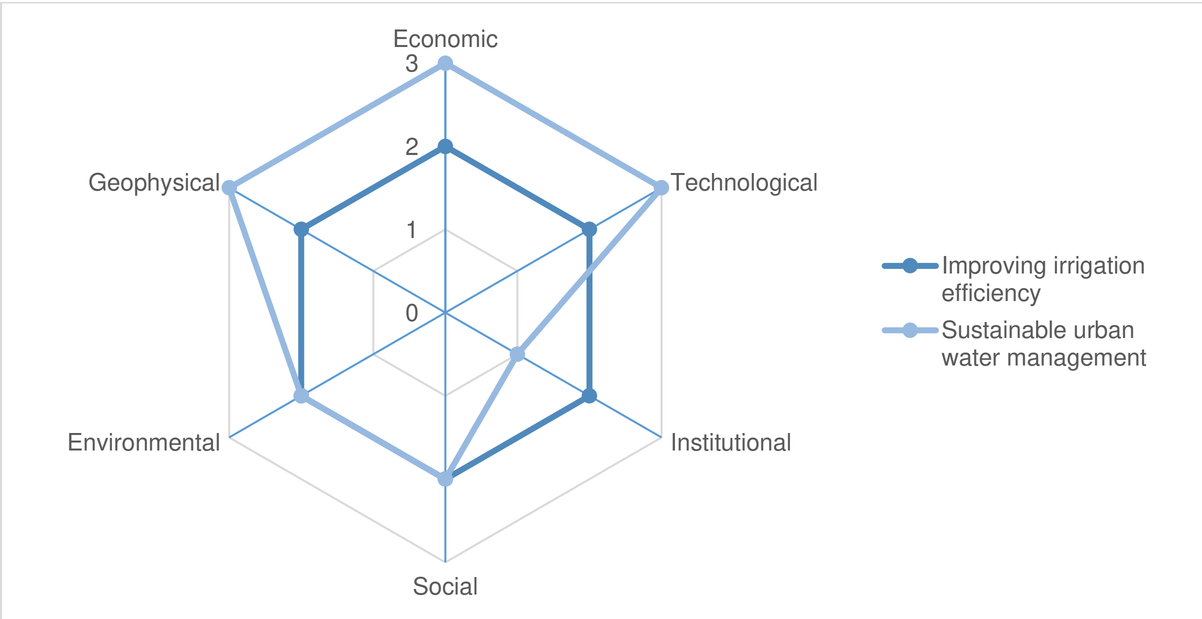
SUWM refers to a suite of infrastructural, behavioural, and policy practices that "support the ability of human society to endure and flourish…without undermining the integrity of the hydrological cycle or the ecological systems that depend on it' (Gleick 1998, p. 574). In addition to meeting goals of sustainable development, SUWM has climate change adaptation co-benefits, for example through flood proofing cities, maintaining ecosystem services, ensuring permeability, and mitigating risks posed by unplanned urbanisation (Hurlimann and Wilson 2018). In this paper, we define SUWM broadly to encompass wastewater recycling, storm water management, flood management, and protecting and maintaining urban water bodies. In the case study (Sec 3.2.2), we focus on flood management as one of the interventions under SUWM.

3 Results

3.1 Feasibility assessment

This section reports the outputs of the feasibility assessment for two adaptation options in the water sector (Figure 2) and identifies which dimensions enable/impede adaptation feasibility.

Figure 2 Feasibility of adaptation options across six dimensions. 1 denotes low feasibility, i.e. presence of blocking factors or barriers; 2 denotes medium feasibility, i.e. the dimension does not have a positive nor a negative effect on the feasibility of the option; 3 denotes high feasibility, i.e. absence of barriers.



3.1.1 Improved irrigation efficiency

Irrigation is currently the largest water use sector, accounting for approximately 70% of global water withdrawals and nearly 90% of consumptive water use (Haddeland et al. 2014). This water demand for irrigation is set to increase with global climate change projections expected to necessitate reversion of 20–60 Mha of cropland from irrigated to rainfed management (Elliott et al. 2014). In this context, improving irrigation efficiency is identified as a key adaptation option in agriculture as it can reduce water demand, water wastage, and associated energy consumption, and directly impacts crop yields and hence agricultural incomes. In practice, improving irrigation efficiency includes measures to reduce loss due to evaporation and seepage (e.g. lining water canals) and changing irrigation practices to reduce water use (e.g. moving from flood to drip/sprinkler irrigation) (Grafton et al. 2018).

The feasibility assessment finds that across the six dimensions, improving irrigation efficiency scores medium (Figure 2), i.e. there are barriers but they are not high. On economic feasibility, there was mixed evidence on the macroeconomic benefits of improving irrigation efficiency through storage interventions such as large dams (Varela-Ortega et al. 2016; Herwehe and Scott 2018). However, at a household level, improving irrigation efficiency has been linked to improving household returns on land and labour by facilitating the production of higher-value commodities, and freeing time and capital for investment

(Levidow et al. 2014). While technological solutions to improving irrigation efficiency exist (e.g. smart irrigation systems, sprinkler irrigation), the feasibility is moderately constrained due to barriers around adoption of technology, and suitability of different technologies to differing agricultural contexts (Jägermeyr et al. 2015; Fishman et al. 2015).

Several studies noted that improving irrigation efficiency is constrained by institutional barriers such as institutions inadequately adapting to new forms and norms of water sharing, inertia when shifting to new technologies, and inadequate market linkages (Pittock et al. 2017; Azhoni et al. 2017). However, where successful, well-designed small-scale irrigation systems can induce emergence of new institutions in support of technology. On socio-cultural feasibility, the literature converges to argue for building local acceptance by incentivising behavioural shifts towards using efficient technology, harvesting water, and reducing demand (Varela-Ortega et al. 2016; Herwehe and Scott 2018). Environmentally, improving irrigation efficiency was assessed as having medium impact on adaptive capacity and ecosystem functioning mainly because while interventions such as drip irrigation can reduce water use, especially during periods of water scarcity, increasing efficiency can often (1) encourage higher dependency on irrigation, creating ‘rebound effects’ such as higher farm-level water consumption, as seen in China (Song et al. 2018) or (2) have negative impacts on water availability at the basin scale, as seen in higher upstream/downstream trade-offs in Spain (García-Llorente et al. 2015).

Importantly, improving irrigation efficiency is closely tied to ecosystem type, cropping patterns and practices, local irrigation practices, and labour availability. Thus, in different social- ecological systems, the feasibility of improving irrigation efficiency will change.

3.1.2 Sustainable urban water management (SUWM)

SUWM is a key adaptation option for cities facing issues of hazards related to water excesses (e.g. flooding, cyclones) and water scarcity (inadequate supply, e.g. drought). It includes a range of specific interventions spanning water supply, drainage, and wastewater treatment and recycling (Larsen and Gujer 1997). We also assessed options related to urban hydrology in general such as storm water management, flood management, and protection and maintenance of urban water bodies.

The feasibility assessment finds that across the six dimensions, SUWM scores high on technological, geophysical, and economic feasibility, medium on environmental and social feasibility, and low on institutional feasibility (Figure 2). Thus, one of the critical constraints to the feasibility of SUWM is how current institutions and policy frameworks plan for and implement SUWM.

The evidence converges to find that rising urban water demand and governance constraints undermine SUWM feasibility significantly (Margerum and Robinson 2015; Hill Clarvis and Engle 2015; Lemos 2015; Liu and Jensen 2018; Deng and Zhao 2015). For example, from the UK, Australia, and USA, inadequate integration of urban spatial planning and water supply policies, reactive approaches focussed on hazard management rather than long-term adaptation, and fragmented, sectoral governance approaches constrain SUWM implementation (Hurlimann and Wilson 2018). Barriers such as inadequate human and institutional capacity, financial resources, and public awareness, and improper management strongly constrain the institutional feasibility of SUWM (Revi et al. 2014).

On socio-cultural feasibility, cities undertaking SUWM demonstrate social co-benefits through positive impacts on health and liveability (Liu and Jensen 2018) leading to a high score. However, the evidence on social/regional inclusiveness and public acceptance were lower (medium score) based on evidence from low-income cities where SUWM outcomes for poor people and women tend to be mixed (Anguelovski et al. 2016).

The high feasibility of technological, geophysical, and economic dimensions reflects the range of existing options available to achieve SUWM (Stavenhagen et al. 2018) which can reduce hazard risk as well as ameliorate some of the impacts of land use change (Lamond et al. 2015; Nur and Shrestha 2017). For example, in China, there is growing evidence on how ‘sponge cities’ are reducing surface runoff, recharging groundwater, mitigating flood risk, and enhancing water quality (Nguyen et al. 2019; Jiang et al. 2018).

3.2 Illustrative case studies[4]

3.2.1 Community-based watershed management in rural India and Central America

Watershed management is a key natural resource management intervention that can have adaptation co-benefits (Bhandari et al. 2007; Rouillard et al. 2014; Singh 2018). It also has particular equity challenges since interventions can have trade-offs across scale (e.g. upstream storage can reduce water availability downstream) and institutional constraints since watershed boundaries often do not mirror administrative and national boundaries (Grafton et al. 2018; Rouillard et al. 2014). In this case, we draw on evidence on community-based watershed management in India and transboundary watershed management in

[4] The case studies are described in text with the underlying feasibility assessment and supporting references given in Supplementary Material 3.

Central America (namely El Salvador, Guatemala, and Honduras, which share the Trifinio transboundary watershed) to demonstrate differences in feasibility when one moves from the global assessment (Section 3.1.1) to national assessments.

In India, 65% of total cultivated area is rainfed, crop yields are heavily dependent on monsoon rainfall, and it is estimated that approximately 600 million Indians face “acute water shortages” (NITI Aayog 2018). Watershed development programmes initiated in the 1970s, have evolved from infrastructure-heavy, top-down interventions to increasingly participatory resource management aimed at building water security and adaptive capacity (Singh 2018; Bhandari et al. 2007; Chaudhari and Mishra 2015). Interventions typically focus on drought proofing and enhancing water security through rainwater harvesting, building check dams and bunds for arresting runoff and recharging groundwater, and desilting lakes; ecological restoration (e.g. planting trees on degraded lands); and ancillary activities such as livelihood strengthening and community empowerment. More recently, these interventions have been leveraged to improve local adaptive capacity to climate change (Singh 2018; Bhandari et al. 2007; Chaudhari and Mishra 2015).

The overall feasibility of watershed development as an adaptation intervention is promising since technological know-how and human and financial resources exist, and physical barriers to implementing watershed development are low. Further, watershed management in India enhances ecosystem services and resilience; e.g. through increased moisture availability and reduced soil erosion (Singh 2018; Bhandari et al. 2007; Ratna Reddy et al. 2017). However, watershed management scores low on institutional and social feasibility because of constraints associated with inadequate ground-level institutional capacity to implement watershed projects that take climate risks into consideration and concerns around “discriminatory and limited” benefits that can be inequitable (Singh 2018; Bouma et al. 2011; Ratna Reddy et al. 2017; Chaudhari and Mishra 2015). Crucially, the net benefits of watershed projects are insufficient to pay back investment costs at a basin level (Bouma et al. 2011) and there is mixed evidence on the extent of impact on income generation (Hope 2007; Ratna Reddy et al. 2017; Karlberg et al. 2015), thus constraining economic feasibility.

In Central America, land tenure issues, high inequality, poverty, and exposure to multiple climate risks, makes countries vulnerable to climate change impacts (Global Water Partnership 2016). The Central American Dry Corridor which spans Southern Mexico to Southern Costa Rica, is especially vulnerable to drought, with impacts on food production, especially of maize and beans (Hidalgo et al. 2019).

Community-based watershed management has been implemented across Central America in transboundary watersheds (Villamayor-Tomas and García-López 2017; Jennewein and

Jones 2016) through interventions such as one or more mini to small-scale run-of-the-river hydroelectric plants, irrigation canals, reforestation programmes, and multi-stakeholder dialogue tables (Ley 2017). Here, we discuss the feasibility of community-based watershed management in the Central American Dry Corridor where the Trifinio transboundary watershed spanning El Salvador, Guatemala, and Honduras (Jennewein and Jones 2016).

Technological feasibility is moderate (Supplementary Material Table 3A) as communities have used proven technologies for irrigation, mini-hydroelectric generation and water pumping as means for income generation through productive use applications (Global Water Partnership 2016; Koff et al. 2020; Ley 2017). The main socio-cultural barriers are the limited role of women within community activities and the limited knowledge of Spanish in Mayan indigenous communities (Lardizabal 2015; Velásquez et al. 2013). However, within the last decade, women's participation has increased considerably with many socio-cultural co-benefits (Ley 2017).

Critically, structural development barriers sharply shape adaptation feasibility: for example, the lack of property papers for many local populations – a consequence of the need for land reform after local communities lost their land from colonization centuries ago – is a significant barrier for project implementation. In cases where there are no property papers, financial feasibility is constrained by insufficient resources to purchase required land or to pay property rights. These land tenure issues and increasing conflicts due to drug trafficking impede community-based adaptation activities (Tellman et al. 2020; Edelman and León 2013). Therefore, land reform is necessary to decrease vulnerability, provide for improved or alternate livelihoods, and improve feasibility of watershed management as an adaptation strategy.

To summarise, in India, the technological and environmental feasibility of watershed management is medium to high but overall feasibility is constrained by sociocultural and equity related barriers as well as poorly functioning institutions. In Central America, medium technological feasibility of community-based watershed management is undermined by structural vulnerabilities of local populations and inadequate institutional and legal mechanisms.

3.2.2 Flood management in Jakarta and Rotterdam

To contextualise the global feasibility assessment of SUWM, we present examples of flood management in Jakarta (Indonesia) and Rotterdam (The Netherlands).

Jakarta is highly vulnerable to coastal, riverine flooding, and extreme rainfall related localised flooding (Ward et al. 2013a; Takagi et al. 2016; Marfai et al. 2015). It is projected that by 2050, land subsidence, sea level rise, and abnormal high tides will increase area under flooding by 110.5 km^2 (compared to 2005) (Takagi et al. 2016). Historical records of flooding in Jakarta reveal that rather than intense precipitation, chronic inundation often results from drainage infrastructure failures, development of informal settlements often along canals or riverbanks, and conversion of urban lakes into residential or commercial areas (Ward et al. 2013a; Garschagen et al. 2018).

Traditional adaptation options in Jakarta focussed on techno-infrastructural measures such as flood-control canals, dams, sea-dikes, and polders (Ward et al. 2013a,b). However, recurrent floods and spatial marginalization on one hand, and community mobilization and increasing public awareness on the other, have widened the suite of feasible adaptation options in Jakarta (Padawangi and Douglass 2015). Consequently, flood management has evolved to include soft strategies such as awareness-raising programmes, instituting early warning and emergency assistance systems, and institutional reform (Ward et al. 2013a; Marfai et al. 2015). Jakarta has also developed its Spatial Plan 2030, aiming to become a leader on flood management in Southeast Asia.

While Jakarta's dedicating financing and technological capacity on flood management gives a medium score on economic and technological feasibility, institutional barriers (Ward et al. 2013a; Marfai et al. 2015; Mulyani Sunarharum et al. 2014), concerns over inequitable benefits of adaptation interventions (Garschagen et al. 2018), constrain ability to build adaptive capacity, especially of the most vulnerable (Salim et al. 2019) leading to low scores on other dimensions (see Supplementary Material 3B).

The coastal city of Rotterdam is highly exposed to flooding, land subsidence, and sea level rise (Francesch-Huidobro et al. 2017). Lauded as a frontrunner in urban adaptation, it has a city-level Rotterdam Climate Initiative which aims to make Rotterdam 100% climate-proof by 2025 (Dai et al. 2018). Common adaptation interventions include dikes that help capture and store rainwater, flood-proofing buildings and public areas, floating communities, and nature-based solutions such as reduced paving, green roofs, and water infiltration zones (Ward et al. 2013b). Through private and public financing, municipal leadership, leveraging a range of water management technologies, and a concurrent focus on building public awareness and incentivising citizen engagement (Spaans and Waterhout 2017; Ward et al. 2013b), the feasibility of SUWM in Rotterdam is high across most dimensions (Supplementary Material Table 3B) with institutional feasibility and socio-cultural acceptance notably medium and high respectively. However, these interventions come at a significant cost: e.g. from 2016-2020, Rotterdam Municipality is investing €5.8 million in rainwater collection and processing alone (Dai et al. 2018).

Jakarta and Rotterdam face relatively similar risks such as sea level rise and flooding but function in very different social and institutional setups, which mediate their approach to adaptation and hence the feasibility assessment. The differences in scores, especially on key indicators such as social and regional inclusiveness, and institutional capacity, demonstrate how local priorities, development needs, existing institutional architectures, and financing options can enable or constrain SUWM. More recently, Jakarta has, as part of the Connecting Delta Cities initiative, exchanged knowledge on flood management with Rotterdam (Ward et al. 2013b), improving technological capacity and demonstrating how adaptation feasibility can potentially change over time.

3.3 Synergies and trade-offs with mitigation and sustainable development

Adaptation actions can have synergies (positive impacts) and trade-offs (negative consequences) with mitigation and sustainable development. In the context of growing climate risks and the need for effective action, identifying and investing in strategies that have ‘triple wins’, i.e. actions that reduce GHG emissions through mitigation action, adapt to current and projected climate change impacts, and meet sustainable development goals is imperative (Suckall et al. 2015; Antwi-Agyei et al. 2017; Roy et al. 2018). Thus, we supplemented the feasibility assessment with an analysis of the synergies and trade-offs (S&Ts) of the two adaptation options with mitigation and sustainable development. Overall, both options have mitigation synergies; however, depending on the type of intervention used, there are differential trade-offs related to increased energy demand or higher fossil fuel dependence (Table 3).

To examine linkages with sustainable development, we examined the implications of the options with specific SDGs. Overall, both options have evidence on synergies with SDGs, especially around SDG 6 on water (as expected) but also SDG 1 (poverty alleviation) and SDG 2 (nutritional security) for improved irrigation efficiency, and SDG 11 (sustainable cities) for sustainable urban water management. The literature on trade-offs with SDGs was less developed with very few papers discussing negative implications of the strategies, although, we found evidence that adaptation actions could have negative implications for SDGs (particularly on reducing inequality SDG 10) when equity consequences were not taken into account.

The S&Ts assessment also provides pointers on potentially maladaptive outcomes of certain adaptation options. By contributing to GHG emissions and/or undermining development goals, the assessment points to possible consequences for maladaptation. While this is beyond the scope of this paper, the S&T assessment can build on other frameworks assessing maladaptive outcomes (Magnan et al. 2016; Juhola et al. 2016).

Table 3 Synergies and trade-offs of select adaptation strategies with mitigation and sustainable development

Adaptation option	Mitigation		Sustainable Development Goals	
	Synergies	**Trade-offs**	**Synergies**	**Trade-offs**
Improved irrigation efficiency	Drip irrigation combined with optimized fertilization reduces direct N_2O emissions by up to 50% (Sanz-Cobena et al. 2017) Solar-powered drip irrigation saves 0.86 tons of carbon emissions/year/farm as compared to liquid fuels like kerosene (Suckall et al. 2015) Integrated watershed management can increase carbon sequestration by enhancing soil carbon storage through enhanced yields and residue returns (Sikka et al. 2018) Micro-irrigation save energy use by 58% compared to conventional gravity irrigation (Suresh Kumar and Palanisami 2019)	Practices to improve conveyance efficiency (e.g. replacing old open channel distribution networks by pressurized systems to provide water 'on demand') increases energy demand significantly (Rodríguez-Díaz et al. 2011)	Drip irrigation increases household income (SDG 1), nutritional intake (SDG 2), and enables households to meet daily water needs (SDG 6) (Suckall et al. 2015; Burney and Naylor 2012; Sikka et al. 2018). Micro-irrigation can save water use by 39% compared to conventional gravity irrigation (SDG 6, 12) (Suresh Kumar and Palanisami 2019).	Investing in water-saving technologies can increase water use and motivate shifting to more water-intensive crops (Suresh Kumar and Palanisami 2019; Singh et al. 2019; Jobbins et al. 2015) as well as lead to groundwater overdraft (Birkenholtz 2017) (SDG 6, 10) Drip irrigation reduces labour requirements, potentially concentrating the economic benefits of agriculture with property owners, while increasing poverty among agricultural labourers (Jobbins et al. 2015) (SDG 1, 10)
Sustainable urban water management	SUWM interventions reduce the need for energy-intensive supply-side measures such as desalination (Miller et al. 2015) Demand-side management, such as rain barrels for rainwater harvesting or low-flow toilets have strong mitigation co-benefits through energy savings and associated CO_2 emissions. E.g. low-flow toilets in NYC can reduce 5–8 ktonnes CO_2/year and energy by 65–92TJ/year (Engström et al. 2017)	Water utilities have significant carbon emissions attached to water extraction, distribution, wastewater treatment, desalination, and recycling (Nair et al. 2014). Wastewater treatment plants in particular, can increase energy use significantly (Gu et al. 2017)	SUWM improves water security of households (SDG 6) and enables sustainable cities (SDG 11) (Hurlimann and Wilson 2018) Interventions such as Sponge Cities in China help balance urban water circulation (SDG 11), create a high-quality living environment for both people and wildlife (SDG 11, 13), and reduce flood risk by up to 70% (Nguyen et al. 2019)	SUWM interventions that build on previously unequal water structures can increase inequities (e.g. racial segregation in Durban mediates benefits from ecosystem-based adaptation interventions) (SDG 5,10) (Chu et al. 2017) Financialising water and sanitation service provision in Indore marginalised informal settlements (SDG 10, 11) (Chu et al. 2017)

4 Discussion and conclusion

The water sector is central to adapting to climate change effectively (Smith et al. 2019). A range of adaptation options in the water sector have been tested and implemented in rural and urban landscapes with mixed outcomes. To enable prioritisation of adaptation interventions, it is essential to examine the feasibility of different options, understand barriers that constrain certain options, and work towards implementing feasible options while addressing barriers to widen the solution space.

To illustrate what such an assessment of feasibility would look like in the water sector, we conducted a multidimensional feasibility assessment of two key adaptation options in the water sector: improved irrigation efficiency and sustainable urban water management (SUWM). Below we highlight the findings from the feasibility assessment and reflect on methodological contributions and areas for future research.

4.1 Summary of findings

Overall, improving irrigation efficiency and SUWM are feasible adaptation options in rural and urban areas respectively. They are systemic interventions that can improve water availability, manage water demand, and reduce leakages. The feasibility assessment shows that for both adaptation options, technological factors are not large barriers but institutional factors such as inadequate human resource capacities or fragmented planning processes tend to constrain feasibility (Section 3.1).

The feasibility of both options is sharply differentiated by local environmental conditions (e.g. water availability, rainfall variability etc.) as well as institutional capacities, governance mechanisms, technological acceptance and adoption, local water use and sharing practices, and local and historical contexts (Section 3.2). Additionally, the overall feasibility of both options are mediated by the scale at which the options are assessed (e.g. plot-level assessments of irrigation interventions can mask basin-level trade-offs and conflicts) and who is targeted (e.g. in cities, the feasibility of certain SUWM interventions are sharply differentiated by who can afford them). Understanding these place-based differences in adaptation feasibility is critical for adaptation planners to prioritise which options are more feasible in their context. While we conduct the feasibility assessment at a global scale (Sec 3.1) and then provide regional examples (Section 3.2), in further iterations, different stakeholders such as governments, funders, implementing agencies, can undertake more localised assessments to identify feasible options and identify a suite of options suitable to their needs and contexts.

The assessment also highlights key synergies and trade-offs associated with the two adaptation options, and mitigation and the SDGs (Section 3.3). The analysis shows that improving irrigation efficiency has mitigation and SDG synergies but type of energy used in micro-irrigation determines the extent of mitigation trade-offs. Also, to minimise SDG trade-offs, attention to what the saved water is used for and by whom is essential to constrain higher water use and/or increased inequalities (as shown in Section 3.2.1 and Table 3). SUWM shows strong synergies with several SDGs such as goals of sustainable cities (SDG 11) and improved household water security (SDG 6) but certain SUWM interventions such as desalination, have high mitigation trade-offs due to significant GHG emissions.

4.2 Methodological contributions

The paper makes methodological contributions by presenting a process to assess the multidimensional feasibility of adaptation options as a way to inform adaptation prioritisation. The feasibility assessment framework uses a barriers approach to identify factors impeding adaptation feasibility (Singh et al. 2020) in an attempt to provide policy-facing directions on two fronts. First, adaptation options that are identified as highly feasible on most dimensions, present low-hanging fruit that can be implemented immediately. Second, for adaptation options with low feasibility on one or several dimensions, the assessment provides pointers on which constraining factors can be addressed to improve feasibility and facilitate effective implementation[5].

The synergies and trade-offs assessment serves as an important complement to the feasibility assessment. It articulates the negative and positive impacts for mitigation and sustainable development associated with an adaptation option, giving a decision-maker a clear understanding of options that present triple wins and those that can have inequitable outcomes or by inadvertently increase GHG emissions, thereby being potentially maladaptive.

[5] One caveat to the feasibility assessment framework is noted. Adaptation options that have many barriers, i.e. low feasibility, can still be essential in particular contexts. For example, despite SUWM showing low institutional feasibility in Jakarta, its salience to risk reduction and urban sustainability makes it a necessary strategy. Thus, low feasibility scores are expected to provide insights into where actions should be concentrated rather than cause decision-makers to drop certain options entirely.

4.3 Areas of future research

Feasibility assessments are critical tools to inform prioritisation and implementation of adaptation strategies. We highlight three key spaces of future work. First, adaptation researchers, funders, and practitioners can conduct feasibility assessments at national and sub-national scales drawing on multiple knowledge systems (peer reviewed, grey literature, and Indigenous and Local Knowledge) to inform prioritisation of adaptation options. Such an assessment can also be paired with an adaptation effectiveness assessment (e.g. Owen 2020) to evaluate the level to which different adaptation options meet their stated goals or reduce risk.

Second, the feasibility assessment framework can be fine-tuned to (1) capture interactions between different feasibility dimensions, (2) link adaptation options to particular risk levels (i.e. how do different risk levels change feasibility of an adaptation strategy?), (3) nuance particular dimensions (e.g. including an explicit indicator on gender under socio-cultural feasibility); and (4) relatedly, provide guidance on sequencing of options.

Third, further empirical evidence is required on the synergies and trade-offs of adaptation options with mitigation and sustainable development. While there are sectoral studies that focus on certain geographies, broadening the empirical evidence base is necessary to inform national and sub-national climate resilient development pathways.

The process of using a feasibility assessment framework helps synthesise existing adaptation evidence, showcase how contextual factors shape adaptation feasibility, and analyse how feasibility of these options can be enhanced by attention to specific enablers, such as financing and governance. The feasibility assessment also showcases how a systems perspective to adaptation decision-making must explicitly examine synergies and trade-offs with mitigation and sustainable development. In the water sector especially, where there are a range of adaptation options, conducting a feasibility assessment and synergies and trade-offs analysis, can help decision-makers prioritise adaptation options.

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