Multicriteria Decision Analysis of Drinking Water Source Selection in Southwestern Bangladesh

Chelsea N. Peters, Ph.D.[1]; Hiba Baroud, Ph.D., A.M.ASCE[2]; and George M. Hornberger, Ph.D.[3]

Abstract: Decision analysis methods provide opportunities to explore alternatives for drinking water resources in impoverished, rural regions of developing countries. With varying success, southwestern Bangladesh communities currently use multiple drinking water sources, including rainwater harvesting, ponds, pond sand filters, managed aquifer recharge (MAR), and tubewells. This study uses a variety of multicriteria decision analysis (MCDA) methods to assess the probable success of these drinking water sources based on various technical, economic, social, and environmental factors. Data include an assortment of physical and social sources including focus group interviews, surveys, and water quality measurements. Additionally, the MCDA methods (multiple attribute value theory, analytic hierarchy process, ELECTRE I, and ELECTRE III) are informed by preferences from three stakeholders—locals, nongovernmental organizations, and environmental science academics—to ensure proper weighting of criteria for success. Across all MCDA methods, we find that rainwater harvesting is the most likely to succeed as a reliable drinking water source in the region. Conversely, MAR is the least preferred alternative. Sensitivity analyses suggest a robust ranking order that is relatively insensitive to model parameters, including water source performance score and stakeholder weighting, across all criteria categories. This case study demonstrates how decision modeling and alternative assessment can be the first step to reach sustainable solutions in complex water management problems. **DOI: 10.1061/(ASCE)WR.1943-5452.0001029.** *© 2019 American Society of Civil Engineers.*

Introduction

Inadequate provision of domestic water services to rural areas of developing countries is still a global challenge. The United Nations set Sustainable Development Goals to achieve universal and equitable access to safe and affordable drinking water for all by 2030 (ECOSOC 2016; WHO and UNICEF 2017); however, this will not be easily attainable. As of 2015, only 55% of the rural populations used safely managed drinking water sources, i.e., sources that are accessible on the premises, available when needed, and free from fecal and priority chemical contamination (WHO and UNICEF 2017). The lack of functioning infrastructure is often attributed to top-down supply-driven planning, which ignores the local context (Cai et al. 2004; Starkl et al. 2013). Decision makers and water resource planners often fail to give attention to what users want and will maintain. To achieve sustainable solutions, underdeveloped, rural regions need transparent, participative, and democratic demand-driven planning (Starkl et al. 2013). Even with thoughtful planning, careful implementation is also necessary to avoid unexpected infrastructure failures. In regions where successful water systems could fail and go undetected, water quality is especially important in order to prevent users from consuming hazardous water (Starkl et al. 2013). These issues can be prevented if decision makers consider solutions to avoid infrastructure failures and robust plans to provide safe and sustainable water sources.

Decision analysis methods offer an opportunity to support public participation and provide structured, rational, and transparent solutions to complex management problems in water resources and environmental projects (Belton and Stewart 2002; Cai et al. 2004; Hajkowicz and Collins 2007; Chowdhury and Rahman 2008; Mutikanga et al. 2011). In particular, multicriteria decision analysis (MCDA) is globally used as a holistic, analytical tool for evaluation of decision options. A variety of MCDA approaches allow decision makers to account explicitly for multiple criteria while ranking, selecting, and/or comparing different alternatives (e.g., products, technologies, policies) (Kirkwood 1997; Belton and Stewart 2002). MCDA approaches generally follow one of three underlying theories: (1) utility function, (2) outranking relation, and (3) sets of decision rules. Unfortunately, the selection of the MCDA method can be tricky and is often chosen based on familiarity and affinity with the approach, rather than an assessment of the decision-making situation and goal (Cinelli et al. 2014). Most often, MCDA approaches are used to tease out stakeholder preferences and formalize the decision-making process among participants. Emerging in the 1960s and 1970s, MCDA has been used in a wide array of applications, including water resources and environmental projects (Stewart and Scott 1995; Cai et al. 2004; Hajkowicz and Collins 2007; Chowdhury and Rahman 2008; Mutikanga et al. 2011; Jha et al. 2014; Scholten et al. 2015). These complex projects are seldom guided by a single objective. MCDA may provide the insight to overcome stakeholder bias and institutional hurdles that prevent the longevity of successful water resource projects. To date decision tools have not been implemented for planning for water resources in rural areas of developing countries, and only considered in a few studies (Chowdhury and Rahman 2008; Calizaya et al. 2010).

Drinking water resources in rural, coastal Bangladesh vary in availability, quality, and susceptibility to hazards and other water security risks. Although the country has immense natural water

---

[1] Postdoctoral Researcher, Dept. of Civil and Environmental Engineering, Vanderbilt Univ., Nashville, TN 37235-1831 (corresponding author). ORCID: https://orcid.org/0000-0001-8668-9790. Email: chelspeters7@gmail.com; chelsea.n.peters@vanderbilt.edu

[2] Assistant Professor, Dept. of Civil and Environmental Engineering, Vanderbilt Univ., Nashville, TN 37235-1831.

[3] Director, Vanderbilt Institute for Energy and Environment, Vanderbilt Univ., Nashville, TN 37235-1831.

Note. This manuscript was submitted on November 22, 2017; approved on August 7, 2018; published online on January 17, 2019. Discussion period open until June 17, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

resources, the monsoon climate is the major control on drinking water quantity and quality. With 80% of the rainfall occurring during June to September (Chowdhury 2010; Abedin et al. 2014), locals must adapt to the subsequent dry season (October to May) by using multiple sources to meet drinking water needs. Inadequate water storage infrastructure intensifies water insecurity, often resulting in communities improperly allocating surface water to meet multiple needs, such as drinking, cooking, bathing, and serving livestock. Microbiological contamination of surface waters occurs due to livestock and human fecal pollution (Abedin et al. 2014; Benneyworth et al. 2016). Salinity from seawater mixing and arsenic contamination from naturally occurring arsenic-laced sediments hinder groundwater resources. Considering the projected climate change and population growth, the vulnerability of Bangladesh water resources inadequacies is likely to intensify (Huq 2001; McGranahan et al. 2007; World Bank 2011; Jongman et al. 2012; Jiménez Cisneros et al. 2014; Wong et al. 2014). In many developing countries, a suitable option for providing adequate safe drinking water can be elusive, with no option free from disadvantages.

The five most frequently used sources (both natural and human engineered) for drinking water across coastal Bangladesh are rainwater harvesting, ponds, pond sand filters, managed aquifer recharge (MAR), and tubewells. A mixture of stakeholders—households, local community members, nongovernmental organizations (NGOs), and governmental agencies—have played key roles in promoting, installing, and maintaining these natural and human-engineered water sources, but success of each source has varied as a result of physical and social factors. Although factors may vary on a case-by-case basis, the planning and decision-making process of water source implementation, maintenance, and overall success are not well understood. Often public participation in water resources management is overlooked in developing countries like Bangladesh (Chowdhury and Rahman 2008), giving power to decision makers outside of the community.

The objective of this paper is to explore the various technical, economic, social, and environmental factors that influence the most frequent drinking water technologies and management schemes in southern Bangladesh. Using MCDA, we assess the probable success of drinking water supply technologies and rank the sources based on their likely success in the future. We consider differences among stakeholder preferences and MCDA methods to investigate the influences of prioritization and process, as well as to ensure robustness of our methods. Although site-specific water quality, treatment actions, and ultimately infrastructure building must be considered in water supply solutions, this study supports the underlying decision making and is the first step toward the selection of preferred options considering local context.

Background

Study Area

The coastal region of Bangladesh is predominantly rural. In the 1960s and 1970s, much of the tidal mangrove forest of the lower delta was converted to 56 agricultural islands that now sustain a population of 150 million through paddy farming, fishing, and aquaculture (Rahman and Salehin 2013). These large islands, or polders, are protected from tidal and storm-surge inundation by constructed earthen embankments (Auerbach et al. 2015). Significant research has been based on one particular polder, Polder 32, located in the Khulna district, Dacope Upazila in southwest Bangladesh, 60 km north of the Bay of Bengal (Fig. 1) (Tasich 2013; Auerbach et al. 2015; Worland et al. 2015; Ayers et al. 2016; Benneyworth et al. 2016). This polder has similar hydrological and geological characteristics of the other 56 polders in the region; however, it provides an extreme case study for environmental hazards and community resilience in coastal Bangladesh due to devastation by cyclone Aila in 2009 (Mehedi et al. 2010; Auerbach et al. 2015). The cyclone breached embankments in several locations, leaving a majority of Polder 32 inundated for 2 years (Auerbach et al. 2015).

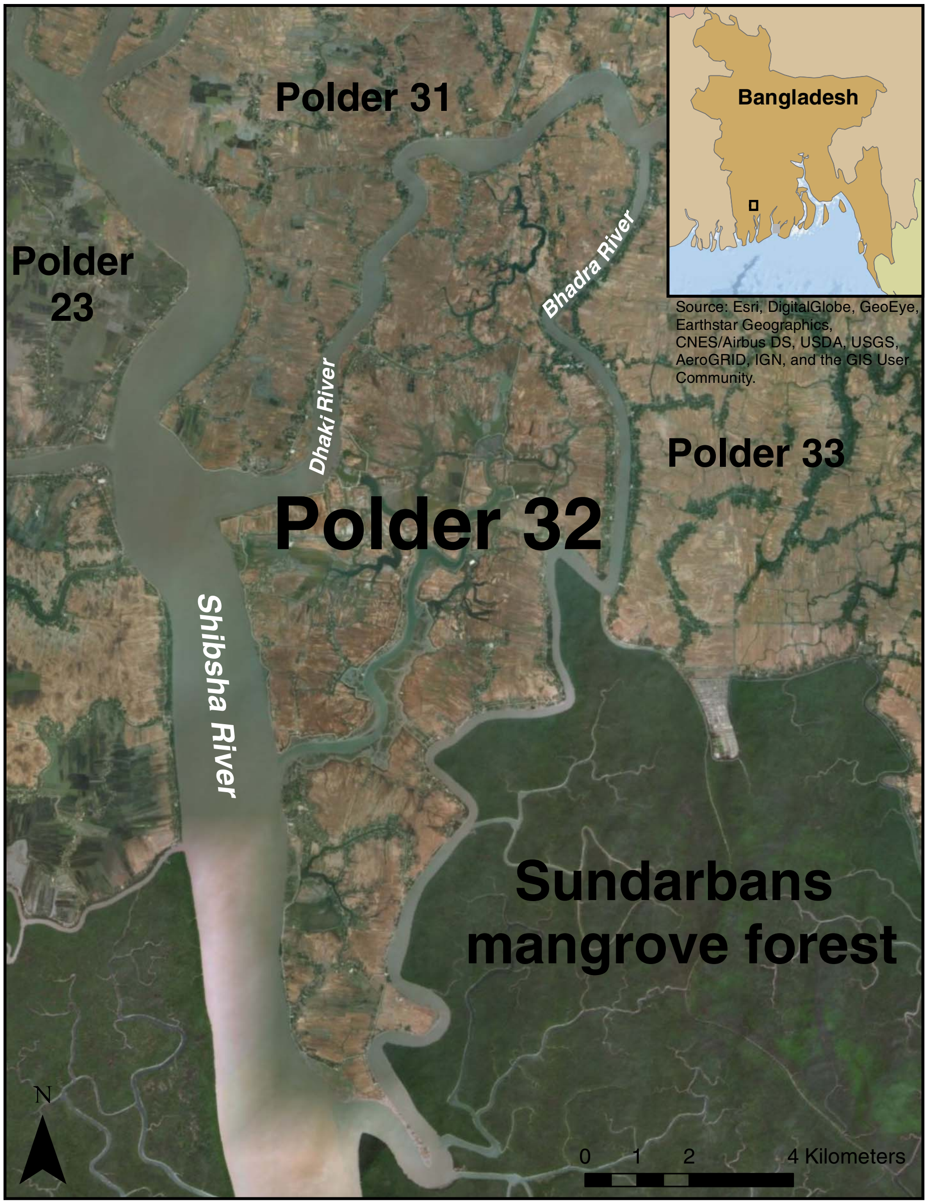
A formerly forested and intertidal system, Polder 32 is bordered by tidal channels that are distributaries of the Ganges River. Its lower half lies adjacent to the protected Sundarbans forest while its upper half is surrounded by other polders. There is no significant local topography for the study area, with an average vertical relief of nearly zero (Auerbach et al. 2015). The shallow hydrogeology of the area consists of a semiconfined, shallow Holocene sand aquifer (Rahman et al. 2011; Burgess et al. 2010) extending 100 m below ground level that is vertically separated from two deeper Pleistocene aquifers by a variably thick, heterogeneous aquitard. The shallow groundwater is primarily brackish with isolated instances where fresher water can be found.

The region experiences a humid, biseasonal climate with a dry season from November to May and wet season from June to October (Chowdhury 2010; Rashid 1977; Shahid 2010). Polder 32 is estimated to receive between 1,500 and 2,100 mm of rainfall per year (Nobi and Gupta 1997). Tropical cyclones typically form over the Bay of Bengal during the transitional monsoon months of May and November (Singh et al. 2000). The tropical cyclone frequency in the Bay of Bengal has a prominent El Niño–Southern Oscillation cycle of 2–5 years during the wet season and transitional monsoon months (Singh et al. 2000). The average temperature ranges from 7°C to 13°C during winter and 24°C to 31°C during summer, with May being the hottest month (Shahid 2010).

Currently, approximately 44,000 people live on this 19 × 7 km-wide polder (Benneyworth et al. 2016; Bangladesh Bureau of Statistics 2012, 2014, 2015). Impoverished in comparison to Bangladesh as a whole, 17% of the rural population on Polder 32 has an electricity connection and 35% has access to sanitary toilets (Benneyworth et al. 2016). Most residents live on monthly family incomes of less that Tk. 3,000 (approximately USD 39) (Islam et al. 2013). Nearly all residents rely on multiple sources for drinking water throughout the year, most of which are surface water sources (Islam et al. 2013). Of these sources, approximately half are maintained by households, rather than by the community or an NGO, and some are not maintained at all (Benneyworth et al. 2016).

Water Sources and Infrastructure

Rainwater harvesting has been used for drinking purposes since people inhabited the coastal region of Bangladesh (Hussain and Ziauddin 1989). In recent years, NGOs and governmental programs have invested in and promoted the installation of several types of household and community-based rainwater harvesting systems (Ansari et al. 2010; Islam et al. 2013). Storage tanks include plastic pitchers and clay jars fed by rooftop runoff, ferrocement storage reservoirs, and plastic tanks. Often the capacity of jars and pitchers is insufficient to last the entire dry season, but the construction cost of larger tanks is prohibitive for lower income families. The rainwater harvesting tanks vary in capacity from 500 to 3,200 L, costing from Tk. 3,000 to Tk. 8,000 (or approximately USD 35 to USD 100) (Ansari et al. 2010; Islam et al. 2013). The primary advantages of rainwater harvesting include the provision of water at or near the point of consumption, the lack of operation and maintenance problems, and the minimal maintenance costs. Generally harvested rainwater is free of contaminants, but it is at risk of developing coliform bacteria if stored for long periods of time (Islam et al. 2007).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Fig. 1. Map of study area showing location of Polder 32. (Satellite image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.)

Although the 2009 cyclone and subsequent inundation left many ponds salty, a few scattered freshwater ponds, locally known as sweet water ponds, survive around the Polder 32. These artificially constructed reservoirs are replenished by rainwater during the monsoon season, and often serve a myriad of purposes including cleaning, cooking, water for livestock, and drinking water. These ponds have a significant risk of biological contamination from livestock and salinization during storm inundation (Alam et al. 2006; Ansari et al. 2010). To remediate contamination, the ponds are occasionally associated with pond sand filters, or slow sand filtration systems. In the pond sand filters system, users hand pump pond water to a large tank to allow water percolation through a bed of fine sand, resulting in the removal of pathogens and fine grain sediments. Initially pond sand filters were designed by the Department of Public Health Engineering in 1984, and now NGOs often administer the installation of the filters in areas that face salinity and arsenic problems (Ansari et al. 2010). Although reliant on a pond water source, pond sand filters' requirement for significant construction costs and regular maintenance to replace dirtied sand necessitates a separate designation and is therefore assessed as an independent source separate from ponds. The lack of proper maintenance often leads to nonfunctioning and abandoned pond sand filters.

Managed aquifer recharge is a technology to induce recharge to aquifers and increase subsurface water storage. This technology has been implemented since the early 2000s in the coastal Bangladesh (Bouwer 2002). Water is collected from ponds and roofs, passed through a sand filter, and injected into the shallow brackish Holocene aquifer through a ring of infiltration wells. The injected water forms a small (couple meter-wide) stagnant freshwater lens in the dense saline groundwater. The stored water can later be extracted according to demand (Holländer et al. 2009). The underground storage offers significant flood protection during regular cyclonic surges. Each MAR scheme can serve several hundreds of people with 15 L of water per day during the dry season, but the pumps, filters, and wells must be maintained regularly (Acacia Water 2011). It is possible that the MAR could provide an average recoverable volume of 750 m^3 per year, based on a 0.75 recovery efficiency (Acacia Water 2011). A pilot MAR was installed and maintained by NGOs and academic institutions, but Polder 32 residents became the sole operators of the source in 2016.

The last most common drinking water source on Polder 32 is a shallow tubewells, which pumps from the same shallow Holocene aquifer as described previously. Across broader Bangladesh the majority of the rural population uses tubewell water as their primary source; however, in the coastal areas both shallow and deep tubewells are used less often because of high salinity groundwater. Only an estimated 13.6% of residents of Polder 32 report using tubewells as a main drinking water source (Benneyworth et al. 2016). Families may own a household tubewell, but they are more often community wells. Typically the water is unfiltered, and some wells are even marked with red to warn against high arsenic contamination. The use of most tubewell is suspected to be a function of perceived water quality, taste, smell, and proximity (Shumaker 2017).

Methods

Decision models allow for an overall ranking and/or utility of alternatives with respect to the achievement of a set of objectives. In multicriteria decision analysis, decision makers examine various alternatives and use a weighting scheme to identify an efficient set, or preferred option (Kirkwood 1997). Although objectivity can be limited by imprecise data and personal preferences, MCDA better informs us of the decision-making process and the structure of the objectives (Figueira et al. 2013). The three basic concepts included in a MCDA are (1) the problem or objective of the model; (2) the potential actions or alternatives that need to be ranked or scored by the decision maker; and (3) a set of criteria, typically measured in a variety of different units. The MCDA model includes an evaluation matrix $\mathbf{X}$ of n_a alternatives and m criteria. The performance score for each alternative i with respect to criteria j is denoted by $x_{i,j}$. The importance of each criterion is denoted in the weights vector $\mathbf{W}$ containing m weights, where w_j denotes the weight assigned to the jth criterion (Table 1).

In this study, the model objective is to determine the most feasible, or successful, freshwater drinking source in coastal Bangladesh. The alternatives we consider, based on their frequent use, include managed aquifer recharge, pond, pond sand filter, rainwater harvesting, and tubewells. Criteria are grouped into four categories: environmental, technical, social, and economic (Fig. 2). The criteria were determined from a literature review and from informal conversations with local community members and academic

Table 1. Stakeholder preferences w_j and alternative performance scores $x_{i,j}$ based on 18 criteria j for five drinking water alternatives i

Weights[a] w_j					Alternative scores $x_{i,j}$				
Academic	NGO	Local	Criteria category	Criteria	RWH	Pond	PSF	MAR	TW
0.88	0.87	0.70	Technical	Variability in supply	43.9	73.3	86.9	41.7	94.7
0.78	0.73	0.60		Variability in quality	100	25	75	75	75
0.95	0.93	0.70		Water quality	97.3	40.3	86.4	64.0	35.9
0.89	0.93	0.80		Maintenance requirements	75	100	0	0	75
0.80	0.67	0.60		Failure rate	100	75	50	50	75
0.80	0.73	0.90	Economic	Construction cost	96.1	59.2	95.4	40.2	79.8
0.82	0.87	1.00		Potential for NGO/governmental help	100	25	100	100	25
0.94	0.93	1.00		Maintenance cost	100	100	97.5	18.8	100
0.74	0.60	0.80		Transportation costs	100	0	100	100	100
0.80	0.87	0.70	Social	Sense of ownership	100	75	50	25	75
0.83	0.73	0.60		Discrimination	50	100	75	50	75
0.78	0.67	0.50		Misinformation	75	75	50	0	50
0.85	0.87	0.60		Persons served	0.6	70.8	71.2	30	8.3
0.63	0.60	0.40		Job creation	0	25	25	25	25
0.82	0.80	0.80	Environmental	Prevalence of source	93.5	55	35	3.5	61
0.82	0.80	0.80		Distance to source	87.3	66.5	68.5	0.0	24.1
0.86	0.73	0.50		Hazard impact	100	0	25	50	100
0.83	0.67	0.50		Resilience	100	25	25	50	100

[a]Weights range from 0 to 1 with 1 denoting the greatest importance. Scores range from 0 to 100 with 100 being the highest performance.

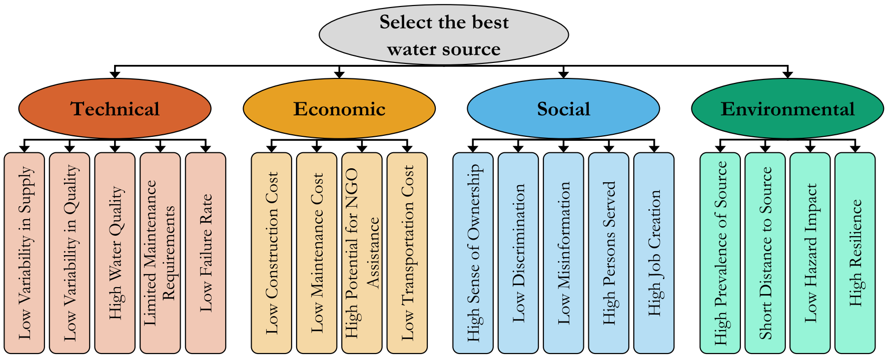


Fig. 2. Objective and criteria used for the evaluation of drinking water alternatives in the MCDA. The best water source is the drinking water source that is most likely to succeed.

experts in the region. Scores for each criteria ranged from 0 to 100, where 100 represents the best performance. For example, if an alternative scores a high value for the failure rate criterion then the alternative shows good performance in this area. This high score can be interpreted as infrequent failure of the alternative to provide drinking water. See Table S1 in Supplemental Data for raw criteria performance scores and formula.

Four MCDA methods are used for this analysis, including multiple attribute value theory (MAVT), analytic hierarchy process (AHP), elimination and choice translating reality (ELECTRE) I, and ELECTRE III, to ensure agreement between methods. The weights were determined from the normalized mean of survey results for academic and NGO stakeholders and from semistructured interviews with local community focus group, as described in the "Data" section. Weights for each criteria range between 0 and 1, with 1 designating the greatest importance.

Multiple Attribute Value Theory

MAVT is a commonly applied value function used to represent the performance of the alternatives. The weighted summation method is expressed as

$$u_i = \sum_{j=1}^{m} \nu_{i,j} w_j \tag{1}$$

In Eq. (1), the alternative's total score u_i is a function of the weights w_j and the normalized performance score $v_{i,j}$ for $x_{i,j}$. Variables w_j and $v_{i,j}$ range between 0 and 1, and 0 and 100, respectively. Under this study, the assumption of mutual preferential independence is considered to be appropriate. The preference between two attributes is not impacted by the value of any one of the other attributes. Though criteria may be correlated with one another, no two or more criteria independently have a large impact on the overall ranking of the options (Von Winterfeldt and Edwards 1993; Angelis and Kanavos 2017).

Analytic Hierarchy Process

AHP is the most widely applied pairwise comparison technique (Saaty 2008). This approach establishes priorities between elements of hierarchies through pairwise comparisons. Criteria are grouped into a hierarchy of elements, which in this case only includes two tiers: criteria category ($n = 4$), and criteria ($4 \le n \le 5$ depending on the criteria category). A priority is assigned to each element of the hierarchy by means of pairwise comparisons. The priorities express the importance of one element over the others, and are given on the 9-point Saaty's scale (Saaty 1988, 1992). See Saaty (2008) or Montis et al. (2000) for a more detailed explanation of the method. For example, all technical criteria elements are pairwise compared to each other (i.e., variability in supply versus variability in quality, variability in supply versus water quality, etc.). Then the higher-level technical category is pairwise compared to the other criteria categories (i.e., technical versus economic, technical versus social, and technical versus environmental).

After taking the geometric mean of each element, the criteria priorities are then weighed by the priority of their higher-level criterion categories to obtain a global priority, or weight w_j, for each criteria. This weight is then applied to the alternative scores $v_{i,j}$ as described in Saaty (2008). The result of each pairwise comparison is determined from survey responses about the importance of each criterion (see Supplemental Data) and the semistructured interviews with local focus groups.

Elimination and Choice Translating Reality I

ELECTRE was developed in 1966 as one of the earliest multicriteria evaluation methods developed among outranking methods (Benayoun et al. 1966; Roy et al. 1986; Roy 1991). The objective of this method is to select a desirable alternative from a subset **F** of alternatives based on two indices, the concordance index and the discordance index. These indices are defined for each pair of alternatives i and i' such that any alternative not included in **F** is outranked by at least one alternative in **F**. The concordance index $c(i, i')$ measures the strength of the information that supports the hypothesis that i is at least as good as i', while the discordance index $d(i, i')$ measures the strength of evidence against this hypothesis. Given a set A of n alternatives and an ordered pair of alternatives (i, i') in A, evaluated by a set of m criteria $(g1, g2, \ldots, gm)$, each criterion is given the following attributes: (1) a weight w_j increasing with the relative importance of the criterion g_j, and (2) a veto threshold $v_j(g_j) > 0$. The concordance index $c(i, i')$ is calculated for each ordered pair of alternatives $(i, i') \in n$ using Eqs. (2) and (3)

$$c(i, i') = \frac{1}{W} \sum_{j:g_j(i)>=g_j(i')} w_j \tag{2}$$

$$W = \sum_{j=1}^{m} w_j \tag{3}$$

The concordance index takes values between 0 and 1 as a measure of a favorable assertion that i outranks i' such that higher values indicate stronger evidence in support of the claim (Shofade 2011).

The discordance index uses the veto threshold defined for each criterion. If the score for i' on any one of these criteria is greater than the score of option i on the same criterion, with a value greater than or equal to the v, then the assertion that "i outranks i'" is refuted

$$d(i, i') = \begin{cases} 1 & \text{if } g_j(i') - g_j(i) > v_j(g_j) \text{ for any } j \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

The final outranking relation iSi', also called the credibility matrix, can be defined by Eq. (5), where $\hat{c}$ and $\hat{d}$ are arbitrary relatively large and small thresholds, respectively (Rogers and Bruen 1998; Montis et al. 2000). In this study, we use the mean of the concordance and discordance matrices as the thresholds

$$iSi' if f \begin{cases} c(i, i') >= \hat{c} \\ d(i, i') <= \hat{d} \end{cases} \tag{5}$$

ELECTRE III

ELECTRE III is a ranking method designed to be less sensitive to inaccuracy, imprecision, and uncertain data. ELECTRE III uses the notion of pseudo-criteria. Instead of assuming that any difference in performance corresponds to a difference in preference, indifference and preference thresholds allow for uncertainty criteria performance and subsequently its preference

$$c_j(i,i') = \begin{cases} 1 & \text{if } g_j(i) + q_j(g_j(i)) >= g_j(i') \\ 0 & \text{if } g_j(i) + p_j(g_j(i)) <= g_j(i') \\ \dfrac{p_j(g_j(i)) - g_j(i) - g_j(i')}{p_j - q_j} & \text{if } g_j(i') - p_j <= g_j(i) <= g_j(i') - q_j \end{cases} \tag{6}$$

In Eq. (6), p_j and q_j denote the indifference and preference thresholds, respectively (Rogers and Bruen 1998). Similarly, the discordance matrix is defined in Eq. (7)

$$d_j(i,i') = \begin{cases} 1 & \text{if } g_j(i') > g_j(i') + v_j(g_j(i)) \\ 0 & \text{if } g_j(i') <= g_j(i) + p_j(g_j(i)) \\ \text{otherwise} & \dfrac{g_j(i') - g_j(i) - p_j(g_j(i))}{v_j(g_j(i)) - p_j(g_j(i))} \end{cases} \tag{7}$$

The overall outranking relation for ELECTRE III is then defined using the credibility matrix in Eq. (8), where $J(i,i')$ is the set of criteria j for which the discordance index is greater that the concordance index. For both ELECTRE I and ELECTRE III, we assume a quantitative value for the overall ranking of the alternatives from the normalized sum of the rows of the credibility matrix

$$\rho(iSi') = \begin{cases} c(i,i') & \text{if } d_j(i,i') <= c(i,i'),\ \forall j \\ c(i,i') & \text{otherwise} \prod_{j \in J(i,i')} \dfrac{1 - d_j(i,i')}{1 - c_j(i,i')} \end{cases} \tag{8}$$

Sensitivity Analysis

In considering results from decision analysis, evaluation of the stability of outcomes in the face of uncertainties in scores and weights is important. This typically is done through sensitivity analyses using either a local or global approach (e.g., Ganji et al. 2016; Hyde et al. 2003; Hyde et al. 2004; Saltelli 2002). We use both approaches. First, we conduct a simple local one-at-a-time sensitivity analysis for each performance score, in which $x_{i,j}$ ranges from the minimum score of 0 to the maximum of 100. Then to test the robustness of our method, we also conduct a generalized sensitivity analysis, which broadens beyond the sensitivity of each individual parameter set. A generalized sensitivity analysis can be used in situations where (1) models contain ill-defined parameters, (2) statistical distributions are used to reflect parametric uncertainty, and (3) results depend on a problem-defining behavioral outcome that can be categorized into a *behavior* and *nonbehavior* (Hornberger and Spear 1981). By categorizing the outcome into a binary behavior (i.e., it either occurs or does not occur for a give scenario and set of parameters), this methodology is a useful technique for identifying inherent uncertainties in the model structure and important parametric relations (Hornberger and Spear 1981).

In this generalized sensitivity analysis, we perform a Monte Carlo simulation of 1,000 runs in which all parameters (either all weights **W** or all scores **X**) are determined from a Gaussian distribution about the given parameter value, where $\bar{X}$ equals the sample mean of x_i or x_j, and s is the sample standard deviation of **W** or **X**, respectively. Scores are treated as parameters because data sources are imperfect due to limited sample size and function assumptions used to calculate $x_{i,j}$ (Tables 2 and S1). Weights (i.e., stakeholder importances) also are parameterized due to the

Table 2. Data sources for MCDA

Group	Criteria	Source	Interpretation
Technical	Variability in supply	Average of number of months used	Usage frequency of the source in a given year
	Variability in quality	Qualitative interviews	Quality variance due to season or location
	Water quality	Function of TDS, salinity, arsenic, and pathogens	Quality of water sources
	Maintenance requirements	Qualitative interviews	Time and effort required for regular maintenance
	Failure rate	Qualitative interviews	Frequency of failure
Economic	Construction cost	Blanchet (2014)	Construction or purchase cost of source
	Potential for NGO or governmental help	Qualitative interviews	Likelihood for economic assistance from entity outside of community
	Maintenance cost	Blanchet (2014)	Cost of regular maintenance
	Transportation cost	Qualitative interviews	Transportation cost from source to household
Social	Sense of ownership	Qualitative interviews	Likelihood that source users feel ownership and responsibility of the source
	Discrimination	Qualitative interviews	Likelihood of discrimination in source usage based on economic status, gender, and relative location to source
	Misinformation	Qualitative interviews	Likelihood that source users are misinformed about ownership, quality, and function of source
	Persons served	Average of how many people use the source	Number of users source can serve
	Job creation	Qualitative interviews	Likelihood of job creation for local community member due to source
Environmental	Prevalence of source	Number of each used for drinking water in Khulna district	Number of each source currently used in the area
	Distance to source	Travel time to source	Time need to travel to source
	Hazard impact	Qualitative interviews	Likelihood that source will be negatively impacted by an environmental hazard, such as cyclone, flood, or drought
	Resilience	Qualitative interviews	Likelihood that source can recover from a negative hazard impact

Note: See Table S1 in the Supplemental Data for additional details, including formulas and scoring for each criterion.

assumption that the limited stakeholder interviews are only a sample of the entire population of possible responses. The simulations were then separated into two outcome groups, based on the resulting ranking.

For this study, we are specifically interested in what weights and parameters are associated with outcomes where either rainwater harvesting or pond sand filter achieves the highest rankings as they avoid salinity problems associated with tubewells and also technological challenges associated with managed aquifer recharge. Simulations are classified as achieving the *behavior* if rainwater harvesting and pond sand filter rank as the highest two alternatives. If outcome differs such that alternatives pond, MAR, and/or tubewell rank in the highest two alternatives, then the simulation is classified as a *nonbehavior.* The distributions of each criterion and weight are then determined and compared based on their behavior or nonbehavior classification.

Data

Data include a variety of physical, social, and economic data collected in southwest Bangladesh. Social data include regional water quality perceptions, perceptions of management/technology success, managed aquifer recharge community surveys, and interviews with nongovernmental organizations partners and academic experts (Table 2). Environmental and technical feasibility factors are determined from regional water quality data and geospatial information. Economic factors are informed from reported cost estimates for the region (Blanchet 2014). Criteria weights come from average responses from a emailed survey given to NGO ($n = 3$) and academic experts ($n = 13$) (see Supplemental Data for survey design) as well as from semistructured interviews during 17 local stakeholder focus groups ($n = 85$) described subsequently (Fig. 3).

Surveys

In the surveys, NGO and academic stakeholders designated criteria from 1 (not at all important) to 5 (extremely important) as a measures of one's perception of the importance of various criteria. The measures of importance were used as weights in subsequent analyses. Stakeholders responses were averaged and divided by the maximum possible weight to obtain the stakeholder group's overall criteria weights (Fig. 3). NGO survey respondents included three Bangladeshi not-for-profit NGOs. Academic stakeholders included eight American and two Bangladeshi environmental scientists as well as two American and two Bangladeshi environmental social scientists. The emailed survey required approximately 5–10 min and ended with three open-ended response questions, which were assessed to ensure quality responses. In every case, respondents answered all 10 questions.

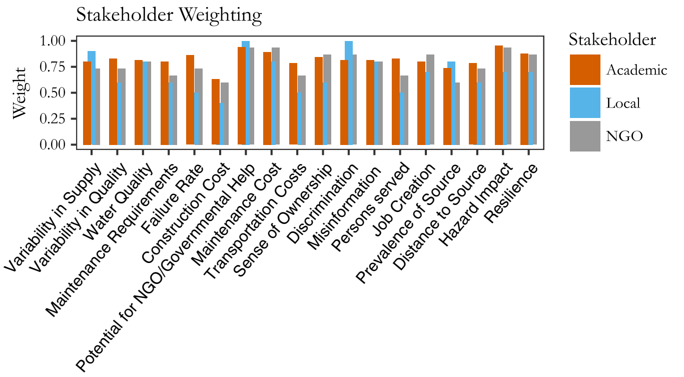


Fig. 3. Weights between 1 and 0 of each criterion as determined by stakeholder surveys.

Focus Groups

Local community member engaged in conversation with the research team in focus groups, ranging from 2 to 30 participants. Participants verbally responded to prompted questions about drinking water source use, success, failure, risks, and user desires. The participants also evaluated drinking water alternatives by providing unprompted criteria and indicators for success. Participants suggested reasons and empirical evidence to support one alternative over another, for example, highlighting problems with implementation design and community values and dynamics. This type of community focus group has been shown to refine decision processes and ensure that communities are fully involved in the final selection of indicators (Reed et al. 2006).

The interviews were led by two Bangladeshi translators and one American from the research team. The translators verbally summarized the responses, which were transcribed by the research team member during the conversation. The conversations lasted 5–15 min depending on the participants' interest and engagement. Translators gave their first impressions from the focus groups after each interview, and the researcher's notes were confirmed during these conversations. The notes and summary of each focus group was reviewed by the research members upon return from the field sites. At this point, criteria weights and alternatives scores (designated by "Qualitative Interviews" source in Table 2) were determined from trends from the combined interviews of all focus groups.

Results

In all methods, rainwater harvesting is the highest ranked alternative and managed aquifer recharge is the lowest (Fig. 4). Pond, pond sand filter, and tubewell rank in the middle with tubewell and pond sand filter generally exceeding the ranking of pond. Differences between the MCDA methods explain more variance than stakeholder preferences, except for AHP, as seen by the overlapping markers in each subplot of Fig. 4.

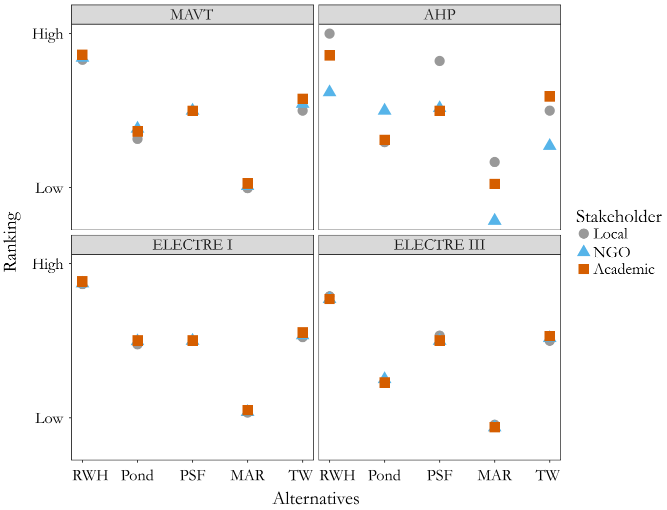


Fig. 4. Ranking (y-axis) of the five alternatives (x-axis) as it varies among the MCDA methods (subplot) and stakeholder preference.

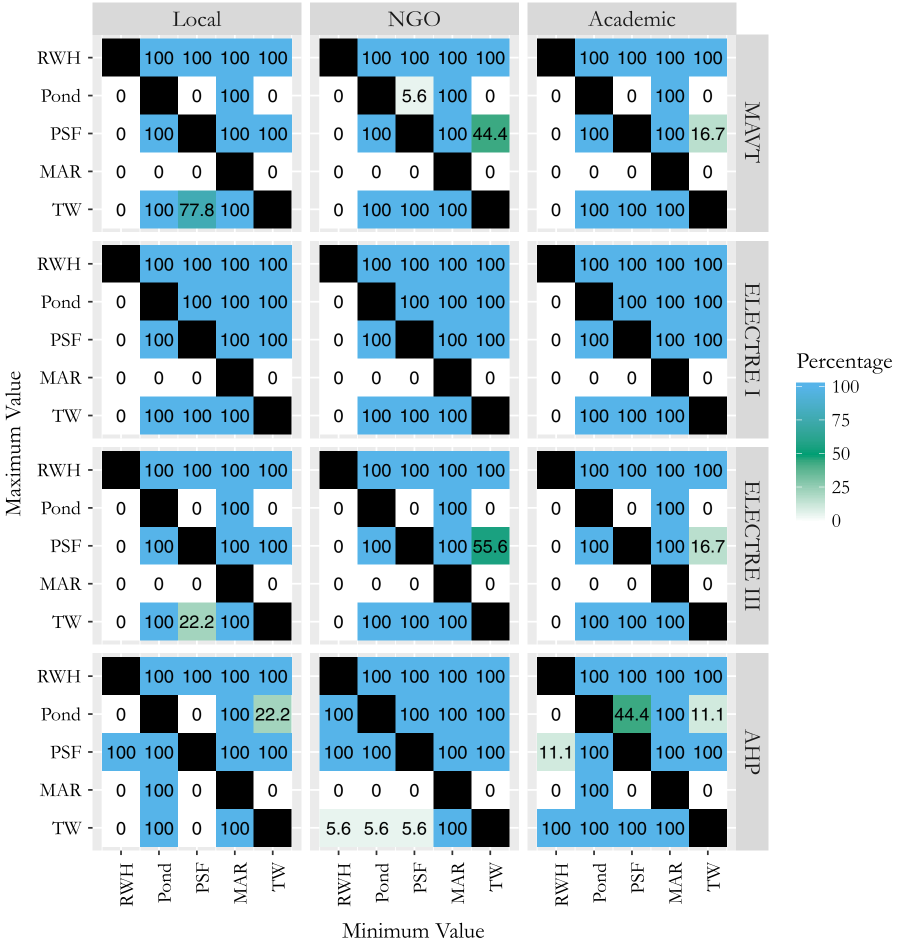


Fig. 5. Heat map of frequency of exceeding ranking of another alternative in one-at-a-time scenarios. If cell equals 100%, then the maximum of the *y*-axis alternative exceeds the minimum value of the *x*-axis alternative in every scenario. If the cell equals 0% then the maximum value of the *y*-axis alternative never reaches the minimum possible value of the *x*-axis alternative.

Even when considering extreme one-at-a-time scenarios, MAR can never outrank rainwater harvesting (Fig. 5). Pond, tubewell, and pond sand filter can only surpass rainwater harvesting as the highest ranked alternative in the AHP method (Fig. 5). MAR can only exceed the pond ranking if using the AHP method (Fig. 5). This robustness of ranking order suggests an insensitivity to extreme values within the scoring matrix **X**. This is further depicted in the narrow range of the possible ranks for each alternative (Fig. 6).

The one-at-a-time sensitivity results also suggest that all criteria categories are equally significant in the overall ranking of the alternatives (Table 3, and Figs. 6 and S1–S3 in the Supplemental Data). However, it is possible that weighting of different criteria leads to differences in the importance of criteria categories between stakeholders (Table 4). Economic criteria are most significant among local stakeholders, whereas technical criteria are most significant with NGO stakeholders (Table 4). The social criteria are most significant with academic stakeholders (Table 4). Nevertheless, no specific criteria are highlighted as extremely significant to the final outcome.

Similarly, the generalized sensitivity analysis does not show any noticeably significant criteria, suggesting that criteria are equal in importance (Figs. 7 and 8). The range for the most significant criteria between behavior and nonbehavior outcomes include weights from all criteria categories—technical, economic, social, and environmental—although the differences in ranges between behavior and nonbehavior outcomes are barely noticeable (Fig. 7). Sensitive criterion weights are different in AHP, ELECTRE I, and ELECTRE III as shown in Figs. S28, S30, and S32 in the Supplemental Data.

The scores of alternate/criterion pairs are more sensitive, albeit only slightly, than the weighting schemes when differentiating between behavior and nonbehavior categories (see slight shifts in parameter distributions in Fig. 8 as compared to negligible shifts in Fig. 7). Across all methods and stakeholder groups, the sensitive $x_{i,j}$ are most often associated with switching of ranking between ponds and tubewells (Figs. S29–S33 in the Supplemental Data). Significant $x_{i,j}$ range across all four criteria categories, suggesting method robustness especially because x_j for rainwater harvesting are often insensitive.

Academic and NGO survey results show differences between expected ranking of alternatives and MCDA ranking (Fig. 9). Academic stakeholders expected rainwater harvesting and pond sand filter to rank as the best alternatives, but considered pond water to be the least preferred option. Similarly, NGO stakeholders ranked rainwater harvesting as top alternative, but considered tubewell, pond sand filter, and MAR as equally preferred sources (Fig. 9).

Discussion

This MCDA allows for a methodical and transparent evaluation of the drinking water alternatives and criteria affecting their success in coastal Bangladesh. After considering multiple MCDA methods

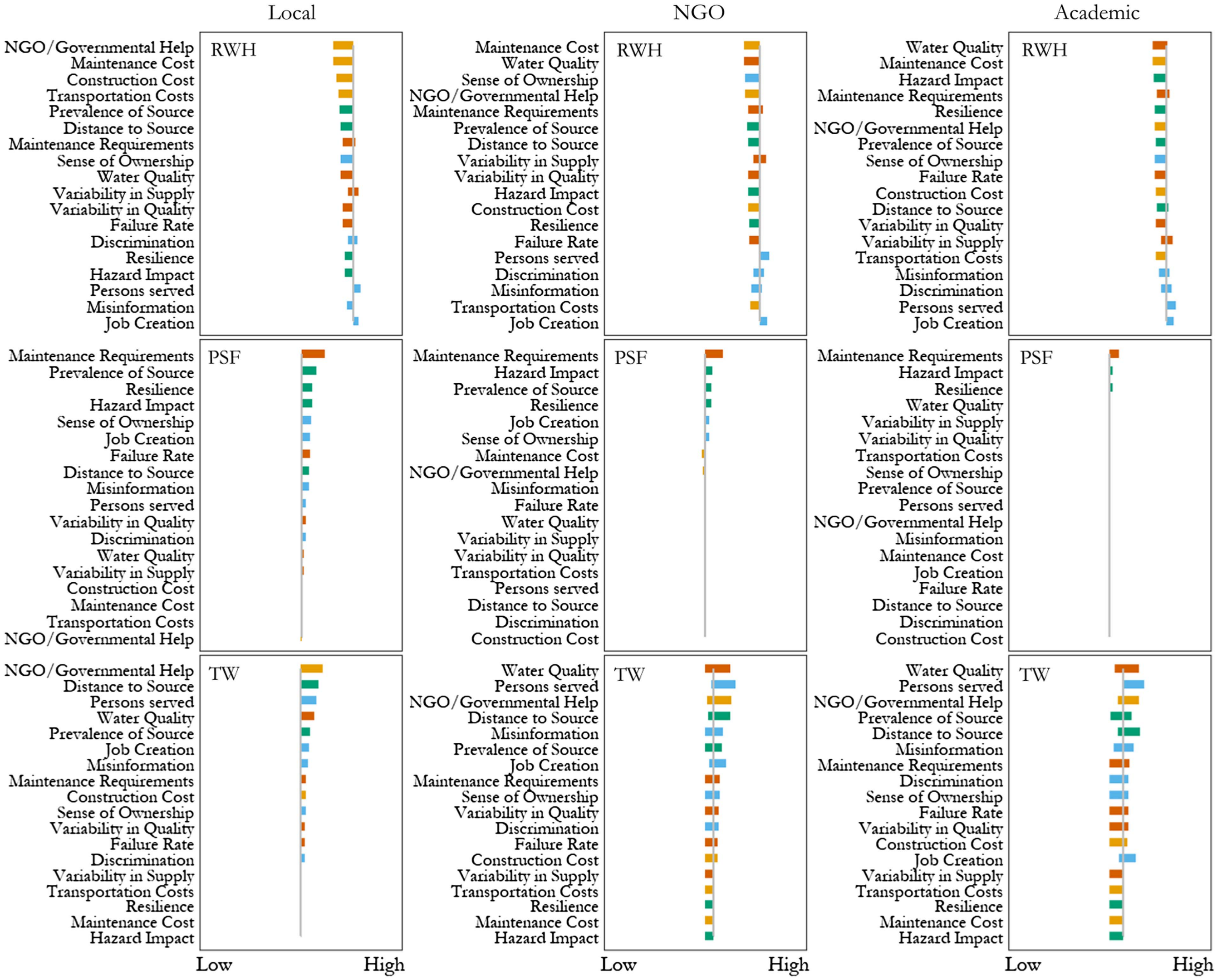


Fig. 6. Tornado diagrams of criteria sensitivity for the top three ranked alternatives in MAVT: rainwater harvesting (RWH), pond sand filter (PSF), and tubewell (TW). See Figs. S1–S3 for all other tornado diagrams.

Table 3. Most significant criteria category for each alternative and method, as determined from the one-at-a-time sensitivity analysis and the tornado diagrams (Figs. 6 and S1–S3 in Supplemental Data)

	Method			
Alternative	MAVT	AHP	ELECTRE I	ELECTRE III
RWH	Economic > technical > environmental > social	Technical > economic > social > environmental	Environmental > technical > social > economic	Economic > environmental > social > technical
Pond	Technical > economic > environmental > social	Technical > economic > social > environmental	Economic > technical > social > environmental	Economic > environmental > social > technical
PSF	Environmental > technical > social > economic	Technical > economic > social > environmental	Economic > technical > environmental > social	Technical > environmental > economic = social
MAR	Technical = economic > environmental > social	Technical > economic > social > environmental	Environmental = social > technical > economic	Social > economic > environmental > technical
TW	Environmental > technical = economic = social	Social > technical > economic > environmental	Environmental > technical > economic > social	Economic > environmental > technical > social

and stakeholder preferences, our results robustly suggest rainwater harvesting is the top ranked drinking water source and is, therefore, most likely to succeed. By demonstrating that differing methods achieve similar results, MCDA tools give confidence that resources should be directed toward supporting, promoting, and even improving the rainwater harvesting sources in the study area.

Alternatively, the consistently low ranking of MAR may suggest unlikely future success of the technology. MAR scored poorly across all criteria categories, which especially low performance scores in social criteria. Local community member interviews pointed to significant misunderstanding concerning ownership and responsibility of maintenance of the MAR system. For example,

Table 4. Most significant criteria category for each alternative and stakeholder, as determined from the one-at-a-time sensitivity analysis and the tornado diagrams (Figs. 6 and S1–S3 in Supplemental Data)

	Stakeholder		
Alternative	Local	NGO	Academic
RWH	Economic > technical > environmental > social	Environmental = technical > economic > social	Social > economic > technical = environmental
Pond	Economic > technical = environmental > social	Technical > economic > environmental > social	Technical = economic > social > environmental
PSF	Technical > economic > environmental > social	Technical > economic > environmental > social	Technical > environmental > economic = social
MAR	Economic > technical > environmental > social	Technical > social = environmental > economic	Social > environmental = technical = economic
TW	Environmental > technical = economic > social	Technical > environmental > economic > social	Social = economic > environmental = technical

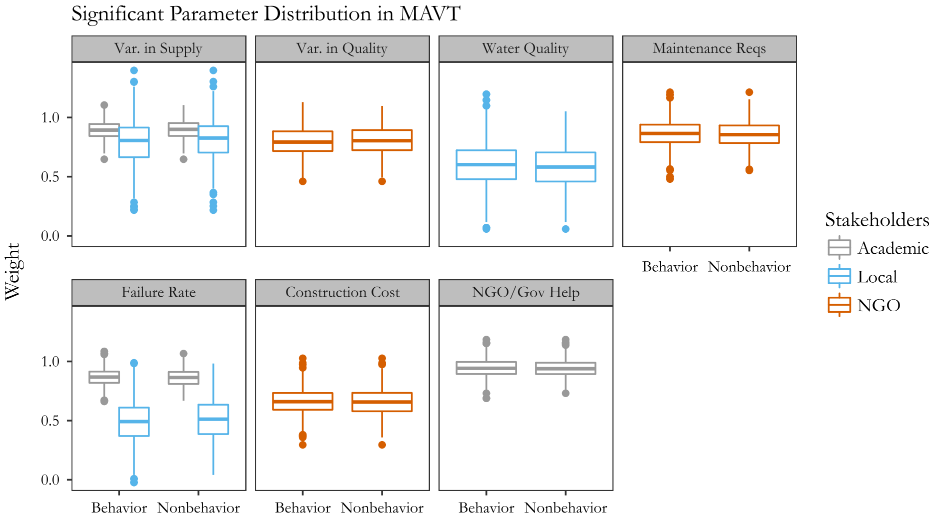


Fig. 7. Distribution of generalized sensitivity analysis weights w_j for top three most significant criteria (based on weighting) in local, NGO, and academic simulations that result in differences between behavior and nonbehavior outcomes in MAVT.

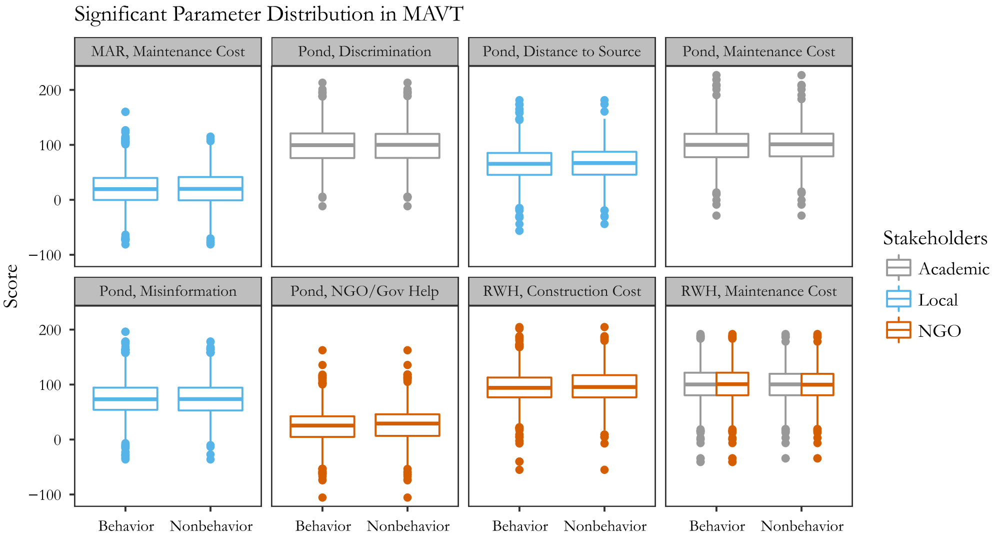


Fig. 8. Distribution of generalized sensitivity analysis scores $x_{i,j}$ for top three sensitive parameters (based on scores) in local, NGO, and academic simulations that result in differences between behavior and nonbehavior outcomes in MAVT.

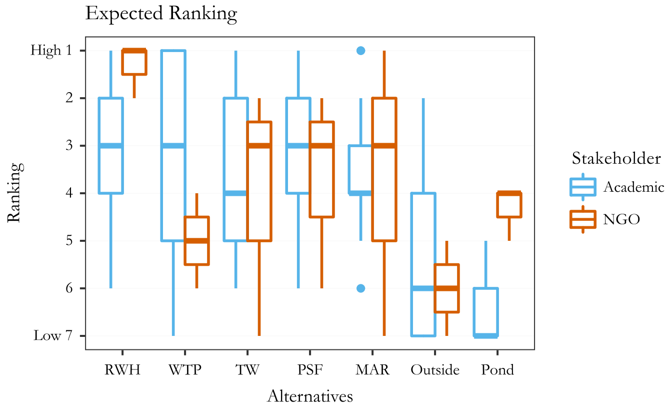


Fig. 9. Expected ranking of alternatives as determined from academic and NGO survey results. Expected ranking refers to the predicted relative ranking of different sources, where RWH = rainwater harvesting; WTP = water treatment plant; TW = tubewell; PSF = pond sand filter; MAR = managed aquifer recharge; outside = water purchased outside the community, and pond = pond water.

community leaders expressed difficulty in collecting enough money for maintenance. Community users would rather wait for a NGO or governmental organization to pay for the maintenance, resulting in communities sometimes going months or years without a functioning MAR system. These types of social discontentments with MAR have also been seen in other studies (Albas et al. 2014; Blanchet 2014). Extensive communication with community users, as well as other social dimensions, must be increased to improve use and performance of MAR (Blanchet 2014).

NGO and academic stakeholders ranked MAR as the second (tied with pond sand filter) and fourth best alternatives, respectively (Fig. 9). It is likely that the stakeholders (1) had limited background knowledge of the MAR technology; (2) felt an affinity toward MAR; or (3) undervalued the importance of the social criteria in MAR success, given that they later gave high importance to the social criteria. This divergence between the stakeholders' initial ranking and MCDA ranking supports the basis for holistic decision analysis methods. MCDA gives potential insights into complex problems that may be misconstrued in a quick assessment. When a decision is based on multiple (often conflicting) weighted criteria, a decision maker may resort to heuristic problem solving and intuition in making the decision. MCDA allows for a more transparent structure the problem and an explicit evaluation of multiple criteria.

In this study, stakeholder preferences, with respect to the importance of different criteria, play little role in the ranking of alternatives. The greater variance between MCDA methods emphasizes the need for appropriate method selection and thorough understanding of method process. Confusion by method choice, especially when different methods do not necessarily recommend the same solution for the same problem, can deter stakeholders and decision makers from using MCDA methods (Ishizaka and Nemery 2013). Because some methods are more analytically rigorous (e.g., ELECTRE I and ELECTRE III), it may be best to build tools that group MCDA methods and allow stakeholders to input parameters and run multiple methods instantaneously under different scenarios (Banville et al. 1998; Kain and Söderberg 2008; Marttunen et al. 2015; Ishizaka and Siraj 2018).

The lack of sensitivity among weights and criteria shows the robustness of different methods in capturing the performance of alternatives, despite imprecise data and uncertain parameter characterization. While it is likely that attributes within and across criteria categories may be interconnected, no one category appears more important than another. For example, we found that social and economic factors are just as important as environmental and technical aspects of water resource management. In problems when social factors may affect the decision outcome, decision makers should seek advice from appropriate socioeconomic experts to better gather and understand social criteria data.

This study assumes a typically high quality of rainwater harvesting systems, but without proper water quality testing and treatment this may not be an adequate assumption at all sites and scenarios (Islam et al. 2015). Alternative assessment and planning is the first step to reaching sustainable solutions, but water managers must also acknowledge the need for robust research in infrastructure failure as well as water quality and treatment. Positive MCDA ranking results do not ensure successful water systems implementation and management. Failure to consider unexpected infrastructure or management obstacles could increase risk of hazardous health implications.

Although this study uses MCDA methods to identify a ranking of single alternatives, it does not consider combinations of drinking water sources acting as discrete alternatives (Montis et al. 2000). Currently all residents use multiple sources (Jakariya 2005; Islam et al. 2007, 2015; Blanchet 2014; Benneyworth et al. 2016), so it is likely that a more realistic water management design would lead to the use of more than one source (McBean et al. 2013). Rainwater harvesting is likely to succeed broadly, but other alternatives could be partial, or backup, sources. For example, it would not be unreasonable to promote rainwater harvesting as the primary drinking water source while still maintaining the occasional functioning of community pond sand filters for use in case of drought. Conversely, rainwater harvesting might be the top single solution, especially if a variety of NGOs or governmental programs promoted and invested in the solution, such that the harvesting storage capacity exceeded the water resource demand (Islam et al. 2007; Alam et al. 2012).

When attempting to factor in local context (Cai et al. 2004; Starkl et al. 2013), decision makers must acknowledge that communities are not homogeneous in terms of needs and preferences. Environmental, demographic, cultural, and historical variables have all been identified as reasons for variations among communities (Jakariya 2005). In this context, we concede that our analysis is calibrated with data from a very small region of coastal Bangladesh. It is likely at both a smaller, site-specific scale and across a broader region, we would find discrepancies in our results. However, it may be possible to extrapolate our methods and results to other regions, especially by applying our insights to inform future data collection and survey implementation.

Another important consideration of decision analysis methods is the complexity of the problem. In every simple method, the decision maker has to assume the appropriate level of complexity to address the problem. In this paper, we group alternatives based on technology. Conversely, we could have incorporated a more precise definition of the various alternatives that would have split alternatives into a greater number of options (e.g., privately-owned rainwater harvesting separated from community rainwater harvesting sources), which would have required further data collection. In our analysis, information on the small details about sources that could contribute to their ultimate success is not considered due to the limited quantity and quality of available data. As we categorized qualitative data from the focus group interviews, we reduced subjectivity by limiting the number of categorizations (see the five categories in Table S1 in the Supplemental Data). Decision models rely on a balance between model accuracy and the expense of data collection and implementation of more complex models.

Despite the limitations of academic conjecture and modeling, the residents of Polder 32 and the surrounding regions are still faced with water insecurity and health risks. This research elucidates the multifaceted approach that will be needed to resolve water management problems, spanning the technical, economic, social, and environmental realms. Our findings support the similar studies that generally regard rainwater harvesting as an effective, high-quality, improved source of drinking water (Ansari et al. 2010; Ahmed et al. 2011; Alam et al. 2012; Islam et al. 2013; Abedin et al. 2014; Blanchet 2014; Arku et al. 2015; Neibaur and Anderson 2016; WHO and UNICEF 2017), but we demonstrate evidence of this assumption with our holistic evaluation of the water source. Stakeholders can begin to focus their efforts on making rainwater harvesting more sustainable through a better understanding of water quality (Ahmed et al. 2011; Arku et al. 2015; Islam et al. 2015), successful implementation of community rainwater harvesting resources (Domènech et al. 2012; Opare 2012; Neibaur and Anderson 2016), and collaboration of local residents and physical and social scientists (Cai et al. 2004; Ansari et al. 2010; Starkl et al. 2013). The overall capacity community and individual rainwater harvesting will likely need to be assessed and increased, while the site-specific testing of water quality should be encouraged. Meanwhile, the adaptation and implementation at local and national levels will require coordination between governments, NGOs, and community stakeholders to pragmatically install additional rainwater harvesting systems at homes, schools, and community structures (Abedin et al. 2014). This integrated approach has the most promising outlook for addressing water insecurities and reducing the overall vulnerability of coastal communities (Hoque et al. 2016; Abedin et al. 2014).

Conclusions

Decision analysis methods highlight the usefulness of thorough data collection and modeling to better understand critical factors in water management. Although decision modeling can be dependent on the particular method process, stakeholder preferences, and imprecise data, method cross checking and sensitivity analysis can ensure for robust results. Often a decision maker's intuition differs from a thorough model analysis. This is likely due to the decision maker's inability to fully structure the decision into (1) an objective, (2) a set of alternatives, and (3) a list of weighted criteria. MCDA can serve as a useful first step in addressing complex water management problems, especially in rural regions where an adequate understanding of the local context is key to success.

Acknowledgments

This study was supported by the Office of Naval Research Grant No. N00014-11-1-0683. This material is also based on work supported by the National Science Foundation Graduate Fellowship under Grant No. 1445197. We would also like to thank the anonymous reviewers for their careful reading of our manuscript and their many insightful comments and suggestions. Data and R code used in this study are available at https://github.com/chelspeters7/BanglaMCDA.

Notation

The following symbols are used in this paper:

$c(i, i')$ = concordance index for an order pair of alternatives i and i';
$d(i, i')$ = discordance index for an order pair of alternatives i and i';
m = number of criteria;
n_a = number of alternatives;
p_j = indifference threshold;
q_j = preference threshold;
u_i = alternative's total score;
$\nu_{i,j}$ = normalized performance score for $x_{i,j}$;
$x_{i,j}$ = performance score of i alternative and j criteria;
$\mathbf{W}$ = weights vector; and
w_j = weight assigned to jth criterion.

Supplemental Data

Appendix S1, Table S1, and Figs. S1–S33 are available online in the ASCE Library (www.ascelibrary.org).

References

Abedin, M. A., U. Habiba, and R. Shaw. 2014. "Community perception and adaptation to safe drinking water scarcity: Salinity, arsenic, and drought risks in coastal Bangladesh." *Int. J. Disaster Risk Sci.* 5 (2): 110–124. https://doi.org/10.1007/s13753-014-0021-6.

Acacia Water. 2011. *Action research: Creating fresh water bubbles in brackish aquifer*. Gouda, Netherlands: Acacia Water.

Ahmed, W., T. Gardner, and S. Toze. 2011. "Microbiological quality of roof-harvested rainwater and health risks: A review." *J. Environ. Qual.* 40 (1): 9–13. https://doi.org/10.2134/jeq2010.0345.

Alam, M., M. Sultana, G. B. Nair, R. B. Sack, D. A. Sack, A. K. Siddique, A. Ali, A. Huq, and R. R. Colwell. 2006. "Toxigenic vibrio cholerae in the aquatic environment of Mathbaria, Bangladesh." *Appl. Environ. Microbiol.* 72 (4): 2849–2855. https://doi.org/10.1128/AEM.72.4.2849-2855.2006.

Alam, R., G. Munna, M. A. I. Chowdhury, M. S. K. A. Sarkar, M. Ahmed, M. T. Rahman, F. Jesmin, and M. A. Toimoor. 2012. "Feasibility study of rainwater harvesting system in Sylhet city." *Environ. Monit. Assess.* 184 (1): 573–580. https://doi.org/10.1007/s10661-011-1989-7.

Albas, I., H. Hagedooren, V. Knook, and H. Pot. 2014. *A field study on the social aspects of the MAR system*. Delft, Netherlands: Delft Univ. of Technology.

Angelis, A., and P. Kanavos. 2017. "Multiple criteria decision analysis (MCDA) for evaluating new medicines in health technology assessment and beyond: The advance value framework." *Soc. Sci. Med.* 188: 137–156. https://doi.org/10.1016/j.socscimed.2017.06.024.

Ansari, M. S., H. M. N. Islam, and K. Roy. 2010. *Functionality and social acceptance of safe water technology-pond sand filter and rainwater harvesting system in south-west coastal region of Bangladesh*. Saarbrucken, Germany: VDM.

Arku, F., S. Omari, B. Adu-Okoree, and A. Abduramane. 2015. "Harvested rainwater: Quality, adequacy, and proximity in Ghanaian rural communities." *Dev. Pract.* 25 (8): 1160–1169. https://doi.org/10.1080/09614524.2015.1081676.

Auerbach, L. W., S. L. Goodbred Jr., D. R. Mondal, C. A. Wilson, K. R. Ahmed, K. Roy, M. S. Steckler, C. Small, J. M. Gilligan, and B. A. Ackerly. 2015. "Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain." *Nat. Clim. Change* 5 (2): 153–157. https://doi.org/10.1038/nclimate2472.

Ayers, J. C., S. Goodbred, G. George, D. Fry, L. Benneyworth, G. Hornberger, K. Roy, M. R. Karim, and F. Akter. 2016. "Sources of salinity and arsenic in groundwater in southwest Bangladesh." *Geochem. Trans.* 17 (1): 4.

Bangladesh Bureau of Statistics. 2012. *Census population and housing census 2011: Socio-economic and demographic report, national series*. Dhaka, Bangladesh: Bangladesh Bureau of Statistics.

Bangladesh Bureau of Statistics. 2014. Vol. 2 of *Census population and housing census 2011: National report, union statistics*. Dhaka, Bangladesh: Bangladesh Bureau of Statistics.

Bangladesh Bureau of Statistics. 2015. *Census population and housing census 2011: Community report: Zila: Khulna*. Khulna, Bangladesh: Bangldesh Bureau of Statistics.

Banville, C., M. Landry, J. M. Martel, and C. Boulaire. 1998. "A stakeholder approach to MCDA." *Syst. Res. Behav. Sci.* 15 (1): 15–32. https://doi.org/10.1002/(SICI)1099-1743(199801/02)15:1<15::AID-SRES179>3.0.CO;2-B.

Belton, V., and T. J. T. Stewart. 2002. *Multiple criteria decision analysis*. Boston: Springer.

Benayoun, R., B. Roy, and B. Sussman. 1966. *ELECTRE: Une méthode pour guider le choix en présence de points de vue multiples*. Note de Travail No. 49. Paris: Direction Scientifique.

Benneyworth, L., et al. 2016. "Drinking water insecurity: Water quality and access in coastal south-western Bangladesh." *Int. J. Environ. Health Res.* 26 (5–6): 508–524. https://doi.org/10.1080/09603123.2016.1194383.

Blanchet, T. 2014. *Up-scaling MAR for providing community water supplies in saline areas: Anthropological study report*. Dhaka, Bangladesh: Drishti Research Center.

Bouwer, H. 2002. "Artificial recharge of groundwater: Hydrogeology and engineering." *Hydrogeol. J.* 10 (1): 121–142. https://doi.org/10.1007/s10040-001-0182-4.

Burgess, W. G., M. A. Hoque, H. A. Michael, C. I. Voss, G. N. Breit, and K. M. Ahmed. 2010. "Vulnerability of deep groundwater in the Bengal aquifer system to contamination by arsenic." *Nat. Geosci.* 3 (2): 83–87. https://doi.org/10.1038/ngeo750.

Cai, X., L. Lasdon, and A. M. Michelsen. 2004. "Group decision making in water resources planning using multiple objective analysis." *J. Water Resour. Plan. Manage.* 130 (1): 4–14. 10.1061/(ASCE)0733-9496(2004)130:1(4).

Calizaya, A., O. Meixner, L. Bengtsson, and R. Berndtsson. 2010. "Multi-criteria decision analysis (MCDA) for integrated water resources management (IWRM) in the Lake Poopo basin, Bolivia." *Water Resour. Manage.* 24 (10): 2267–2289. https://doi.org/10.1007/s11269-009-9551-x.

Chowdhury, N. T. 2010. "Water management in Bangladesh: An analytical review." *Water Policy* 12 (1): 32–51. https://doi.org/10.2166/wp.2009.112.

Chowdhury, R. K., and R. Rahman. 2008. "Multicriteria decision analysis in water resources management: The Malnichara channel improvement." *Int. J. Environ. Sci. Technol.* 5 (2): 195–204. https://doi.org/10.1007/BF03326013.

Cinelli, M., S. R. Coles, and K. Kirwan. 2014. "Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment." *Ecol. Indic.* 46: 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011.

Domènech, L., H. Heijnen, and D. Saurí. 2012. "Rainwater harvesting for human consumption and livelihood improvement in rural Nepal: Benefits and risks." *Water Environ. J.* 26 (4): 465–472. https://doi.org/10.1111/j.1747-6593.2011.00305.x.

ECOSOC (United Nations Economic and Social Council). 2016. "Progress towards the sustainable development goals." Accessed January 1, 2017. https://unstats.un.org/sdgs/.

Figueira, J., S. Greco, B. Roy, and R. Slowinski. 2013. "An overview of ELECTRE methods and their recent extensions." *J. Multi-Criteria Decis. Anal.* 20 (1–2): 61–85. https://doi.org/10.1002/mcda.1482.

Ganji, A., H. R. Maier, and G. C. Dandy. 2016. "A modified Sobol' sensitivity analysis method for decision-making in environmental problems." *Environ. Model. Software* 75: 15–27. https://doi.org/10.1016/j.envsoft.2015.10.001.

Hajkowicz, S., and K. Collins. 2007. "A review of multiple criteria analysis for water resource planning and management." *Water Resour. Manage.* 21 (9): 1553–1566. https://doi.org/10.1007/s11269-006-9112-5.

Holländer, H. M., R. Mull, and S. N. Panda. 2009. "A concept for managed aquifer recharge using ASR: Wells for sustainable use of groundwater resources in an alluvial coastal aquifer in eastern India." *Phys. Chem. Earth Parts* 34 (4–5): 270–278. https://doi.org/10.1016/j.pce.2008.05.001.

Hoque, M. A., P. F. D. Scheelbeek, P. Vineis, A. E. Khan, K. M. Ahmed, and A. P. Butler. 2016. "Drinking water vulnerability to climate change and alternatives for adaptation in coastal south and south east Asia." *Clim. Change* 136 (2): 247–263. https://doi.org/10.1007/s10584-016-1617-1.

Hornberger, G. M., and R. C. Spear. 1981. "An approach to the preliminary analysis of environmental systems." *J. Environ. Manage.* 12: 7–18.

Huq, S. 2001. "Climate change and Bangladesh." *Science* 294 (5547): 1617. https://doi.org/10.1126/science.294.5547.1617.

Hussain, M. D., and A. Ziauddin. 1989. "Rainwater use in Bangladesh: A case study in Dacope Upozilla." In *Proc., Int. Conf. on Rain Water Cistern Systems*. Manila, Philippines.

Hyde, K. M., H. R. Maier, and C. Colby. 2003. "Incorporating uncertainty in the PROMETHEE MCDA method." *J. Multi-Criteria Decis. Anal.* 12 (4–5): 245–259. https://doi.org/10.1002/mcda.361.

Hyde, K. M., H. R. Maier, and C. B. Colby. 2004. "Reliability-based approach to multicriteria decision analysis for water resources." *J. Water Resour. Plan. Manage.* 130 (6): 429–438. 10.1061/(ASCE)0733-9496(2004)130:6(429).

Ishizaka, A., and P. Nemery. 2013. *Multi-criteria decision analysis*. Chichester, UK: Wiley.

Ishizaka, A., and S. Siraj. 2018. "Are multi-criteria decision-making tools useful? An experimental comparative study of three methods." *Eur. J. Oper. Res.* 264 (2): 462–471. https://doi.org/10.1016/j.ejor.2017.05.041.

Islam, M. A., A. K. Azad, M. A. Akber, M. Rahman, and I. Sadhu. 2015. "Effectiveness of solar disinfection (SODIS) in rural coastal Bangladesh." *J. Water Health* 13 (4): 1113–1122. https://doi.org/10.2166/wh.2015.186.

Islam, M. A., H. Sakakibara, M. R. Karim, and M. Sekine. 2013. "Potable water scarcity: Options and issues in the coastal areas of Bangladesh." *J. Water Health* 11 (3): 532–542. https://doi.org/10.2166/wh.2013.215.

Islam, M. M., M. Kabir, and F. N. F. Chou. 2007. "Feasibility study of rainwater harvesting techniques in Bangladesh." In *Rainwater and Urban Design 2007*, 726–733. Sydney, Australia: Engineers Australia.

Jakariya, M. 2005. "Sustainable safe water options in Bangladesh: Experiences from the arsenic project at MATLAB (AsMat)." In *Natural arsenic in groundwater: Occurrence, remediation and management*, edited by J. Bundschuh, P. Bhattacharya, and D. Chandrashekharam, 319–330. London: Taylor & Francis Group.

Jha, M. K., V. M. Chowdary, Y. Kulkarni, and B. C. Mal. 2014. "Rainwater harvesting planning using geospatial techniques and multicriteria decision analysis." *Resour. Conserv. Recycl.* 83: 96–111. https://doi.org/10.1016/j.resconrec.2013.12.003.

Jiménez Cisneros, B., T. Oki, N. W. Arnell, G. Benito, J. G. Cogley, P. Döll, T. Jiang, and S. S. Mwakalila. 2014. "Freshwater resources: Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects: Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change." Accessed July 6, 2017. https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap3_FINAL.pdf.

Jongman, B., P. Ward, and J. Aerts. 2012. "Global exposure to river and coastal flooding: Long term trends and changes." *Global Environ. Change* 22 (4): 823–835. https://doi.org/10.1016/j.gloenvcha.2012.07.004.

Kain, J. H., and H. Söderberg. 2008. "Management of complex knowledge in planning for sustainable development: The use of multi-criteria decision aids." *Environ. Impact Assess. Rev.* 28 (1): 7–21. https://doi.org/10.1016/j.eiar.2007.03.007.

Kirkwood, C. W. 1997. *Stategic decision making: Multiobjective decision analysis with spreadsheets*. Belmont, CA: Cengage Learning.

Marttunen, M., J. Mustajoki, M. Dufva, and T. P. Karjalainen. 2015. "How to design and realize participation of stakeholders in MCDA processes? A framework for selecting an appropriate approach." *Euro J. Decis. Process.* 3 (1–2): 187–214. https://doi.org/10.1007/s40070-013-0016-3.

McBean, E. A., M. A. Rajib, and M. M. Rahman. 2013. "Improved sustainability of water supply options in areas with arsenic-impacted groundwater." *Water* 5 (4): 1941–1951. https://doi.org/10.3390/w5041941.

McGranahan, G., D. Balk, and B. Anderson. 2007. "The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones." *Environ. Urban.* 19 (1): 17–37. https://doi.org/10.1177/0956247807076960.

Mehedi, H., A. K. Nag, and S. Farhana. 2010. *Climate induced displacement: Case study of cyclone Aila in the southwest coastal region of Bangladesh*. Khulna, Bangladesh: Humanitywatch.

Montis, A. D., P. D. Toro, B. Droste-franke, I. Omann, and S. Stagl. 2000. "Assessing the quality of different MCDA methods." In *Alternatives for environmental valuation*, edited by M. Getzner, C. L. Splash, and S. Stagl, 99–184. London: Routledge.

Mutikanga, H. E., S. K. Sharma, and K. Vairavamoorthy. 2011. "Multi-criteria decision analysis: A strategic planning tool for water loss management." *Water Resour. Manage.* 25 (14): 3947–3969. https://doi.org/10.1007/s11269-011-9896-9.

Neibaur, E. E., and E. P. Anderson. 2016. "An examination of factors affecting sustainability of domestic rainwater harvesting systems in a rural, semi-arid region of Mexico." *Water Sci. Technol. Water Supply* 16 (5): 1388–1397. https://doi.org/10.2166/ws.2016.066.

Nobi, N., and A. D. Gupta. 1997. "Simulation of regional flow and salinity intrusion in an integrated stream-aquifer system in coastal region: Southwest region of Bangladesh." *Groundwater* 35 (5): 786–796. https://doi.org/10.1111/j.1745-6584.1997.tb00147.x.

Opare, S. 2012. "Rainwater harvesting: An option for sustainable rural water supply in Ghana." *GeoJournal* 77 (5): 695–705. https://doi.org/10.1007/s10708-011-9418-6.

Rahman, M. A. T., R. K. Majumder, S. H. Rahman, and M. A. Halim. 2011. "Sources of deep groundwater salinity in the southwestern zone of Bangladesh." *Environ. Earth Sci.* 63 (2): 363–373. https://doi.org/10.1007/s12665-010-0707-z.

Rahman, R., and M. Salehin. 2013. *Disaster risk reduction: Approaches Bangladesh*, edited by R. Shaw, F. Mallick, and A. Islam, 65–90. New York: Springer.

Rashid, H. E. 1977. *Geography of Bangladesh*. Boulder, CO: Westview Press.

Reed, M. S., E. D. Fraser, and A. J. Dougill. 2006. "An adaptive learning process for developing and applying sustainability indicators with local communities." *Ecol. Econ.* 59 (4): 406–418. https://doi.org/10.1016/j.ecolecon.2005.11.008.

Rogers, M., and M. Bruen. 1998. "Choosing realistic values of indifference, preference and veto thresholds for use with environmental criteria within ELECTRE." *Eur. J. Oper. Res.* 107 (3): 542–551. https://doi.org/10.1016/S0377-2217(97)00175-6.

Roy, B. 1991. "The outranking foundations approach and the methods." *Theory Decis.* 31 (1): 49–73. https://doi.org/10.1007/BF00134132.

Roy, B., M. Present, and D. Silhol. 1986. "A programming method for determining which Paris metro stations should be renovated." *Eur. J. Oper. Res.* 24 (2): 318–334. https://doi.org/10.1016/0377-2217(86)90054-8.

Saaty, T. L. 1988. *Decision making for leaders*. Pittsburgh: RWS Publications.

Saaty, T. L. 1992. *Multicriteria decision making: The analytic hierarchy process*. Pittsburgh: RWS Publications.

Saaty, T. L. 2008. "Decision making with the analytic hierarchy process." *Int. J. Serv. Sci.* 1 (1): 83–98.

Saltelli, A. 2002. "Sensitivity analysis for importance assessment." *Risk Anal.* 22 (3): 579–590. https://doi.org/10.1111/0272-4332.00040.

Scholten, L., N. Schuwirth, P. Reichert, and J. Lienert. 2015. "Tackling uncertainty in multi-criteria decision analysis: An application to water supply infrastructure planning." *Eur. J. Oper. Res.* 242 (1): 243–260. https://doi.org/10.1016/j.ejor.2014.09.044.

Shahid, S. 2010. "Recent trends in the climate of Bangladesh." *Clim. Res.* 42 (3): 185–193. https://doi.org/10.3354/cr00889.

Shofade, O. 2011. "Considering hierarchical structure of criteria in ELECTRE decision aiding methods." Master's thesis, Escola Tecnica Superior d'Enginyeria, Universitat Rovira i Virgili Escola.

Shumaker, R. 2017. "Perceptions of drinking water quality in southwestern Bangladesh." Master's thesis, Dept. of Earth and Environmental Sciences, Vanderbilt Univ.

Singh, O. P., T. M. A. Khan, and M. S. Rahman. 2000. "Changes in the frequency of tropical cyclones over the north Indian ocean." *Meteorol. Atmos. Phys.* 75 (1–2): 11–20. https://doi.org/10.1007/s007030070011.

Starkl, M., N. Brunner, and T.-A. Stenström. 2013. "Why do water and sanitation systems for the poor still fail? Policy analysis in economically advanced developing countries." *Environ. Sci. Technol.* 47 (12): 6102–6110. https://doi.org/10.1021/es3048416.

Stewart, T. J., and L. Scott. 1995. "A scenario-based framework for multi-criteria decision analysis in water resources planning." *Water Resour. Res.* 31 (11): 2835–2843. https://doi.org/10.1029/95WR01901.

Tasich, C. M. 2013. "Groundwater-surface water interactions in the tidally-dominated coastal region of the Bengal basin: A one-dimensional numerical analysis of tidal and surface water controls on local aquifer systems." Master's thesis, Dept. of Earth and Environmental Sciences, Vanderbilt Univ.

Von Winterfeldt, D., and W. Edwards. 1993. *Decision analysis and behavioral research*. Cambridge, MA: Cambridge University Press.

WHO and UNICEF (World Health Organization and United Nations International Children's Emergency Fund). 2017. "Launch version July 12 main report progress on drinking water, sanitation and hygiene." Accessed January 7, 2017. https://www.wssinfo.org/.

Wong, P., I. J. Losada, J. P. Gattuso, J. Hinkel, A. Khattabi, K. L. McInnes, Y. Saito, and A. Sallenger. 2014. "Coastal systems and low-lying areas: Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects: Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change." Accessed July 6, 2017. https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap5_FINAL.pdf.

Worland, S. C., G. M. Hornberger, and S. L. Goodbred. 2015. "Source, transport, and evolution of saline groundwater in a shallow Holocene aquifer on the tidal delta plain of southwest Bangladesh." *Water Resour. Res.* 51 (7): 5791–5805. https://doi.org/10.1002/2014WR016262.

World Bank. 2011. *The cost of adapting to extreme weather events in a changing climate*. Rep. No. 67845. Washington, DC: World Bank.