Journal of Hydrology 514 (2014) 15–29

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Exploring parameter effects on the economic outcomes of groundwater-based developments in remote, low-resource settings

Adam Abramson[a,*], Eilon Adar[a], Naftali Lazarovitch[b]

[a] Department of Environmental Hydrology and Microbiology, Zuckerberg Institute for Water Research, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Midreshet Ben-Gurion, Israel

[b] Wyler Department of Dryland Agriculture, French Associates' Institute for Agriculture and Biotechnology of Drylands, The Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Midreshet Ben-Gurion, Israel

A R T I C L E   I N F O

Article history:
Received 17 January 2014
Received in revised form 21 March 2014
Accepted 1 April 2014
Available online 12 April 2014
This manuscript was handled by G. Syme, Editor-in-Chief

Keywords:
Water policy
Groundwater development
Low-resource settings
Cost–benefit analysis
Decision support

S U M M A R Y

Groundwater is often the most or only feasible safe drinking water source in remote, low-resource areas, yet the economics of its development have not been systematically outlined. We applied *AWARE* (Assessing Water Alternatives in Remote Economies), a recently developed Decision Support System, to investigate the costs and benefits of groundwater access and abstraction for non-networked, rural supplies. Synthetic profiles of community water services ($n = 17{,}962$), defined across 13 parameters' values and ranges relevant to remote areas, were applied to the decision framework, and the parameter effects on economic outcomes were investigated. Regressions and analysis of output distributions indicate that the most important factors determining the cost of water improvements include the technological approach, the water service target, hydrological parameters, and population density. New source construction is less cost-effective than the use or improvement of existing wells, but necessary for expanding access to isolated households. We also explored three financing approaches – willingness-to-pay, -borrow, and -work – and found that they significantly impact the prospects of achieving demand-driven cost recovery. The net benefit under willingness to work, in which water infrastructure is coupled to community irrigation and cash payments replaced by labor commitments, is impacted most strongly by groundwater yield and managerial factors. These findings suggest that the cost–benefit dynamics of groundwater-based water supply improvements vary considerably by many parameters, and that the relative strengths of different development strategies may be leveraged for achieving optimal outcomes.

1. Introduction

In remote areas, water networks are uncommon due to cost, and groundwater is the most widely used source for supplying communities with the United Nations Millennium Development Goal (MDG) of "access to safe water", measured by access to an "improved water source" (United Nations, 2013). It is estimated that the ubiquitous hand-pump-fitted-borehole serves 1.3 billion users worldwide, 80% of whom live in rural areas (UNICEF and WHO, 2012). These sources are chosen for their durability, low maintenance requirements, and dependence on human rather than electric power. Other configurations, though much less common, are used in remote areas. These include boreholes fitted with motorized pumps powered by grid, diesel, wind, or solar photovoltaic (PV) power (Purohit, 2007; Bouzidi and Haddadi, 2009; Burney et al., 2010). Alternatively, low-cost manual well-drilling techniques are emerging as viable and cost-effective approaches for developing both household and community water supplies (Ball and Danert, 1999; Carter et al., 2001, 2006; Ball, 2004; Danert, 2009). Groundwater is often the most or only feasible water source for safe drinking use in these areas because of its high spatiotemporal availability, its resilience to seasonal and climate-related fluctuations and effective protection from surface pollution (Calow et al., 1997; MacDonald and Calow, 2009). Groundwater-based sources will doubtlessly continue to constitute a major proportion of the developments necessary for reaching the remaining 636 million residents of rural areas without access to improved sources (WHO and UNICEF, 2013).

The economics of expanding access to improved water services has been the focus of many studies since the MDGs were

* Corresponding author.
E-mail address: dr.adam.abramson@gmail.com (A. Abramson).

http://dx.doi.org/10.1016/j.jhydrol.2014.04.002
0022-1694/

formulated in 2000 (Cosgrove and Rijsberman, 2000; GWP, 2000; WHO and UNICEF, 2000; WSSCC, 2000; Devarajan et al., 2002; Smets, 2003; Winpenny, 2003; Mehta et al., 2005; Haller et al., 2007; Hutton et al., 2007; Hutton, 2012). Low availability of data and high levels of variability associated with the technical, environmental, and managerial aspects of non-networked rural water services make such estimates difficult. As a result, various simplifications and assumptions were applied in these studies within vastly different social, political and economic contexts. A common approach has been to model new expansions of water access by extrapolating mean unit costs of past improvements to the unreached population. This approach, however, overlooks the importance of variability in non-networked water services and simplifies a complex socio-hydro-fiscal landscape. Within sub-Saharan Africa, for example, costs for groundwater improvements have been shown to range greatly, both within and between nations, due to variations of economic, technical and environmental factors; Xenarios and Pavelic (2013) found the mean costs of a well to range from $6028 (SD $1507) in Zambia to $23,268 (SD $6980) in Ethiopia.

An important gap to fill, therefore, regarding estimates of the resources required to reach water development goals, is to sufficiently define the parameters necessary for modeling such improvements, and to outline their impacts on economic outcomes. By doing so, assumptions can be removed and a general picture of groundwater costs and benefits may be formed that captures the wide variation within communities still in need of water service improvements. The main objective of this study, therefore, is to provide a general exploration of the economic outcomes associated with water service improvements and model both the magnitude of and variation in costs and benefits of non-networked, groundwater-based water improvements across the globe. Exploring parameter effects on economic outcomes under a realistically wide range of values enables policymakers and water practitioners to better understand and respond to variations within the rural water sector.

This study applied *AWARE* (Assessing Water Alternatives in Remote Economies) a recently developed Decision Support System (DSS), to outline the importance of various parameters on the cost–benefit outcomes of groundwater-based water supply improvements in remote areas. Several parameter sensitivity analyses were conducted. According to Hamby (1994), these approaches enable (1) the strengthening of knowledge and the reduction of uncertainty and (2) the elimination of unimportant parameters, as well as determining (3) the most important parameters; (4) the parameters with the highest correlation to the output; and (5) the consequences of changing a given input value. Reducing uncertainty (1) is often achieved through a parameter error analysis, which was conducted in our companion study (Abramson et al., forthcoming). In the effort to provide policy-relevant insights into achieving global water development goals, this study focuses on parameter importance and effects (points 3 and 5 above) related to determining the costs and benefits of such improvements. Unlike conventional sensitivity analyses in which synthetic data are input to investigate model behavior, this study inputs representative values to model outcomes under real-world variations.

A range of techniques was used to explore this, including regression analysis and recursive partitioning, as well as qualitative plots of input vs. output across a wide range of the parameters included in *AWARE*'s framework. Section 2 outlines these methodologies and their applications to explore parameter effects on the costs and net benefits of water improvements. Section 3 presents results, and Section 4 outlines their relevance to the formulation of water development strategies. Conclusions and areas for further research are presented in Section 5.

2. Materials and methods

AWARE[1] models the process of improving water services in non-networked communities through improvements to existing sources, as well as the development of new water points. A wide range of economic, environmental and management parameters are included in the decision process. From the set of technological arrays chosen by the user, a combinatorial optimization procedure is run to identify all possible configurations for reaching a given water service level. An exhaustive search is performed on these configurations, and the results of the DSS include those achieving the lowest total cost and highest net benefit under three financing approaches. These include Willingness To Pay (WTP), Willingness To Borrow (WTB) and Willingness To Work (WTW)—defined as conventional cash payments, cash payments coupled to a microfinance program, and work payments applied to community irrigation, respectively (Abramson et al., 2011). WTW represents the coupling of domestic water service improvements to productive water uses (from irrigation) and, therefore, requires an additional modeling component and additional agronomic parameters. Thus, the *AWARE* framework considers drinking water services with irrigation potential, in line with the recent focus on multiple use water services (Renwick et al., 2007). This is done by exploring the suitability of conducting community-based irrigation from either existing or newly developed drinking water sources, using "extra" water that is defined as the potential volume extractable from a given water point less the amount that is consumed by households for domestic use. Both hand-watering and low-cost drip irrigation, an emerging technology with demonstrated poverty impacts in remote areas (Burney et al., 2010), are considered.

Fig. 1 outlines the flowchart and main parameters involved in *AWARE*. In the Agronomic Decision Support module, *AWARE* models seasonal crop transpiration using the HYDRUS-1D software (Simunek et al., 2009). This public domain platform numerically solves the Richards equation and the advection–dispersion equations for modeling water flow, solute transport and root water uptake (Richards, 1931). *AWARE* then applies these results to calculate the yield and revenue derived from irrigation. For more details on *AWARE*, see Abramson et al., forthcoming.

We use the platform to investigate the economics of providing water improvements to remote communities reliant on groundwater as their only, or most feasible, water source.

2.1. Parameter set development and experimental design

In order to investigate the impact of specific parameters on the cost–benefit outcomes of water service improvements, ensembles of model parameters ($n = 17{,}962$) were defined and introduced into the *AWARE* framework. These profiles were drawn from sets of discrete values for each of 13 relevant parameters, corresponding to a range expected among remote communities (Table 1). Only one value of the water quality target was included in the experimental design because of the focus on meeting the MDG drinking water targets, which are based on guidelines set by the World Health Organization. The targets require at least 20 L per capita per day of water from an improved source that takes no more than 30 min to fetch (WHO and UNICEF, 2013). In this study, we expand the target beyond the use of an improved water source to include the treatment of unimproved water sources. Recent studies are revealing that "improved" does not necessarily mean "safe," and

[1] *AWARE* was developed at the Blaustein Institutes for Desert Research of the Ben-Gurion University of the Negev by A. Abramson, N. Lazarovitch, S. Massoth & E. Adar in 2013. It is available online at https://dl.dropboxusercontent.com/u/24352729/DSS.zip.