Heterogeneity, Household Co-Production, and Risks of Water Services -Water Demand of Private Households with Multiple Water Sources

Article *in* Water Economics and Policy · May 2022

DOI: 10.1142/S2382624X22500060

4 authors, including:

Heinrich Zozmann
Helmholtz-Zentrum für Umweltforschung

OPEN ACCESS
Water Economics and Policy, Vol. 8, No. 1 (2022) 2250006 (38 pages)

DOI: 10.1142/S2382624X22500060

Heterogeneity, Household Co-Production, and Risks of Water Services — Water Demand of Private Households with Multiple Water Sources

Heinrich Zozmann [*,‡], Christian Klassert [*], Bernd Klauer [*] and Erik Gawel [*,†]

[*]Department of Economics
Helmholtz Centre for Environmental Research — UFZ
Permoser Str. 15, 04318 Leipzig, Germany

[†]Faculty of Economics and Business Management
Institute of Infrastructure and Resources Management
Leipzig University, Grimmaische Str. 12, 04109 Leipzig, Germany
[‡]heinrich.zozmann@ufz.de

Received 6 October 2021
Revised 28 January 2022
Accepted 7 March 2022
Published 19 May 2022

Private households around the world use and combine multiple water sources, including diverse forms of market services and self-supply. The reasons for this have so far not been explained in a coherent framework, nor have the implications for water management and policy been sufficiently analyzed. Here, we examine how heterogeneity of water services, household co-production, and risks of provision influence household demand patterns. We apply an economic household production model that incorporates two water quality levels for different household activities to exemplary situations. We derive a number of explanations why households use and combine water services that expand the current state of research. Relevant findings include: (i) The diverse characteristics of available water services result in different time requirements for water procurement and varying degrees of suitability for household activities. (ii) Differences in the value placed on time can induce households to demand heterogeneous water services because these enable them to find a balance between using time and money to access water. (iii) Certain water services may be demanded because they function as insurance against both uncertain and unreliable supply. Our insights are relevant for water policy, in particular for developing and managing demand-responsive systems, and for the implementation and monitoring of normative goals for access to water.

[‡]Corresponding author.

Keywords: Multiple water sources; residential water demand; Sustainable Development Goal 6; right to water; new consumer theory; household allocation of time.

1. Introduction

The international community has recognized access to water as a human right and aims to achieve “universal and equitable access to safe and affordable drinking water for all” (Target 6.1 of Sustainable Development Goal 6) by the year 2030 (UN Water 2018). Given that water is a scarce resource with competing uses and manifold environmental impacts, it is essential to precisely understand the economic conditions of water services provision. Better understanding household demand for water services in particular is a prerequisite to develop policies that effectively and sustainably implement access goals. Traditionally, economic perspectives originating in industrialized countries have considered “water” as a homogeneous good with no direct substitute which is demanded quantitatively in dependence of its (marginal) price or a volumetric network tariff (Nauges and Whittington 2010). Frequently, however, the situation is by far more complex: There is ample evidence that private households across low- and middle-income countries use and combine diverse forms of *market water services*, for example, from intermittent piped networks, public standposts, water kiosks, automated water dispensing units (“water ATMs”), tanker trucks, and other water vendors (Elliott *et al.* 2019; Wutich and Ragsdale 2008; Nganyanyuka *et al.* 2014; Kariuki and Schwartz 2005; Gurung *et al.* 2017; Evans *et al.* 2013). In addition to or instead of such services, many households access water by *self-supplying water services* from private wells, boreholes, springs, and surface water bodies (Elliott *et al.* 2019; World Health Organization 2017; Majuru *et al.* 2016). Frequently, households complement market or self-supplied water services by a variety of strategies such as storing, recycling and treating water, or constraining their consumption (Majuru *et al.* 2016; Cook *et al.* 2016; Elliott *et al.* 2017). As a result, particularly in rapidly urbanizing areas, complex systems have evolved around the supply and demand for water services. Allen *et al.* (2006), for instance, compared household water consumption in five metropolitan areas and found a “dizzying array of non-conventional and often officially un-recognized means such as informal operators, privately operated wells, gifts from neighbors, rainwater harvesting and clandestine connections” (p. 334).

To better understand these complexities is relevant for at least two main reasons. On the one hand, the international community has to monitor whether and under what conditions such systems deliver a degree of access to water commensurate with Sustainable Development Goal (SDG) 6. On the other hand, the use of multiple water sources in private households "must be understood by the global WaSH [Water, Sanitation & Hygiene; *note from the authors*] community to design appropriate and effective interventions," as a recent review by Elliott *et al.* (2019, p. 1) concluded. A common existing explanation for the use of multiple water sources by private households is that absent, rationed, or unreliable network supply induces households to demand "alternative" water sources (Abubakar 2018; Pattanayak *et al.* 2010; Majuru *et al.* 2016). This seems straightforward given that an estimated one billion people receive intermittent network supply (Rawas *et al.* 2020). However, the explanation may be incomplete: Various water researchers have argued that households choose water sources in dependence on many factors (Nganyanyuka *et al.* 2014), for example, due to their availability (World Bank 1994), the ease of collection (Evans *et al.* 2013), because water quantities from different sources are allocated to specific activities (Rosenberg *et al.* 2007; Elliott *et al.* 2017) or to avoid overreliance on one specific option (Elliott *et al.* 2019).

In this paper, we aim to systematically analyze what drives residential demand for multiple water services and how households choose among these. We argue that demands for water services are shaped by a variety of determinants beyond mere pricing and discuss relevant implications for water management and policy. Drawing on microeconomic theories, in particular the new theory of the consumer, the theory of time allocation, and the theory of uncertainty and information, we focus on three key aspects of household demand for water services. These are as follows:

1. **Heterogeneity of water services and uses:** The wide array of existing water services cannot be considered homogeneous. Rather, water-related goods and services are bundles of different characteristics (Lancaster 1966) that determine their utility for households. We use insights from the literature on the right to water (Albuquerque 2014) to explore which characteristics may distinguish available water services from the perspective of a consumer. Relevant characteristics are water *quality* and *acceptability*, as well as spatial *accessibility* and temporal *availability* of supply. Together, these characteristics can be assumed to influence which water source(s) a household selects. Household decisions may also be determined by heterogeneous *uses* of water (e.g., drinking vs. flushing the toilet) for which specific characteristics (e.g., quality) may be more or less relevant.
2. **Households (co-)produce water services:** To obtain water quantities, households combine available market goods and services with their time and, possibly, physical effort. In economic terms, such activities are referred to as household production (Becker 1965). Productive activities of the household

could be complementary to an existing market service, e.g., when time is used to fill storage vessels under intermittent supply, or substitutional, for example, when households obtain water through private wells. The time households spend in order to procure and process water has an opportunity cost, which can be viewed as non-pecuniary cost of access. Given that these costs differ considerably depending on the service level (Gawel and Bretschneider 2016; Moriarty *et al.* 2013) of market water services, households may combine multiple water services to reduce the pecuniary and non-pecuniary costs associated with access (Acharya and Barbier 2002).

3. **Risk and uncertainties of characteristics and cost:** These exist and can impact which water sources households choose. There may be limited certainty with respect to certain characteristics of supply, e.g., about the water quality and the available quantities, and the cost of household production, for instance when the time required to obtain a specific water quantity is unknown due to queuing or fluctuating water pressures.

These ideas were drawn from concepts well established in other strands of the economic literature (Hamermesh 2008; Verbooy *et al.* 2018; Rosen 1974). As we discuss in the following section in higher detail, individual contributions in the water literature have also dealt with some of these concepts. Econometric studies focused on household selection of water sources (Cheesman *et al.* 2008; Nauges and Strand 2007; Persson 2002) have developed predictive choice models that incorporate some of the characteristics discussed above as independent variables. Household production theory is the theoretical foundation for a number of studies estimating water demand functions based on monetary prices and opportunity cost of travel time (Uwera and Stage 2015; Nauges and Strand 2007; Acharya and Barbier 2002) and for another strand of literature inferring willingness-to-pay for improved services based on coping cost (Pattanayak *et al.* 2005; Gurung *et al.* 2017). Finally, (perceived) quality risks have been shown to impact household water treatment behaviors and the selection of drinking water sources (Onjala *et al.* 2014; Grupper *et al.* 2021).

Despite these advancements, however, we are not aware of an economic analysis that has systematically considered all three aforementioned aspects of household demand for water services. We aim to fill this gap and develop a nuanced economic perspective that incorporates heterogeneity, household production and risk in one conceptual framework. To demonstrate the usefulness of this approach, we (i) develop hypotheses about the demand for heterogeneous water services and (ii) subsequently test these by applying a household co-production model, which we adapt to account for supply characteristics and multiple uses of water. We discuss why the insights of the analysis are highly relevant for water policy, in particular for developing and managing demand-responsive supply systems, and for the implementation and monitoring of normative goals for access to water (SDG6, right to water). By doing so, our paper aims to lay a conceptual foundation for later empirical work through case studies.

The remainder of the paper is structured as follows: In Section 2, we present theoretical and empirical foundations for our framework and define hypotheses. In Section 3, we apply a household production model to test these hypotheses and derive insights on household use of multiple water sources. Relevant implications for water policy and limitations of the analysis are discussed in Section 4. Section 5 concludes.

2. Heterogeneity, Household Co-Production, and Uncertainties of Water Services

In this section, we combine insights from different strands of the economic and water-related literature to clearly define our concepts and derive three hypotheses for the subsequent analysis.

2.1. *Heterogeneity of services*

The academic literature has made numerous attempts to describe what sets the various existing forms of water services apart, typically dependent on the context and focus of analysis. In the following, we concentrate on the perspective of a specific group of consumers of water services, private households. We, therefore, do not consider debates regarding the ownership (Bakker *et al.* 2008) of water service providers.[1] Irrespective of whether a service is rendered by a public or private entity, informally or not, we ask: Which factors are likely to influence household demand for water services and the selection of specific water sources? The economic literature dealing with residential water demand originally assumed that water services from a piped network have no close substitutes and focused on estimating single-equation demand functions in dependence of prices and socio-economic variables such as income (Arbués *et al.* 2003; Nauges and Whittington 2010). This is still the most commonly used approach and is applicable for various types of analyses. In settings where households use multiple water sources, researchers have estimated demands for one particular water source (Basani *et al.*

[1]We also exclude the "improved/unimproved" dichotomy applied for the monitoring of SDG 6.1 (WHO & UNICEF 2017), which arguably is more relevant for classification in reporting than for household choices.

2008) or assumed that several are homogenous goods and thus substitutable. The tiered-supply-curve approach, for example, assumes that consumers choose among available bulk water services exclusively in dependence on their prices (Srinivasan *et al.* 2010; Klassert *et al.* 2015; Zozmann *et al.* 2019). Other approaches explicitly address the heterogeneity of water services and have conducted discrete analyses of water source choice (Persson 2002) or combined models of source choice with demand estimations for the selected water sources (Nauges and van den Berg 2009; Cheesman *et al.* 2008). Some of these studies consider specific attributes of water services, such as the associated water collection time, the distance to the source, the pressure and hours of availability for water supply, or potential household uses of water as independent variables relevant for source selection. The contributions of this body of the literature and the respective econometric methods have been reviewed in detail by Nauges and Whittington (2010).

These insights, particularly those derived from case studies dealing with selection criteria for water sources, point toward relevant aspects of the choice problem that a household selecting among multiple water sources is confronted with. Consider the example of a private household that can obtain water quantities from (i) a piped network that intermittently supplies drinking water at a specific tariff or (ii) from a borewell close to the household's residence, from which water in non-drinking quality can be abstracted free of charge. It is rather straightforward that the monetary price alone will not determine the household's choice, as it does not account for relevant differences in the *water collection* process, in this example the ease of an in-house supply vs. hauling water back to one's residence. Even if this is accounted for by placing a value on the opportunity cost of time needed for traveling to the well and back (Nauges and Strand 2007), the difference in water quality remains; and depending on the *intended use* within the household, groundwater may not be appropriate without treatment. A further differentiation is introduced through the span of time during which each service is available: While piped supply is intermittent in this example, the borewell may allow abstractions without temporal limitation. This brief example encapsulates key factors that might be weighed by households when deciding between multiple water sources. It seems clear that the decision problem would be further complicated through a multitude of other potentially available water services, such as bottled water services or rainwater harvesting. These water services are so distinct from one another that they should be considered heterogeneous goods and/or services (Nauges and Whittington 2010). Acknowledging heterogeneity raises new questions, in particular whether and to which extent diverse water services are in fact comparable and substitutable. To address this, it can be useful to consider factors such as the availability or quality of a water service as elements in a bundle of attributes or characteristics which distinguish individual services.

Framing household consumption decisions as a choice among bundles of characteristics has first been proposed by Lancaster (1966) who contended that these characteristics are what households actually derive utility from, as opposed to the goods or services themselves.[2] Applying this perspective to the choice of multiple water sources is useful because it allows comparing individual characteristics (e.g., the quality) of different water services, without assuming that these are fully homogenous goods. The determination of what the most relevant characteristics are, however, is non-trivial due to the strong differences between water services and the wide array of potential uses for water quantities in household activities.

For the purposes of this analysis, the water access dimensions identified in the debate on a right to water (Albuquerque 2014; United Nations Committee on Economic Social and Cultural Rights 2003) are assumed to encompass the most relevant characteristics for both the collection and intended use of water. Five key dimensions have been identified as relevant for access: These include the price or *affordability* of a service and the water *quality*, here referring to levels of chemical and biological substances contained in water quantities that may cause harm to human health. Beyond these, there is the *acceptability*, i.e., taste, odor, and color of water, its physical *accessibility*, i.e., the distance between the location of water abstraction and the consumer's residence, and the temporal *availability* of service (United Nations Committee on Economic Social and Cultural Rights 2003). The latter dimension not only refers to the time span during which water is available but also to the timing and — in some definitions (Moriarty *et al.* 2011) — punctuality of supply. In a small number of empirical studies, heterogeneous water services have been distinguished through some or all of these properties (Flores Baquero *et al.* 2016; Thompson *et al.* 2000; Deal and Sabatini 2020). Flores Baquero *et al.* (2016), for example, use nine indicators to assess which degree of access two water services (community-based supply vs. self-supply) bring about. The access dimensions have also been discussed for cost efficiency assessments of water services (Moriarty *et al.* 2011). Their explanatory power with respect to households choosing between multiple water sources, however, has not been fully exploited yet.

Re-framing the access dimensions as bundles of characteristics that distinguish water services from the perspective of a household is useful because together these

[2]According to this theory, a household demands, for example, not a cup of coffee itself but rather its flavor, caffeine content, nourishing effect, or function for social interactions.

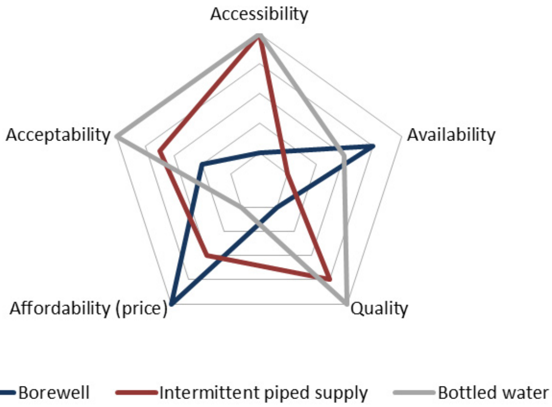

Figure 1. Comparing Characteristics of Exemplary Water Services. (Illustration adapted from Flores Baquero *et al.* (2016), where similar diagrams were developed for comparing two water sources in a case study in Nicaragua)

contain crucial aspects relevant for water collection and treatment, such as how far away the point of access is and at which time water services are supplied, and for the intended use. Through these characteristics, it is possible to characterize the example used above adequately: Water fetched from the borewell has a lower accessibility than an in-house piped water connection but may have a higher temporal availability, as the piped supply is intermittent. The piped services may score higher on quality and acceptability, while the affordability of the water services from the well is higher. In Figure 1, exemplary characteristics for both water services are plotted alongside a third example, home-deliveries of bottled water, to illustrate how heterogeneous water services may be differentiated through this lens.

2.2. *Household production*

While the perspective discussed in the previous paragraphs may be useful to distinguish the different characteristics of water services, it does not fully characterize the cost of access, and particularly the contribution of private households to generating "access." Associated with each water source available to a household are not only expenditures of money, but also of time and effort. This further layer of complexity can be approached effectively through Becker's (1965) theory of time allocation, which is based on the premise that households combine market goods and services with their time to produce final "commodities." Households are assumed to allocate their full income to produce such commodities, for which they essentially decide how much time to allocate to market work to generate disposable income and how much time to spend in other productive activities and leisure. The economic literature on other household-related services, for example dealing with food production (Hamermesh 2008; Velarde and Herrmann 2014) or care work (Verbooy *et al.* 2018; Niehof 2002), has used this theory to analyze household decision-making or to value unpaid work.

Applications dealing with household production of water services have been limited in their number, but a growing body of literature has evolved in the past two decades. The review of literature conducted for this article revealed two relevant types of studies: First, the literature investigating *coping cost* or averting cost of “unreliable supply” (Amit and Sasidharan 2019; Gurung *et al.* 2017; Pattanayak *et al.* 2005), which quantifies how much households spend to gain access to drinking water services. This includes spending on durables, such as storage tanks or water filters, on “alternative services” and the use of time to fetch water from remote sources. Focusing on drinking quality water as an input to the production of health, Pattanayak *et al.* (2005) demonstrate how a household production model can be used to infer a lower bound on willingness-to-pay for supply improvements through an estimation of coping cost. Second, a less extensive strand of economic literature based on household production theory (Nauges and Strand 2007; Cheesman *et al.* 2008; Uwera and Stage 2015) estimates demands for water services based on their *full price* or *total cost*, i.e., monetary charges and the time required for traveling to remote water access points, valued at the wage rate of household members.

A key contribution of both types of studies is to extend the traditional understanding of cost related to access. This expanded concept of cost includes, besides the monetary price of the service, (i) spending on complementary goods and services and (ii) monetary values of household expenditures of time. In areas with low levels of service quality, time cost can make up to 50% of all costs related to access (Pattanayak *et al.* 2010; Cook *et al.* 2016) and are therefore highly relevant for water demand and questions of access. Studies and conceptual models (e.g., Pattanayak *et al.* 2005) dealing with time cost have thus far focused on time spent *traveling* to remote water sources. Assessing travel time alone, however, excludes the amounts of time spent on other activities aimed at generating access, within and outside of the households’ residence, which can be substantial. These include expenditures of time to fill storage vessels if water pressure is very low or to improve the water quality through boiling and filtering (Aini *et al.* 2007; Laughland *et al.* 1993) or to wait for the beginning of supply. Even with very comprehensive water services such as home-deliveries of drinking water, there is an associated time cost for organizing the delivery, negotiating prices (Wutich and Ragsdale 2008) and implementing the transaction.

Therefore, it seems useful to clearly define the scope and boundaries of household production and its relationship to demand for water services and the question of access. For this, the debate on the implementation of a right to water can again be insightful. Bretschneider (2016) proposed the idea of *hurdles to access*, in order to characterize the degree of access to water by what stands in its way (Gawel and Bretschneider 2017). Access hurdles can be of pecuniary and non-pecuniary nature: When paying for network water services, for instance, a household overcomes a pecuniary hurdle in form of a tariff to attain access. Non-pecuniary hurdles, on the other hand, are of spatial, temporal, or qualitative nature and are for instance surmounted by walking to a public access point, by storing water at home or by boiling or filtering water quantities to improve their safety and acceptability.[3] According to Gawel and Bretschneider (2016, p. 76), "the extent to which the non-pecuniary access hurdles are lowered by the supplier" defines the service level. The service level is also closely related to the characteristics of water services discussed previously, which point toward specific hurdles. The accessibility characteristic, for example, is inversely related to the extent of remaining spatial hurdles.

We can consider the example of "producing" a water-related commodity, such as a cup of tea, to demonstrate how this delimitation may become practical and concrete. Multiple inputs are required to make a cup of tea: Potable water, water-heating devices and energy, a cup, tea leaves or bags, perhaps sugar, and household time. To carve out what is immediately tangible for questions of access and demand for water services, the water-related components of household productions can be divided into two phases, namely, (i) *procurement and processing* and (ii) *direct use*, as shown in Figure 2.

This distinction is useful because it allows to treat the procurement and processing phase in isolation and, therefore, to assign a specific cost to the act of accessing water. Depending on the service level and the extent of necessary household production, specific pecuniary and non-pecuniary costs can be attributed to generating access. When choosing between multiple water services on different service levels, a household has to decide which hurdles to overcome through monetary expenditure and which to overcome through the use of time and effort (a *make or buy* decision). The activities carried out in the procurement and production phase could be directed at complementing existing market water services or at substituting these altogether.

The following example may clarify these facets: Consider a household that can obtain water in potable quality from three potential water sources, which are all characterized by different degrees to which service providers are lowering access hurdles — and thus require different activities in household production to overcome remaining hurdles. First, there is the entirely self-supplied water service, e.g.,

[3]From an economic point of view, household activities aiming to overcome the three non-pecuniary hurdles to access may all be considered expenditures of time (Gawel and Bretschneider 2016).

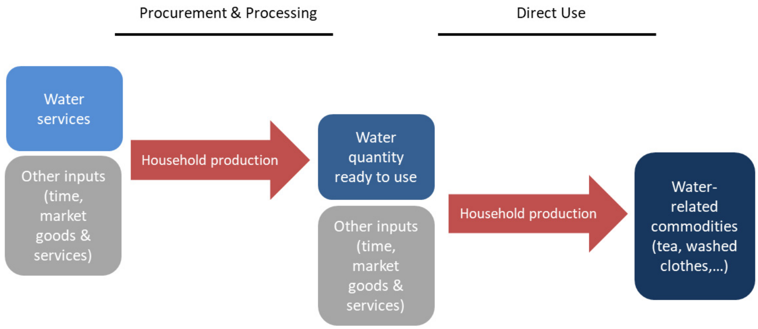

Figure 2. The Two Phases of Water-Related Household Production. During the procurement and processing phase, water quantities are made available and ready to use, for which water services and other inputs such as time and storage tanks are required. This precedes the phase of direct use, during which these water quantities are combined with other inputs (e.g., tea bags) to produce final water-related commodities. Note that this distinction of the two phases is not trivial, as the meaning of "ready to use" may differ considerably between individual uses of water (e.g., tea vs. flushing the toilet).

a private well, from which drinking water can be made available by pumping and filtering water. Second, there is water service A, rendered at a comparatively low service level such as a shared tap in the household's yard, where households members might wait and then haul water back to their residence. Finally, consider water service B, rendered at a comparatively high service level leaving small effort to the household, e.g. home-delivered canisters of drinking water. Figure 3 illustrates the relationship between service level, market provision of services, and household production associated with each of these examples.

Assuming that no other factors play a role, heterogeneous services become substitutable through household activities in the procurement and processing phase. By implication, the demand for these services should then depend on the quantities and prices of all the factor inputs used during household production. This includes the monetary prices charged for market water services but also the opportunity cost of the amount of time spent to make the required water quantities "ready to use," which may differ strongly. Depending on the specific water service and household production technologies, the considered cost may further include the prices of complements such as capital services from durable goods (storage vessels, well systems, pumps, and water filters) and additionally used goods and services, such as electricity or fuels.

2.3. *Risk and uncertainty over characteristics and cost*

In the concepts presented so far, a crucial aspect shaping the reality of many private households has not yet been addressed: The service level of specific options may

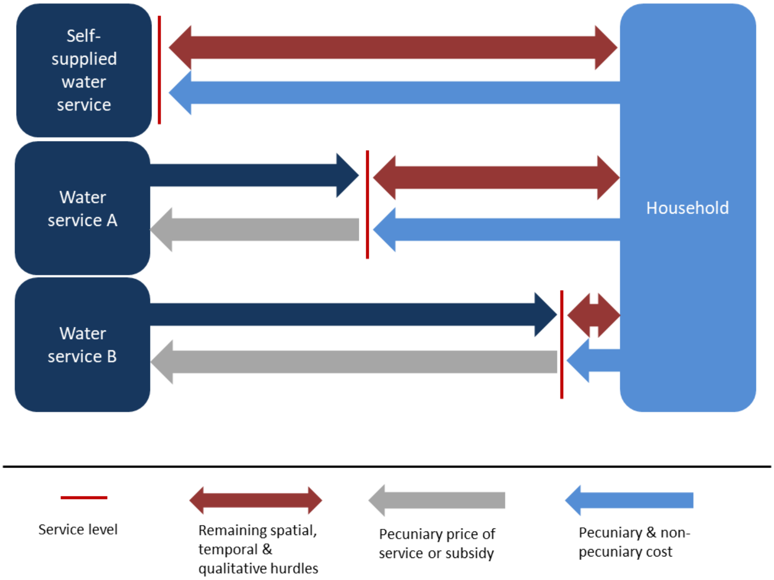

Figure 3. Access Hurdles and Household Production Cost for Water Services on Three Exemplary Service Levels (illustration adapted from Gawel and Bretschneider (2016, p. 75))

not be reliable. The literature has dealt extensively with the reliability of water services, a term that is not clearly defined (Majuru *et al.* 2018). In most cases, reliability concepts encompass characteristics such as availability and quality presented above. In other studies (Nganyanyuka *et al.* 2014), reliability itself has been considered a characteristic of service. We, however, propose and use the following definition: Water services are defined as unreliable if there is *limited certainty* with respect to (i) the characteristics of the service and/or (ii) the full cost associated with making water quantities available and ready to use. Here, limited certainty encompasses both risks, i.e., situations in which the decision-maker knows potential outcomes (and their probabilities), and uncertainty, i.e., situations in which outcomes and their probabilities are unknown at the time of decision-making.

Empirical studies provide abundant documentation for the existence of risk and uncertainty over the characteristics of water services. Quality and acceptability of water services can fluctuate or become unpredictable due to global changes (Garrote 2017), extreme events and accidents (Zhang *et al.* 2011), interruptions of supply resulting in degradation of infrastructure (Brocklehurst and Slaymaker 2015), lack of control or oversight in water markets (Cain and Mulenga 2009; Rachmadyanto *et al.* 2016) and, frequently, seasonal variability (Kostyla *et al.*

2015; Sappa *et al.* 2015; Wutich and Ragsdale 2008). The temporal availability of water services may be uncertain due to fluctuations in the timing, duration, or pressure of supply (Subbaraman *et al.* 2013) or due to queuing and waiting times. There are reports of how emergency situations lead to the failure of primary water sources (Subbaraman *et al.* 2013), inducing households to seek for alternatives (Nganyanyuka *et al.* 2014), which may have lower accessibility, for example walking to a remote access point if piped supply is interrupted for several days.

Limited certainty over the service level reduces the predictability of the expected cost of access. This, in turn, may affect household behaviors during the procurement and processing phase and their choice of the water source. The (perceived) quality risk associated with specific water services is strongly correlated with household decisions whether and how to treat water (Aini *et al.* 2007; Onjala *et al.* 2014). Grupper *et al.* (2021) have shown that it also influences the choice of water services, for instance in the use of bottled water by households with higher risk perception. There are also other conceivable cases in which risk affects the choice of water source, e.g., if households are unable to predict the procurement time associated with a specific service or the quantities they can obtain, due to fluctuating pressure or waiting time.

Analytically, such situations can be approached through established concepts from information economics, particularly if households face risk rather than uncertainty.[4] There are a number of conceivable cases in which households are able to assign probabilities to outcomes based on past experiences, for example, if they regularly queue at a water kiosk or have a good estimate of piped supply fluctuations. In this case, expected utility theory (Neumann and Morgenstern 1947) postulates that a household chooses the water service(s) associated with the highest expected utility. Depending on the relationship of individual households to risk, specific effects on demand patterns can be predicted. For risk-averse households, for instance, the utility gained from reducing risks about the characteristics and cost of water services may outweigh the decline in utility associated with paying a higher price or risk premium. This explains, for example, why wealthy households (given the ability) choose water services that reduce risk over characteristics and

[4] If households face uncertainty, as may be the case in extreme weather events or under unpredictable supply conditions, intertemporal consumption decisions must be made. Baisa *et al.* (2010) modeled the optimal use of household storage if it is uncertain when the next delivery of water arrives and calculated welfare losses compared to reliable supply. In water markets, the insights of information economics on quality uncertainty, here referring to uncertainty over *service* quality, can be applied (Akerlof 1978). While these insights offer potential for analyzing certain aspects of water services provision, such as signaling in tanker water markets (Wutich *et al.* 2016), their applicability for this analysis is limited, which is why they are not explored in further detail.

cost, for instance by constructing private wells (World Bank 1994) or by using vendor services (Raina *et al.* 2020; Graham *et al.* 2013).

2.4. *Definition of hypotheses*

To demonstrate how the extension of economic thinking on household demand for water services outlined in this section can deepen our understanding of real-world problems, we define three hypotheses that will be examined through the lens of a household production model. In particular, we aim to find consistent explanations for why households choose and combine multiple water services as a foundation for developing and implementing effective policies concerning access goals.

Hypothesis 1: Heterogeneity. *We hypothesize that heterogeneous water services are demanded and combined by households due to differences in the characteristics of service (see above, Section 2.1, "Heterogeneity of services"). We analyze in particular, how differences in characteristics can result in different levels of time cost and suitability for water uses within households.*

Hypothesis 2: Inputs of household production. *We further hypothesize that the demand for heterogeneous water services responds in a predictable way to variations in the input prices of the determinants of household production (see above, Section 2.2, "Household production"). We investigate in particular the effect of the opportunity cost of time on selection and combination of multiple water services through variations in household wages.*

Hypothesis 3: Risk aversion. *Based on expected utility theory, we hypothesize that the demand for heterogeneous water services responds in a predictable way to risk over characteristics and cost of market water services (see above, Section 2.3, "Risk and uncertainty over characteristics and cost"). We investigate under which circumstances risk-averse households may choose water services that provide certainty of outcome (with respect to respective characteristics such as waiting time) against the payment of a premium.*

We proceed to analyze these three hypotheses through our model in the next section and subsequently discuss relevant implications for water policy.

3. Analytical Model and Hypothesis Testing

In this section, we apply Becker's (1965) household production model to the problem of household choice on multiple water sources. We assume that households produce water quantities in two quality levels available for different end uses by combining market inputs and time. The characteristics or the service level of a water source are assumed to determine the time a household spends to procure and process water quantities. We explore the implications of the modeled interdependencies for the hypotheses posed above with exemplary situations observable in the real world.

3.1. *Analytical model*

In the household production framework (Becker 1965), households derive utility from *time-consuming goods*[5] z_i, which they produce by combining market input goods with their own time.

$$u = u(z_1, z_2, \ldots, z_n) \to \max!, \tag{1}$$

with

z_i: time-consuming good z_i with $i \in \{1, 2, \ldots, n\}$.

The utility function is restricted by household budgets of time and money, which are linked. The use of time for household production entails foregoing potential pecuniary income from wage labor. Based on this concept, we define the disposable maximum household income $Y_{\max}$ as a hypothetical budget, resulting from a household spending all disposable time working for income in the market, while assuming that the household receives no non-wage income. Both constraints on u can therefore be summarized under the following equation[6]:

$$Y_{\max} - \sum_{i=1}^{n} z_i \pi_i \geq 0, \tag{2}$$

with

$$Y_{\max} = T \cdot w, \tag{3}$$

$Y_{\max}$: (Hypothetical) disposable maximum income;
T: Maximum amount of time available in a period for both work and consumption activities, excluding time for personal care and sleeping. Note that consumption activities include the consumption of leisure time.
w: wage rate of the private household.

and

$$\pi_i = x_i \cdot p_i + t_i \cdot w, \tag{4}$$

[5]In Becker's classic work (Becker 1965), z_i are referred to as 'commodities'. Due to some ambiguity in the term commodity, we follow the approach of Hoyer and Rettig (1983) and refer to them as *time-consuming goods*.
[6]A more detailed formal derivation of budget in the household production model can be found in Hoyer and Rettig (1983).

π_i: full price of one unit of z_i;
x_i : vector of market good(s) used for the production of one unit of z_i. When capital goods are used, x_i refers to the services yielded by these goods (Becker 1965, p. 494);
p_i: vector of market price(s) of x_i;
t_i: time spent for the production of one unit of z_i.

In the previous section, we have differentiated between two phases of water-related household production, out of which the procurement and processing phase is the most important for this analysis. To incorporate this and reduce complexity, we assume that two z_i are produced during the procurement and processing phase, namely the water quantities z_j, defined here as drinking water (z_d) and non-drinking water quantities (z_{nd}), available for immediate use in the intended location.

z_j: water quantities of quality level $j \in \{d, nd\}$.

Here, our model differs from previous household production models (e.g., Pattanayak *et al.* 2005), as we consider not only the production of health or drinking water services, but all other forms in which water quantities may contribute to utility. While we use two z_j for simplicity, note that the following analysis also holds for more quality levels. We assume that z_j encompass the water-access-related utility obtained from the various z_i that require water quantities as an input. Similar to any other time-consuming good, we assume that z_j is produced by a household combining (intermediate) input market goods and their time.

$$z_j = z(x_k, t_{j,k}), \tag{5}$$

with

x_k: Vector of market goods or services used for the procurement of one unit of water from source $k \in \{1, 2, \ldots, n\}$. This could, for example, include a tanker water delivery and/or capital services yielded by water storage or filters.
$t_{j,k}$: Quantity of time associated with the production of z_j for a given water source k. This could, for example, be the time required to organize the tanker water delivery or to walk to the river and carry water to the location of use. $t_{j,k}$ depends, in essence, on the service level.

The price π_j of z_j then consists of the following elements:

$$\pi_j = x_k \cdot p_k + t_{j,k} \cdot w, \tag{6}$$

p_k: monetary price of x_k.

Consider the two-goods case for z_j and another time-consuming good z_σ to analyze household production decisions for "producing" water quantities of a specific quality level, while taking into consideration all other household uses of time and market input goods. Household utility u is defined as follows:

$$u = u(z_j, z_\sigma) \rightarrow \text{max!}. \tag{7}$$

Incorporating the constraints from Eqs. (2) to (4) results in the following Lagrange function:

$$L = u(z_j, z_\sigma) - \lambda(Y_{\max} - z_j \cdot \pi_j - z_\sigma \cdot \pi_\sigma) \rightarrow \text{max!}, \tag{8}$$

$$\frac{\delta L}{\delta z_j} = \frac{\delta u}{\delta z_j} + \lambda \cdot \pi_j = 0, \tag{9}$$

$$\frac{\delta L}{\delta z_\sigma} = \frac{\delta u}{\delta z_\sigma} + \lambda \cdot \pi_\sigma = 0. \tag{10}$$

Equations (9) and (10) can be transformed into

$$\frac{\frac{\delta u}{\delta z_j}}{\frac{\delta u}{\delta z_\sigma}} = \frac{\pi_j}{\pi_\sigma}. \tag{11}$$

This implies that the utility-maximizing consumer choice occurs when the ratio of the marginal utilities of z_σ and z_j is equal to the ratio of their prices. This is analogous to the traditional perspective on optimal consumer choice but includes the extension of the concept of price by the opportunity cost of time (Becker 1965).

For the purpose of deriving insights about household demand for water quantities from different sources k, it is useful to divide the full price π_j into its components:

$$L = u(z_j) - \lambda\Big(Y_{\max} - \sum(x_k \cdot p_k + t_{j,k} \cdot w)\Big) \rightarrow \text{max!} \tag{12}$$

$$\frac{\delta L}{\delta x_k} = \frac{\delta u}{\delta z_j} \cdot \frac{\delta z_j}{\delta x_k} + \lambda \cdot p_k = 0, \tag{13}$$

$$\frac{\delta L}{\delta t_{j,k}} = \frac{\delta u}{\delta z_j} \cdot \frac{\delta z_j}{\delta t_{j,k}} + \lambda \cdot w = 0, \tag{14}$$

$$\frac{\frac{\delta z_j}{\delta x_k}}{\frac{\delta z_j}{\delta t_{jk}}} = \frac{p_k}{w}. \tag{15}$$

Given an output quantity of z_j the optimal choice of a household would combine quantities of x_k and $t_{j,k}$ which result in a ratio of their marginal productivities ($\delta z_j/\delta x_k$ and $\delta z_j/\delta t_{j,k}$) equal to the ratio of their prices. This is a key outcome of Becker's model and relevant for the purposes of this analysis. Implicit in Eq. (15) is the compensated utility-maximizing demand for the factor inputs used in producing z_j, i.e., the demands for market inputs and household time, according to their respective price and according to the source of water. In analytical form, the demand function for x_k for a specific output level $\bar{z}_j$ takes the following form:

$$x_k = x_k(p_k, w, \bar{z}_j). \tag{16}$$

Relaxing the assumptions of a fixed output level and income compensation, (16) can be re-written in the general form:

$$x_k = x_k(p_k, w, p_\sigma). \tag{17}$$

While the own-price elasticity of demand for each of the factor inputs should be negative according to the law of demand (Eq. (18)), we assume a substitutability between market goods/services and household time common in household production models (more on this below). This implies a positive cross-price elasticity between these factor inputs, exemplified in Eq. (19) for the elasticity of demand for x_k in dependence of w.

$$e(x_k) = \frac{\Delta x_k}{\Delta p_k} \cdot \frac{p_k}{x_k} < 0, \tag{18}$$

$$e_c(x_k) = \frac{\Delta x_k}{\Delta w} \cdot \frac{w}{x_k} > 0. \tag{19}$$

3.2. *Hypothesis testing*

Having formulated the adapted household production model and clarified key assumptions, we now employ it to investigate the hypotheses posed in Section 2.4. To facilitate our analysis and provide examples for real-world cases, we will use a consistent set of examples in the following section. In Table 1, four sets of market inputs x_k required to procure and process water from a water source k are listed and briefly described. Note that these are examples and not a generalized assessment of characteristics of a type of water service. Piped network supply, for instance, can have significant differences in the service level and higher degrees of availability or accessibility are possible. The insights derived in the following analyses thus always refer to the specific examples in Table 1.

Hypothesis 1. *Heterogeneous water services are demanded and combined by households due to differences in the characteristics of these services, which result in differences in time requirements and suitability for intended water uses.*

Table 1. Examples of market inputs in household production of water services

Market Inputs	Water Source	Description of Example
x_1	Piped supply on low service level	Intermittent water supply on the household's premises, with variations in water pressure and timing of supply, requiring storage devices and a water filter or boiling to make water quantities potable.
x_2	Home-delivered drinking water	Delivery of canisters of treated and potable water to the household's residence, requiring no other inputs (ready-to-use).
x_3	On-site groundwater well	Groundwater well on the household's premises, requiring durables such as a pump and other inputs such as energy and a water filtering system, if the abstracted water is used for drinking.
x_4	Bottled drinking water from kiosk	Kiosk selling bottled water, in vicinity of the household's residence, requiring no other inputs.

The characteristics of service are, in our model, assumed to result in a specific time requirement t_{jk} to produce z_j. If we further assume a household can select between water services with different characteristcs and — as a result — different time requirements, the question is: what is the "right" amount of household production, given the service level and other costs? Equation (15) postulates that households would choose a combination of factor inputs x_k and $t_{j,k}$ through which the ratio of their prices (p_k/w) equals the ratio of their marginal productivities.

While in reality, available water services may only allow for specific combinations of x_k and $t_{j,k}$, it is useful for the exploration of this hypothesis to first consider what households would do if x_k and $t_{j,k}$ could be combined in marginal quantities. In this case, the ratio of their marginal productivities could be interpreted as the slope of an isoquant line, which represents constant levels of output produced with different combinations of the two-factor inputs. In Figure 4, two exemplary isoquant lines (curves IQ1 & IQ2) have been plotted convex to the origin, under the standard assumption of a diminishing marginal rate of substitution. The isocost lines IC1 and IC2 in the figure represent combinations of inputs x_k and $t_{j,k}$ which result in a specific level of cost. In this hypothetical example, optimal combinations of factor inputs specified in Eq. (15) are indicated by the points E1 and E2.

What this implies for reality is that unless an available water service offers such an optimal combination of expenditures of time and money, it is likely that households will combine several services. This is because the combination of water services with different characteristics, resulting in different ratios of market inputs and time, allows the household to move closer to its optimum. In the real

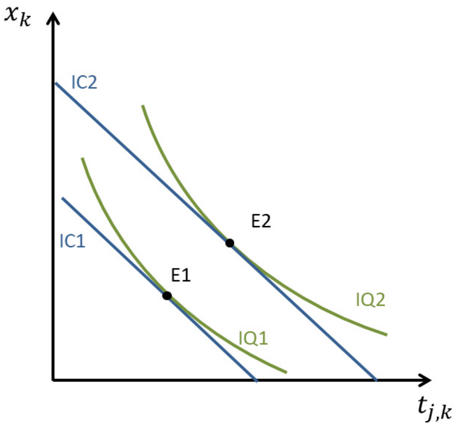

Figure 4. The isoquant lines represent exemplary levels of output, produced by different combinations of market inputs and household time under the assumption of a diminishing marginal rate of substitution. At their intersection with the blue isocost lines, an optimal combination of inputs is accomplished for this level of cost

world, multiple water services on diverse service levels may imperfectly enable the substitutability of time and market inputs assumed in our model.

Suppose there are two options to produce drinking water z_d available to a household. There is a time-intensive source, e.g., the example of a network connection described in Table 1, from which water can be obtained by using low cost[7] market inputs x_1 but which requires relatively high time inputs $t_{d,1}$. Second, there is a service-intensive source, e.g., deliveries of canisters of treated drinking water, which is associated with comparatively high levels of market services x_2 and comparatively low time requirements $t_{d,2}$. The two options are assumed to be marginally combinable and — after the procurement and processing of water is complete — close substitutes. In Figure 5, the production possibilities for both options are depicted as rays from the origin, assuming fixed proportions of time and market goods in the production process. We further assume for the sake of this example that the household is endowed with a specific budget that can be allocated for drinking water production. This budget allows the household to reach a particular point on both rays (points A & B). Under the aforementioned assumption of a diminishing marginal rate of substitution between x_k and $t_{j,k}$, the isoquants IQ1 and IQ2 mark output-constant combinations of inputs. Now suppose the household can combine marginal quantities of the market goods x_1 and x_2 with $t_{d,3}$, the time

[7]While households may at times face no per-unit charges, e.g., for using tap water, they still frequently use market goods such as storage tanks or energy to boil water for their household production activities, thus resulting in monetary cost of access to some (minimal) extent.

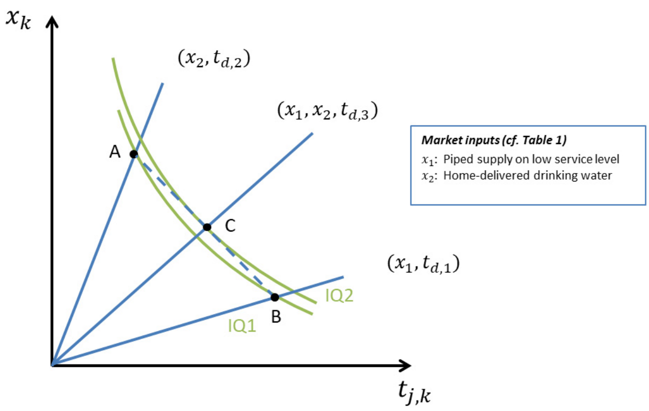

Figure 5. Three exemplary combinations of market inputs x_1 and x_2 with different amounts of household time $t_{j,k}$. Assuming a fixed budget and the dashed blue line as the frontier of possible input combinations, point C indicates a higher level of output accomplished by the combination of the two water services

required to produce drinking water with this specific combination of market goods. The ray in the center of Figure 5 results. In Point A (B), the marginal productivity of market goods (time) is lower than the marginal productivity of time (market goods), which implies that substituting for the other factor input — graphically illustrated through the dotted line — results in a higher utility level, until an optimal point C is reached.[8] We thus find that a corner solution, using predominantly one water service, is — at least formally — limited to the case where the optimal combination of market goods and time is exactly found in one of the available options (or if the price of all options but one exceeds the maximum willingness-to-pay of the household). In all other cases, it increases the utility of the household to combine water sources, which results in demands for heterogeneous market services on different service levels.

The characteristics of water services may also be particularly relevant for specific *uses* of water within the household. In other words, heterogeneous uses for water can result in demand for heterogeneous services. In the model presented here, this can be explained with variations in the full price π_j due to the relative significance of specific characteristics of service to individual usage forms. Water in non-drinking quality, for instance, can be used immediately for non-consumptive applications, while it needs treatment, i.e., additional inputs of x_k and $t_{j,k}$, to be used for drinking purposes. Consider the following example: A household produces two water quantities z_j. z_d is for a purpose requiring high quality and low

[8]In analytical terms, this is represented in Eq. (15).

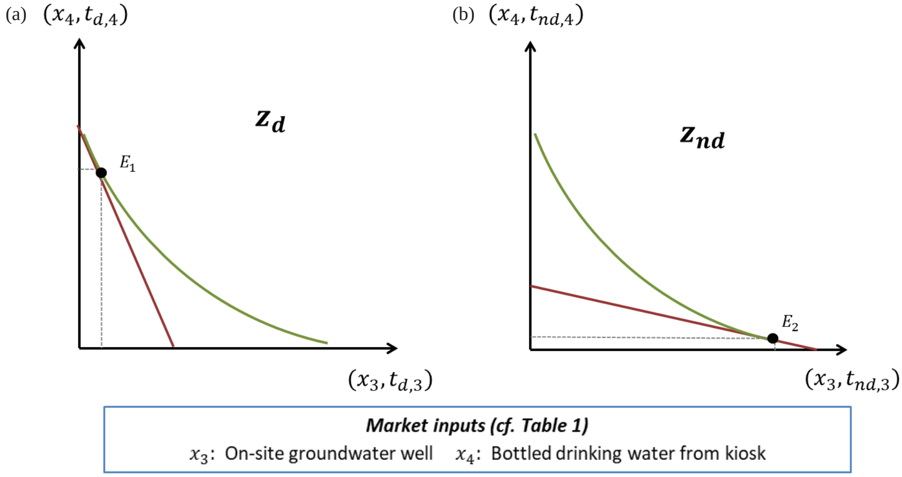

Figure 6. Depending on the intended use of water, the required time to procure and process water quantities varies: (a) High-quality requirements for the produced water quantity result in increased time requirements to produce z_d from x_3 and therefore high demand for x_4. (b) Higher quantity and lower quality requirements result in x_3 as the predominantly used set of market inputs

quantity, e.g., making a cup of tea, and z_{nd} is for a purpose requiring high quantity, while quality is of secondary concern, for example flushing the toilet. Two water sources are available: There is a groundwater well on-site (market inputs x_3, as described in Table 1), which can be used almost immediately for z_{nd} but requires extensive treatment for z_d. For the specific time requirement of each production process, this implies $t_{d,3} > t_{nd,3}$. The household can also purchase bottled water from a kiosk (x_4), in which case the per-unit procurement time is equal $(t_{d,4} = t_{nd,4})$, but the monetary cost is significantly higher $p_4 > p_3$. For this example, we assume that larger quantities of water are required of z_{nd} than of z_d.

As Figure 6 illustrates, the differences in the full price π_j for each of the applications of water results in a shift in the budget line, holding all other things equal: In relative terms, x_3 is more expensive for a consumptive use than for flushing the toilet, resulting in different optimal combinations (E_1 in Panel (a), E_2 in Panel (b)) depending on the intended use.

In sum, these results confirm hypothesis 1. Households demand water services with different characteristics because these can facilitate an imperfect substitutability between market services and household time. This, in turn, enables households to choose and combine services to find a balance between using time and money to access water. Moreover, households demand heterogeneous water services due to the relative utility of individual characteristics in their water-related activities, which can result in variations of the cost associated with water procurement and processing. Note, however, that markets for water services are rarely perfect in empirical reality, which may result in corner cases (Acharya and Barbier 2002) and will be discussed in Section 4.

Hypothesis 2. *Demand for heterogeneous water services responds in a predictable way to variations in the input prices of the determinants of household production.*

Another relevant implication of the assumption that the two types of factor inputs market goods/services and household time become (albeit imperfectly) substitutable through multiple sources of water is characterized in Eqs. (18) and (19), which indicate that the own-price elasticity of each factor input is negative, whereas their cross-price elasticity should be positive. The effects of this relationship are exemplified by considering an increase in an individual's wage rate w and the implications for the choice between two available market water services. For the sake of convenience, the above-mentioned choice between the market inputs x_1, x_2 and their respective time requirements can be considered once more. The effect of the wage rate increase is a shift in the household's demand for water services away from x_1, shown in Figure 7.

The second hypothesis can thus be confirmed on the basis of our model. Differences in the opportunity cost of time can explain why households with a higher income tend to use more goods- or service-intensive production technologies (e.g., larger storages and private wells) or rely on water deliveries (Majuru *et al.* 2016). Another conceivable implication of this result is that in areas characterized by strong differences in income levels, a higher diversity of market water services

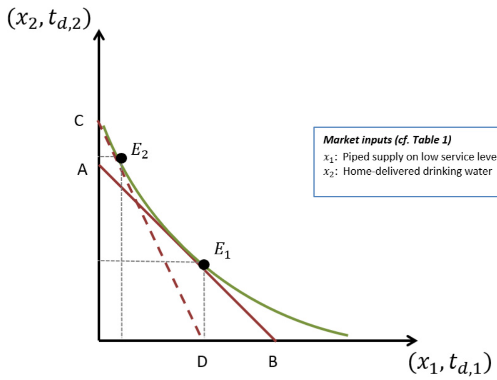

Figure 7. A wage rate increase ($\Delta w > 0$) results in an inward shift of the budget line, from AB to CD because the higher use of the factor input time associated with x_1 decreases the amount producible under a given budget. A substitution toward the service-intensive option ($\Delta x_2 > 0$) results and the equilibrium moves from E_1 to E_2. Note that for the sake of clarity, we ignore the income effect associated with a wage rate increase here

would be demanded, as a result of diverging preferences for combinations of market services and time. This fits the empirical reality of many rapidly urbanizing areas in the Global South.

Hypothesis 3. *Demand for heterogeneous water services responds in a predictable way to risk over characteristics and cost of market water services.*

To approach situations in which there is a risk, for example with respect to the procurement time $t_{j,k}$, the perspective is now shifted. A household dealing with risk is assumed to select a strategy that maximizes the expected utility from a set of potential outcomes (Neumann and Morgenstern 1947). This can be made tangible with a real-world example. A household can obtain water quantities z_j by storing intermittent piped supply (x_1), for which a storage tank and time to fill the tank is required. The pressure of piped supply is fluctuating, however, so filling the storage tank may require either a large amount of time $t_{j,1}$ or a moderate amount of time $t'_{j,1}$, with $t_{j,1} > t'_{j,1}$. We assume that due to past experience, the household is able to estimate the probability of each event (low pressure/high pressure) at 50%. Due to the variation of time requirements depending on the water pressure, a different full price per unit $\pi_j > \pi'_j$ results in each event. If the output quantity filled into the storage tank is fixed, the expenditure for each event and an average expenditure, weighted by the probability of each event, can be computed.

These expenditures of time and money reduce the full income of the household to varying degrees, i.e., they affect how much of $Y_{\max}$ can be allocated to other ends that the household derives utility from. It is, therefore, possible to connect each event to a level of utility which is a function of remaining income. If we assume a risk-averse household, the marginal utility of full income is diminishing,

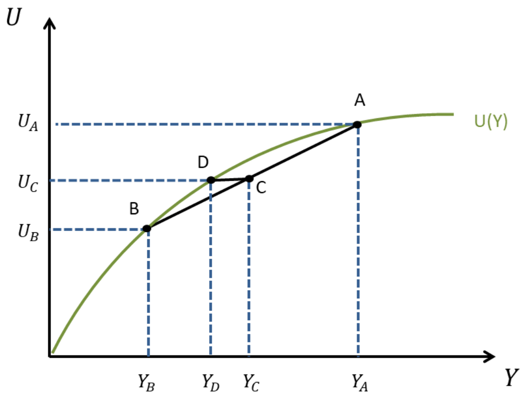

Figure 8. Expected cost and willingness-to-pay for risk premiums among risk-averse households under unreliable supply conditions

indicated by the concave function U(Y) in Figure 8. In point A, the household incurs a moderate procurement time because the water pressure is high ($t'_{j,1}$), resulting in a higher remaining full income Y_A. In point B, on the other hand, low water pressure has resulted in $t_{j,1}$. The associated higher expenditure results in a lower remaining income Y_B. On the ordinate axis, each outcome is associated with a level of utility indicated by points U_A and U_B. Point C, located in the middle of line AB in Figure 8, marks the average expected cost of both events, which results in Y_C and is associated with the expected utility level U_c.

Consider now that the second market water service is available to this household, e.g., the household may have the ability to reliably obtain water from a private well. We assume that this outcome is certain, e.g., not affected by groundwater shortages, which enables the household to reach the utility level U_c, i.e., the same utility as associated with the expected utility at point C. This is indicated by point D in Figure 8. To limit risk, the household in this example would be willing to pay more than the average expected cost. Marked by the distance CD is the maximum premium the household would be willing to pay for certainty. Whether such forms of insurance are attractive to households depends on their relationship to risk. If the utility function is non-concave, i.e., the household is risk-neutral or risk-tolerant, this reasoning does not apply.

This example demonstrates how it can be rational for risk-averse households to pay premiums for the reliability of water services, confirming the third hypothesis. Transferred to reality, this implies that for certain households, a higher price per unit is acceptable, simply to avoid the risk of high cost or inadequate levels of a specific characteristic. Given that drinking water in particular is essential to human welfare, it is plausible that such risk-averse behaviors might occur in reality, for example through purchases of bottled water.

4. Discussion

Understanding household water demand comprehensively is a prerequisite to implement goals of international water policy and for an effective management of resources. In the previous sections, we analyzed how heterogeneity of services, household co-production, and risk impact residential demand for water services. To our knowledge, the framework we presented is the first to systematically integrate two crucial concepts: (i) that water services have heterogeneous characteristics and (ii) that they are co-produced by households under varying levels of pecuniary and non-pecuniary cost. Besides fusing these pre-existing concepts, we contributed new ideas to each: On the one hand, we proposed to re-frame the water access dimensions as the most relevant characteristics of heterogeneous services. On the other hand, we clearly delineated which household production activities are relevant for the problem of access to water and established a clear connection between characteristics, service level and full cost. To account for the lack of reliability experienced by many water users, we enriched our framework with insights from information economics to account for risk-averse behavior with respect to essential resources.

We applied our framework in this paper to expand the set of explanations for the use of multiple water sources in private households. Previous studies had explained this by rationing or inadequacy of network supply, through "preferences" or the quality level of water required for specific household uses. While these reasons still hold, we were able to demonstrate that heterogeneous water services can also have the function of providing households with a choice. We assumed that through expenditures of time and money, water services become substitutable. Based on this premise, we found that combinations of heterogeneous services allow households to find a balance between spending their money and time to access water. This balance, essentially, reflects the value households assign to their time. With this, we contributed a theoretical grounding for the frequent empirical observation that wealthier households tend to invest in capital goods or rely on market services to meet their water needs, while poorer households use water sources that require mainly time inputs (Majuru *et al.* 2016). That individual valuations for time differ have been substantiated by numerous studies from other fields (Asensio and Matas 2008) and for the case of water by Cook *et al.* (2016). Considering the opportunity cost of time as a determinant of demand for water services can explain why a multitude of services is found particularly in rapidly urbanizing areas of the South, where high differences in income levels exist. We also showed how households may choose to avert risks associated with unreliable services, for instance by self-supplying through private wells as a form of insurance against unpredictable costs.

Our insights on household demand for heterogeneous water services are highly relevant for water management and policy. Beyond the frequently applied focus on finding the "right" price (Massarutto 2020), our analysis points toward considering service levels of water supply, which others have advocated before us (Moriarty *et al.* 2011), and underscores that there are no one-size-fits-all solutions. Given detailed data and a situation where households combine different sources of water, their choices may reveal preferences for the characteristics that certain services offer and allow the computation of shadow prices. The ability to differentiate between characteristics of service and, potentially, willingness-to-pay for these could enable the estimation of demands for different water services under given supply constraints. This would also produce valuable insights for allocating limited funds in water supply planning. While demand-responsive systems are no panacea,[9] they arguably have the potential to circumvent lock-ins in inadequate service levels on the one hand, or supply systems that cannot be maintained and fall into disrepair on the other hand. This may help to avoid future situations where "hundreds of millions of dollars have been spent by donors on projects that households do not want and that are subsequently abandoned" (Nauges and Whittington 2010, p. 266). The perspective of household production and the extension of cost of access may also indicate, as others have argued (Pattanayak *et al.* 2005), what the urban poor in particular are already paying for water services, which should be considered in cost-benefit analyses of supply enhancements.

The insights of this analysis are highly relevant for the normative goals on access to water (SDG 6, right to water). Water supply systems characterized by multiple water services on diverse service levels do not necessarily produce outcomes in line with the minimal standards the international community agreed on, and may thus require public interventions to meet these. As Moriarty *et al.* (2013) put it: "It is an inescapable reality that, where the aim is to provide service levels that meet the minimum levels commensurate with the human right to water, there will be a need for ongoing subsidy" (p. 338). In many cases, expanding piped networks will likely still remain a key measure for implementing SDG 6 or the right to water. The dominant logic of considering access goals implemented if a network exists, however, can be challenged by the perspective centered on service levels. If these become the key focus of water policy,[10] a combination of non-piped supply forms may continue to improve access in certain contexts, as it has already been the case in the Millennium Development Goals era in regions such as Sub-Saharan Africa, South Asia and South-East Asia (WHO/UNICEF 2015). Multiple water services may also increase the resilience of the overall system, as Elliott *et al.* (2019) have pointed out, by avoiding overreliance on one option. This stands in contrast with arguments put forward against "alternative water service suppliers" such as tanker water vendors, claiming that their services are too expensive

[9] Whittington *et al.* (2009) find that while rural demand-responsive community supply systems have come a long way, they rarely cover more than their operation cost and cannot finance infrastructure maintenance or expansion of the system.

[10] If water policy focuses on improvement of service levels in water supply, this may bring about synergies between SDG6 and other sustainability goals regarding gender, health, livelihoods and education, among others. To name one relevant synergy: Reducing non-pecuniary cost of access can free time for other activities, particularly for female household members. While there is mixed evidence that higher service levels lead to enhanced female participation in labor markets (Ilahi and Grimard 2000; Koolwal and van de Walle 2013), they result in improved safety of women during water collection and increased school attendance of girls (UN Water 2006; Koolwal and van de Walle 2013).

(O'Donnell and Garrick 2019; Raina *et al.* 2020). Such services can be more reliable or offer levels of characteristics, e.g., availability or quality, which are otherwise unattainable in the respective supply system. Thus, there are reasons beyond mere quantity constraints for why such services are demanded, sometimes at considerably higher prices than the network tariff.[11]

The conceptual framework developed here may also be relevant for the ongoing debates on the monitoring of access goals, an aspect that this paper did not investigate in detail. Prevailing systems of reporting whether access goals are met often use indicators "far from perfect in the eyes of many water managers and experts" (Guppy *et al.* 2019, p. 502). that "do not count the access to drinking water that counts for citizens" (Nganyanyuka *et al.* 2014, p. 358). Various indicators have been proposed to investigate water access conditions (Roaf *et al.* 2005; Albuquerque 2014; Schiff 2019). These range from "excessively simplistic" indicators (Flores Baquero *et al.* 2016, p. 755) attempting to compare highly diverse water services through one figure, to extensive sets of indicators with strong data needs. The framework presented in this paper could contribute to a central question in this debate, namely how to operationalize the *reasonableness of burden* (Gawel and Bretschneider 2016), which asks whether the money, time and effort a household spends to overcome access hurdles is considered acceptable in a specific situation. Our framework does not address the normative question of determining the degree to which access hurdles are reasonable or even functional from the perspective of sustainability (Gawel and Bretschneider 2017). It may, however, be capable of establishing a calculable (albeit imperfect) comparability between water services by relating their full cost to their service levels. This may still be a simplification and will not replace other relevant indicators, but would allow the computation of one figure to compare water services that are more consistent than merely discussing their monetary prices, as is frequently done in assessments of "affordability".

4.1. *Limitations and perspectives*

While we presented a consistent conceptual framework, care needs to be taken when transferring insights into real-world situations. Markets for water services and labor are frequently imperfect. As a result, many households will not have the ability or information to freely choose between multiple available water services, nor will they be able to freely choose how many hours to allocate to market work.

[11]Notwithstanding this, there is ample empirical evidence for market and governance failures in urban water markets which highlights that these bring about specific challenges for monitoring and regulation and may result in excessive market power and extortion (O'Donnell and Garrick 2019).

Thus, there are many conceivable reasons for "corner cases" in reality, for instance when opting for specific water services requires households to invest in a connection fee, a sufficiently large storage, an electric pump or a private well which thus create path-dependencies for the choice of supply. In addition, available quantities may be smaller than household demands. Certain supply options, may not allow the purchase of marginal quantities as is frequently the case for tanker water vendors (Nganyanyuka *et al.* 2014). Thus, many of the choices we constructed as continuous may in fact be discrete. Notwithstanding, our framework is better equipped to deal with these complexities than standard demand models and the key interdependencies that our analysis dealt with arguably still hold. Future applications of this framework can potentially lift some of the assumptions we operated under or analytically extend our approach with insights from other strands of economic literature. An example for this would be to extend the household production approach to analyze behavior in queues (e.g., Barzel 1974) for public water taps. One could, for instance, assess at which point time cost associated with obtaining a "free" water quantity equals or exceeds the benefits derived from it, applying differing personal valuations of time (Suen 1989) to determine in which cases public tabs might become congested and whether there is a need to install additional ones. For analyzing household decisions in dependence of the behavior of others in a queue, a dynamic game-theoretic approach would be adequate to capture non-cooperative behavior, resulting in a process of bidding for time slots or property rights at the tap with one's time (Holt and Sherman 1982). Similarly, future refinements of our approach may address some theoretical limitations. For one, we (deliberately) neglected market mechanisms by assuming water supply forms as given, due to the focus on individual consumer behavior. Criticisms frequently directed at household production models (e.g., Pollak and Wachter 1975) also apply to this work, particularly the neglect of joint production and uncertainties with regard to intra-household allocation of time. Joint production refers to the idea that households might be capable of producing several time-consuming goods in parallel (Baumgärtner *et al.* 2006). The collection of water from a shared tap may, for example, be an activity during which members of the community socialize and can therefore yield utility beyond the "produced' water quantities. This would limit the extent to which different water services can be compared by exclusively considering their full prices. Our neglect of intra-household allocation of time results in a somewhat reductionist view of the household as one homogeneous unit, whereas it usually consists of individuals with different potentials and capabilities for market and household work. Household production theory (Becker 2008) suggests that the household members with the strongest comparative disadvantage in market employment would be the first to allocate their time to water collection. This consideration, however, can perpetuate existing gender inequality in the labor market and may in reality be impacted by gendered power relations and socio-cultural factors (Sultana 2009). Thus, economic reasoning and the logic of household production theory may have limitations in this discussion. There are furthermore standard criticisms of expected utility theory that may be transferred to this analysis: As Kahneman and Tversky (2013) have demonstrated, the framing of options influences choice, and many people may not have a purely "rational" approach to the choice of water services under risk.

Furthermore, there are relevant challenges for empirical studies that should test the implications raised by this framework. While our framework enables a deeper understanding of the demand for water services, it generates more extensive data needs about household activities requiring time and water quantities. These data needs may also impede the application of our framework in the monitoring of international goals, where "required estimation variables are not available from surveys" (Hutton 2012, p. 43). Likewise, researchers applying this framework cannot rely, at least in most cases, exclusively on available panel data but need to gather more detailed data for their assessment (Zozmann *et al.*, 2022). Notwithstanding such challenges, the practical use of the insights derived in this paper needs to be evaluated in empirical studies to fully assess its potential.

5. Conclusions

In this analysis, we contributed to economic thought on household demand for water services, particularly in situations where multiple and diverse services are used. We incorporated the crucial concepts of heterogeneity of services, household co-production and risk in one framework, which has to the best of our knowledge not been done previously. As a result, we were able to analyze more comprehensively why households use and combine multiple water sources and find consistent explanations for observations from real-world, complex water supply systems. This allowed us to expand the typical view that multiple water services are consumed due to inadequacies of intermittent network supply. We showed that multiple water sources can also enable households to find their individual balance between using money and their time to access water. Where strong differences in individual valuations of time exist, this can result in demands for water services on heterogeneous service levels. We further showed that certain services are demanded because they reduce risks over the characteristics of the service, such as water quality or timing of supply, and thus the expected cost for risk-averse households.

The framework we developed is highly relevant for water management and policy. Its nuanced understanding of the demand for water services substantiates that a key focus of policy should be on service levels, not on infrastructure alone. The characteristics of water services impact both the full cost and quality of access as well as for which household uses they are applicable. Our framework has practical significance in this regard because it establishes a clear conceptual connection between the service level of supply and households' willingness-to-pay. A simultaneous consideration of all relevant service characteristics and their impacts would help to explain the individual supply situation and the market prices much more precisely. If this relationship, in turn, can be quantified with empirical data, it could prove to be useful to allocate scarce funds and supply water services on levels that are demanded by the respective communities. In complex supply systems, where households access water through various ways, it is essential for policy makers to understand that heterogeneous services, their characteristics and uses, as well as the resulting monetary and non-monetary cost are interrelated and influence consumption decisions. Service levels as well as service characteristics, therefore, at the same time, provide a complex system of policy variables that may be used to meet sustainability goals. Effectively regulating tanker water markets or groundwater abstractions, for instance, requires understanding why these services are demanded, what kind of burden is imposed on households and which aspects of access (e.g., availability, affordability etc.) are addressed. Furthermore, our framework can help to examine whether and under which conditions supply systems with multiple water services produce outcomes commensurate with international access goals such as Target 6.1 of the Agenda 2030. Our framework can be used to empirically estimate the full cost (including the cost of time or cost of household co-production) of diverse water services and compare these, which could provide a foundation for the normative consideration of whether a sufficient degree of access exists in a specific situation and the associated costs are a reasonable burden for households to bear.

Moreover, a sound understanding of "sustainable access" to water is interrelated with many prominent debates in terms of water supply, i.e., the improved analysis of water markets with different types of water provision, the debate on pricing water and affordability, and the debate on how to organize supply (privatization) (Gawel and Bretschneider 2017).

Therefore, this analysis can be a starting point for future research, which has manifold potentials for expanding the approach. Future efforts should focus on (i) refining the model we presented, for instance by developing detailed theories on capital investments for generating access to water and (ii) substantiating the developed hypotheses and the previously discussed implications for water policy in empirical studies. A challenge for empirical applications of this framework, however, is obtaining reliable data about household use of multiple water services and time. It is therefore an important avenue for future research to develop methods that can measure and disaggregate the full cost of access to water in the presence of multiple sources (Wutich 2009; Hoque and Hope 2020; MacDonald *et al.* 2016; Whittington 2000). Such research will help to determine the merits and limitations of the practical implications that can be derived from this analysis.

Funding

This work was conducted as part of the Belmont Forum Sustainable Urbanisation Global Initiative (SUGI)/Food-Water-Energy Nexus theme for which coordination was supported by the US National Science Foundation under grant ICER/EAR-1829999 to Stanford University. Also as a part of the Belmont Forum, the German Federal Ministry of Education and Research provided funding to the Helmholtz Centre for Environmental Research (UFZ) (033WU002). Any opinions, findings, conclusions, or recommendations expressed in this material do not necessarily reflect the views of the funding organizations.

ORCID

Heinrich Zozmann https://orcid.org/0000-0002-5642-7826
Christian Klassert https://orcid.org/0000-0003-0676-2455
Bernd Klauer https://orcid.org/0000-0003-3484-2903
Erik Gawel https://orcid.org/0000-0003-3634-9717

Acknowledgement

We would like to thank Raphael Karutz and Yuanzao Zhu at UFZ for their helpful feedback on this paper.

References

Abubakar, IR (2018). Strategies for coping with inadequate domestic water supply in Abuja, Nigeria. *Water International*, 43(5), 570–590.

Acharya, G and E Barbier (2002). Using domestic water analysis to value groundwater recharge in the Hadejia'Jama'are Floodplain, Northern Nigeria. *American Journal of Agricultural Economics*, 84(2), 415–426.

Aini, MS, A Fakhrul-Razi, O Mumtazah and JM Chen (2007). Malaysian households' drinking water practices: A case study. *International Journal of Sustainable Development & World Ecology*, 14(5), 503–510.

Akerlof, GA (1978). The market for "lemons": Quality uncertainty and the market mechanism. In *Uncertainty in economics*, pp. 235–251, Elsevier.

Albuquerque, CD (2014). *Realizing the Human Rights to Water and Sanitation*. Portugal: United Nations Office of the High Commissioner.

Allen, A, JD Dávila and P Hofmann (2006). The peri-urban water poor: Citizens or consumers?*Environment and Urbanization*, 18(2), 333–351.

Amit, RK and S Sasidharan (2019). Measuring affordability of access to clean water: A coping cost approach. *Resources, Conservation and Recycling*, 141, 410–417.

Arbués, F, MÁ Garcıa-Valiñas and R Martınez-Espiñeira (2003). Estimation of residential water demand: A state-of-the-art review. *The Journal of Socio-Economics*, 32(1), 81–102.

Asensio, J and A Matas (2008). Commuters' valuation of travel time variability. *Transportation Research Part E: Logistics and Transportation Review*, 44(6), 1074–1085.

Baisa, B, LW Davis, SW Salant and W Wilcox (2010). The welfare costs of unreliable water service. *Journal of Development Economics*, 92(1), 1–12.

Bakker, K, M Kooy, NE Shofiani and E-J Martijn (2008). Governance failure: rethinking the institutional dimensions of urban water supply to poor households. *World Development*, 36(10), 1891–1915.

Barzel, Y (1974). A theory of rationing by waiting. *The Journal of Law and Economics*, 17(1), 73–95.

Basani, M, J Isham and B Reilly (2008). The determinants of water connection and water consumption: Empirical evidence from a Cambodian household survey. *World Development*, 36(5), 953–968.

Baumgärtner, S, MM Faber and J Schiller (2006). *Joint Production and Responsibility in Ecological Economics*. Cheltenham, UK & Northampton, MA: Edward Elgar.

Becker, GS (1965). A theory of the allocation of time. *The Economic Journal*, 75(299), 493–517.

Becker, GS (2008). *The Economic Approach to Human Behavior*. Chicago: Univ. of Chicago Press.

Bretschneider, W (2016). *Versorgungsgerechtigkeit in einer nachhaltigen Trinkwasserwirtschaft*. Dissertation, Universität Leipzig.

Brocklehurst, C and T Slaymaker (2015). Continuity in drinking water supply. *PLoS Med*, 12(10), e1001894.

Cain, A and M Mulenga (2009). *Water Service Provision for the Peri-urban Poor in Post-conflict Angola*. London: Institute of Economic Development.

Cheesman, J, J Bennett and TVH Son (2008). Estimating household water demand using revealed and contingent behaviors: Evidence from Vietnam. *Water Resources Research*, 44(11), W11428.

Cook, J, P Kimuyu and D Whittington (2016). The costs of coping with poor water supply in rural Kenya. *Water Resources Research*, 52(2), 841–859.

Deal, P and D Sabatini (2020). Evaluating the level of the household water service provided by a private water enterprise in Ghana. *Water*, 12(3), 693.

Elliott, M, T Foster, MC MacDonald, AR Harris, KJ Schwab and WL Hadwen (2019). Addressing how multiple household water sources and uses build water resilience and support sustainable development. *NPJ Clean Water*, 2(1), 9106.

Elliott, M, MC MacDonald, T Chan, A Kearton, KF Shields, JK Bartram and WL Hadwen (2017). Multiple household water sources and their use in remote communities with evidence from Pacific Island Countries. *Water Resources Research*, 53(11), 9106–9117.

Evans, B, J Bartram, P Hunter, AR Williams, J-A Geere, B Majuru, L Bates, M Fisher, A Overbo and W Schmidt (2013). *Public Health and Social Benefits of At-House Water Supplies*. University of Leads: Leeds, UK, pp. 1–61.

Flores Baquero, O, A Jiménez Fdez. de Palencia and A Pérez Foguet (2016). Measuring disparities in access to water based on the normative content of the human right. *Social Indicators Research*, 127(2), 741–759.

Garrote, L (2017). Managing water resources to adapt to climate change: Facing uncertainty and scarcity in a changing context. *Water Resources Management*, 31(10), 2951–2963.

Gawel, E and W Bretschneider (2016). *Content and Implementation of a Right to Water: An Institutional Economics Approach*. Marburg, Germany: Metropolis.

Gawel, E and W Bretschneider (2017). Specification of a human right to water: A sustainability assessment of access hurdles. *Water International*, 42(5), 505–526.

Graham, S, R Desai and C McFarlane (2013). Water wars in Mumbai. *Public Culture*, 25(1(69)), 115–141.

Grupper, MA, ME Schreiber and MG Sorice (2021). How perceptions of trust, risk, tap water quality, and salience characterize drinking water choices. *Hydrology*, 8(1), 49.

Guppy, L, P Mehta and M Qadir (2019). Sustainable development goal 6: Two gaps in the race for indicators. *Sustainability Science*, 14(2), 501–513.

Gurung, Y, J Zhao, B Kumar, KCX Wu, B Suwal and D Whittington (2017). The costs of delay in infrastructure investments: A comparison of 2001 and 2014 household water supply coping costs in the Kathmandu Valley, Nepal. *Water Resources Research*, 53(8), 7078–7102.

Hamermesh, DS (2008). Direct estimates of household production. *Economics Letters*, 98(1), 31–34.

Holt, CA and R Sherman (1982). Waiting-line auctions. *Journal of Political Economy*, 90(2), 280–294.

Hoque, SF and R Hope (2020). Examining the economics of affordability through water diaries in coastal Bangladesh. *Water Economics and Policy*, 6(3), 1950011.

Hoyer, W and R Rettig (1983). *Grundlagen der mikrokonomischen Theorie*. Düsseldorf: Werner-Verl.

Hutton, G (2012). Monitoring “Affordability” of water and sanitation services after 2015: Review of global indicator options. A paper submitted to the UN Office of the High Commissioner for Human Rights. https://washdata.org/sites/default/files/documents/reports/2017-07/Hutton-2012-monitoring-affordability-of-water-and-sanitation-services.pdf [06.10.2021].

Ilahi, N and F Grimard (2000). Public infrastructure and private costs: water supply and time allocation of women in rural Pakistan. *Economic Development and Cultural Change*, 49(1), 45–75.

Kahneman, D and A Tversky (2013). Prospect theory: An analysis of decision under risk. In *Handbook of the Fundamentals of Financial Decision Making: Part I*. L MacLean and W Ziemba, 99–127. Singapore, World Scientific.

Kariuki, M and J Schwartz (2005). *Small-scale Private Service Providers of Water Supply and Electricity: A Review of Incidence, Structure, Pricing, and Operating Characteristics*. Washington: World Bank.

Klassert, C, K Sigel, E Gawel and B Klauer (2015). Modeling residential water consumption in Amman: The role of intermittency, storage, and pricing for piped and tanker water. *Water*, 7(7), 3643–3670.

Koolwal, G and D van de Walle (2013). Access to water, women's work, and child outcomes. *Economic Development and Cultural Change*, 61(2), 369–405.

Kostyla, C, R Bain, R Cronk and J Bartram (2015). Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. *Science of the Total Environment*, 100(514), 333–343.

Lancaster, KJ (1966). A new approach to consumer theory. *Journal of Political Economy*, 74(2), 132–157.

Laughland, AS, LM Musser, WN Musser and JS Shortle (1993). The opportunity cost of time and averting expenditures for safe drinking water. *JAWRA Journal of the American Water Resources Association*, 29(2), 291–299.

MacDonald, M, M Elliott, T Chan, A Kearton, K Shields, J Bartram and W Hadwen (2016). Investigating multiple household water sources and uses with a computer-assisted personal interviewing (CAPI) survey. *Water*, 8(12), 574.

Majuru, B, M Suhrcke and PR Hunter (2016). How do households respond to unreliable water supplies? A systematic review. *International Journal of Environmental Research and Public Health*, 13(12), 1222–1242.

Majuru, B, M Suhrcke and PR Hunter (2018). Reliability of water supplies in low and middle-income countries: A structured review of definitions and assessment criteria. *Journal of Water, Sanitation and Hygiene for Development*, 8(2), 142–164.

Massarutto, A (2020). Servant of too many masters: Residential water pricing and the challenge of sustainability. *Utilities Policy*, 63, 101018.

Moriarty, P, C Batchelor, C Fonseca, A Klutse, A Naafs, K Nyarko, C Pezon, A Potter, R Reddy and M Snehalatha (2011). *Ladders for Assessing and Costing Water Service Delivery*. The Hague: IRC.

Moriarty, P, S Smits, J Butterworth and R Franceys (2013). Trends in rural water supply: Towards a service delivery approach. *Water Alternatives*, 6(3), 329–349.

Nauges, C and J Strand (2007). Estimation of non-tap water demand in Central American cities. *Resource and Energy Economics*, 29(3), 165–182.

Nauges, C and C van den Berg (2009). Demand for piped and non-piped water supply services: Evidence from Southwest Sri Lanka. *Environmental and Resource Economics*, 42(4), 535–549.

Nauges, C and D Whittington (2010). Estimation of water demand in developing countries: An overview. *The World Bank Research Observer*, 25(2), 263–294.

Neumann, LJ von and O Morgenstern (1947). *Theory of Games and Economic Behavior.* Princeton: Princeton University Press.

Nganyanyuka, K, J Martinez, A Wesselink, JH Lungo and Y Georgiadou (2014). Accessing water services in Dar es Salaam: Are we counting what counts? *Habitat International*, 44, 358–366.

Niehof, A (2002). The household production of care. In *Changes at the Other End of the Chain; Everyday Consumption in a Multidisciplinary Perspective*. CAA Butijn, JP Groot-Marcus, M van der Linden, LPA Steenbekkers and PMJ Terpstra, 179–188. Maastricht, Shaker Publ.

O'Donnell, EL and DE Garrick (2019). The diversity of water markets: Prospects and perils for the SDG agenda. *Wiley Interdisciplinary Reviews: Water*, 6(5), 1.

Onjala, J, SW Ndiritu and J Stage (2014). Risk perception, choice of drinking water and water treatment: Evidence from Kenyan towns. *Journal of Water, Sanitation and Hygiene for Development*, 4(2), 268–280.

Pattanayak, S, C Poulos, J-C Yang and SR Patil (2010). How valuable are environmental health interventions? Evidence from a quasi-experimental evaluation of community water projects. *Bulletin of the World Health Organization*, 88, 535–542.

Pattanayak, SK, J-C Yang, D Whittington and KC Bal Kumar (2005). Coping with unreliable public water supplies: Averting expenditures by households in Kathmandu, Nepal. *Water Resources Research*, 41(2), W02012.

Persson, TH (2002). Household choice of drinking–water source in the Philippines. *Asian Economic Journal*, 16(4), 303–316.

Pollak, RA and ML Wachter (1975). The relevance of the household production function and its implications for the allocation of time. *Journal of Political Economy*, 83(2), 255–278.

Rachmadyanto, H, MP van Dijk and SO Kwarteng (2016). Mapping pro-poor water supply services: what are the technical and institutional options for the utility and private provision in Accra? *International Journal of Water*, 10(2/3), 246.

Raina, A, Y Gurung and B Suwal (2020). Equity impacts of informal private water markets: case of Kathmandu Valley. *Water Policy*, 22(S1), 189–204.

Rawas, F, R Bain and E Kumpel (2020). Comparing utility-reported hours of piped water supply to households' experiences. *NPJ Clean Water*, 3(1), 1–9.

Roaf, V, A Khalfan and M Langford (2005). *Monitoring Implementation of the Right to Water: A Framework for Developing Indicators*. Berlin: Heinrich-Böll-Stiftung.

Rosen, S (1974). Hedonic prices and implicit markets: Product differentiation in pure competition. *Journal of Political Economy*, 82(1), 34–55.

Rosenberg, DE, T Tarawneh, R Abdel-Khaleq and JR Lund (2007). Modeling integrated water user decisions in intermittent supply systems. *Water Resources Research*, 43(7), W07425.

Sappa, G, S Ergul, F Ferranti, LN Sweya and G Luciani (2015). Effects of seasonal change and seawater intrusion on water quality for drinking and irrigation purposes, in coastal aquifers of Dar es Salaam, Tanzania. *Journal of African Earth Sciences*, 105, 64–84.

Schiff, J (2019). Measuring the human right to water: An assessment of compliance indicators. *Wiley Interdisciplinary Reviews: Water*, 6(1), e1321.

Srinivasan, V, SM Gorelick and L Goulder (2010). Sustainable urban water supply in south India: Desalination, efficiency improvement, or rainwater harvesting? *Water Resources Research*, 46(10), W10504.

Subbaraman, R, S Shitole, T Shitole, K Sawant, J O'brien, DE Bloom and A Patil-Deshmukh (2013). The social ecology of water in a Mumbai slum: Failures in water quality, quantity, and reliability. *BMC Public Health*, 13(1), 1–14.

Suen, W (1989). Rationing and rent dissipation in the presence of heterogeneous individuals. *Journal of Political Economy*, 97(6), 1384–1394.

Sultana, F (2009). Fluid lives: Subjectivities, gender and water in rural Bangladesh. *Gender, Place and Culture*, 16(4), 427–444.

Thompson, J, IT Porras, E Wood, JK Tumwine, MR Mujwahuzi, M Katui-Katua and N Johnstone (2000). Waiting at the tap: Changes in urban water use in East Africa over three decades. *Environment and Urbanization*, 12(2), 37–52.

UN Water (2006). *Gender, Water and Sanitation: A Policy Brief*. UN, New York.

UN Water (2018). *Sustainable Development Goal 6: Synthesis Report on Water and Sanitation*. New York: United Nations.

United Nations Committee on Economic, Social and Cultural Rights (2003). *General Comment No. 15. The Right to Water*. Geneva: United Nations Committee on Economic, Social and Cultural Rights.

Uwera, C and J Stage (2015). Water demand by unconnected urban households in Rwanda. *Water Economics and Policy*, 1(1), 1450002.

Velarde, M and R Herrmann (2014). How retirement changes consumption and household production of food: Lessons from German time-use data. *The Journal of the Economics of Ageing*, 3, 1–10.

Verbooy, K, R Hoefman, J van Exel and W Brouwer (2018). Time is money: Investigating the value of leisure time and unpaid work. *Value in Health*, 21(12), 1428–1436.

Whittington, D (2000). Chapter 14: Environmental Issues. In *Designing Household Survey Questionnaires for Developing: Lessons from 15 Years of the Living Standards Measurement Study (Volume 2)*. M Grosh and P Glewwe, Volume 2, 5–31. Washington, D.C.

Whittington, D, J Davis, L Prokopy, K Komives, R Thorsten, H Lukacs, A Bakalian and W Wakeman (2009). How well is the demand-driven, community management model for rural water supply systems doing? Evidence from Bolivia, Peru and Ghana. *Water Policy*, 11(6), 696–718.

WHO & UNICEF (2017). *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. Geneva: World Health Organization (WHO) & United Nations Children's Fund (UNICEF).

WHO/UNICEF (2015). *Progress on Sanitation and Drinking Water: 2015 Update and MDG Assessment*. Geneva: World Health Organization.

World Bank (1994). *World Development Report 1994. Infrastructure for Development*. Oxford: Oxford University Press.

World Health Organization (2017). *Safely Managed Drinking Water: Thematic Report on Drinking Water 2017*. Geneva, Switzerland: World Health Organization.

Wutich, A (2009). Estimating household water use: A comparison of diary, prompted recall, and free recall methods. *Field Methods*, 21(1), 49–68.

Wutich, A, M Beresford and C Carvajal (2016). Can informal water vendors deliver on the promise of a human right to water? Results from Cochabamba, Bolivia. *World Development*, 79, 14–24.

Wutich, A and K Ragsdale (2008). Water insecurity and emotional distress: Coping with supply, access, and seasonal variability of water in a Bolivian squatter settlement. *Social Science & Medicine*, 67(12), 2116–2125.

Zhang, X, C Chen, P Lin, A Hou, Z Niu and J Wang (2011). *Emergency Drinking Water Treatment During Source Water Pollution Accidents in China: Origin Analysis, Framework and Technologies*. Washington: ACS Publications.

Zozmann, H, C Klassert, K Sigel, E Gawel and B Klauer (2019). Commercial tanker water demand in Amman, Jordan — A spatial simulation model of water consumption decisions under intermittent network supply. *Water*, 11(2), 254.

Zozmann, H, C Klassert, B Klauer and E Gawel (2022). Water procurement time and its implications for household water demand — Insights from a water diary study in five informal settlements of Pune, India. *Water*, 14, 1009, https://doi.org/10.3390/w14071009.