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**Characterizing the Economic Abundance of Water
Through a Theoretical and Empirical Framework**

by

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**CHARACTERIZING THE ECONOMIC ABUNDANCE OF WATER THROUGH A
THEORETICAL AND EMPIRICAL FRAMEWORK**

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Abstract:

Water is a naturally heterogeneous good. It is valued, priced, and provided differently around the world. Physical abundance is generally represented by the absolute quantity of a resource available, typically relative to the size of a population or the current rate of consumption. Economic abundance is typically measured by “price” of some form and captures what the average person must give up to obtain a certain quantity of the resource, or more precisely, a certain benefit from the resource. This project examines empirical practices of water provision and characterizes economic abundance through a theoretical model of provision, identifying four primary mechanisms: (1) an unregulated, profit-maximizing private firm (“private provision”) (2) non-governmental organization (NGO) provision with water charges used to recover costs (“community-based provision”, (3) NGO provision without water charges (“NGO-aid provision”), and (4) a public provision system with a wide range of possible pricing mechanisms (“public provision”). We then consider a theoretical weighted price metric that would describe the affordability of water in an economy with these four mechanisms serving different portions of the population.

A comprehensive empirical analysis of the economic abundance of water requires understanding and incorporating three primary determinants of abundance: quality, affordability and accessibility. We take this tripartite approach to characterizing abundance through an individual case study of Ethiopia. With regards to trends in the economic abundance of water in Ethiopia, we have reason to be optimistic. First, the percentage of the population served by improved water sources has increased significantly in the last two decades (from 25% in 2000 to 69% in 2017) and continues to increase nationally. Second, water utility charges constitute a relatively small and decreasing portion of monthly household income over time. Lastly, while access to public water utilities is inconsistent in Ethiopia, access to both piped and non-piped water sources has increased significantly over the last two decades, with non-piped access outpacing piped access.

In summary, this project demonstrates that characterizing the economic abundance of water is much more complex than for other goods and natural resources. Such a characterization must necessarily incorporate widely varying provision mechanisms as well as water quality and accessibility in addition to affordability. Our analysis supports a qualified conclusion of increasing global economic abundance of water, and we discuss the implications of this finding in the context of population growth, climate change, technological advancement and increased investment in international economic development.

Keywords: scarcity, water pricing, resource provision, abundance

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Introduction

*"Hold your hat - our supplies of natural resources are not finite in any economic sense. Rather, if history is any guide, natural resources will progressively become less costly, hence less scarce, and will constitute a smaller proportion of our expenses in future years."*¹

- Julian Simon, *The Ultimate Resource II* (1996, p. 6)

Scarcity is fundamental to the study of economics. It is understood as a primary force behind market shifts, often in the context of perfectly competitive or established markets. But what happens when a resource or commodity is not defined by a single market price (or by a well-functioning market at all)? This is the very real case for water, an essential commodity for survival. Without a clear price signal for water, our understanding of its scarcity is incomplete. Headlines of the world running out of water, or the prospect of water wars, have populated the news in today's age. Just recently, the U.S. State of California began trading water futures based on the forecast cost for an acre of water primarily for agricultural use². Is water becoming more scarce and more costly to obtain for the average person? How can we measure and evaluate the economic abundance of a resource for which a common market-based price signal does not generally exist? How would we know if such a resource were becoming economically scarcer, or more abundant? The purpose of this project is to provide insight into these questions through a theoretical and empirical analysis of the economic abundance of water.

As we first theoretically model water provision mechanisms, we find that different provision mechanisms provide water at different prices to the consumer. More so, we expect that households would consume different amounts of water based on the price charged. Our modeling of these provision mechanisms highlights the differing pricing structures and provision levels of water within any region and using these modeled provision mechanisms, we extend our understanding into empirical work that attempts to characterize "economic abundance" of water to the consumer based on these determinants.

Empirical analysis of economic abundance in this project follows a three-part approach of analyzing affordability (as a measure of percentage of income spent on water consumption), accessibility of water sources, and the quality of water provided at the sources. Together, these determinants make up a proposed Water Abundance Index (WAI) which we apply to Ethiopia and yield notable initial results. Per the WAI, this project finds that access to improved water sources increased by ~15.5% from 2011-2017, while quality steadily increased by about 1%, and overall "abundance" increased by just over 8% in the same time frame. For the scope of this project, we find overall increasing "economic abundance" of water by our definition motivated by a key hypothesis.

Johns Hopkins economist Julian Simon famously disagreed with the generally held presumption that population growth would lead to increased resource scarcity. He posited that economically, natural resources would become a smaller proportion of our income and hence

¹ Wendy Gill and Julian Simon, "The Ultimate Resource 2", 1996, 6.

² "California Water Futures Begin Trading Amid Fear of Scarcity - Bloomberg," accessed February 24, 2021, <https://www.bloomberg.com/news/articles/2020-12-06/water-futures-to-start-trading-amid-growing-fears-of-scarcity>.

less costly to obtain. In his hypothesis, Simon makes a distinction between scarcity in an economic versus a physical sense (hence, the quote to open this paper). Expanded to water, this distinction becomes an interesting question to pursue: How do we characterize the “economic abundance” of water? In the spirit of the Simon hypothesis, this project has two main goals: (1) it seeks to develop and apply a theoretical unified framework of water provision to explain the observed pattern of prices and accessibility, and (2) it will attempt to measure to what extent water is becoming economically more abundant, on average, through the development and application of an abundance metric.

Importantly, the Simon hypothesis relies heavily on the assumption of property rights and well-functioning markets. As Simon notes,

“More people, and increased income, cause resources to become scarcer in the short run. Heightened scarcity causes prices to rise. The higher prices present opportunity, and prompt inventors and entrepreneurs to search for solutions. Many fail in the search, at cost to themselves. But in a free society, solutions are eventually found. And in the long run the new developments leave us better off than if the problems had not arisen. That is, prices eventually become lower than before the increased scarcity occurred.”³

In the Simon hypothesis, behavioral responses of consumers to price rises as well as the actions of entrepreneurs to innovate, improve efficiencies in production, and make new discoveries leads to increasing abundance of resources, and effectively lower prices in the long run. Population growth tends to enhance this process through the specialization and division of labor that a larger population allows. Although population growth also leads to a growth in demand for resources, the increased supply of resources has (according to the Simon hypothesis) generally outpaced the growth in demand as a result of well-functioning markets. Falling real prices and increased consumption of most market-based commodities and resources is the ultimate result.

While the treatment of water as a good or resource varies considerably around the world, it is not generally bought and sold through markets to anything near the extent of other similar resources, such as oil. However, the same general forces that may lead to increased abundance of oil in the Simon hypothesis may also be at work to increase abundance in the case of water. Indeed, we believe that the data bears this out to a large extent. Water, in general, has become increasingly more accessible and less costly to obtain for the average person on earth, and this increasing abundance is particularly apparent in less developed countries where access to clean water has historically been a challenge. However, we are unaware of any systematic attempt to characterize the economic abundance of water in a comprehensive way. The goal of this project is to help fill that gap.

In Section 1, we analyze the characteristics of water as a good and the challenges that they pose for the development of well-functioning water markets, and the synthesis of the literature highlights the primary considerations and takeaways on water scarcity that guides the project’s methodology. In Section 2, we provide an overview of the project methodology: a dual attempt to empirically analyze the affordability of water and theoretically model water provision.

³ Gill and Simon, “The Ultimate Resource 2”, 1996, 59.

In building both methods, we identify the challenges and expectations that come with each approach.

Section 3 lays out the theoretical modeling of water provision under four expected mechanisms: private, NGO-community, NGO-Aid, and public provision. In Section 4, preliminary empirical work is conducted in order to observe “affordability” in relation to monthly income (proxied by monthly GNI per capita). This is, with the present resources, the most direct application the Simon Project’s “time price” for household water consumption. Section 4 then identifies a “complete affordability metric”: a weighted price index that combines the price for water consumption with the percentage of the population served by the mechanism in the region.

Section 5 builds the background on understanding water “accessibility”. Section 6 outlines the importance of water quality in defining abundance within this project. Section 7 proposes and describes a Water Abundance Index (WAI) that we intend to apply to a case study. In Section 8 of the paper, we investigate Ethiopia as a developing country where we can apply our analysis of an economic abundance index within the three key determinants: affordability, accessibility, and quality. In our application of the Abundance Index to the case of Ethiopia, we find consistent increases in each element over time. Ultimately, we conclude that water, while still a central focus in Ethiopia, is becoming increasingly abundant for the average household – a sign of progress with room for future development.

Section 1: Background and Literature Review

Section 1.1: Physical versus Economic Scarcity

The distinction between physical scarcity and economic scarcity is important to define. Prominent economists have been central to the discussion, but often specifically focus on population growth and resource allocation. Thomas Malthus’ model of population growth has laid a crucial foundation for future works in a “doom-sayer” lens of finite resources. The primary tenet of the Malthusian growth model is that while resources will increase arithmetically, population will grow geometrically. Essentially, population would outgrow resources and inevitably lead to widespread shortages⁴. This theory is firmly posited in physical abundance. According to Malthus, continual diminishing returns exist and one of the only options is population control: a “check on man”. Paul Ehrlich, a biologist at Stanford University, echoed Malthus’ ideas, while additionally discussing the probability of famines and crises in upcoming decades in his book, *The Population Bomb*. When revisiting *The Population Bomb*, Ehrlich later conceded that initial claims may not have happened, but that in a more micro-environment such as Africa, population growth has been rapid and outpacing resource abundance⁵. Contrastingly, Julian Simon contended that when looked at through an economic lens, that it is actually getting better for the average person. He makes the distinction between

⁴ Thomas Malthus London, “An Essay on the Principle of Population,” 1998, <http://www.esp.org>.

⁵ Paul R Ehrlich and Anne H Ehrlich, “The Population Bomb Revisited,” *The Electronic Journal of Sustainable Development*, 2009, www.ejsd.org.

physical scarcity and economic scarcity in explaining his belief that over time it costs less on average to acquire resources.

One of the first avenues of understanding affordability is through real prices. But the way real prices are measured does not capture the full story this project intends to tell. It is widely understood that real prices are the prices of the good relative to another good or bundle of goods⁶. Real price metrics show a decrease over time in the relative prices to bundles of goods, but prices relative to bundles do not capture this project's intended goal of understanding the affordability directly to the consumer. Thus, a step further is required to understand a more complete "economic scarcity".

A few organizations are working towards quantifying an idea of economic scarcity in Simon's school of thought. Particularly, Simon's theories have been at the forefront of the CATO Institute's Simon Project, which works to identify the results of population growth on resource scarcity today (Humanprogress.org). A key component of their analysis is "time prices". Time prices combine the nominal price of a commodity and hourly wage to provide a ratio of how much that commodity costs in terms of labor⁷. In doing this, the Simon Project can effectively standardize the costs of each commodity. Time prices bridge the gap between purely monetary figures and labor figures that provide income context. The Simon Project then compares the change in time prices to the change in population in order to visualize a commodity's change in abundance. While the project measures a swath of commodities and resources, it does not measure water.

In the calculation of time prices, the nominal price of a resource is compared with the nominal wage of hourly labor. It is important to note that they calculate "hourly income" by using World Bank data on GDP per capita divided by annual hours worked. Where nominal price has often risen (due to inflation), when compared to the hourly wage, the Simon Project shows that, on average, time prices dropped a considerable amount over the past ~40 years. One example of substantially decreased time prices is a resource often thought as becoming more scarce: crude oil. According to the Simon Project, the nominal price of a barrel of crude oil increased 43.2% from roughly \$32.87 to \$52.81 (1980-2017)⁸. But, using just nominal price to understand affordability of a barrel of crude oil will not yield any useful understanding of what it costs to the consumer. The use of real prices for oil is more often used but presented as a price relative to a bundle of all commodities – also not the most apt in characterizing the abundance to a consumer. But by using collected data from the World Bank and The Conference Board, the Simon Project estimates a time price of 10 hours in 2017:

⁶ "Real, Relative, and Nominal Prices - Econlib," accessed April 22, 2021, <https://www.econlib.org/library/Topics/College/realrelativenominalprices.html>.

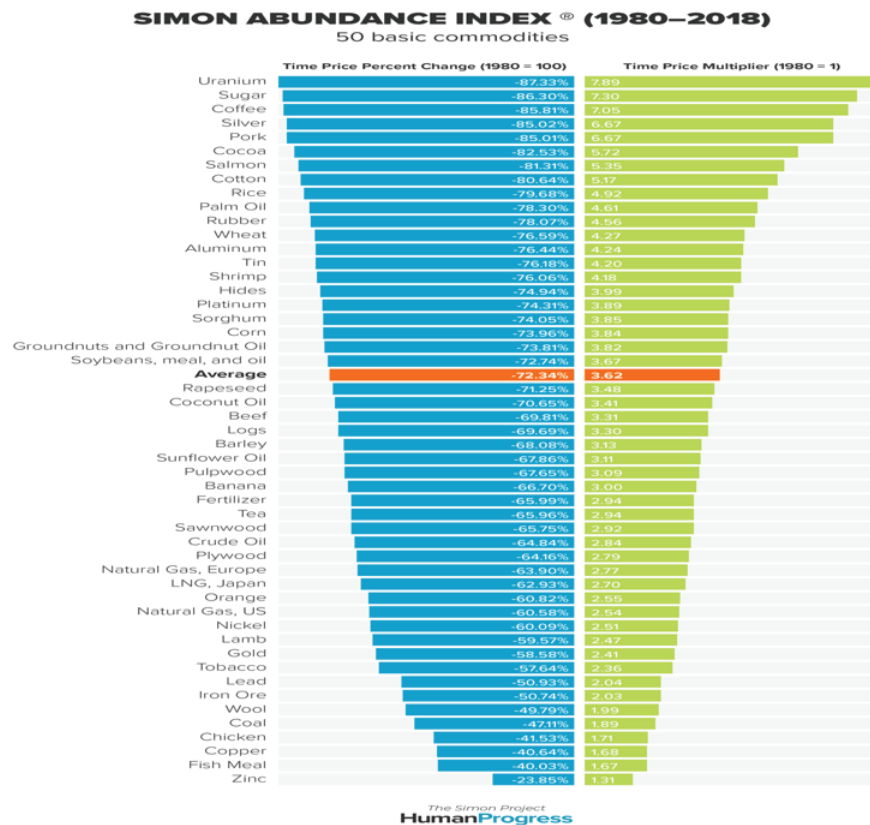
⁷ "HumanProgress: The Simon Project," accessed January 1, 2020, <https://humanprogress.org/simonproject>.

⁸ David M Simon and Gale Pooley, "CATO Institute: Simon Abundance Index," CATO Institute: Simon Abundance Index (April 26, 2019), https://www.cato.org/events/simon-abundance-index-new-way-measure-availability-resources?utm_source=Cato+Institute+Emails&utm_campaign=6dfd966389-20190315-CPF_COPY_01&utm_medium=email&utm_term=0_395878584c-6dfd966389-145257849&goal=0_395878584c-6dfd966389-145257849&mc_cid=6dfd966389&mc_eid=bdee09e746--.

$$\frac{\text{Nominal Price}_{1980}}{\text{Hourly Income}_{1980}} = \frac{\text{Nominal Price}_{1980}}{\frac{\text{GDP Per Capita}}{\text{Annual Hours Worked}_{1980}}} = \frac{\$32.87}{\frac{\$2,516}{2168}} = \frac{\$32.87}{\$1.16} = 28.34 \text{ Hours (1980)} \quad (1)$$

$$\frac{\text{Nominal Price}_{2017}}{\text{Hourly Income}_{2017}} = \frac{\text{Nominal Price}_{2017}}{\frac{\text{GDP Per Capita}}{\text{Annual Hours Worked}_{2017}}} = \frac{\$52.81}{\frac{\$10,495}{1964}} = \frac{\$52.81}{\$5.34} = 9.89 \text{ Hours (2017)} \quad (2)$$

Effectively, a person may have paid a nominal price of \$32.87, but 28.34 hours of work in 1980. In 2017, they pay almost double in nominal price, but 1/3 less hours of work (9.89 hours). Almost a directly opposite change, the decrease in time price for a barrel of crude oil is significant and tells us that the overall labor cost has drastically fallen in the past 37 years. In economic theory (specifically for Simon), this makes sense as new technological innovations allow for easier oil excavation, discovery of new oil reserves, and more efficient use of oil resources. This result appears directly contrary to anecdotal claims that oil is becoming scarcer over time, a perspective that the Simon Project attempts to buck using time price calculations. But oil is not the only example, as the Simon Project has created the Simon Abundance Index for a plethora of commodities.



(Figure 1.1: Simon Abundance Index from 1980-2018)⁹

⁹ Figure 1.1. The Simon Abundance Index for 50 commodities from 1980-2018, Figure, “HumanProgress: The Simon Project.”, accessed January 5, 2020, <https://humanprogress.org>.

Shown in Figure 1.1 is the Simon Project's time price percent change from 1980 to 2018 for various commodities, developed to show the change in hours required to work in order to afford the commodity. The average change for these commodities is around -72%, with many common household resources dropping even greater percentages. For a common household meal like chicken, the time percent change from 1980 is -41.53% percent. And while the cost of a barrel of crude oil might not be as pertinent to a household, the cost of chicken is far more relevant. Overall, the Simon Project's time price analysis presents an optimistic outlook for projections of economic scarcity. Noticeably, though, the Simon Project does not estimate time price percent change for water, arguably the most essential resource to human survival and subsistence.

While not applied to water, the time price analysis does pave the way for analysis into a possible expanded time price of water, which this project will estimate and analyze. Furthermore, time prices are incorporated into their "Simon Abundance Index" that measures percent change in population over percent change in time price. This gauges, in effect, the abundance of resources and its change over time.

Examining the economic abundance of water using this measurement may be similar to "time prices", although the notion of "price" has to be expanded for water given its lack of commodification and a clear price signal. The Simon Project's analysis of time prices is not all-encompassing as it understates the differences in GDP per capita across the world as well as the hotspots within developing regions. As a heterogeneous good, prices are bound to be different between regions/countries, and between provision mechanisms, making it much harder to approach a nominal price to any amount of water. In principle, this can be done, although it requires a broader view of the "cost" of water to the average person, to potentially include service fees, taxes, physical time or transportation costs (in some cases) as well as an actual price paid per unit. This is most feasible in a public provision mechanism by which clearly metered costs exist. Developing such a measure requires an accurate understanding of the potential provision mechanisms and their implications for price/cost. Our attempt in developing a metric for abundance will better characterize the affordability within regions over time, and between regions. But with no "price", we must first understand the idea of a "price paid per unit".

A broader discussion of price per unit comes from literature that calls them "true prices". William Nordhaus coins this term when he investigates lighting. In his methodology, Nordhaus attempts to build a true price of light in contrast to the common real price indices that he describes as understating the technological advancements that vastly increase quality of life and affordability¹⁰. His primary finding is that estimating real income is heavily dependent on the pricing indices and mechanisms for the commodity, but that commodities without traditional indices are not as easily characterized¹¹. He proposed that in constructing a true price, lighting needed to be considered via "price of a service characteristic" vice a clear price. This bears some similarity to the heterogeneity of water as a commodity, where there is no set price mechanism to easily analyze. Our attempt is to see if we can adopt similar methods in characterizing

¹⁰ William D. Nordhaus, "Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not," in *The Economics of New Goods*, 1996.

¹¹ Ibid.

“economic abundance” for a resource like water – which we must start with an understanding of water as a commodity.

Section 1.2: Water as a Commodity

Water’s unique issue comes from its nature as a resource. Water is a renewable resource, and as such is difficult to manage in water markets. As is abundant in the literature, water is not easily commodifiable – and in cases where it is commodified, private markets are vastly different from region to region^{12,13}. Additionally, because there no clear price signal, there are a multitude of factors that go into characterizing water from an affordability stand point. One key factor is the allocation of property rights.

The property rights issues with water stems in part from its low mobility¹⁴. This lack of mobility complicates attempts to commodify water, as it is unclear whether a right to water is a “right to a share of the flow or a right to a specific quantity”¹⁵. Because there is natural unequal distribution, the question often becomes how property rights protections may be most effectively implemented. Furthermore, clearly establishing property rights for water tends to be a difficult endeavor, albeit desirable for allocative efficiency¹⁶. This proves to be one of the biggest challenges in creating equitable and efficient water markets.

While water has an unclear price, this situation is exacerbated by an unclear and unequal value. Because consumers hold different values to consumption of water, a regular demand-based management system of provision has become a central focus. Through demand-side provision, measures are taken by governments or providers to influence more efficient water usage or pricing¹⁷. The rise of alternative provision mechanisms is directly attributed to water’s unorthodox nature, and attempt to take some of these demand-side measures in their soft-structures of provision. While the world is still primarily providing water via public utilities, rises in private (or quasi private) models try to address the equity/efficiency question, to a varying degree of success.

Water privatization is a broad alternative approach to water provision in a more commoditized fashion. While varied in methods, privatized water provision is rare, but typically associated with English privatization. Water privatization in England was championed 30 years ago as an opportunity to increase the efficiency and equity of provision – but to this point, the

¹² Richard Damania, “The Economics of Water Scarcity and Variability,” *Oxford Review of Economic Policy* 36, no. 1 (2020): 24–44, <https://doi.org/10.1093/oxrep/grz027>.

¹³ Dustin E Garrick, Michael Hanemann, and Cameron Hepburn, “Rethinking the Economics of Water: An Assessment,” *Oxford Review of Economic Policy* 36, no. 1 (2020): 1–23, <https://doi.org/10.1093/oxrep/grz035>.

¹⁴ Ibid.

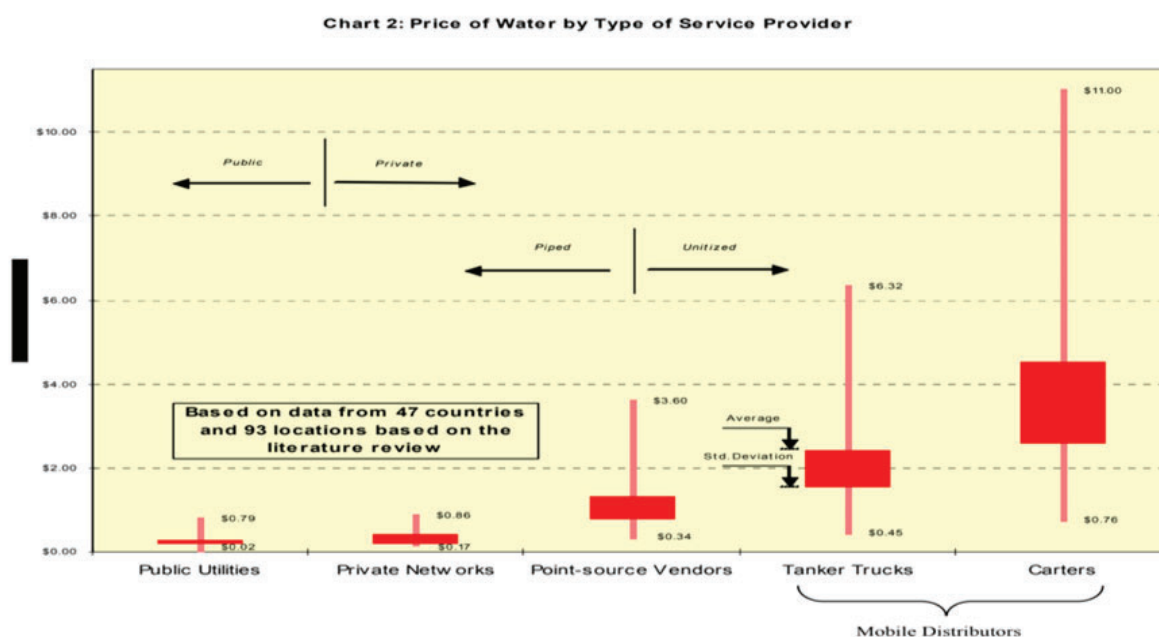
¹⁵ Ibid.

¹⁶ Sarah Ann Wheeler and Dustin E Garrick, “A Tale of Two Water Markets in Australia: Lessons for Understanding Participation in Formal Water Markets,” *Oxford Review of Economic Policy* 36, no. 1 (2020): 132–53, <https://doi.org/10.1093/oxrep/grz032>.

¹⁷ Sarah Ann Wheeler et al., “Developing a Water Market Readiness Assessment Framework,” *Journal of Hydrology*, 2017, <https://doi.org/10.1016/j.jhydrol.2017.07.010>; C.W. Claudia W. Sadoff et al., *Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth*, 180, 2015, <https://doi.org/http://dx.doi.org/>.

English model has produced no significant improvements on the more ubiquitous public (or public derivative) models¹⁸. The commoditization of water, then, varies on the provision authority and is regionally dependent.

The World Bank has done extensive work on discussing the incidence of Small-Scale Private Service Providers (SPSPs) and their operations. In an Energy and Water Department review, the discussion centers around the role of SPSPs in developing economies, particularly to what characteristics they have as firms¹⁹. While there has been speculation from the humanitarian community, the presence of SPSPs in developing countries has often taken the place of insufficient efforts by public governments to provide an efficient and effective water supply. The World Bank also has found that most SPSPs have incorporated new cost-effective technological innovations that typically would not be found in public providers²⁰. The financing associated with SPSPs is usually funded from private capital, but more often from loans taken by the firm (at high interest rates near 5%)²¹. We expect to model this in our water provision modeling component of the project. Additionally, it was found through pricing analysis that prices per cubic meter of water were comparable to public provision prices in a utility format (private pumping networks).



(Figure 1.2: World Bank Analysis of Price of Water by Provider)²²

¹⁸ Dieter Helm, "Thirty Years after Water Privatization—Is the English Model the Envy of the World?," *Oxford Review of Economic Policy* 36, no. 1 (2020): 69–85, <https://doi.org/10.1093/oxrep/grz031>.

¹⁹ R Kariuki and Jordan Schwartz, "Small-Scale Private Service Providers of Water Supply and Electricity: A Review of Incidence, Structure, Pricing, and Operating Characteristics," *The World Bank, Policy Research Working Paper Series*, January 1, 2005, <https://doi.org/10.1596/1813-9450-3727>.

²⁰ Kariuki and Schwartz., 21.

²¹ Ibid, 23.

²² Fig. 1.2. An analysis of water prices by provider type, Figure, R Kariuki and Jordan Schwartz, "Small-Scale Private Service Providers of Water Supply and Electricity: A Review of Incidence, Structure, Pricing, and Operating

Figure 1.2 outlines the difference in water pricing types and prices when compared with the level of privatization in the provider. The disparity is quite extreme, ranging from \$0.79/m³ to \$11/m³. World Bank has indicated that there is room (and a need) for further research in associating such pricing analysis with geographic locations of water sources and providers²³. Overall, the World Bank finds that while there is evidence of the varied nature to SPSPs, there needs to be further analysis in the sustainability of their business models. Dalberg echoes this in their 2017 report on Safe Water Enterprises (SWEs).

SWEs, as described by the Dalberg Report, are quite similar to SPSPs²⁴. As they range in terms of size, scope, and financing background, it continues to be unclear how best to pinpoint one specific model that works. One characteristic that is universal for SWEs is the scale of people they service: on average about 200,000 people²⁵. This decentralized structure, as the title suggests, may be the key to providing an actual larger-scale efficient model of water management and delivery from SWEs. But like (and unlike) some commonly traded commodities, water scarcity is central to its consumption.

The term “water scarcity” is just as varied in definition as water is in price and value. The literature presents many of these discussions in a piecemeal fashion, not necessarily arriving at any specific standard for water scarcity. Physical water scarcity is often analyzed through physical water resources in relationship to population²⁶. This perspective is, often, not the most optimistic of outlooks. When analyzing renewable freshwater resources per capita over time, we find it decreasing steadily for the past 60 years (Figure 1.3). While the cause of this is the Earth’s massive population growth, this one lens does not spell the whole story on water scarcity. At the same time, the percentage of population with access to improved water sources has increased significantly in the past 60 years²⁷. The world, on average, has increased this percentage by 10% (Figure 1.4) - contrasting the nearly 75% drop in freshwater resources per capita. Where, then, is an answer on the water situation in the world? As pointed to by a great deal of the literature, analyzing water’s scarcity comes from considering the demand side of water provision just as importantly as we consider the supply side management.

Characteristics,” The World Bank, Policy Research Working Paper Series, January 1, 2005, 26, <https://doi.org/10.1596/1813-9450-3727.26>

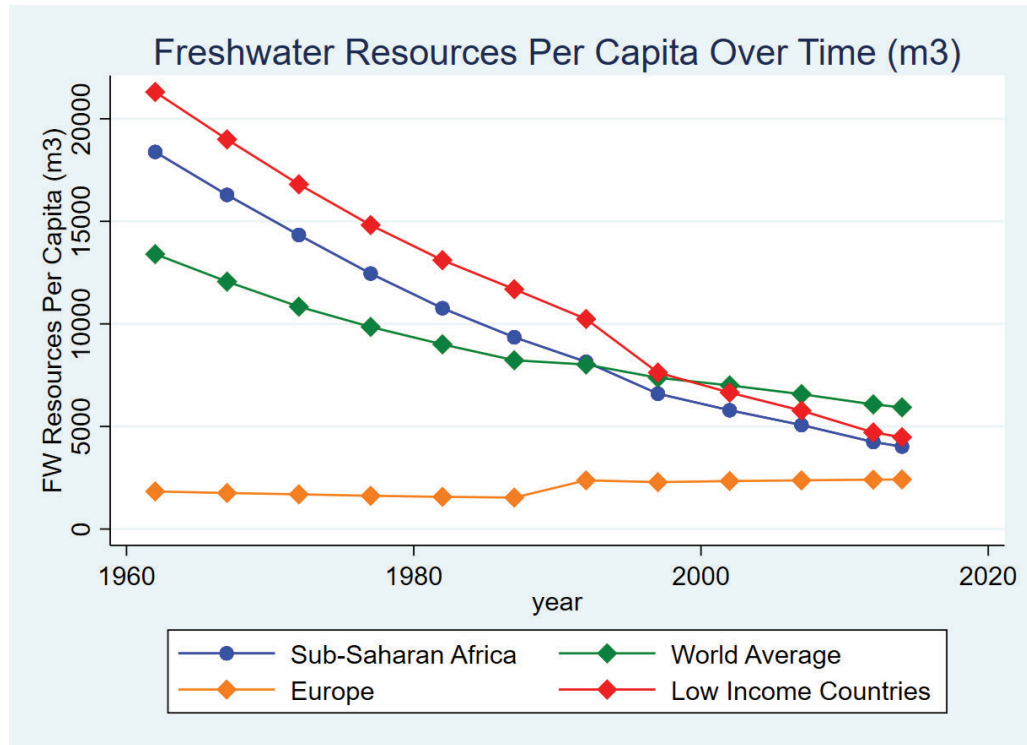
²³ Ibid, 26.

²⁴ “The Untapped Potential of Decentralized Solutions to Provide Safe, Sustainable Drinking Water at Large Scale,” 2017, [https://www.dropbox.com/s/e8xg7or8dgv7wu/20170208 Water Kiosk Study Sector Report_vSS.PDF?dl=0](https://www.dropbox.com/s/e8xg7or8dgv7wu/20170208%20Water%20Kiosk%20Study%20Sector%20Report_vSS.PDF?dl=0).

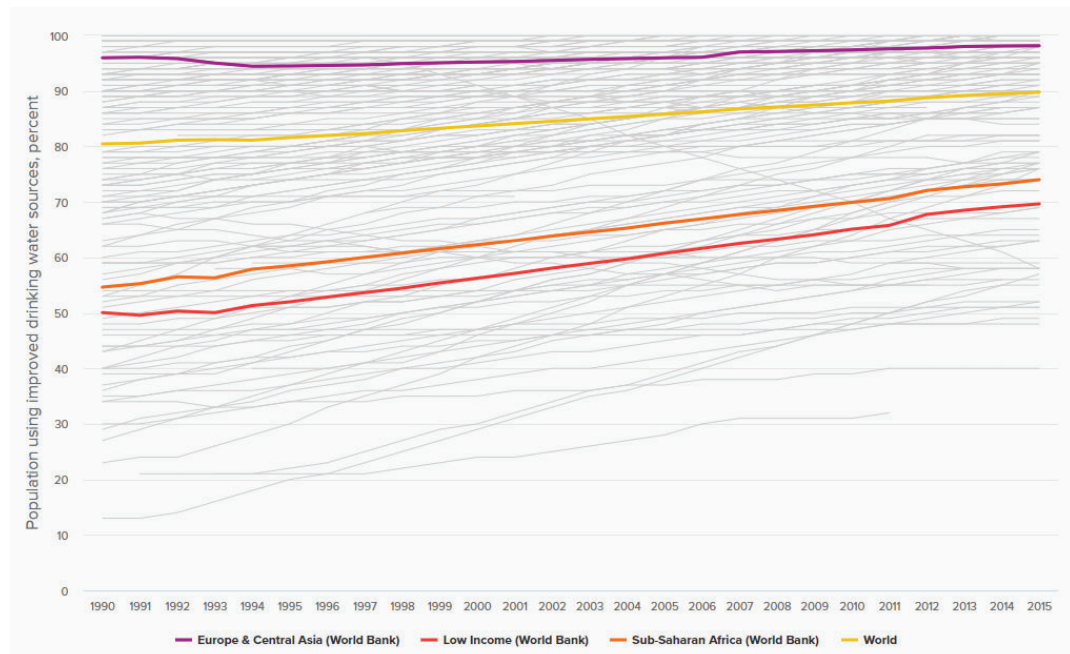
²⁵ Ibid, 5.

²⁶ “Renewable Internal Freshwater Resources per Capita (Cubic Meters) | Data,” accessed November 23, 2020, <https://data.worldbank.org/indicator/ER.H2O.INTR.PC>.

²⁷ “Population Using Improved Drinking Water Sources - HumanProgress,” accessed November 23, 2020, <https://www.humanprogress.org/dataset/population-using-improved-drinking-water-sources/>.



(Figure 1.3: Freshwater Resources per Capita 1960-2020)



(Figure 1.4: Percentage Population Using Improved Water Sources by Country 1990-2015)²⁸

²⁸ Fig. 1.4. The population with accessed to improved water sources by country 1990-2015, Figure, "HumanProgress: Percent of Population Using Improved Drinking Water Sources," accessed November 12, 2020, <https://humanprogress.org/dwline?p=524&yf=1990&yl=2015&high=0®=3®1=0>.

Literature on water abundance and “water stress” in developing countries has been a focus of recent research institutes. Christopher Tatlock of the Council on Foreign Relations describes the term “water stress” as water inadequacies regarding supply, safety, and affordability²⁹. Tatlock identifies that the severity of water stress is extreme in Sub-Saharan Africa because of a lack of delivery and storage infrastructure, as well as political boundaries and inter-country water laws³⁰. While this has been identified, it is ambiguous just how clearly one can measure the factors. Dr. Mark Giordano has done research on the effects of these transboundary water laws and treaties. National disputes over internationally owned water sources in Africa provide extra strain on developing countries who cannot easily measure or regulate water access³¹.

In terms of water abundance, a “paradox” has been brought up: whether abundance is a sign of effective water infrastructure or is the result of underutilization of water services and resources³². In a case study involving Mato Grosso, Brazil, this abundance spelled a level of laze that the community took on properly managing water services³³. While the state had bountiful water supplies, their effective provision and management of water is quite low. This research points to an intercountry question of whether the “double-edged” nature of water abundance is more than just a regional, Mato Grosso case. Ultimately, this illustrates how fragile water is as a commodity in developing regions, but also the stress on demand-side management in water provision, that may be more feasible in developed regions.

While “water scarcity” is often discussed in regard to developing countries, water infrastructure issues are not unknown to the developed world. The primary issue, though, for water insecurity in developed countries is how water is underpriced on the margin of social cost of provision^{34,35,36}. By this, it is meant that water is underpriced to the point where it is not valued properly in accordance with its relative finite resources, especially regionally. Because of this underpricing, the social cost outweighs the social benefits from provision. One particular example of this is addressed as an issue in the Okanagan Basin in Canada. The underpricing of water piped from the basin has led to overconsumption that overextends the public utilities’

²⁹ From Christopher Tatlock, “Water Stress in Sub-Saharan Africa | Council on Foreign Relations,” accessed January 2, 2020, <https://www.cfr.org/background/water-stress-sub-saharan-africa>.

³⁰ Ibid.

³¹ Mark Giordano, “A Review of the Evolution and State of Transboundary Freshwater Treaties,” 2013, [https://transboundarywaters.science.oregonstate.edu/sites/transboundarywaters.science.oregonstate.edu/files/Publications/Giordano et al. Treaty Update 4-13.pdf](https://transboundarywaters.science.oregonstate.edu/sites/transboundarywaters.science.oregonstate.edu/files/Publications/Giordano%20et%20al.%20Treaty%20Update%204-13.pdf).

³² Christopher Schulz and Antonio Ioris, “The Paradox of Water Abundance in Mato Grosso, Brazil,” *Sustainability* 9, no. 10 (October 4, 2017): 1796, <https://doi.org/10.3390/su9101796>.

³³ Ibid.

³⁴ R Quentin Grafton, Long Chu, and Paul Wyrwoll, “The Paradox of Water Pricing: Dichotomies, Dilemmas, and Decisions,” *Oxford Review of Economic Policy* 36, no. 1 (2020): 86–107, <https://doi.org/10.1093/oxrep/grz030>.

³⁵ Steven Renzetti, “Wave of the Future: The Case for Smarter Water Policy,” *C.D. Howe Institute Commentary*, no. 281 (2009): COV, http://uvic.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMw3V1LT8MwDLbYLnBBvN8oJy5Tqz7S0iJxQIVpnCZgwHFK00TaYS3aCvv7xE36GNL-AJeqSiW3-VzFTvzZBvA927H-rAluLNxIU-i-NZRh5kqc8k5HMWMCFT31G17PJmgao7dh_UPwn9hMykX9dMaTmbnBlSspa4XJeMTkHK4bXr7Y0cF2ywH60B6NiJTpcAswkQZ.

³⁶ Damania, “The Economics of Water Scarcity and Variability.”

ability to allocate efficiently³⁷. As a result, the Okanagan Basin is suffering from severe inefficiencies in provision. In these cases, it may exacerbate physical limitations in aquifers or geographic regions, thus making “scarcity” more prominent in developed areas.

Ultimately, we find that, the complexities of water provision require a multi-faceted approach to characterizing its resource abundance. As a result, we come to a few main conclusions from the literature:

1. *Water is partially commoditized*^{38,39}

Water ranges from completely unpriced in aid-based provision to highly privatized per-bottle provision in private markets. Water markets are certainly unique, but they are not universal, just as piped public provision is not universal. Because of these varied “treatments” of water, we can characterize water as a partially commodified resource.

2. *Water is provided via multiple mechanisms, each with different pricing structures*⁴⁰

Due to water’s partial commoditization, we subsequently understand that it is provided through different physical mechanisms and with largely varied prices. These varied prices and pricing structures highlight the complexities that come with trying to define an “affordability” metric. Our theoretical modeling is intended to bridge this gap and understand what we expect to see under four main identified mechanisms.

3. *The price of water is almost always less than its marginal social value or cost (particularly in public provision)*⁴¹

A price of water that fully covers the marginal social costs of water provision is almost impossible, largely because of the lack of a clear price signal in water pricing. It may be possible, still that certain mechanisms are more likely to price closer to marginal social cost than others (i.e. some regulated private markets). From an efficiency standpoint, this is where we see inefficiencies rise that can hurt sustainability of water provision.

4. *Underpricing of water leads to excessive consumption, higher provision costs, and strains public utilities/infrastructure*⁴²

³⁷ Oliver M. Brandes and Lynn Kriwoken, “Changing Perspectives — Changing Paradigms: Taking the ‘Soft Path’ to Water Sustainability in the Okanagan Basin,” *Canadian Water Resources Journal* 31, no. 2 (2006): 75–90, <https://doi.org/10.4296/cwrj3102075>.

³⁸ Sheila M Olmstead, W Michael Hanemann, and Robert N Stavins, “Water Demand under Alternative Price Structures,” *Journal of Environmental Economics and Management* 54 (2007): 181–98, <https://doi.org/10.1016/j.jeem.2007.03.002>.

³⁹ Helm, “Thirty Years after Water Privatization—Is the English Model the Envy of the World?”

⁴⁰ Olmstead, Hanemann, and Stavins, “Water Demand under Alternative Price Structures.”

⁴¹ Brandes and Kriwoken, “Changing Perspectives — Changing Paradigms: Taking the ‘Soft Path’ to Water Sustainability in the Okanagan Basin.”

⁴² Steven Renzetti, “Wave of the Future: The Case for Smarter Water Policy,” *C.D.Howe Institute Commentary*, 2009.

Discussed in the public provision literature, excessive consumption is identified as a key result from underpricing. As a result, the overall cost of providing water is anticipated to rise as resources are constrained. More so, it is expected that over time, excessive consumption will likely drain physical resources in ways that could cause environmental challenges as well.

Section 2: Methodology

While the literature on water pricing and provision worldwide is extensive, there has not been, to our knowledge, a clear attempt to systematically characterize the economic abundance of water across regions or across time. The approach to this project follows four primary steps:

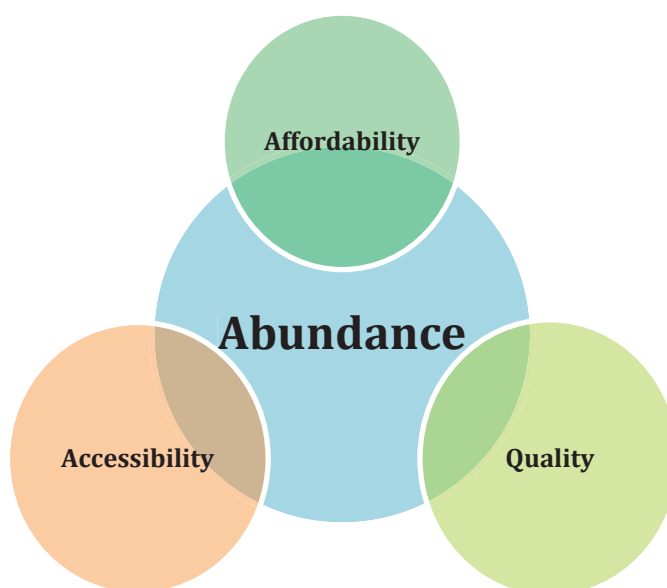
- 1. Theoretically model four key provision mechanisms through which we would expect water to be provided and consumed in order to better understand pricing structures and dynamics.**
- 2. Develop a Water Abundance Index that could be applied anywhere water is provided, incorporating key determinants of abundance.**
- 3. Apply the Index to a country case study that will provide insight into water abundance over time.**
- 4. Analyze and understand case study results as they broadly apply to characterizing water's economic abundance.**

The goal in theoretical modeling is to provide a framework by which we could describe the majority of water provision mechanisms that will highlight changes in the quantity of households provided water as well as how much each household is provided. By understanding the driving mechanisms within the theoretical model, we are able to identify the primary determinants that would change the explicit price paid by the consumer. Additionally, the theoretical modeling provides insight into the equity efficiency tradeoff that comes from water provision, especially in developing regions. Answering how we would expect water to be priced under certain provision mechanisms gives context to the mechanisms in practice and where they may diverge from theoretical expectations, while also providing implications on the effects of price and accessibility between the four mechanisms.

Empirical methodology stems in the analysis of metrics that traditionally define “affordability”, while qualitatively analyzing how different provision mechanisms may change the time cost element of water consumption – particularly with regards to the alternative mechanisms such as privatized provision or community-based fee provision. Developing a quantitative metric for affordability most empirically discusses how the price of water offsets a person’s income used for their household to consume the water. Expansion of this metric is intended to develop a more holistic measure beyond pure municipal charges. At the moment, the measure was built using the measurable volumetric charges from each utilities provider in different regions, then analyzed in accordance with the average monthly income (GNI per capita) for that region specifically.

Price as discussed in Section 4 is the most direct measure of affordability in our metric as we attempt to describe “time cost” in the water utilities realm. An indicated declining percentage of monthly income on water utilities would constitute a “decreasing cost of consumption”. Further discussed in Section 6, defining the quality of consumed water is the next step in focusing our lens on the water pertinent to the household. As such, “drinking water” classifications exclude the extreme amounts of water used for agricultural and industrial uses. While these are excluded, the significant usage of water for industry and agriculture affects household consumption indirectly⁴³.

The general structure of this project’s methodology towards a metric of abundance is grounded in the consumption cost of water provided (broadly considered affordability), its accessibility, and the quality of the drinking water. Illustrated below is a visualization of the theoretical framework for a metric of abundance. In this relationship, we assume that the overarching “economic abundance” is driven by the three aforementioned determinants: quality, price, and accessibility.



(Figure 2.1: Determinants of Economic Abundance)

In Julian Simon’s hypothesis, over time the cost of consuming natural resources would constitute a lesser amount of our income – a “cornucopian” perspective on the relationship between population growth and scarcity. But with water, the time price method does not accurately prove or disprove Simon’s conjecture. Using the theoretical framework previously laid out, we translate this into an empirical case study of water in a developing country where we might expect changing water scarcity (increasing or declining). In considering an appropriate case study, this project identifies a country where water is not uniformly priced or provided. While this is true for nearly every country, developing countries are particularly interesting because of the higher incidence of alternative provision (non-piped) mechanisms.

⁴³ Garrick, Hanemann, and Hepburn, “Rethinking the Economics of Water: An Assessment.”

The focus of our case study on a particular country will be to analyze the conditions for characterizing water as more or less economically abundant. Through this, the concentration will be on the determinants identified previously: Affordability, Accessibility, and Quality. These three together provide a snapshot for our case study and offers an initial answer for the state and progress of “economic abundance” of water through our proposed Water Abundance Index (WAI).

Section 3: Modeling Water Provision Mechanisms

Section 3.1: Base Assumptions and Background

In the economic modeling component of this project, the focus is on four specific scenarios of water provision: private market, NGO-aid, NGO-community, and public (a few variations). The basis of these models is developing the mechanism by which we equate budget constraints of the provider with the price, household provision, and quantity of households. For all cases, we initially will assume a one-period model. Across all provision mechanisms, we have a unified financing constraint that captures all possible revenues and costs of providing water. While this constraint is standard across different mechanisms, factors within each may change the overall particular financing constraint. The financing constraint is constructed as:

$$D + R(P, q, n) - C(F, q, n, D, i) \geq 0 \quad (3)$$

with variables,

D = The external funds of provision (generally capital)

$R(P, q, n)$ = Revenue given price P , $\frac{\text{quantity}}{\text{household}}$ q , and number of households n

$C(F, q, n, D, i)$

= costs for q units of water to n households with external funds D , fixed costs F , and interest rate i

The financing constraint variables denote important aspects of water provision. The external funds of provision (D) may differ in source dependent on the nature of the provider, such as donations and upstart capital for an NGO-aid based provider. D is a crucial part of the financing constraint, though, because more external funds would allow for the provider to charge lower prices or increase the amount of water provided. In specific cases where an explicit price is not charged, there will be no revenues for the provider that require them to rely on their external funds, which will have to be much higher to cover losses. A standard price function is also defined with parameters (a , b) that would be clearly defined in an empirical market. For now, we just use them as (a) and (b) for theoretical modeling of the price function, which is simply a downward-sloping demand function for water:

$$P = a - bq \quad (4)$$

If assumed that all households demand the same quantity of water (q), we can then substitute P in the revenue function.

$$R(P, q, n) = nPq = n(a - bq)q = n(aq - bq^2) \quad (5)$$

The cost function can be incorporated back into the initial constraint.

$$C(F, q, n, D, (i)) = F - \delta D + c_h n + c_w qn + i\delta D \quad (6)$$

with variables:

F = Fixed costs of water provision services (not subject to actual q or n)

c_h = Marginal maintenance cost per household for an additional household

c_w = Marginal cost of providing water

i = interest rate on loans for financing (if applicable)

δ = Percentage of financing funded by loans (expressed as a decimal 0-1)

D = External financing

To summarize, the model makes three primary simplifying assumptions:

1. *N identical households*
2. *Time-invariant household water demand function of $P=a-bq$*
3. *Non-discrimination in household water prices*

Application of this model for the project requires these simplifying assumptions for tractability. While these assumptions may be relaxed, doing so would not significantly change the overall results and would only increase the complexity of the model.

Section 3.2: Pure Private Provision

In an “unregulated private provision” model, we assume that the firm follows a market-based provision to maximize profits. Of note, this model requires the firm to act as a single price monopolist. This assumption is based on the understanding that the feasibility constraints must be fulfilled by a single-price monopolist in order for them to also be fulfilled in a more competitive market for provision. Because the firm intends to maximize profit, per household revenue must exceed per household variable costs. This is the per household feasibility constraint on the firm for providing water to that particular household. At the same time, the firm has a total feasibility constraint for provision that total revenues must exceed total costs – the short-term shutdown condition.

Assuming external funds (D) are zero, we set up the profit maximization function as:

$$\max \pi = R(P, q, n) - C(F, q, n, D) \quad (7)$$

Following substitution of the revenue and cost functions (with $D = 0$ and loans 0%),

$$\max \pi = [n(a - bq) * q] - [F + c_h n + c_w qn] \quad (8)$$

Deriving profit with respect to number of households (n) and quantity of water provided (q) and solving for optimal (q) via substitution yields

$$q^* = \frac{a - c_w}{2b} \quad (9)$$

which allows us to solve for the optimal price,

$$P^* = \frac{a + c_w}{2} \quad (10)$$

Our resulting optimal price and quantity correspond to those which would satisfy the feasibility condition for the firm to provide water such that revenues exceed costs (maximizing profit):

$$P^* q^* \geq c_w q^* + c_h \quad (11)$$

The existence of an unregulated private firm operating in practice is somewhat unlikely, as some form of regulation is highly probable in a water market. But, in a market-based provision model, an optimal outcome is expected to maximize profit subject to (11). As a result, it is expected under a purely private model that the accessibility of water sources would not be prioritized if not profitable. We also have some good reasons to model a single-price monopoly as the private mechanism – primarily because economies of scale is crucial to the early development of a water market. Additionally, while it is possible to see competition, it would not necessarily be perfectly competitive. Duopoly or oligopoly models may exist where Bertrand pricing is observed (effectively at the marginal cost of provision). For this model, an unregulated, single-price monopoly represents the upper bound for price levels under a private model – but it is possible that introduction of competition could drive price levels down.

The price paid by consumers in an unregulated private model is expected to be higher, leading to a lower level of water consumption per household. While a fee may be charged in the following NGO-Community based model, it is expected to be a lower cost to the consumer – at a possible detriment to quality and accessibility.

Section 3.3: NGO-Community Based

The modeling of an NGO-Community based mechanism operates similarly to a private model with one distinct difference: the price charged for water provision is aimed at recovering the costs of provision rather than maximizing profit. As a result, we would expect that the price is intended to at least break even for the costs of provision. This price naturally would be lower than the price charged in an unregulated private model. For the firm to sustain provision, the

combination of their external funds (D) and revenues must together exceed the variable and fixed costs of provision. This is important to consider as, unlike the private model, this firm may operate on a loss if they have substantial external funds that can offset the overall costs. The provision constraint is described as equation (1), simplified to net revenues and external funds minus fixed capital costs:

$$D + n * (P * q - c_w * q - c_h) - F \geq 0 \quad (12)$$

Because the NGO is not seeking to maximize profits, we can solve for the inequality to hold for an optimal quantity of water provided (q^*).

$$q^* = \frac{(a - c_w) \pm \sqrt{(a - c_w)^2 - 4b(\frac{F - D}{n} + c_h)}}{2b} \quad (13)$$

Substituting this optimal quantity into the price function yields the optimal price (P^*)

$$P^* = \left(\frac{(a + c_w) - \sqrt{(a - c_w)^2 - 4b(\frac{F - D}{n} + c_h)}}{2} \right) \quad (14)$$

We expect q^* to change based off of parameters a and b , but additionally to change based on the level of external funds (D) that are accessible. Should the marginal cost of water provision (c_w), per household costs (c_h), and capital costs (F) all increase, the optimal quantity (q^*) per household is expected to decrease due to further constrained provision.

In the case of the NGO-Community based model, the price to the consumer should be less than the price to the consumer in a private model as the provider is breaking even on pricing. In terms of quality, this result could be more ambiguous. Because revenues are returned to operation of the water provision, we expect that the maintenance costs and operation costs are covered by operation. For both the unregulated private model and the NGO-community model, it is expected that all households will consume some amount of water, dependent on the price charged. Since the price is expected to be higher in an unregulated private model, households are expected to consume less. NGO-based provision becomes more complex, though, under a more common form of provision: NGO-Aid based.

Section 3.4: NGO-Aid Based

NGO-Aid provision is unlike NGO-Community in that they do not charge water fees and subsequently have zero revenues of provision. As a result, the firm is constrained by their external funds (D) for provision. Because $P = 0$ and $R = 0$, quantity of water (q) is completely determined by the parameters (a) and (b). Thus, the decision the firm must make is the number of households (n) to provide to.

$$D - (F + \frac{c_w n a}{b} + c_h n) = 0 \quad (15)$$

which, when solved for (n), results in

$$n^* = \frac{(D-F)}{(c_w \frac{a}{b} + c_h)} \quad (16)$$

The NGO-Aid mechanism will be constrained by the number of households they can serve, and it is expected to be less than the number of households provided by a private or NGO-Community mechanism albeit with no price. For the household provided water, the lack of an explicit price is preferable, but less of the community is provided water via the firm. As a result, we expect to see more affordability (in explicit terms) for water, but a possible decreased accessibility due to the constrained financial resources of the provider and no revenues. Additionally, even though the explicit price under NGO-Aid might be zero, there may be non-monetary costs associated with water provision that are not captured in the theoretical modeling. We can expect to see these in practice as possibly travel costs or unreliable provision.

Section 3.5: Public Provision

Public provision is the most ubiquitous form of water provision across the world, but operates under several variations. Three primary variations we identify are a **Tax-Financed Provision**, **Resource Constrained**, and an ideal **Efficient and Equitable provision**. Under each of these, we expect the public provider (usually a local government or Water Authority) to be often operating on a larger scale than other mechanisms. But because governments and Water Authorities are varied themselves, all three of these (and possibly more) are implemented across the world.

1. Tax-Financed Provision

- a. Tax-Financed Provision follows a similar model to the NGO-Aid in the fact that a price is not explicitly paid by the consumer for water. As such, the quantity of water provided is determined completely by parameters (a) and (b), with a $P = 0$. Ultimately the feasibility constraint is that taxes must equal the costs of provision. Issues that arise from universal tax-financed provision are often that the water provided is overconsumed because its price is lower than the marginal social cost of provision. This is the case observed in many municipal water provision systems that have low or no water charges.

2. Resource Constrained Provision

- a. In a case where the provider is unable to use tax-financed provision due to limited external funds, they may operate either as an NGO-Aid (pricing zero, but providing to a limited number of households) or an NGO-Community by providing water at negative net revenues and relying on water charges to recover provision costs. This case is expected to be observed in developing regions by countries that may not have the complete external resources to provide water as universally as a high-income country.

3. Equitable and Efficient Provision (ideal)

- a. The efficient outcome is a result of pricing at the marginal cost of water provision, while also charging a flat/fixed fee for connection that covers the cost of adding the household to provision. In this case, it is considered that the pricing recovers both the per-unit water costs (c_w) and per household variable costs (c_h). This is illustrated below:

$$P_w = c_w \quad (16)$$

$$P_h = c_h + \frac{F}{n} \quad (17)$$

Since $P = a - bq$, we can substitute to find the optimal quantity:

$$q^* = \frac{a - c_w}{b} \quad (18)$$

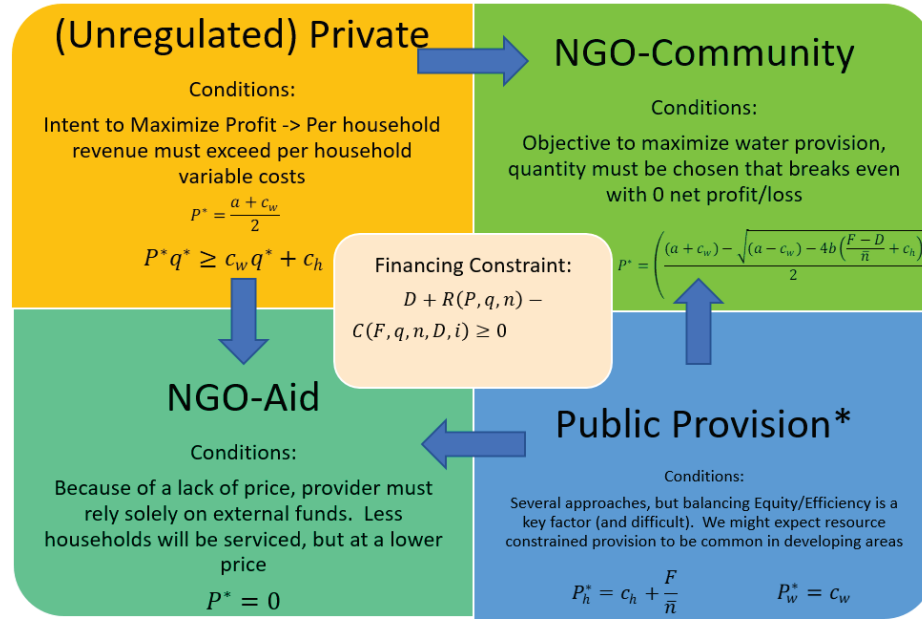
This instance is becoming of increasing focus for how piped service may be able to more equitably and efficiently provide water to communities while also avoiding overconsumption. In practice, the ideal outcome is unlikely, but represents a way to increase provision efficiency.

Section 3.6 Theoretical Overview

In order to understand the relationship between these mechanisms and expected levels of price and water provided, we must directly compare the expected outcomes under each provision for the optimal price and quantity (Figure 5). In the graphic we have modeled the conditions and expected price/quantity for each mechanism, with the arrows pointed towards the mechanism where we would expect a lower optimal price.

Additionally, when comparing total levels of water consumption, we observe different levels of consumption based on the price observed (at least in the three where a price is charged). If there are N homogenous households and an identical quality good, we observe that total consumption is effectively a function of price based off of the per household and total feasibility constraints. Because of these conditions, we model that if it is affordable to serve one household, the provider can serve all households.

If ranked by total consumption as a function of price, we expect that the pure private model would have the lowest consumption with the highest price. The NGO-community model would follow with a higher consumption level as price falls below profit-maximizing (although we understand it may be ambiguous given the price changes from private). The public provision model would likely have a higher total consumption than NGO-community based on the provider's intent to meet demand while minimizing price to consumers. While harder to model or estimate because of no observed price, the NGO-aid model is likely going to maximize consumption by consumers. With no expected price, consumers would intend to consumer as much water as they desire, but the provision would be constrained solely by the external financial resources of the provider.



(Figure 3.1: Unified Model of Water Provision)

The comparison of these four expected mechanisms provides insight into how the three determinants of “abundance” are largely dependent on the provision mechanism that translates water supply to household consumption. In particular, measuring affordability via price is an early method this project takes in attempting to measure abundance.

Section 4: Water Affordability

Section 4.1: Costs for Water Consumption

As discussed in the literature review, it is understood that water is partially commoditized in some forms of provision. For the purpose of this project, we have focused on the instances where there is a transaction of water from a provider to household consumer, whether an explicit price is paid or not. The problem with this is that because of the unclear price signal with water, defining an all-encompassing metric of affordability is difficult to accomplish in one step. The costs of water consumption to the household can broadly be divided between explicit and implicit costs paid. The challenge to understanding water affordability is that water is not like oil – there is not a clear price to observe. Additionally, even with a partially commoditized water, prices that actually are paid are far from uniform. The intent in this project is to develop a metric of abundance that attempts to characterize abundance as universally for those paying water charges as possible. To start, the metric must identify the “unit” of water to be measured.

Water provided through pumped municipal services is provided in large volumes and often measured in cubic meters (m^3). The data used from the International Benchmarking Network measures water units in cubic meters for the majority of their data, forming the basis of our metric.

Section 4.2: Time Price

The Simon Project’s “Abundance Index” works for their purposes because the commodities they are using have the particularly measurable and clear price signal. But, by the nature of water, using the nominal price is impossible. In this project, the closest thing to a nominal price for water on the municipal side is the per-unit charge to consumers of pumped water utilities. These water charges paid by consumers vary across regions as well, so a uniform per-unit charge is not realistic either.

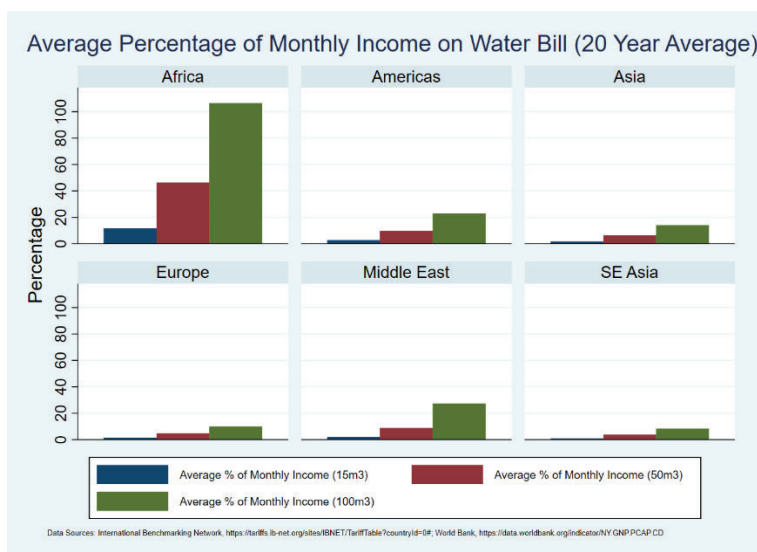
The Simon Project also uses nominal GDP per capita as a representation of income for the consumer of a commodity. While GDP per capita broadly describes the economic status of a country and its inhabitants on average, it does not fully capture the state less-developed countries are in, especially with the countries that are likely to suffer from some form of physical water scarcity. For this project, it is more apt to use GNI per capita (via World Bank) so that it captures more of the direct income measurements than a broader GDP per capita metric may understate or overlook. The price metric we propose is most reminiscent of a “percentage of income” measurement, where we model municipal water affordability by region subject to the EPA’s threshold for water consumption affordability being at maximum 2.5% of the consumer’s income⁴⁴.

Lastly, the scope of the Simon Project is based in global metrics. The use of global GDP per capita and annual hours worked both correspond with the time price analysis of globally traded goods with well-established markets. Because water scarcity issues are often identified regionally, applying the same global scope is not as applicable in this project. More apt is the analysis of region-specific and interregional cases of affordability. Thus, focusing on country GNI per capita and country municipal utilities sets an appropriate scale for defining an “affordability” determinant for water abundance.

Section 4.3: Municipal Affordability

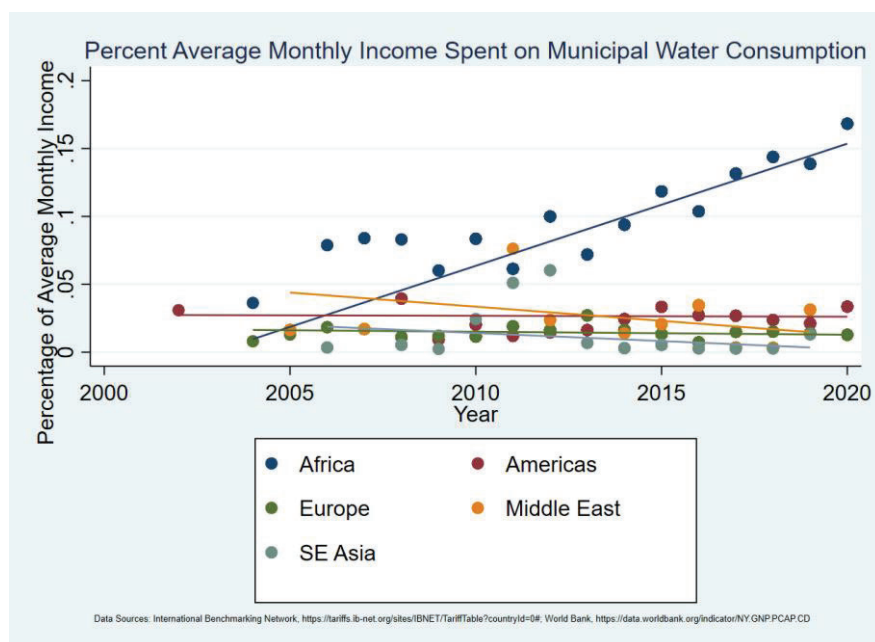
The empirical combination of municipal water charges for consumption subject to the average monthly income per capita is an early effort to characterize “affordability” past just price terms. We have broken this down into three primary categories: low consumption (15m³ per person per day), medium (50m³), and high (100m³). Expected from most, if not all, pumped systems are that the households consuming at medium or high would pay more than those consuming at low, but it is not necessarily given that the percentage of income spent on water charges would change proportionally. Divided into continents, we analyzed the changes in monthly income percentages dependent upon quantity for a 20-year average focusing on low-consumption users and the cost of low-consumption water levels relative to income as most residential water is expected to be on these levels (Figure 4.1). Most notably, the African region shows a sharp spike in percentage of monthly income with changes in quantity consumed.

⁴⁴ “AWWA Affordability Assessment Tool for Federal Water Mandates,” 2013.



(Figure 4.1: Average Percent of Monthly Income on Water Bill 20-year Average)⁴⁵

Cross-regionally, it is evident that even on the lowest consumption levels Africa regionally has the highest average percentages of income spent on water utilities. Zooming in on the African region to better analyze why these rising percentages may be occurring, and what story is told from this, is crucial to expanding the metric of “abundance” (Figure 4.2).



(Figure 4.2: Trends in Municipal Water Affordability by Region from 2000-2020)⁴⁶

⁴⁵ International Benchmarking Network, <https://tariffs.ib-net.org/sites/IBNET/TariffTable?countryId=0#>; World Bank, <https://data.worldbank.org/indicator/NY.GNP.PCAP.CD>

⁴⁶ Ibid.

Such incidence of increasing income percentages is motivation to analyze the change in percentage over time – which is the basis of a changing “affordability” over time that this project seeks to understand and characterize. Shown in Figure 4.2 is the initial time series analysis over a 20-year period of the monthly income percentage paid for low levels (15m³) of water consumption. The shown trends corroborate the previous look across region for the 20-year average, but further reinforce that the African region is a potential case study for further research, as it is the clear outlier in changing income percentages.

These empirical observations capture the view on municipal water charges in relation to the income of the consumer. Rising percentage of monthly income on water consumption may spell decreasing affordability, at least monetarily. But, it does not highlight that over time, there may be significant shifts in populations using municipal water provision – especially in emerging economies. And within the African region, these may be crucial factors in why we observe a relatively opposite trend from other regions.

A more ideal price metric is a weighted price that incorporates the expected price under the three other expected mechanisms and the portion of the population that they serve. This weighted price would partially overcome the lack of a uniform price for water provision. In Section 5, we will introduce and outline this metric as it plays a crucial role in “Affordability” for the final Abundance Index.

Section 4.4: A Complete Affordability Metric

The theoretical modeling of water provision discussed in Section 4 introduced four provision mechanisms that we would expect to see in water markets. In each case, we derived the optimal price, P^* , that a consumer would pay if they acquired their water through that mechanism. For other resources, we are able to identify a single, often market-determined price. But, as previously discussed with water, no clear market price exists here. Thus, for us to find a “standardized price” of water, we must focus on a region-specific metric that incorporates these modeled mechanisms. An ideal metric for water affordability would be a nominal weighted price index that:

- Weights the “prices” of each mechanism by the fraction of the population they serve
- Incorporates consumption amounts (averaged per household)
- To the best of its ability, captures both monetary exchange prices and “time costs” (evaluated at local hourly wage rates) in the price, P , of water acquisition.

This complete metric would, in essence, describe the evolution of water provision in a specific region while also providing a weighted price that explains a type of “true price”. There are a few assumptions required for a fully contained metric that describes regional weighted water prices – primarily in defining consumers and water provision. Firstly, this model assumes that the consumers of water are residential consumers, vice industrial or agricultural consumers. The reasons for this distinction are two-fold: (1) for industrial and agricultural uses, the purpose of water acquisition is not household consumption and (2) because we intend to capture “scarcity”, we want to focus on the purchase of water for personal welfare.

Secondly, we assume that the consumers are those who obtain water from a provider, excluding personal wells or fetching water from common property locations (e.g. surface water basin). Essentially, we are focusing on water transactions where the consumer *purchases* water from a seller or firm (public, private, NGO).

We formalize the weighted price index as the double sum of price (p) multiplied by the fraction of the population (λ) being served by mechanism (j) in region / market area, (k) within country (i). This is denoted as:

$$P_i = \sum_{j=1}^4 \sum_{k=1}^N p_{ijk} * \lambda_{ijk} \quad (19)$$

with variables:

P_i = Weighted price of water provision in country (i)

p_{ijk} = Price of water provision by mechanism (j), in region (k)

λ_{ijk} = Fraction of population within country (i) and region (k), served by mechanism (j)

N = Number of regions (k)

Theoretically, the weighted price index hopes to account for the mechanism differences in water provision pricing by giving a price for all water provided in the region. In an attempt to bring together the theoretical mechanisms, this ideal index would provide a summative description of the economic abundance that could be tracked in a country over time.

Section 4.5: Dissecting Price Determinants

The primary components of the metric are the prices via certain mechanisms as well as the fraction of population served via certain mechanisms. In every mechanism, we consider a price, p_{ijk} , and a fraction served, λ_{ijk} . But these values (or expected values) almost certainly differ between the provision mechanisms. A visual table is provided below.

Water Acquisition Method	Price	Fraction Served
Public/public-private (Piped)	$p \geq 0$	Anecdotally, Public utilities provides a majority of water provision in urban/peri-urban regions. Expected to be a high portion of the population
Private, for-profit (non-piped, tanker, etc)	$p > 0$	Observed in developing countries as general substituted to lacking utilities or other mechanisms

Private, non-profit (well, network, non-piped to residences)	(dependent, see below)	Incidence likely low, and often isolated to regions in need of aid
a) Community-Based	$p > 0$	
b) Aid-Based	$p = 0$	
Private Well	$p = 0$	Possibly high dependent upon the region. In developed nations such as the United States, private wells may be cheaper in suburban areas with possible improvements over publicly piped water
Self-service Commons	$p = 0$	Simplest form of common property resource usage such as sharing surface water sources. Expected to be most common in the least developed states

(Table 4.1: Comparison of Water Provision Methods by Price and Fraction Served)

Table 4.1 takes the four previously modeled provision mechanisms (plus unimproved self-served commons) and pairs them with the expected prices charged for water and the fraction of the population they are expected to serve. When applied to the weighted water price, we have a qualitative understanding of which mechanisms have certain effects on the resulting metric.

Section 5: Water Accessibility

Section 4 identified the role affordability plays in determining abundance, but that it is not the only determinant at play. Just as crucial is “accessibility”, which is broadly defined as access to an improved water source. As multiple development agencies and organizations work to characterize accessibility, they often identify key variables at play. The International Benchmarking Network describes two indicators that group accessibility: The Water Utilities Vulnerability Index (WUVI) and APGAR score for utility health⁴⁷. In both of these, the IBNet uses a combination of indicators that provide an image of the utility’s strengths and vulnerabilities. In the WUVI indicator, they aggregate water coverage (1), sewage coverage (2), non-revenue water (3), “affordability” (4), and collection period (5) if it exists⁴⁸. Measuring factors of efficiency and reliability, these indicators capture aspects of accessibility that ensure water is adequately provided to the households they are responsible for. More broadly, many of these variables influence an overall access to improved water sources for a population.

⁴⁷ Ibid.

⁴⁸ Ibid.

Figure 1.4 was included in the introduction to highlight a contrasting view to the incidence of decreasing freshwater resources per capita. In the figure, we cite an average increase in population with access to improved water sources over the 1990-2015 time period. For developing countries within the graph, this change can be massive and represents an early leap towards overall better water infrastructure.

This project considers accessibility one of the key determinants of abundance due to its implications on reliability and efficiency of water provision. The accessibility of a water source can be a limiting factor to measuring affordability, but it is possible for a household to still consume expensive water if quality and accessibility are satisfied. This scenario could be observed in a pure private model (Section 3.2) where the water is safely managed and accessible in its provision, but priced much higher than through other mechanisms due to the profit maximizing motivation of the firm.

While water quality is inherent in an element of accessibility, measuring accessibility as a threshold for water provision will provide insight into the development of water infrastructure and ease of consumption for the household.

Section 6: Water Quality

It is important to define water as it pertains to household consumption in these models. For the water sold by a provider and purchased by a consumer in this project, we are focusing on improved water sources that provide safe drinking water. But just as prices are not uniform for water, neither is quality. Often in line with the provision mechanisms by which it is provided, water quality is highly varied temporally and spatially⁴⁹. As a result, the reality is that a sizable portion of a population served by one of the modeled mechanisms is consuming “unsafe water”.

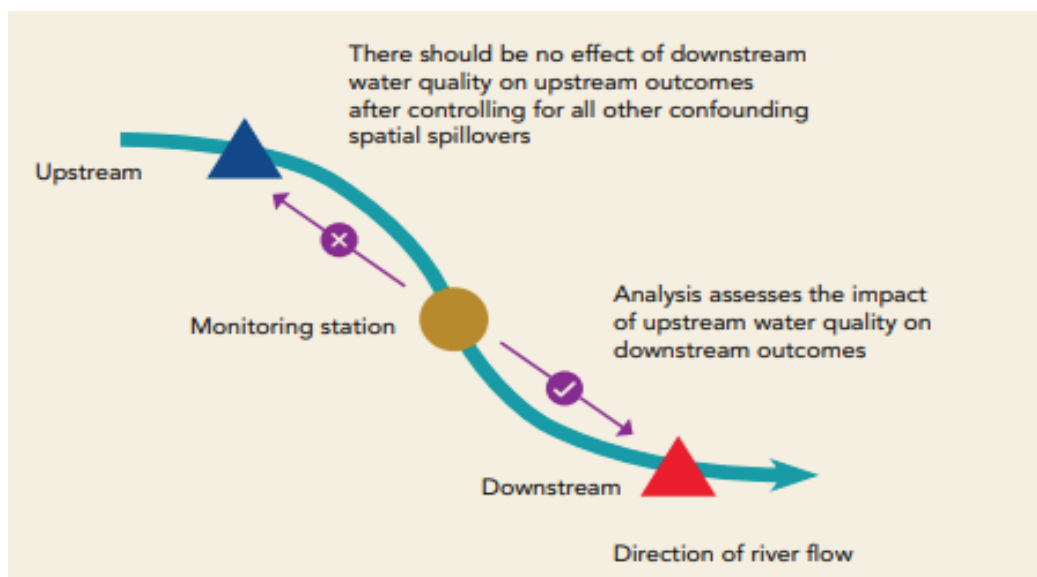
Specifically within non-networked water provision, the variability in water quality can be drastic and regionally dependent. More susceptible to the environment around it, unimproved surface water resources could lead to waterborne illnesses that lead to consumer death⁵⁰. When this project considers “improved water sources”, it hopes to consider (as much as possible) the safe and potable water provided to consumers. Unfortunately, just like a price of water, there is no clear standard for quality of water. As the *Quality Unknown* report on water quality suggests, international organizations attempt to set standards that are often contradictory or subsequently disputed⁵¹. What they attempt to measure water quality by is Biological Oxygen Demand (BOD). Via this measurement, the economic impact of water pollution on development is analyzed through a regression that compares the upstream BOD to the downstream Gross Domestic Product (GDP). This is also illustrated in Figure 6.1 (below). Their primary findings are that GDP growth is slowed based on the size of BOD in that region⁵². Problematic for the least developed regions, polluted surface water becomes an important factor in safe and sustainable water provision.

⁴⁹ Garrick, Hanemann, and Hepburn, “Rethinking the Economics of Water: An Assessment.”

⁵⁰ Richard Damania et al., “QUALITY UNKNOWN,” n.d.

⁵¹ Damania et al.

⁵² Ibid, 10.



(Figure 6.1: “Using Streamflow Direction to Identify Impacts of Water Quality”)⁵³

Identifying water quality has to be the baseline to identifying water scarcity in developing regions, for a few key reasons. Firstly, as shown by Dr. Damania in *Quality Unknown*, water pollution has a direct effect on GDP growth and physical health. With a rising incidence of plastics and pharmaceutical drugs in wastewater, water pollution becomes more complex. Secondly, water quality varies widely and, until recently, often not as addressed as water quantity in specifically transboundary water resources⁵⁴. These two considerations point to water quality being just as difficult to define as a water price.

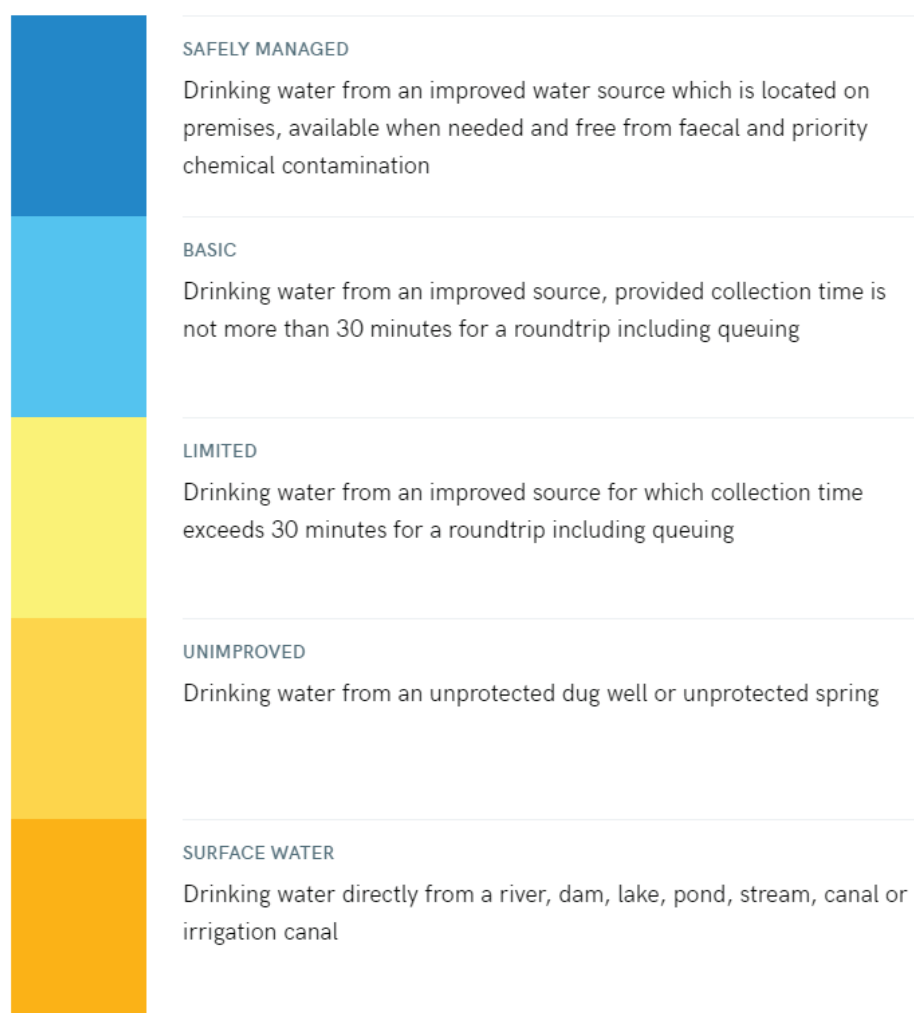
This project’s use of World Bank data encourages us to work with World Bank’s definition of “clean water”. As part of their data collection on water supply, World Bank Group defines an improved water source as “The improved drinking water source includes piped water on premises (piped household water connection located inside the user’s dwelling, plot or yard), and other improved drinking water sources (public taps or standpipes, tube wells or boreholes, protected dug wells, protected springs, and rainwater collection)”⁵⁵. While this is a broad category, it understates the inconsistent qualities between one region’s “improved drinking water source” versus another. WHO-UNICEF’s Joint Monitoring Programme (JMP) expands upon this category by building a “ladder” of water quality that better describes the water situation on a variety of factors (Figure 6.2).

⁵³ Fig. 6.1. An analysis of water streamflow to understand impacts on water quality through biological oxygen demand, Figure, Richard Damania, *Quality Unknown: The Invisible Water Crisis* (International Bank of Reconstruction and Development, 2019), 9.

⁵⁴ Giordano, “A Review of the Evolution and State of Transboundary Freshwater Treaties.”

⁵⁵ “Improved Water Source (% of Population with Access) | Data Catalog,” accessed February 16, 2021, <https://datacatalog.worldbank.org/improved-water-source-population-access>.

Drinking water ladder



(Figure 6.2: “WHO-UNICEF Drinking Water Ladder”)⁵⁶

As shown in the ladder, “Limited” to “Safely Managed” are all considered to be improved water sources – with varying degrees of accessibility or convenience. And while an “improved source” is described as having the potential for safe water delivery, it is not always the case. The highest level of the ladder is the “safely managed” water which has to meet three standards⁵⁷:

1. The water is accessible on the household premises
2. It is available on demand
3. It is non-contaminated

Each condition has a slightly different implication for household water provision. For the water being accessible on the premises, it would have to be some kind of improved source that is piped

⁵⁶ Fig 6.2. The WHO-UNICEF Drinking Water Ladder of different water qualities, Figure, “Drinking Water | JMP,” accessed February 16, 2021, <https://washdata.org/monitoring/drinking-water>.

⁵⁷ “Drinking Water | JMP.”

to the household via a network, or a private dug well. Second, the water being available on demand also functions as an indicator of accessibility. The reliability of water provision through whatever mechanism determines the availability of said water. Lastly, non-contaminated water requires that the water is free from fecal contamination, quantitatively measured as E. Coli per 100mL of drinking water⁵⁸.

Figure 1.3 in Section 1 shows the percentage of population using improved water sources from 1990-2015. The overall trend of increasing access in the world is a good sign, but an “improved water source” has varying degrees on the water ladder and is not as clear as would be necessary to identify truly safe drinking water. The “Safely Managed” tier of drinking water does provide this specificity in what constitutes “safe”. For our theoretical framework, this base assumption of “safely managed” water presumably excludes the water provision that is not on household premises (failing to satisfy the first condition), but is available on demand and non-contaminated (holding for the second and third). Therefore, our focus on water quality includes safely managed water, but additionally includes those improved sources which are potable but may not be on the premises: basic and, possibly, limited. JMP categorizes “basic” and “limited” as improved sources of water that do not satisfy one of the conditions under “safely managed”⁵⁹. In the 2017 World JMP Report, Sustainable Development Goal baselines indicated that 92% of the world’s population is served by improved water sources; but that only 73% of the world’s population is drinking water considered free from contamination⁶⁰.

In our metric for affordability, the water we must consider is that which is able to be safely consumed by the household that has purchased it. In the majority of developed countries, the quality question is often not of concern. But for the developing nations where water scarcity is anecdotally expected to occur, the quality question is central to developing an accurate measure of accessibility. Because the contamination measure is E. Coli per 100mL, a steady decreasing incidence of waterborne illnesses such as E. Coli, dysentery, or cholera could be a healthy indicator of increasing water quality and improving infrastructure within water provision. For an apt country within our theoretical framework, the regions analyzed hopefully show this decreasing incidence in contamination so that the analysis of accessibility is more accurate and uniform across water qualities.

Quality, like price, has a significant impact on accessibility and affordability of water for household consumption⁶¹. In summary, water quality is at the foundation of water scarcity analysis because the household depends on potable water for adequate consumption. Should the quality of water be inadequate, efforts towards accessibility and affordability are less important to characterizing abundance overall.

⁵⁸ Ghana Statistical Service, “Survey Findings Report Ghana Multiple Indicator Cluster Survey 2017/18 Republic of Ghana Ghana Statistical Service,” 2018.

⁵⁹ “Drinking Water | JMP.”

⁶⁰ Ibid.

⁶¹ “The IBNET Water Supply and Sanitation Blue Book 2014: The International ... ” - Alexander Danilenko, Caroline van Den Berg, Berta Macheve, L. Joe Moffitt - Google Books,” accessed March 2, 2021, https://books.google.com/books/about/The_IBNET_Water_Supply_and_Sanitation_Bl.html?id=61BjBAAAQBAJ.

Section 7: A Water Abundance Index

The proposed theoretical framework attempts to, in an ideal scenario, provide an indicator of a country's water "abundance". In order to accomplish this, we propose a Water Abundance Index (WAI) that, based on the three determinants of abundance, provides a score from 0 to 1 that outlines the level of water abundance in the country. The Abundance Equation is defined as

$$Abundance = \alpha_1 Affordability + \alpha_2 Accessibility + \alpha_3 Quality \quad (20)$$

where

$$\sum_{i=1}^3 \alpha_i = 1$$

and

$Abundance = 1$ implies "perfect abundance"

$Abundance = 0$ implies "perfect scarcity"

with variables:

α_1 = Weight of Affordability Measure

α_2 = Weight of Accessibility Measure

α_3 = Weight of Quality Measure

To reflect the importance of water quality demonstrated in the literature, we propose an initial weighting of 50% for Quality, 30% for Accessibility, and 20% for Affordability, although we recognize that these weights are subjective for time being. The hypothesized weights for each component in the abundance index were developed based on careful review of the literature on water consumption and pricing. However, the weights remain a largely subjective decision lacking strong empirical validation. How we weight each component matters for tracking economic abundance, particularly if individual components move in opposite directions (for example, if affordability is decreasing while quality and accessibility are increasing). We believe this to be an important area for future research given the implications for the developing world and the data presented earlier on the overall trend of decreasing affordability of water in Africa. Of note, these desired weights are not equal, but sum to 1 as with the three measures. For each sub-element of the abundance equation, we propose a weight thought to best reflect the significance of that determinant in defining "abundance" as defined in this project.

Section 7.1: Affordability

In Section 5, an ideal weighted price index was outlined that would represent a “true price” of water consumption across the outlined provision mechanisms: public provision, NGO-community, NGO-aid, and private. This average weighted price of water consumption is a crucial factor in determining “affordability” of water consumption in relation to income (in the spirit of Simon’s time price theory). For the abundance metric, affordability is measured in relation to the 2.5% of monthly income threshold defined by the EPA in their water pricing analyses⁶². We define this equation as γ , the percentage difference the monthly percentage of income spent on water consumption is from the stated threshold:

$$\gamma = .025 - \frac{AvgWeightedWaterCost}{Monthly\ Per\ Capita\ GNI}$$

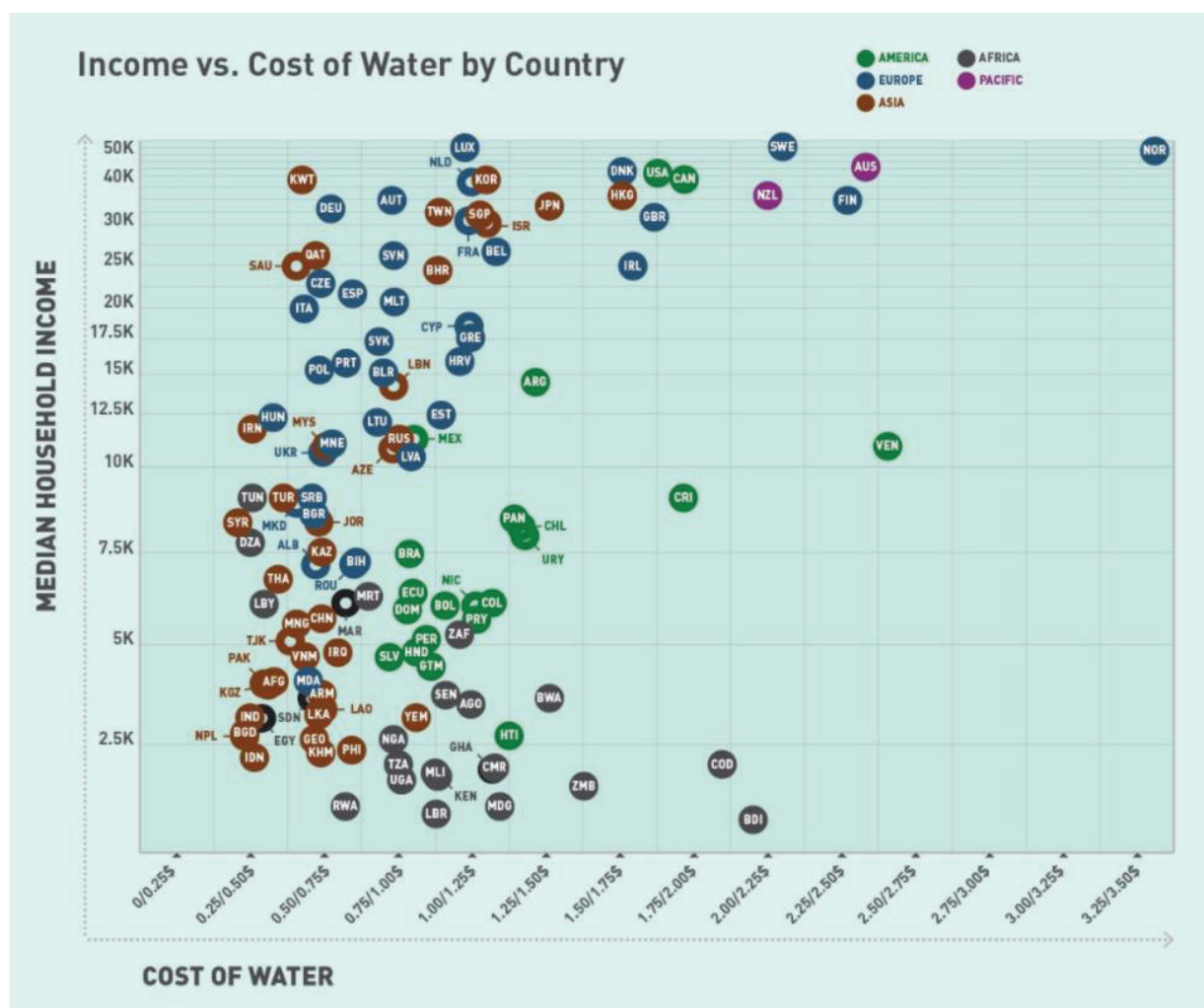
The value of affordability is determined by the value of γ , specifically if negative – indicating that the monthly expenses exceed 2.5%. The upper and lower bounds of γ are defined as [-.975, 0.025] by the maximum percent of income someone could pay on water (100%) and the minimum (0%). Thus, affordability is broken down into a function with two sets of values:

$$(1) \text{ Affordability} = \min\{1, 1 + \gamma\}$$

Through these values, affordability is bounded between 0 and 1, and driven down by negative values of γ (where expenses exceed the threshold). Should $\gamma < 0$, the resulting affordability is less than 1 while any $\gamma > 0$ results in affordability equal to 1. The resulting Affordability number then describes the level of affordability for water consumption from perfectly affordable (0% of income paid) and prohibitively expensive (100% of income paid).

The discussion of a proposed weight for affordability must consider the importance of affordability for the final product of “economic abundance”. These considerations include the variability of water prices in relation to income and the place affordability lies in achieving water abundance. While regional and country difference in GNI per capita may differ wildly based on development, so may the weighted water prices across those same regions. At least in consumer prices, residents of wealthier countries (by GNI per capita) may pay higher portions of their income for water consumption (Figure 7.1).

⁶² “AWWA Affordability Assessment Tool for Federal Water Mandates.”



(Figure 7.1: Income vs. Cost of Water by Country⁶³)

Figure 7.1 compares the average price for a 1.5-liter bottle of water to the country's median household income. On the private end of the water provision spectrum, Figure 7.1 also indicates a variable relationship between income and price – a relationship that could drive affordability down by our metric but understate the overall abundance in that nation. One example of this would be Norway, at the highest cost of water. If a household in Norway was consuming only bottled water, this consumption could prove prohibitively expensive by the affordability metric.

Furthermore, by this metric's definition, affordability of water consumption by a household implies that the water they are consuming is potable and through an improved water source: in essence satisfying the quality and accessibility elements of the WAI. Because a household is consuming "affordable" water, to some extent that water is at least an improved source in quality and accessible when needed for that household. The resulting abundance then is mostly high because of the already satisfied other elements.

⁶³ Fig. 7.1. The income vs. cost of a bottle of water, Figure, "The Affordability of Water Around the World | TitleMax," accessed March 21, 2021, <https://www.titlemax.com/discovery-center/money-finance/affordability-of-water-around-the-world/>.

While not an exactly derived weight, this Water Abundance Index proposes a weight for affordability (α_1) of 20% (or 0.20). The least of the three weights, this 20% weight still places importance on what percentage of income the household gives up to *consume* water beyond just *access* to it.

Section 7.2: Accessibility

Accessibility, simply, is a measure of the percentage of the population with access to an improved water source – a strong sign of increasing (or decreasing) development. In line with the anecdotal evidence presented in Section 1, access to improved water sources worldwide appears to be increasing⁶⁴. Outlined by the Joint Monitoring Programme and World Bank, an improved water source is a source classified as either limited, basic, or safely managed.

The accessibility element of the Abundance metric is likely to be a high value directly correlating with development. With the world on average increasing in accessibility, it is a reasonable expectation that this number over time will increase for most case study countries. We formalize the value of the accessibility element between 0 and 1 to be the percentage of the country's population with access to an improved water source:

$$\text{Accessibility} = \text{Percent improved } [0,1]$$

Because this number is likely to be extremely high (90%+) for the most developed countries in the world, the accessibility indicator may be less effective for the countries on that end of the spectrum. But, for countries where improved water sources are not universal, there is great value in understanding the level of base development that has been done within water provision for countries in between.

In consideration of weighting accessibility, we place great emphasis on what access to an improved water source means for the household. While price and quality enhance the understanding of access, base access to an improved water source is a significant indicator of household welfare. As a result, this index proposes a weight for accessibility (α_2) of 30% (or 0.30). The middle of the three weights, this 30% weighting provides an educated estimate of the ultimate effect accessibility has on the resulting “abundance” for water consumption.

Section 7.3: Quality

The quality of water consumed, as discussed in Section 7, remains crucial to securing water abundance. The Drinking Water Ladder's delineation of “improved water sources” provides deeper insight into how the water management world characterizes water quality within the “accessibility” threshold. The index hopes to provide, similar to the weighted price index, a weighted average of the country's water quality in line with the JMP's Drinking Water Ladder. We formalize this quality element as:

⁶⁴ “Population Using Improved Drinking Water Sources - HumanProgress,” n.d.

$$\text{Quality} = \frac{\text{AvgWeightedWaterQuality}}{5}$$

where

Safely managed = 5

Basic = 4

Limited = 3

Unimproved = 2

Surface water = 1

No water access = 0

The resulting quality indicator will yield a score from 0 to 1 that best gauges that country's level of development beyond the more binary "improved" or "unimproved" water source. This will be particularly useful in providing more accurate assessments of current water management between countries.

When considering the weight of quality, the index must consider the value placed on water quality by the literature and evidence suggested by JMP's drinking water reports. As the JMP finds, quality in improved water sources is the primary limiting factor towards progress in increasing population served by safely managed water sources⁶⁵. So, while the national access to improved water sources is often increasing, the focus on increasing the access to improved and non-contaminated water sources is crucial to continued progress in water quality. In conjunction with the discussion in Section 7, the priority of securing the highest quality water is of the highest importance. This index's proposed weight for quality is 50% (or 0.5), considering quality is the base of access to improved water sources and is often a pre-requisite for affordability and accessibility.

Section 7.4: An Ideal Case Study

The Water Abundance Index's primary goal is to characterize the abundance of water via the three primary determinants: affordability, accessibility, and quality. In a perfect case study this index would be able to capture, over time, the change in this abundance score indicating a trend towards a better quality of life for the household. A suitable initial case study for this index would be a developing country with a history of water scarcity and/or water management issues. Earlier in the project, we identified the historical case of Africa in water scarcity – a primary focus of developing nations and foreign aid for decades. When selecting a case study, this project intends to consider under which circumstances the Index would be most accurate:

1. Within the most developed countries, it is expected that accessibility, quality, and affordability are highly correlated or possess a direct relationship between each other. Thus, it may not be as useful to apply the index to countries on the extremely high end of these elements. In other words, developed countries, by a measure, tend to have a water abundance very close to or equal to 1.

⁶⁵ CSA Ethiopia, "Drinking Water Quality in Ethiopia. Results from the 2016 Ethiopia Socioeconomic Survey," no. December (2017): 22., 37.

2. The proposed weights of each element are educated estimations that, in actuality, are not going to be universally important. In the same highly developed countries where we'd expect correlation between the elements to be high, the expected weights may be closer to uniform weights (33% each) or even inverse (a higher weighted affordability).

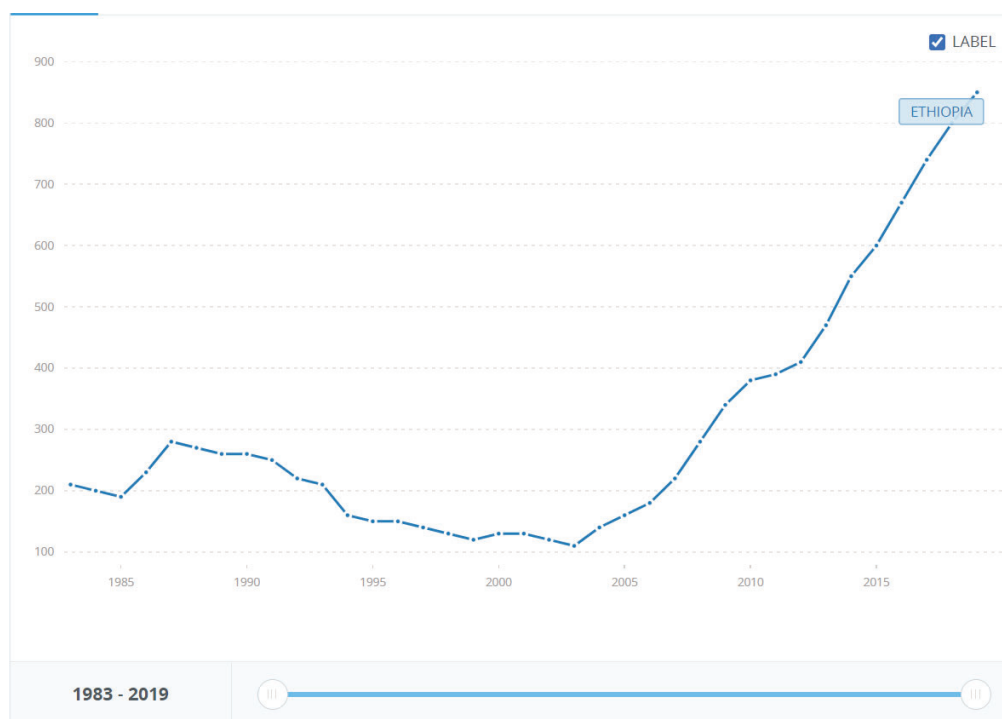
The WAI Case Study presented in Section 9 hopes to ultimately characterize the economic abundance of water in a select developing country in Africa: Ethiopia. From this characterization, we provide policy implications and recommendations that aim to contextualize the current abundance score and project for the development in the future of that country. Ideally, this index can provide a panel analysis of “abundance” across countries and over time. Within the scope of this project, the Abundance Index will be applied to Ethiopia and, where the data permits, calculate a score of abundance for the country.

Section 8: Ethiopia: A Case Study

Ethiopia is the 13th most populous country in the world, and 2nd most in Africa with a population of almost 102 million⁶⁶. A developing and poor country located on the Horn of Africa, Ethiopia is a member of World Bank's Low Income Country bracket with a GNI per capita of \$850⁶⁷. While GNI per capita is low, the average 10% annual economic growth of the country has accompanied a steep rise in GNI per capita over the past 16 years. Shown in Figure 8.1, Ethiopia's GNI per capita has increased by ~531%, an indicator of great strides in improving quality of life.

⁶⁶ “Ethiopia | History, Capital, Map, Population, & Facts | Britannica,” accessed March 4, 2021, <https://www.britannica.com/place/Ethiopia>.

⁶⁷ “Ethiopia Overview,” accessed March 10, 2021, <https://www.worldbank.org/en/country/ethiopia/overview>.



(Figure 8.1: GNI per Capita – Ethiopia 1983-2019⁶⁸)

But improving quality of life does not necessarily indicate a high quality of life in Ethiopia's case. Ethiopia is a heavy recipient of foreign aid, receiving billions from developed countries such as the United States every year. In particular, this aid funds healthcare services, WASH infrastructure and AIDS care⁶⁹. The aid towards economic development is a key contributor to increasing the affordability of household water consumption: part 1 of this analysis.

Section 8.1: Affordability

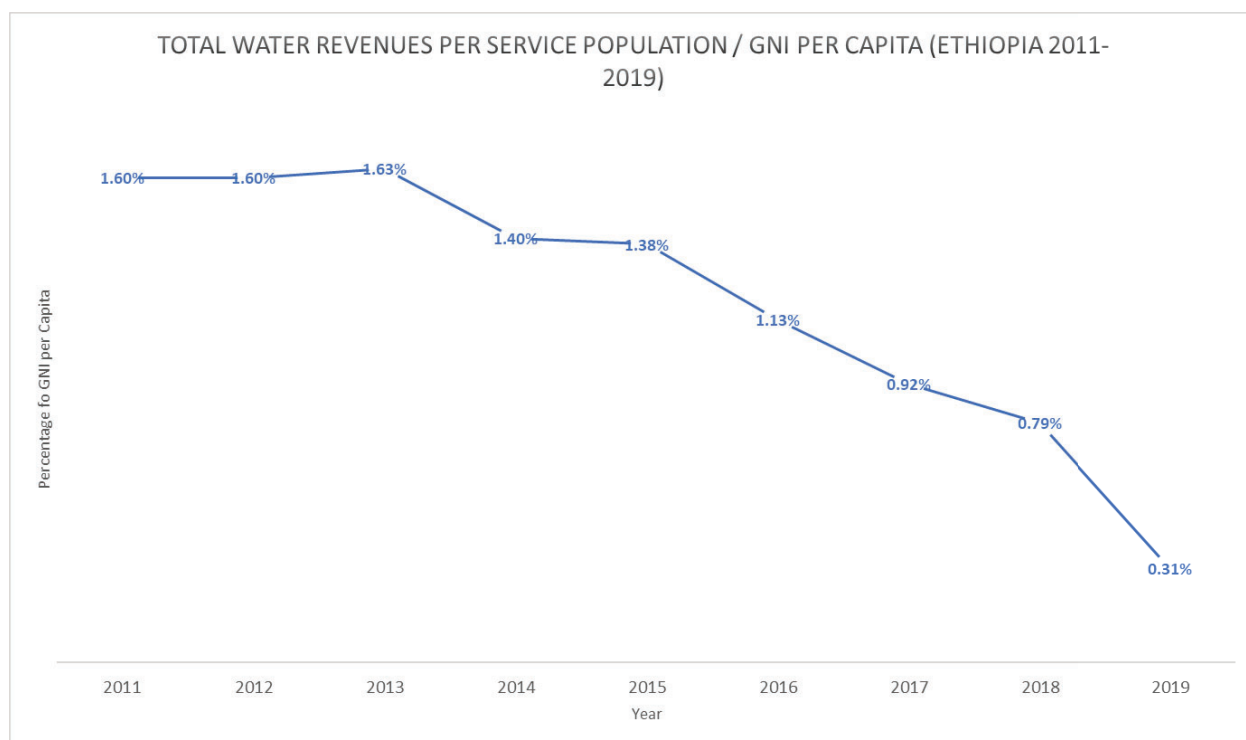
In an ideal analysis of Ethiopia's water affordability, this index would compare the country's weighted water price to the income per capita – akin to a “time price” for water consumption. In reality, the price data on the alternative water provision mechanisms defined by the theoretical framework in Section 3 is much less reliable or accurate. But while this may be the case with the alternative mechanisms, public piped provision has been relatively well documented by the International Benchmarking Network (IBNet) in the form of utilities charges.

An increasing number of water authorities in Ethiopia have self-reported water tariffs since 2004, albeit with a slight drop in recent years⁷⁰. Tracked against GNI per Capita, the “affordability” metric has effectively been mapped over the 2011-2019 time period (Figure 8.2).

⁶⁸ Fig. 8.1. Ethiopia GNI per capita, 1983-2019 “Ethiopia GNI per Capita, Atlas Method (Current US\$) - Ethiopia | Data,” accessed March 10, 2021, <https://data.worldbank.org/indicator/NY.GNP.PCAP.CD?locations=ET>.

⁶⁹ “How Foreign Aid Helps Ethiopia | The Borgen Project,” accessed March 4, 2021, <https://borgenproject.org/how-foreign-aid-helps-ethiopia/>.

⁷⁰ “Country Profile Ethiopia - IBNet,” accessed April 5, 2021, https://database.ib-net.org/Country_Profile?ctry=10.



(Figure 8.2: Total Water Revenues per Service Population / GNI Per Capita⁷¹)

When translated to the Water Abundance Index via the Affordability Equation, we yield the following results:

Year	Percentage of Income (%)	Affordability Point
2011	1.60	1
2012	1.60	1
2013	1.63	1
2014	1.40	1
2015	1.38	1
2016	1.13	1
2017	0.92	1
2018	0.79	1
2019	0.31	1

(Table 8.1: Weighted Affordability Metric for Ethiopia 2011-2019)

With all years resulting in a <2.5% of income spent on water utilities (an average of 1.03%), by this metric the affordability “perfect” for Ethiopia. In actuality, we understand that this result would be misleading as it does not capture a weighted average price across multiple mechanisms. For the affordability metric to accurately reflect a more complete affordability

⁷¹ “Total Water Revenues per Service Population/ GNI Per Capita - IBNet,” accessed April 5, 2021, <https://database.ib-net.org/Reports/Indicators/InCountry?itemId=62&countryId=10&viewWeight=false>.

metric, this project would need extensive data on the average price paid by the consumers as well as the fraction of the population served by that mechanism. But while this project does not have that data, it can glean insight on the opposite end of water pricing: privatized bottled water.

The “Affordability Around the World” discussion in the index’s theoretical framework modeled the price of a 1.5 liter bottle of water in relation to median household income. Within this project’s index, we are able to provide an affordability view on the other end of the spectrum. While the data is not exhaustive over time for Ethiopia, Numbeo’s Cost of Living Calculator lists a 1.5 L bottle of water costing between \$0.3 and \$0.9⁷² for 2021. Using the same Affordability calculations as the metered water charges, we can calculate a percentage of income spent on one 1.5L bottle as ranging from 0.4% to 1.2% (using Ethiopia’s most recent GNI per capita figure of \$850)⁷³. Should the household choose to only consume bottled water, this could be expanded out to cover a monthly percentage of income of 12% at the 15m³ consumption level used in municipal analysis. Assuming the household consumes multiple bottles of water, especially if bottled water is their only source, this could quickly become prohibitively expensive. Thus, it is not expected that a household consumes privately provided bottled water except where necessary.

In a positive sign towards increasing affordability, though, is the result of JMP’s 2016 report on Ethiopian drinking water which listed the reasons for insufficient water availability across all sources of drinking water.

	Unimproved Sources	Improved Sources	Total
Water not available from source	72.2	83.1	80.7
Water too expensive	(*)	(*)	(*)
Source not accessible or too far away	(14.8)	(*)	4.8
Other	(10.8)	14.3	13.5
Total	100.0	100.0	100.0

Note: Values in brackets are estimates from small observations (number of unweighted cases less than 50 but greater than 24). The symbol, (*), denotes suppressed values for less than 25 observations.

(Figure 8.4: Reasons for Insufficient Water Availability⁷⁴)

Within the JMP report, water being too expensive was rarely listed as a reason for insufficient water (Figure 9.3). But while this may be the case of Ethiopia in JMP’s 2016 report, we expect

⁷² “Cost of Living in Ethiopia. Prices in Ethiopia. Updated Mar 2021,” accessed March 28, 2021, https://www.numbeo.com/cost-of-living/country_result.jsp?country=Ethiopia.

⁷³ “Ethiopia | History, Capital, Map, Population, & Facts | Britannica.”

⁷⁴ Fig. 8.4. Survey results for reasons of insufficient water availability, Figure, CSA Ethiopia, “Drinking Water Quality in Ethiopia. Results from the 2016 Ethiopia Socioeconomic Survey.”, 18.

that this would not hold in different countries of the same region. Ultimately, this leaves the weight of affordability within each country’s Abundance Index variable and ambiguous – especially when data on alternative provision mechanisms is sparse.

Section 8.2: Accessibility

We have reason to be optimistic on overall increasing access to improved water sources in Ethiopia, as the percentage with access has increased from 53% in 2011 to 69% in 2017 in a constant manner⁷⁵. Applying to the Water Abundance Index, we translate these percentages to a fraction of population with access to improved water sources in the table below:

Year	Percent Improved Water Sources (%)
2011	53.43
2012	56.06
2013	58.66
2014	61.25
2015	63.81
2016	66.37
2017	68.9

(Table 8.2: Accessibility Metric for Ethiopia 2011-2017)

The steadily increasing percentage of Ethiopian population with access to improved water sources is a positive sign for increasing “economic abundance” per our index. While “improved water source” is more binary than the water quality ladder, measuring the change in access gives an overall perspective on ease of consuming water. Beyond physical water resources, our measurement builds a base for the infrastructure that makes those resources more attainable to the household. An important part of the abundance metric, Accessibility expands this project’s scope in illustrating that, with water, price is not the whole story.

Section 8.3: Quality

The Joint Monitoring Programme for Water Sanitation and Supply (JMP) extensively monitors the world’s water situation in two veins: quality and accessibility. In the former, quality is measured via the drinking water ladder discussed in Section 7. In Ethiopia’s context, the analysis of water quality progress is promising, with an increasing number of Ethiopians having access to an improved water source (limited, basic, and safely managed).

Ethiopia’s water situation over the past few decades has been marked by examples of physical water scarcity in the form of droughts, population growth, and transboundary conflicts. The 2015/2016 drought affected approximately 10 million Ethiopians

⁷⁵ “JMP - Ethiopia Drinking Water,” accessed March 10, 2021, <https://washdata.org/data/household#!/dashboard/new>.

with water and food insecurity throughout the country⁷⁶. Primarily caused by the irregular, late, and low rainfall seasons, this drought exposed the physical dependence on rainfall and surface water resources and the crutch of this reliance. The country is still experiencing the effects of this ongoing drought today, and subsequent below average rain seasons have slowed a full recovery. While primarily affecting harvests and food security, the portion of the population using unimproved or surface water sources is just as directly affected⁷⁷. Ethiopia's history has been marked by numerous droughts and famines, the worst of which in modern history occurring from 1983-1985 – killing approximately 1.2 million people⁷⁸. Repeated in 2003, droughts affected close to 13.2 million people, primarily with food shortages and malnutrition. Altogether, these issues have stemmed from the geographical effects on the country, disproportionately affecting those in rural and agricultural areas⁷⁹. Droughts and famines continue to be a severe problem for Ethiopia, but the increasing incidence and access to improved water sources decreases the number of households relying on surface and unimproved water.

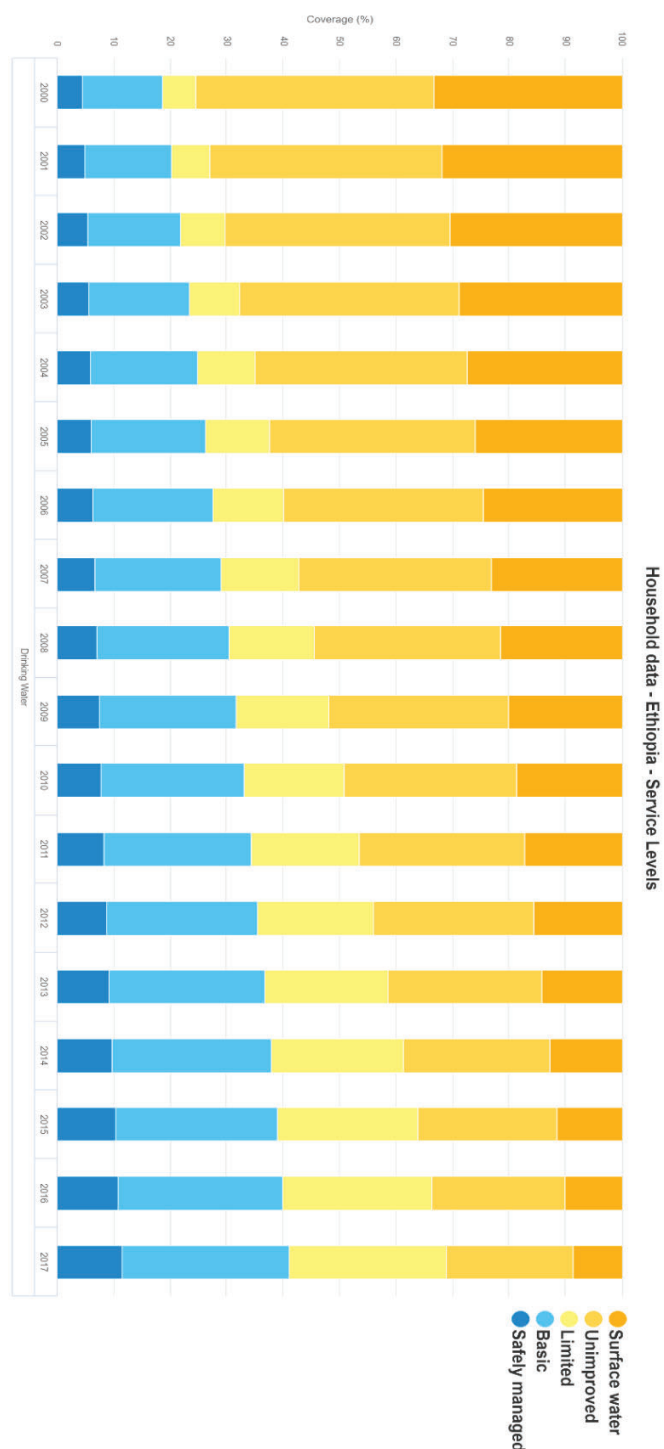
Figure 8.6 shows the progression of increasing water quality in Ethiopia from 2000 to 2017 with a steady trend from approximately 24.51% consuming from an improved source to 68.9% in 2017. Conversely, the portion consuming from unimproved or surface water sources has shrunk steadily. From this visual representation, it can be readily stated that the access to quality water has been improving in Ethiopia – but is important to discuss the context in which this water quality trend has occurred. In particular, the context of the situation before, during, and after this time frame must be discussed.

⁷⁶ “Science Summary: The Drought in Ethiopia, 2015 - Ethiopia | ReliefWeb,” accessed March 9, 2021, <https://reliefweb.int/report/ethiopia/science-summary-drought-ethiopia-2015>.

⁷⁷ Ibid.

⁷⁸ Theodore M Vestal, “Famine in Ethiopia: Crisis of Many Dimensions,” *Africa Today* 32, no. 4 (1985): 7–28, <http://www.jstor.org/stable/4186321>.

⁷⁹ “Ethiopia - Drought Fact Sheet #15, Fiscal Year (FY) 2003 - Ethiopia | ReliefWeb,” accessed March 9, 2021, <https://reliefweb.int/report/ethiopia/ethiopia-drought-fact-sheet-15-fiscal-year-fy-2003>.

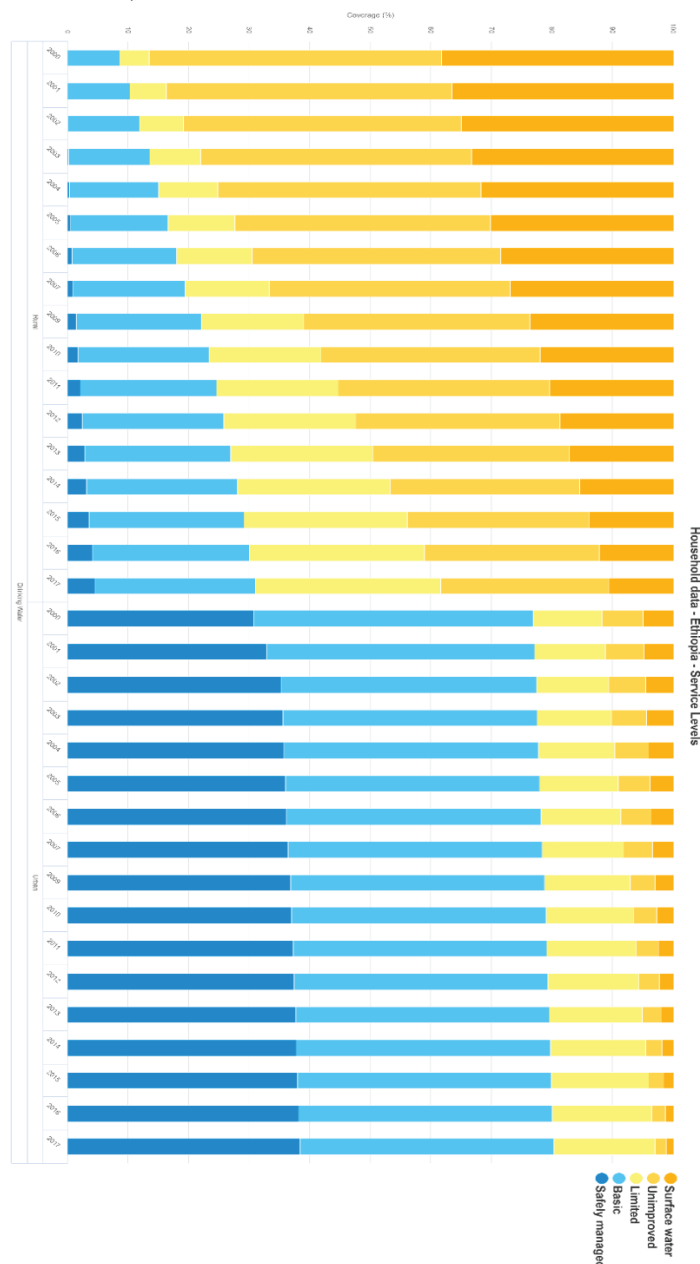


(Figure 8.6: National Percentage of Ethiopians with Access to an Improved Water Source⁸⁰)

For a developing country like Ethiopia, the increasing prevalence of improved water sources points to an improving situation within the country. But, within a developing country that is substantially rural, the disparities in access to improved water sources are often noticeable.

⁸⁰ Fig. 8.6, National percentage of Ethiopians with access to an improved water source, Figure, “JMP - Ethiopia Drinking Water.”, <https://washdata.org/data/household#!/table?geo0=country&geo1=ETH>.

In the case of Ethiopia, the difference between the percent of population using improved water sources in rural and urban regions is around 7.16% in 2017, as illustrated in Figure 8.7 (down from an 11.03% difference in 2000)⁸¹.



(Figure 8.7: Rural and Urban Percentages of Ethiopians with Access to an Improved Water Source⁸²)

Observing these disparities provides context to intra-country dynamics and changes between population groups. This tightening gap is an optimistic sign of progress towards

⁸¹ “JMP - Ethiopia Drinking Water.”

⁸² Fig. 8.7, Rural and urban percentages of Ethiopians with access to an improved water source, Figure, “JMP - Ethiopia Drinking Water.”, <https://washdata.org/data/household#!/table?geo0=country&geo1=ETH>.

homogenized quality across Ethiopia, but with regards to the highest level of water quality outlined, Safely Managed Water, Ethiopia still lags behind in national access.

The nearly 45% increase in access to improved water sources has been a tremendous mark of progress for Ethiopia, but at the same time the percentage of population using safely managed water sources has only marginally increased. Nationally, this percentage with access has only increased 6.91% over 17 years (Figure 8.6). To satisfy “Safely Managed”, the water must be (1) accessible on the premises, (2) available when necessary, and (3) free from contamination. For Ethiopia, the condition shown to be holding this back is #3: the quality of water being free from contamination. JMP’s 2016 Water Quality Report on Ethiopia outlines the *E. Coli* risk in a glass of household drinking water by source, geographic location, and wealth quintile – where they primarily find that the wealthiest, urban Ethiopians with piped sources on their premises had the lowest risk of contamination⁸³. This result is in line with general trends globally, but the regional and source-based data highlights similar disparities between urban and rural regions. In particular, the rural regions of Ethiopia had substantially higher risks of *E. Coli* contamination than urban – with 91.1% of sources with very high risk coming from rural settings and being categorized as unimproved or surface water⁸⁴. For a primarily rural country, this percentage is an indicator that the progress towards improved water sources still requires direct attention towards decreasing contamination risk.

To apply the quality sub-element to Ethiopia, we must first build the average weighted water quality for Ethiopia nationally. Using JMP household data, we can effectively model the trends within water quality over time. Average Weighted Water Quality is defined as:

$$\begin{aligned} \text{AvgWeightedWaterQuality} \\ = 5 * (\% \text{ pop5}) + 4 * (\% \text{ pop4}) + 3 * (\% \text{ pop3}) + 2 * (\% \text{ pop2}) + 1 \\ * (\% \text{ pop1}) + 0 * (\% \text{ pop0}) \end{aligned}$$

where:

Safely managed = 5
Basic = 4
Limited = 3
Unimproved = 2
Surface water = 1
No water access = 0

Ethiopia’s Average Weighted Water Qualities from 2011-2017, consistent with affordability and accessibility data, are detailed in Table 8.1 below:

⁸³ CSA Ethiopia, “Drinking Water Quality in Ethiopia. Results from the 2016 Ethiopia Socioeconomic Survey.”, 39.

⁸⁴ Ibid, 10.

Year	% No Ac	% Surface W	% Unimproved	% Limited (3)	% Basic (4)	% Safely Managed	AvgWeightedWat	Quality Element	Quality w/ Weight
2011	0	17.12	29.44	19.11	26.02	8.3	2.79	0.56	0.279
2012	0	15.67	28.27	20.5	26.78	8.78	2.85	0.57	0.285
2013	0	14.24	27.1	21.92	27.47	9.27	2.9	0.58	0.290
2014	0	12.81	25.94	23.37	28.1	9.78	2.96	0.59	0.296
2015	0	11.4	24.79	24.83	28.67	10.31	3.02	0.60	0.302
2016	0	9.99	23.64	26.33	29.17	10.87	3.07	0.61	0.307
2017	0	8.6	22.5	27.84	29.62	11.44	3.13	0.63	0.313

(Table 8.3: Ethiopia Average Weighted Water Quality 2011-2017⁸⁵)

From 2011 to 2017, the Average Weighted Water Quality increased by 0.34 points nationally in Ethiopia, with a baseline of 0% of households reporting no water access. But while the overall proportion of increase is towards Limited and Basic services, Safely Managed is still quite sparse. While this set of water data is limited to these years, in ideal practice this experiment can provide a time-series look through several decades: an ultimate illustration of Ethiopia through development of water infrastructure and modernization.

Section 8.4: Water Abundance Index for Ethiopia

The ultimate Abundance Index outlined in Section 9 is defined as:

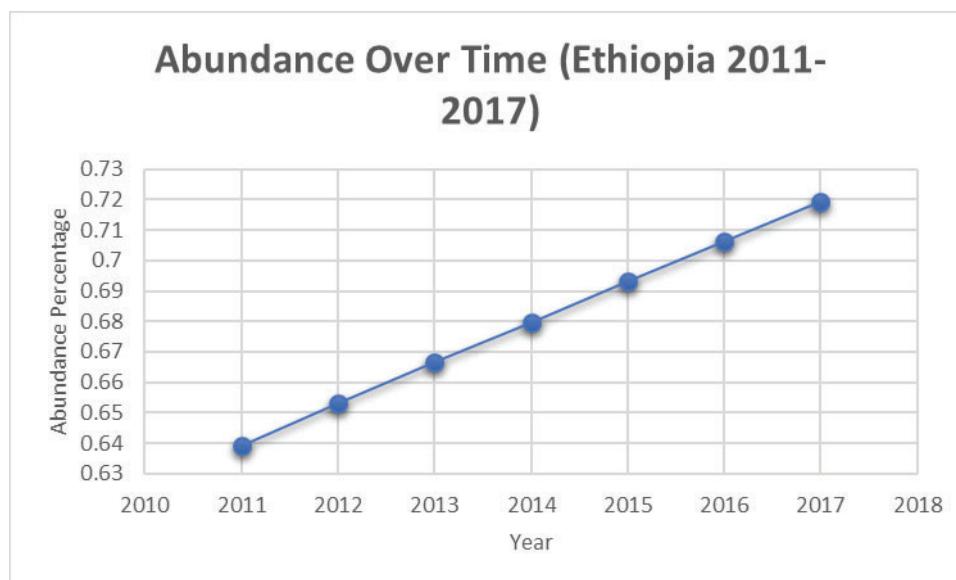
$$Abundance = \alpha_1 Affordability + \alpha_2 Accessibility + \alpha_3 Quality$$

Sections 8.1, 8.2, and 8.3 have directly applied each element to the case study of Ethiopia and described the trend of each in the recent decade. Pulling these three elements together, we can characterize the “economic abundance” of water in Ethiopia from 2011-2017, illustrated in Figure 8.8.

Year	Affordability	w/ Weight (0.2)	Accessibility	w/ Weight (0.3)	Quality	w/ Weight (0.5)	ABUNDANCE	% Change
2011	1	0.2	0.534	0.160	0.558	0.279	0.639	0.00%
2012	1	0.2	0.561	0.168	0.569	0.285	0.653	1.37%
2013	1	0.2	0.587	0.176	0.581	0.290	0.666	1.35%
2014	1	0.2	0.613	0.184	0.592	0.296	0.680	1.34%
2015	1	0.2	0.638	0.191	0.603	0.302	0.693	1.33%
2016	1	0.2	0.664	0.199	0.615	0.307	0.706	1.33%
2017	1	0.2	0.689	0.207	0.626	0.313	0.720	1.31%

(Table 8.4: The Water Abundance Index for Ethiopia)

⁸⁵ “JMP - Ethiopia Drinking Water.”



(Figure 8.8: Economic Abundance of Water in Ethiopia 2011-2017)

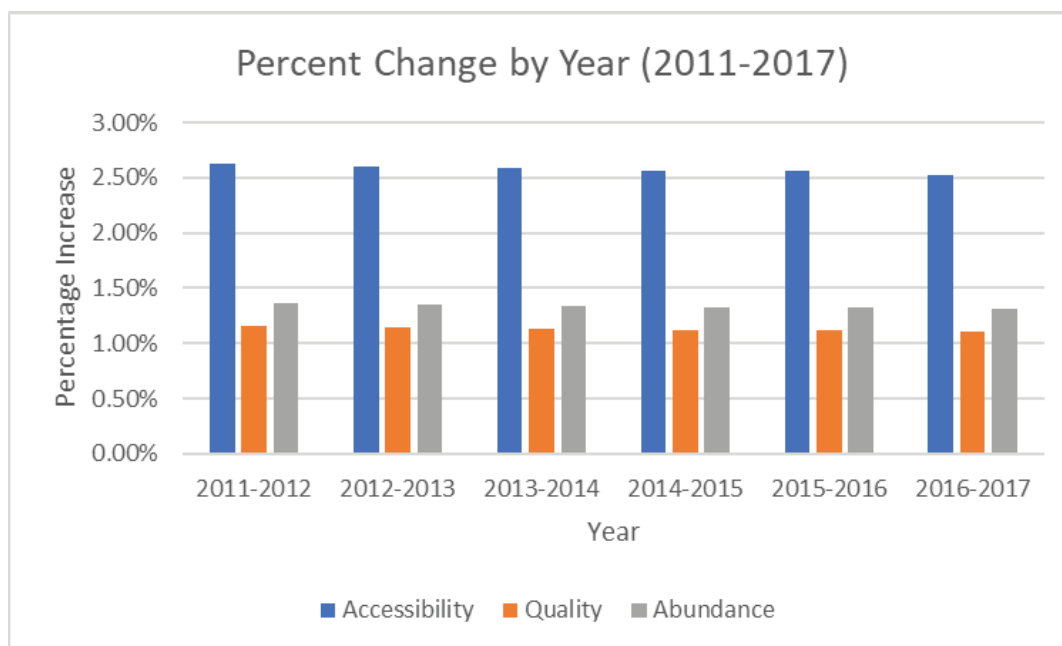
Over the 7 years, Ethiopia’s Water Abundance score increased from 0.639 to 0.720, or 8.03%, at a remarkably constant rate. Averaging a 1.34% increase per year, the Abundance measure was most impacted by the strong increase in access to improved water sources with a more modest increase in overall average quality of water. In analyzing the relative changes in each element, we find that accessibility’s increase far outpaces quality and the resulting abundance change (Figure 8.9).

The oddly constant rate of increase within Ethiopia might be cause for questioning the reliability of monitoring data, but logically is understandable in the context of Ethiopia’s development. When analyzing the overall change from 25% population with access to improved water sources increasing to 69% over the 2000-2017 period, we find an element of diminishing returns to increased access. While the average percentage change in access is 2.61% per year, the per year unit change has ranged between 2.53% in 2017 to a height of 2.69% in 2008. While slight, the diminishing returns to increasing access is a sign of progress in development past early stages where we might expect large increases in access.

As a country receiving billions of USD in aid, Ethiopia has dedicated investment in water security and WASH infrastructure⁸⁶. A consistent rise in increased access to improved water sources constitutes a possible piece of anecdotal evidence for this investment both boosting economic growth and strengthening infrastructure. According to the US Agency for International Development (USAID), extensive agency aid activities have included increasing the accessibility of improved drinking water sources nationwide⁸⁷. While 69% with access to improved water sources is still not ideal, the vast increase from 25% less than two decades earlier marks a measure of success for development activities and investment in Ethiopia.

⁸⁶ “How Foreign Aid Helps Ethiopia | The Borgen Project.”

⁸⁷ “Water | Ethiopia | U.S. Agency for International Development,” accessed April 5, 2021, <https://www.usaid.gov/ethiopia/water-and-sanitation>.



(Figure 8.9: Percentage Change by Year 2011-2017)

In final analysis of our results, we find that in the case of Ethiopia:

1. *The indicator for Affordability provides an ambiguous result in its current state. For it to more effectively capture “affordability” through the lens of the weighted water price, it requires more extensive data on the provision mechanisms implemented within the country and the price associated with consuming water from it. At the moment, the project has modeled using public provision water charges – the most accessible and measurable.*
2. *The rise in access to improved water sources is an optimistic sign of increasing development of cleaner and more reliable water infrastructure. While still lagging behind, the rise in use of Safely Managed services trends in the upwards direction: an indicator of broadly increasing quality at the highest end.*
3. *The “Economic Abundance of Water” in Ethiopia, as we describe it, has increased steadily from 2011-2017. While bound by water charge data, this project has the ability to describe accessibility and quality at large for the past two decades across multiple countries*

Conclusion

This paper started with a quote from Julian Simon where he discussed his hypothesis that over time resources would become a smaller and smaller portion of our expenses and thus more

“abundant”. In 1990, he was proven correct (partially) by winning a wager with Paul Ehrlich on the real prices of precious metals. This hypothesis has transcended into modern-day cornucopian thinking that resources may not be in such dire circumstances as previously thought. Using market goods, the Simon Abundance Index has built a time price that supports Simon’s hypothesis. But water is not a clear market good, and as such, price is not the whole story.

Center to understanding water’s “abundance” is how water acts in a market. This project theoretically outlines how water is provided and where we would expect to see those provision mechanisms. Within the four primary mechanisms, we identify differences in pricing that would be largely dependent on the marginal cost of provision to households as well as the external financing. Expected within developing nations, non-piped water provision might constitute a larger portion of a household’s income – but it ultimately depends on the water situation within the region or country at large. As a further point of analysis, explicit prices in reality do not account for the unquantifiable costs that come from water consumption: travel, wait, or manual labor. In the ideal scenarios, all costs to the consumer would be well captured within a weighted water price that describes the situation of the country with all mechanisms incorporated.

The weighted water price index was the primary component of the affordability metric within the proposed Water Abundance Index. The index, as this project describes, is a weighted value that attempts to characterize “economic abundance” in the spirit of Simon and Nordhaus but to a non-market good such as water. As a result, we identify that affordability is not alone for water’s “abundance”. As important, if not more, are the facets of quality and accessibility of water sources that lay the foundation for affordability to even be feasible. At the base of the Index (and holding most in proposed weighting) is water quality.

Measuring quality for water has long been the focus of international development organizations such as World Bank and USAID. In developing countries with aging or insufficient drinking water infrastructure, this priority is often the forefront within aid and development. For countries to meet “Safely Managed” criteria as defined by the Joint Monitoring Programme, extensive focus must be placed on decontaminating and providing clean water rather than providing through an unimproved source. This project classifies accessibility more as the binary move to an “improved water source” on the Drinking Water Ladder. As a broader scope, accessibility attempts to characterize the trend of progress in water infrastructure where water quality improvements may accompany. Altogether, the triplet approach to characterizing economic abundance attempts to provide the larger picture of water provision beyond the pure price a consumer pays.

When applied to Ethiopia, the Water Abundance Index provides a result partially in line with Simon’s hypothesis. While this project is limited in data access for the alternative provision mechanisms, it shows that each element of the index is improving over time in one of the poorest developing nations. Further, it identifies which elements are primarily driving an increasing abundance: in this case, the consistent rise in accessibility of improved water sources for the population. Lagging behind is the increase in use of safely managed water services, where future development and investment should, in large part, be directed towards. In our initial case study, we find the case of water abundance to be greatly driven by the investment and technological interest in developing better water infrastructure. In addition to population growth and climate

change, these factors are influential in the three determinants of abundance. For a country like Ethiopia, continued foreign aid and directed infrastructure projects directly affect the quality and accessibility of water sources for the population. Similarly in line, population and economic growth in Ethiopia have directly boosted the GNI per capita – a factor in driving up affordability for the WAI. That said, we return to seemingly contradictory empirical results.

Figure 4.2 in Section 4.3 shows a general pattern of decreasing affordability in Africa. While the region broadly was shown to have increasing percentages of income spent on water utilities, our application of the WAI to Ethiopia indicates otherwise – at least for Ethiopia. It is possible that there are more unidentified determinants at play that would influence the African region more broadly. Additionally, by our determinants, increasing water costs could possibly be offset by increased accessibility and quality that would provide insight into the case presented in Figure 4.2. This contradiction is potentially fruitful for future research into why this is the case.

With water, the answer is often unclear, and the price is not the whole story. This project has attempted to develop an index the international world can use to evaluate water situations within countries and across regions. In future projections, this index can be used to understand trends and shifts in how water is provided across the world. While Julian Simon may have won his wager on precious metals, his methodology and hypothesis could survive in the world's most precious resource.

References

- Ann Wheeler, Sarah, and Dustin E Garrick. “A Tale of Two Water Markets in Australia: Lessons for Understanding Participation in Formal Water Markets.” *Oxford Review of Economic Policy* 36, no. 1 (2020): 132–53. <https://doi.org/10.1093/oxrep/grz032>.
- Beck, Michael Bruce, and Rodrigo Villarroel Walker. “On Water Security, Sustainability, and the Water-Food-Energy-Climate Nexus.” *Frontiers of Environmental Science and Engineering*, 2013. <https://doi.org/10.1007/s11783-013-0548-6>.
- “California Water Futures Begin Trading Amid Fear of Scarcity - Bloomberg.” Accessed February 24, 2021. <https://www.bloomberg.com/news/articles/2020-12-06/water-futures-to-start-trading-amid-growing-fears-of-scarcity>.
- CSA Ethiopia. “Drinking Water Quality in Ethiopia. Results from the 2016 Ethiopia Socioeconomic Survey,” no. December (2017): 22.
- “Cost of Living in Ethiopia. Prices in Ethiopia. Updated Mar 2021.” Accessed March 28, 2021. https://www.numbeo.com/cost-of-living/country_result.jsp?country=Ethiopia.
- Damania, Richard. “The Economics of Water Scarcity and Variability.” *Oxford Review of Economic Policy* 36, no. 1 (2020): 24–44. <https://doi.org/10.1093/oxrep/grz027>.
- Damania, Richard, Sébastien Desbureaux, Aude-Sophie Rodella, Jason Russ, and Esha Zaveri. “Quality Unknown: The Invisible Water Crisis,” 2019.
- “Drinking Water | JMP.” Accessed February 16, 2021. <https://washdata.org/monitoring/drinking-water>.
- Ehrlich, Paul R, and Anne H Ehrlich. “The Population Bomb Revisited.” *The Electronic Journal of Sustainable Development*, 2009. www.ejsd.org.
- “Ethiopia | Globalwaters.Org.” Accessed March 4, 2021. <https://www.globalwaters.org/wherewework/africa/ethiopia>.
- “Ethiopia - Drought Fact Sheet #15, Fiscal Year (FY) 2003 - Ethiopia | ReliefWeb.” Accessed March 9, 2021. <https://reliefweb.int/report/ethiopia/ethiopia-drought-fact-sheet-15-fiscal-year-fy-2003>.
- “Ethiopia GNI per Capita, Atlas Method (Current US\$) - Ethiopia | Data.” Accessed March 10, 2021. <https://data.worldbank.org/indicator/NY.GNP.PCAP.CD?locations=ET>.
- “Ethiopia | History, Capital, Map, Population, & Facts | Britannica.” Accessed March 4, 2021. <https://www.britannica.com/place/Ethiopia>.

- “Ethiopia Overview.” Accessed March 10, 2021.
<https://www.worldbank.org/en/country/ethiopia/overview>.
- Garrick, Dustin E, Michael Hanemann, and Cameron Hepburn. “Rethinking the Economics of Water: An Assessment.” *Oxford Review of Economic Policy* 36, no. 1 (2020): 1–23.
<https://doi.org/10.1093/oxrep/grz035>.
- Ghana Statistical Service. “Survey Findings Report Ghana Multiple Indicator Cluster Survey 2017/18 Republic of Ghana Ghana Statistical Service,” 2018.
- Gill, Wendy J., and Julian L. Simon. “The Ultimate Resource 2.” *The Geographical Journal*, 1998. <https://doi.org/10.2307/3060381>.
- Giordano, Mark. “A Review of the Evolution and State of Transboundary Freshwater Treaties,” 2013.
[https://transboundarywaters.science.oregonstate.edu/sites/transboundarywaters.science.oregonstate.edu/files/Publications/Giordano et al. Treaty Update 4-13.pdf](https://transboundarywaters.science.oregonstate.edu/sites/transboundarywaters.science.oregonstate.edu/files/Publications/Giordano%20et%20al.%20Treaty%20Update%204-13.pdf).
- Grafton, R Quentin, Long Chu, and Paul Wyrwoll. “The Paradox of Water Pricing: Dichotomies, Dilemmas, and Decisions.” *Oxford Review of Economic Policy* 36, no. 1 (2020): 86–107.
<https://doi.org/10.1093/oxrep/grz030>.
- Helm, Dieter. “Thirty Years after Water Privatization—Is the English Model the Envy of the World?” *Oxford Review of Economic Policy* 36, no. 1 (2020): 69–85.
<https://doi.org/10.1093/oxrep/grz031>.
- “HumanProgress: Percent of Population Using Improved Drinking Water Sources.” Accessed January 12, 2020.
<https://humanprogress.org/dwline?p=524&yf=1990&yl=2015&high=0®=3®1=0>.
- “Improved Water Source (% of Population with Access) | Data Catalog.” Accessed February 16, 2021. <https://datacatalog.worldbank.org/improved-water-source-population-access>.
- “JMP - Ethiopia Drinking Water.” Accessed March 10, 2021.
<https://washdata.org/data/household#!/dashboard/new>.
- Jones, Charles I. “Paul Romer: Ideas, Nonrivalry, and Endogenous Growth*.” *Scand. J. of Economics* 121, no. 3 (2019): 859–83. <https://doi.org/10.1111/sjoe.12370>.
- Liu, Junguo, Hong Yang, Simon N. Gosling, Matti Kummu, Martina Flörke, Stephan Pfister, Naota Hanasaki, et al. “Water Scarcity Assessments in the Past, Present, and Future.” *Earth’s Future* 5, no. 6 (June 2017): 545–59. <https://doi.org/10.1002/2016EF000518>.
- London, Thomas Malthus. “An Essay on the Principle of Population,” 1998. <http://www.esp.org>.

Nordhaus, William D. “Do Real-Output and Real-Wage Measures Capture Reality? The History of Lighting Suggests Not.” In *The Economics of New Goods*, 1996.

Olmstead, Sheila M, W Michael Hanemann, and Robert N Stavins. “Water Demand under Alternative Price Structures.” *Journal of Environmental Economics and Management* 54 (2007): 181–98. <https://doi.org/10.1016/j.jeem.2007.03.002>.

Renzetti, Steven. “Wave of the Future: The Case for Smarter Water Policy.” *C.D.Howe Institute Commentary*, no. 281 (2009): COV.
http://uvic.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMw3V1LT8MwDLbYLnBBvN8oJy5Tqz7S0iJxQIVpnCZgwHFK00TaYS3aCvv7xE36GNL-AJeqSiW3-VzFTvzZBvA927H-rAluLNxIUi-NZRh5kqc8k5HMWMCFT31G17PJmgao7dh_UPwn9hMykX9dMaTmbnBlsSpa4XJeMTkHK4bXr7Y0cF2ywH60B6NiJTpcAswkQZ.

Rijsberman, Frank R. “Water Scarcity: Fact or Fiction?” In *Agricultural Water Management*, 80:5–22, 2006. <https://doi.org/10.1016/j.agwat.2005.07.001>.

“Real, Relative, and Nominal Prices - Econlib.” Accessed April 22, 2021.
<https://www.econlib.org/library/Topics/College/realrelativenominalprices.html>.

Sachs, Jeffrey D, and Andrew M Warner. “The Curse of Natural Resources,” n.d.

Sadoff, C.W. Claudia W., Jim W. Hall, D. Grey, Jeroen C.J.H. Aerts, M. Ait-Kadi, C. Brown, A. Cox, et al. *Securing Water, Sustaining Growth: Report of the GWP/OECD Task Force on Water Security and Sustainable Growth*. 180, 2015. <https://doi.org/http://dx.doi.org/>.

“Science Summary: The Drought in Ethiopia, 2015 - Ethiopia | ReliefWeb.” Accessed March 9, 2021. <https://reliefweb.int/report/ethiopia/science-summary-drought-ethiopia-2015>.

Seckler, David, Randolph Barker, and Upali Amarasinghe. “Water Scarcity in the Twenty-First Century.” *International Journal of Water Resources Development* 15, no. 1–2 (1999): 29–42. <https://doi.org/10.1080/07900629948916>.

Shi, Minjun, Xiaojun Wang, Hong Yang, and Tao Wang. “Pricing or Quota? A Solution to Water Scarcity in Oasis Regions in China: A Case Study in the Heihe River Basin.” *Sustainability (Switzerland)* 6, no. 11 (2014): 7601–20. <https://doi.org/10.3390/su6117601>.

Tatlock, Christopher. “Water Stress in Sub-Saharan Africa | Council on Foreign Relations.” Accessed January 2, 2020. <https://www.cfr.org/backgrounder/water-stress-sub-saharan-africa>.

“The IBNET Water Supply and Sanitation Blue Book 2014: The International ... - Alexander Danilenko, Caroline van Den Berg, Berta Macheve, L. Joe Moffitt - Google Books.” Accessed March 2, 2021.

https://books.google.com/books/about/The_IBNET_Water_Supply_and_Sanitation_BI.html?id=61BjBAAAQBAJ.

“The Untapped Potential of Decentralized Solutions to Provide Safe, Sustainable Drinking Water at Large Scale,” 2017. [https://www.dropbox.com/s/e8xg7or8dgxv7wu/20170208 Water Kiosk Study Sector Report_vSS.PDF?dl=0](https://www.dropbox.com/s/e8xg7or8dgxv7wu/20170208_Water_Kiosk_Study_Sector_Report_vSS.PDF?dl=0).

“Total Water Revenues per Service Population/ GNI Per Capita - IBNet.” Accessed April 5, 2021. <https://database.ib-net.org/Reports/Indicators/InCountry?itemId=62&countryId=10&viewWeight=false>.

Tupy, Marian L. “Desalination Shows Tech Can Solve Environmental Problems.” Accessed January 5, 2020. <https://humanprogress.org/article.php?p=1337>.

Vestal, Theodore M. “Famine in Ethiopia: Crisis of Many Dimensions.” *Africa Today* 32, no. 4 (1985): 7–28. <http://www.jstor.org/stable/4186321>.

“Water | Ethiopia | U.S. Agency for International Development.” Accessed April 5, 2021. <https://www.usaid.gov/ethiopia/water-and-sanitation>.

“Water Scarcity Assessments in the Past, Present, and Future - Liu - 2017 - Earth’s Future - Wiley Online Library.” Accessed January 2, 2020. <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1002/2016EF000518>.

“Water Wars: Ethiopia and Kenya | Pulitzer Center.” Accessed March 9, 2021. <https://pulitzercenter.org/projects/water-wars-ethiopia-and-kenya>.

“World Bank Country and Lending Groups – World Bank Data Help Desk.” Accessed March 4, 2021. <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups>.

Young, Sera L., Godfred O. Boateng, Zeina Jamaluddine, Joshua D. Miller, Edward A. Frongillo, Torsten B. Neilands, Shaleen M. Collins, Amber Wutich, Wendy E. Jepson, and Justin Stoler. “The Household Water InSecurity Experiences (HWISE) Scale: Development and Validation of a Household Water Insecurity Measure for Low-Income and Middle-Income Countries.” *BMJ Global Health* 4, no. 5 (2019). <https://doi.org/10.1136/bmjgh-2019-001750>.