Plan B water assessment: Efficiency and circularity for agricultural and municipal adaptation to water scarcity

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ABSTRACT
Municipal supply of water under climate variations, growing population, uncertainty, and scarcity, requires water planners to devise feasible and sustainable water sourcing plans; especially for territories relying on groundwater. The conventional ways to cope with water scarcity will no longer guarantee reaping the maximum benefits of declining available water resources. Efficiency and circularity of water are claimed as essential criteria for seeking solutions in designing long-term supply management. A Plan B water assessment applied to a group of municipalities in dry areas of Colombia, is proposed as a hydro-economic model aimed at providing inputs for water resources planning, in which the depletable and common-pool character of aquifers are incorporated. A declination speed index is introduced in two ways: the surface \( \rightarrow \) water table distance and water table \( \rightarrow \) saturated thickness distance. This issue should not be overlooked if spatial differentiation in water tables is incorporated in groundwater extraction permits analysis for multiple and convergent water users. Research results are promising for sustainability of water management in dry areas around the world. Respect to status quo situation a 22% of efficiency gain might be achieved in the next 20 years in Sucre – Colombia, under an efficient model of water consumption. If an efficient and circular water management model is endeavored, multiple gains would be harvested for the benefit of water users and ecosystems relying on aquifers. Increased efficiency is mostly driven by 30 million m\(^3\) sewage water recirculated in agriculture, which in turn would prevent aquifer extraction for this activity. In business-as-usual scheme, water efficiency gap will be wider; extraction costs will rise to prohibitive levels for low income municipalities; the declining water tables will oblige to make new punches by simultaneous water users and water declination index calculated would reflect a precipitous decay. Research results provide empirical evidence to the discussion on possible solutions for sustainable and efficient water management as stated in Sustainable Development Goals; specifically target goal 6.4 determines that water efficiency and sustainability in water withdrawals should be accomplished. Local setting on water resources availability, competition on resources, types of users, sewage water treatment technology, energy costs, and institutions in time and place, would determine the replicability of research results.

1. Introduction

Different cities in the Caribbean of Colombia are exhibiting perilous signs of vast pressures on water systems. Surface water are suffering of water flow attenuation and groundwater tables of aquifer are declining even in rainy seasons. Municipal supply of water under climate variations, growing population, uncertainty, and scarcity, requires water planners to devise feasible and sustainable water sourcing plans; especially for territories relying on groundwater such as municipalities over Morroa Aquifer (Sucre and Córdoba Departments), in which water supply to match demand is running down groundwater at a high rate.

Managing water supply to match levels of water demand is a reasonable economic and management approach, since tense situations created by water shortages are to be circumvented. Despite the environmental and water authorities’ efforts, to implement economic and political instruments to manage groundwater competition and efficient water allocations (OECD, 2015; 2017a), repeated water shortages create perceptions of government failure (World Bank, 2018). Whether plentiful or scarce, water managers are told to bring abundant water to all who demand it (Zetland, 2011). Notwithstanding, when referring to...
groundwater management the analysis might not be so simple as matching supply with demand.

Shared aquifer systems by different municipalities, represent a case in which groundwater stocks exhibit a puzzling interdependent matter. Different municipal water utilities abstracting from shared aquifer cells, might be independently confident that their aquifer water supply is enough to satisfy demand in their jurisdictions. However, one municipality’s demand may impinge a limited supply onto other neighboring municipalities. For instance, some adjacent municipalities endowed with less technological capacity for water abstractions, would reap less benefits from groundwater resources in comparison to the better equipped ones.

Since every single municipality must independently manage water resource, it does not mean that interdependent aquifer resources may prevent that an interdependent water resources management plan by multiple municipalities might be devised. Interdependency in groundwater resources is palpable through different hydrogeological variables. More outstandingly groundwater and surface water exhibit unnoticed water flow interactions (Glennon, 2002; Winter et al., 1998). For illustration, the steady groundwater abstraction in waterwells under operation create a cone of depression. The interdependent feature arises when cones of depression are overlapped when multiple wells are active.

Another two factors demonstrating this interdependence, make reference to Environmental Flow Requirements (EFR)1 and groundwater extraction costs. Water contamination impair streams and lakes due to point and non-point sources (Peterson, J. and Smith, 2012) and natural flow regimes is essential in sustaining the health of river ecosystems (Richter et al., 2012). Because EFRs are ignored, the quantity of water available for human consumption globally is probably overestimated (Gerten et al., 2013). Second factor refers to rising extraction costs when water table declines (Krucze, D., Roumasset, J., & Wilson, 1997). Indeed, this is part of the externalities arising in typical common-pool resources (CPR).2 Neighbor municipalities sharing a single cell aquifer may experience different extraction costs. Some of them might be located over more productive spots, meanwhile the others might be placed over deeper water tables, which oblige them to incur in higher cost to collect needed water units.

Groundwater table declination and droughts are pervasive phenomena in Western USA, Australia, Morocco, Mexico, Iran, Jordan, Iran, India, parts of China and other areas in South Asia (World Bank, 2018). Climate shocks are taking a toll on many urban centers and amplifying the unpredictability of freshwater availability, which is exacerbated due to increasing numbers of prolonged droughts affecting competing users (World Bank, 2018). Different municipalities in the Caribbean region of Colombia relying on groundwater for domestic and agricultural purposes, exhibit frequent water scarce and drought situations (IDEAM, 2014) and water use altogether entail interdependent effects of water extractions.

The interdependency of extractions should be assessed and incorporated in water planning. Water supply should be consistent with the declining water tables, and all the pressures upcoming from climate change and the hidden competition of water in shared aquifers. Similarly, given the observed pervasive declinations of water tables in the area of study and around the world, there is an urgent call to pursue a sustainable management of water resources. Therefore, how to design and implement groundwater sustainability plans for interdependent water users, represent the main research question of this article. One may think of sustainability of water resources in terms of matching water demanded to actual and forecasted water supply. Otherwise, one may prefer to challenge extant water demand patterns and drive it towards efficient water consumption levels; consequently, efficiency would probably imply consuming less than different water users are accustomed to.

In reference to efficiency, one may question whether consuming 110 l/person/day3 at household levels is an excessive volume of water or not; whether actual volumes of water applied to agricultural activities are efficient enough to reap the greatest efficiency potential per cubic meter applied to the crops, and whether each volume of water consumed by industries is treated simply as another production input or as a resource which is potentially subject to reuse or recycling. Since water use interdependency appears, and indeed is complex, it should not prevent water planners to trigger water resources efficiency and sustainability plans as part of serious water policies. Managing any resource efficiently (“Pareto efficiency”) occurs when a water allocation can provide no further gains in production or satisfaction without simultaneously creating a loss (Harou et al., 2009). Efficiency, refers to the capacity of water applied to the agricultural and industrial processes to apprehend the maximum potential of water consumed without creating losses to neighbor users. For this aim, best available agricultural practices are used as benchmarks as a mean to address sustainability in consumptive water use. The benchmarks do not necessarily represent a verified sustainable case in terms of environmental footprints; instead, they show that reductions in water consumption in agriculture, industry and households are possible.

The present research is relevant to Sustainable Development Goals (SDG). The research question aim is related to providing empirical evidence about possible strategies to sustainable and efficient water management. The target goal 6.4 of SDGs, states that by 2030 water efficiency and sustainability in water withdrawals should be accomplished. For this SDG efficiency and circularity of water are taken as key criteria for sustainability.

An efficient and circular Plan B is proposed. Plan A represents the status quo in which supply is matched with the demand. The proposed models do not pretend being all-encompassing; but it incorporates the need for water from neighboring municipalities, it includes the Environmental Flow Requirement of ecosystems depending on groundwater as well. An Optimal Control Theory model is utilized to optimize extractions for each municipality (i) given the optimal extraction of the neighbor municipalities (-i). In this case, Sincelejo (Sucre) is used as the initial point of departure for optimization analysis.

This article is organized as follows; introductory statements and justifications are included in this section 1. Problem statement is added to summarize some stylized facts and to make it comparable with other regions of the world. In Section 2, a short description of literature review of relevant publications is developed, keywords such as water management, scarcity and groundwater were used. Section 3, presents the research methods mainly focused in Optimal Control Theory application to calculate optimal extractions. Section 4 consists of research results. It includes water efficiency gap, water table declination index calculated and scenarios presented to discuss efficiency gains. Finally, in discussion and conclusions (sections 5 and 6) attention is drawn on the need to abandon the inertial water supply management scheme of simple matching supply with demand.

1.1. Problem statement

Since the aquifer stock is not part of the observed key variables in municipal long-term planning, the exhaustible nature of aquifers is rarely embedded in ex-ante analysis of municipal water planning. Focusing only on water table declination, does not guarantee complete knowledge of aquifers as a water source for ecosystems and humans, whose resources may end exhausted. Water planning instruments such

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1 Quality, quantity and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (IRF - International River Foundation, 2007).
2 For discussions about the nature of Common-Pool Resources see (Negril, 1989; Ostrom, 2015; Ostrom et al., 1994).
3 Reported water consumption level in Sucre up to 2018.
as Water Efficient Use and Saving Plans and Aqifer Environmental Management Plans reflect a sort of myopic analysis in terms of the unattended interdependent effects of water abstractions. Municipalities relying on aquifers for freshwater provision and agricultural activities may impose negative effects onto other municipalities. This is especially relevant for municipal water companies, industries and farmers’ boreholes built over single-cell aquifers.

The problem statement is relevant for more locations in Colombia and water scarce cities around the world. For this particular context, urban and rural areas reliance on abstraction aquifers is a tough issue to manage in Sucre (Colombia) because there is a sort of invisible myopia for water resources between water users and the municipal water facilities. In Sucre, more than 90% of municipalities rely on groundwater to provide water for domestic and agricultural uses. Public entities in charge of water management use powerful pumps to collect water from the underground and distribute it to households. Some waterwells have experienced declinations around 17 m/year which threaten aquifer sustainability (Cansucrè, 2003). Aside, up to 2011 there existed 1,788 water wells under operation. It shows that there is not a unique centrally-managed water distribution system but a collection of private and public boreholes which are jeopardizing water resources.

However, competition for groundwater reserves is not symmetric. When observing Map 1, groundwater access is uneven for a single municipality (for instance in Ovejas or Sampués) since pretending to punch water wells in south-east locations may result fruitless. Consequently, alternative Plan B water sourcing analysis for some locations should be consciously devised. This is especially the case of actual circumstances, in which some locations better endowed with underground water are overexploiting reserves. Which are the feasible scenarios for asymmetric water access and declining water tables for each municipality for next 10, 30, 50 and more years? How to assess and implement future municipal water sourcing plans to meet water demand under the challenges of interdependent water abstractions from neighboring municipalities?

In this research, the Plan B Water Assessment is introduced as an alternative approach which might be useful to support municipalities in adapting to declining water resources. Plan B is based on some criteria named efficiency and interconnectedness of the effects of water extraction. This interconnection is close to the circular economy of water approach, since some opportunities arise in reaping multiple benefits from water while using this resource in the economy.

1.2. Common-pool resources, efficiency and circular economy approach

One municipality relying on surface water for freshwater provision and agricultural activities, might be prone to explore groundwater sources when surface water flows are declined to critical levels. However, new water wells should not be built over randomly selected places, since every well spot represents differing implications in terms of adequacy for aquifer sustainability analysis. Some well spots might not be convenient due to possible deep-water tables, presence of recharge zones, cones of depression confined underground and other key hydrogeological aspects worth to be noted if sustainability becomes a priority. Similarly, if one municipality devise a plan to explore alternative water sources, the need to access water by other neighboring municipalities and users, should not be ignored if bad-mannered competition over water stocks and flows does not want to be sparked.

Each municipality is demanded to take a further inward look at their water flows management. A take – make – waste model (Leonard, 2011) in water management should no longer persist as the status quo. Water should not be wasted few steps after it is taken out from underground and similarly, sewage water should not waste surface water systems at the end of the flow. Since this is the reported case in Sucre for last 20 years, water wasted from the underground source and degenerative flows driven by sewage water at the end, seems to be the social norm. In regional water management and comptroller’s documents, excessive non-accounted water is reported and main creeks serve as point of sewage discharge. Despite the intended efforts to tackle so high undetected water squandering, non-accounted water is still kept as the social norm. Non-accounted water reported in 2003 was 46% (Defensoria del Pueblo, 2005). Shockingly, water losses in Sincelejo were greater than 67% and greater than 55% in Corozal in 2017 (Aguas de la Sabana, 2017) and reduction goals for next five years are conservative, since expected water losses are 55% and 43% respectively (Aguas de la Sabana, 2017). Reducing water losses represent a tough endeavor. Notwithstanding, the urgent need to efficiently manage and adapt to water scarcity and climate variability, demand serious exertions to reduce pressure on groundwater systems. There are rooms for improvements stemming from reduction of water losses; however further opportunities exist in order to turn to water use efficiency. A claim is placed on the need to reap the maximum benefit of water flows.

Pressures on groundwater might be reduced by means of a change in water management paradigm as well. Instead of continuing exerting more water outflows to distribute it to water users, a halt should be made in the logic of outflows allocation. Actual water management dynamic is governed by the logic of bringing abundant water to all who demand it (Zetland, 2011) and increase water supply at the pace of population demand, is how things stand. Water volume outflows should be treated as a valuable resource object to a circular logic as a planned design. A circular approach of water would definitely assist in reaping the maximum potential benefit of water volumes until the last drop of utility is attained. Water used at industries and households should not use water as a simple raw material or as an input for products processing or indoor domestic activities. In its place, a new logic aimed at attaining the highest potential of each liter of water should be imperative.

2. Literature review

Groundwater may have been put to beneficial use for many thousands of years, but the fundamental principles of sustainable groundwater management are very young (Howard, 2015). Conceivably, the more comprehensive concept encompassing the aspirations of efficiency, sustainability and water management refers to Integrated Water Resources Management (IWRM). IWRM is aimed at promoting the coordination in development and management of water, land and related resources, in order to maximize the economic and social welfare in an equitable manner without jeopardizing the sustainability of vital ecosystems (GWP, 2000). One of the recommendations of Paris Statement 2007 to promote sustainable development of water resources, refer to using the entire water cycle (including groundwater) with all its components and their interactions, as a unifying framework for effective management (Howard, 2015). Adding the concept of water cycle might become IWRM as a more complex issue to implement and operationalize. Indeed, IWRM does not provide any real guidance to water professionals and policy makers, so as to make planning, management and decision-making processes, more rational and efficient to achieve (Biswas, 2008).

As an alternative, hydro-economics offer practical applications for the integration of different disciplines supporting sustainable water resources management. Hydro-economic models represent spatially distributed water resource systems, infrastructure, management options and economic values in an integrated manner, to address the complexity of urban water supply arising from consumers’ dependence on multiple interconnected sources of water (Harou et al., 2009; Srinivasan et al., 2010).

Hydrogeological models play a key role in building conceptual maps encompassing basic hydrological variables. These models are aimed at providing relevant information in regard of estimated water storage,
recharge levels of aquifer and the water balance at regional level. Gauging groundwater reserves and recharge of aquifer should be a priority for municipalities/regions relying on aquifers. Ignoring stock and recharging levels simply face municipalities and regions to a sort of blind planning, which might surprise water managers to unadvertised severe depletions of water table, contamination and saltwater intrusion; due to limited capacity to systematically monitor aquifer characteristics. This in turn would prevent water planners to devise timely plans to adapt to water scarcity and climate change. In short, water managers relying on aquifers should get a grip on the overarching relevance of hydrogeological knowledge. Notwithstanding, the hydrogeological dimension of aquifer systems planning, fall short in understanding the complex dimensions of optimal water use. Different approaches might be useful to make a wide-ranging counterpart for water demand and water supply analysis to guarantee clean water provision in the cities. 

In the developing world it will be important for the future that groundwater be used much more widely on an efficient and sustainable basis for urban water-supply (Foster, S. and Hirata, 2011). Promoting efficiency and sustainability of aquifer systems demand interdisciplinary planning. Engineering and hydrogeology are well equipped with the essential knowledge to understand aquifer characteristics. However, multiple dimensions would remain missing or unattended if groundwater planning if not supported by other disciplines. In many cases, groundwater is either ignored, or it is simply lumped together with surface water, despite the fact that groundwater and surface water operate on distinctly different scales of time and space (Howard, 2015). Hydro-ecology may help in understanding water stocks and flows essential to sustain freshwater and estuarine ecosystems. Sociology may help in approaching water users and understand how reliance on aquifers affects water literacy, well ownership and water awareness; it may emphasize on the ethics of conserving and staying mindful of aquifers as well (Ternes, 2018). Achieving the Sustainable Development Target Goal 6.4, demand the understanding of the complex factors shaping water-use efficiency and sustainable withdrawals.

However, it is important to not largely focus on the supply-side of the problem, but on the demand and behavioral side. Sustainable water withdrawals5 entails puzzling social dimensions worth to incorporate in project design and implementation to curb water consumption (Asprilla Echeverría, 2020). For this reason, further research of social sciences would play a key role in disentangling the reductions in urban water consumption.

The economics of natural resources is equipped with robust economic and mathematical tools aimed at analyzing optimality in resource extractions. Despite all criticism to economic sciences due to sophistication of models and strong and unreal assumptions, it may provide valuable inputs for efficiency and sustainability analysis. In Burt (1964) the method of dynamic programming is used, using the principle of Bellman optimality for aquifers in California. A net profit function is built which depends on the amount of resource used and the amount for the remaining per period. As a general condition of optimality, it is concluded that the level of production must be expanded to the point where the net marginal product per unit of water is equal to the negative of the marginal cost of pumping with respect to the water in the storage. In Burt (1967) applied to San Joaquin Valley in California as well, the author uses first order differences equations to solve the model of dynamic programming. In this model, the net marginal product with respect to the extraction rate is equal to the net marginal product capitalized with respect to the stock. Besides, it determines the existence of a balance stock level from which recharge and optimal extraction depend on.

(Provencer and Burt, 1994b) discuss the effectiveness and convenience of comparing centralized groundwater management control schemes with respect to models such as privatization, understood as the allocation of property rights for the Madera County in California. The authors demonstrate that, with the privatization model (which provides a marketable permit endowment of the on-site stock, which agents control over time), higher earnings are obtained in well-being of water users than traditional forms of centralized control, because the market allows the management of risks (Kruize, D., Roumasset, J., & Wilson, 1997). use the optimal control theory for coastal aquifer analyses in Hawaii, where they model desalinated water as a replacement or backstop technology for water extracted from the ground. In this exercise an optimal control problem is built with infinite time horizon and there are three optimal stages are found. Firstly, an increasing stage in which the height of the aquifer must be retained; in the following period there is an “overdraft” or reduction and the water table is decreasing and a final stage in which the height of the aquifer follows a steady state to infinity.

In another relevant models such as (Noel et al., 1980) the optimal control theory is employed as well. The research calculates socially optimal temporal and spatial allocations between agricultural and urban uses, with a quadratic linear control model with economic and hydrologic components to model the joint use of ground and surface water. This model is applied to several watersheds in Yolo County in California.

Based on the fact that possibly users who live in the present would not be willing to sacrifice their consumption (Pitafi and Roumasset, 2009) propose a model that allows to increase the political feasibility of regulating the use of aquifers in Hawaii. This is done through a mechanism whereby those experiencing welfare losses can be compensated for the efficient management of the resource and applied to a spatial-temporal context.

More recently, an optimal path of extraction of groundwater was built for the Chitradurga District in India (Patil, K., Mahadev, C., Bhat, G., & Manjunatha, 2015). The authors applied the Maximum Principle of Pontryagin. A linear inverse demand function, a linear cost function and also a total rainfall-dependent recharge function were used. With this information, coupled with information on characteristics of agricultural producers, an optimal control model for steady state equilibrium was estimated.

In reference to application of optimal control theory different models might be developed to calculate optimal extraction rates of control variables. Some models might incorporate different specifications for the transversality condition. This condition applies for the terminal condition for state variable (for this research aim, state variable refer to aquifer stocks – see 3.3 below). Terminal condition of zero, means that the shadow price of aquifer stock should be driven to zero at the terminal time, consequently reaping benefits from aquifer extraction within the period [0, T] would matter, and that whatever water stock that still exists at time T, being too late to put to use, would have no economic value to water users or water planners.6

Despite being plausible in providing an image of possible time for aquifers getting exhausted, there are still missing issues in resource economics models. For instance, I would stress the need to manage minimum stock level of groundwater, so as to not approaching the water as resource subject to exhaustion. Real aquifer sustainability models should treat terminal state variable (stock of aquifer S(t)), as \( S(T) - S(t)_{\text{max}} \) instead of \( S(T) - S(t) \). A closer look to the concept of groundwater sustainability may refer to aquifer sustainable yields. Sustainable yields can be derived from conservation of mass principles.

5 Conceptualization of sustainability in groundwater resources is quite complicated and subject to current discussions among hydrogeologist and water planners. For some cases there has to be recognition that groundwater resource is not renewable and its use therefore be sustainable (Kalf and Woolley, 2005).

6 Adapted from Chiang (1992).
in a groundwater basin \( \text{Inflow}(t) - \text{Outflow}(t) = \Delta S/t \) (Kalf and Woolley, 2005). Inflows are mostly determined by nature while outflows are mostly driven by social dimensions (abstractions) and to a lesser extent by the nature (natural discharges). A sustainable groundwater management system would benefit from greater inputs than outputs through the time.

Sustainability of aquifer systems, mass equilibrium in groundwater basin, time dimensions and variables determining the groundwater flow properties are discussed in (J. Bredehoef, 1997; Kalf and Woolley, 2005). The time taken to attain equilibrium will depend on the magnitude of the abstraction rate aquifer characteristics, and distances to recharge boundaries (Kalf and Woolley, 2005). Notwithstanding in (J. Bredehoef, 1997; J. D. Bredehoef, 2002; Kalf and Woolley, 2005) groundwater system planning takes social dimensions for granted and more importantly do not recognize the common-pool nature of the resource. The CPR characteristic of aquifers, means there exists competition to reap the most of benefits of abstraction in the present; the free-rider problem; variations in time horizon perceptions about the resource value and other issues leading to productive or destructive outcomes as appointed by Hardin (1968); Negri (1989); Ostrom (2015).

3. Methods

Before embarking in designing empirical methods, a document analysis of water policy and regional water planning documents was developed. Special attention to the approaches made to tackle water scarcity was paid; and the way how water supply of groundwater resources has been addressed by water managers is discussed. Basic descriptive analysis of water consumption reports released by water companies were analyzed as well. Monthly data on households, industries and commercial uses are available since 2002 through 2018. Data on agricultural water consumption, were more disperse but mostly obtained from the recent National Agricultural Census and official General Comptroller environmental reports. Information and data on the hydrogeological characteristics of aquifer were collected from different sources such as research thesis, environmental authority conceptual hydrogeologic maps and the National Institute of Geological Service. With all this information, water balances needed to prepare scenarios to analyze changes in water flows were performed. This included the analysis of modifications of water flows aimed at estimating changes on environmental pressures on groundwater systems.

Reducing the burden on groundwater makes sense, since aquifer stocks are rarely unlimited resources. Despite replenishment of aquifers may provide the control mechanism to convert it into a renewable resource, extant aquifer recharge in dry areas tend to be scanty. Certainly, in Sucre, for more than 40 years groundwater reserves have been running out because people annually extract more water than it seeps into the ground (Carsucre, 2015).

Consequently, one key assumption utilized in building models, refer to treat aquifer as a non-renewable resource due to scant replenishment and forecasted reductions in precipitations in the area of Sucre and the Caribbean (IDEAM, PNUD, MADS, DNP, & CANCELLERIA, 2017). Some additional assumptions refer to policy measures that might not be implemented; for instance, efficiency analysis may estipulate sewage water treatment for recycling, which might not be put in place shortly, in order to reduce pressure on surface and groundwater systems. Some assumptions in regard of new activities demanding water are incorporated as well. Population would rise at a 1.0% growing rate (keeping actual rates according to DANE). It is also assumed that people would continue moving to urban areas.

\[ \Delta S = (I - O) \text{L}^3/\text{T} \]

\[ \text{Inflow}(t) - \text{Outflow}(t) = \Delta S/t \]

Natural processes such as recharge led by infiltration of precipitation, leakage from streams and lakes, artificial recharge (Kalf and Woolley, 2005).

3.1. Hydro-economic methods

Given the complex characteristics of efficiency and interdependency of groundwater extractions, research methods combine different disciplines such as hydrology, hydrogeology and economics. Hydrologic models provide key elements such as groundwater inventory, aquifer recharge and stocks; hydraulics of groundwater offer relevant aspects such as water flows, permeability and storage capacity. Hydrogeologic variables were used to estimate water balance, which are represented through water flow diagrams to facilitate representation of water flows in the territory.

Economics provide useful tools to understand and assess efficiency of water resources. Optimization of water consumption is supported on Optimal Control Theory. Optimal control formulation of a dynamic optimization problem focuses upon one or more control variables that serve as instruments of optimization. Optimal control foremost aim is the determination of the optimal time path for a control variable \( u(t) \) (Chiang, 1992; Chiang and Wainwright, 2005). Control variables influence state variables paths. The former includes examples such as the extraction rates, pumping timing and waterwells location and the latter refer to variables such as aquifer stock and aquifer saturated thickness.

Optimal control entails the specification of the objective functional subject to maximization, the definition of state function, initial and end values for state variables and the specifications regarding boundaries and control set. For instance, the control set might be an open or a closed set. The most important result in optimal control theory – a first-order necessary conditions – is known as the Maximum Principle (Chiang and Wainwright, 2005). The research aim focused on sustainably integrate socio-physical interdependence in regional water planning, entail the definition of the management scheme in defining the economic models. This definition is relevant to determine the role of stakeholders, the control and state variables subject of analysis. It is also assumed that actual water management system of central planning is kept. The main interest of the environmental authority as a central planner is maximizing the net present economic value of the added benefit of water consumption. It refers to the benefits in production for relevant agricultural crops, environmental flow requirement and domestic groundwater demand function for Sincelejo, Corozal, Sampués, Morroa, Los Palmitos and Ovejas in Sucre.

In addition to this, the authority is interested in maintaining water units for other neighboring municipalities and ecosystems depending on ground and surface water. Therefore, the optimal water extraction rates for the major types of beneficiaries should be chosen by the environmental authorities.

The economic model consists of two state variables given by the stock or water reserves, denoted as \( S(t) \) and the height of the aquifer \( h(t) \). The dynamics of state variables are driven by the nature but are influenced by control variables as well.

Extraction permits entitled to water petitioners who approach before the Regional Environmental Corporation provide the mechanism of how control variables are chosen. \( W_a, W_m, W_v \) and \( W_y \) represent the extraction of water by domestic consumers, maize, yam and yucca producers respectively. The extraction can take values less than or equal to the aquifer stock size, thus \( 0 \leq (W_a + W_m + W_v + W_y) \leq S_0 \). \( S_0 \) correspond to initial exploitable stock which is estimated in 3247

\[ \text{There exists an important difference in the type of aquifer reserves. Exploitable reserves are different from total reserves, elastic reserves and stored reserves (Carsucre, 2003).} \]
millions m$^3$ (Carsucre, 2003). In addition, it is assumed that this stock is stored in an irregular aquifer. In economic and physical terms, the stock is constituted in a state variable that the hydrogeology defines as the total amount of water that is confined in the rocks and that can be drained or not, according to characteristics like porosity, the specific retention, among others (IDEAM, 2014). As part of sustainability approach, the environmental authority is concerned with the intergenerational justice and the common-pool character of aquifer used by other neighbor municipalities. Consequently, a minimum level of stock of the aquifers is considered, so that total water availability is not jeopardized. The randomness of rainfall as a source of aquifer recharges makes this issue worth noted.

3.1.1. Specification of economic models

The functions of benefit for water used are specified for main agricultural activities and domestic users. Efficient and sustainable groundwater allocation to main water users represent one of the key policy instruments for environmental authorities pursuing sustainable use of groundwater reserves. In Table 1 a summary of function of benefits is presented. For more details and explanation on the equations see Annexes section.

3.1.1.1. Extraction cost function. Cost function is represented as a reserve dependent model for which (Krucele, D., Roumasset, J., & Wilson, 1997) is followed. In this model, $h$ corresponds to the vertical distance between the level of the water table and the depth of the saturated thickness of the aquifer. This saturated thickness is the lower physical limit of the aquifer. The lower the level, the more costly the water withdrawal. As the aquifer approaches exhaustion ($h = 0$), the extraction costs grow rapidly. In this sense, the average cost of water extraction of the aquifers is modeled as a convex, positive and decreasing function of the height of the aquifer as follows:

$$ c(h) \geq 0, \quad c(h) < 0, \quad c(h^+) \geq 0 $$

$$ \lim_{h \to \infty} c(h) = \infty $$

So, the total water extraction cost for $W_d$, $W_r$, $W_a$ and $W_{sum}$ summarized in $W$ corresponds to $c(h)W$. It is assumed that investment costs for boreholes and maintenance are lower compared to recurrent monthly energy costs. Besides, when the aquifer is dry, the costs lean towards infinite since there would be no available water and the energy cost and pumping time are increased.

Therefore, the cost function is adjusted by incorporating the energy costs ($c_{ener}$):

$$ c(h) = c_{ener} \left[ \frac{h}{k_r} \right]^2 \sum W_i $$

(6)

Where $h_0$ is the initial height of the water table (distance from land surface to water table). $k_r$ corresponds to the rate at which water table approaches zero, for this case it is equal to 0.8% given the average actual water table declination speed. $h_0 = 275$ m is the average well-depth observed in Sincelejo, Morroa and Corozal (Carsucre, 2003). The cost of energy will be taken as a cost per kilowatt-hour for the study area.

3.1.1.2. State variable functions. Variables subject to rules of nature correspond to aquifer stock ($S_t$) and the height ($h_t$) of water table (Provencher and Burt, 1994b). Propose a recursive function given by

$$ S_{t+1} = S_t + r_t - W_t $$

where the resource status depends on the recharge of the aquifer $r_t$ and extractions by different users.

![Land surface](image)

Bottommost of aquifer

The depth of the aquifer is represented by the following linear model:

$$ h_t(S_t, W_t) = h_0 - \beta \left( S_t - \sum_{i=1}^{W_t} W_i \right) $$

(7)

$h_0$ refers to the distance between saturated thickness and actual water table for municipality $i$ in time $t$; ($h_0 = [100, 500]$ m). $\beta$ represent a conversion factor to transform volume units into height units, in this case $\beta = 3.82 \times 10^{-8}$. $S_t$ refers to the aquifer stock over time, initiating in $S_0$.

4. Results

Excel Solver functionalities were utilized to run optimization model. Fig. 1 shows a sort of a water stock efficiency gap. The forecasted evolution of Morroa Aquifer stock is shown for the status quo situation and for the groundwater reserves under optimality circumstances. The gap measures the groundwater foregone reserves, which is a lost valuable opportunity in pursuing sustainable management of aquifer systems.

A steady widening efficiency gap is observed as the time passes. Stock decay has implications in water tables. Water table declination is spatially unevenly distributed. Municipalities placed over deeper saturated aquifers may be benefitted from more productive water spots. Plan B incorporates differentiations in spatial and underground characteristics of water table. In doing this, the distance between surface → water table ($h_0$) and the distance between water table → saturated thickness $h_t$ is used in the hydro-economic model. Making this distinction is meaningful since more probably, Morroa Aquifer is characterized as a synclinal one, with deeper inclination to the east of Sucré (Carsucre, 2003) and in some moment in the future, punches over the surface will result unfruitful while in other sites, it still will result feasible. For the former, water sourcing alternatives shall be devised while in the latter, there would be water available for them and for closer neighboring municipalities. The steeper the $h_0/h_t$, index the quicker the water table gets farther from the surface and, the quicker it approaches the saturated thickness. Consequently, a steeper $h_0/h_t$ index represents a sort of a precipitous declination velocity. This issue should not be overlooked if spatial differentiation in water tables is incorporated in groundwater extraction.
Sincelejo. For Sampu which the saturated thickness is approached. This speed relationship is accessibility.

authorities, extraction permits petitions by sparsely distributed water building, maintaining and operating a borehole cost. A water user might

proaches the bottommost of the aquifer, is quicker than it gets distant

The feasibility of water extraction depends on how much

Consumption of yam in Sucre is pervasive and part of the essence of people’s gastronomic tradition. According to (DANE, 2015) data, there existed around 2000 ha of yam planted in six municipalities of this study area. A water productivity of 1.3 kg/m³ was found for the critical period (Mercado et al., 2014).

Table 1
A summary of function of benefits for water use.

<table>
<thead>
<tr>
<th>Type of user</th>
<th>Function of benefit for water use</th>
<th>Description</th>
</tr>
</thead>
</table>
| Domestic users | $BM_i(W_2(t)) = -4 \times 10^4 e^{-0.4 \times W_2}$ | Demand curve is used to calculate marginal benefit of consumption according to the following expression: $BM_i(W_2(t))$ corresponds to yucca yield in gha$^{-1}$. Using the sequence of marginal benefits of water consumption from unit $w_1$ to $w_{n-1}$ ($i = 1, 2, ..., w$ water units)

Maize producers

Using the sequence of marginal benefits of water consumption from unit $w_1$ to $w_{n-1}$ ($i = 1, 2, ..., w$ water units) Maize crops are sensitive to water stress and water productivity losses due to stress are difficult to compensate despite stress period is overcome with water applied through irrigation or precipitation (Steduto et al., 2012). $W_i$ represents irrigation water applied in m$^3$ and $M_i$ corresponds to maize yield in Mg ha$^{-1}$. At some high stress level, the plant would not be able to produce grain and harvest index would be zero (Trout and De Jonge, 2017).

Yucca producers

Cassava crops tolerate well the prolonged water deficit (De Tafur, El-Sharkawy and Cadavid, 1998). The characteristic of tolerance to droughts and unfertile soils, underlie the increasing importance of the crop in dry and semiarid environments (DANE, 2016; De Tafur et al., 1998). $W_i$ represents irrigation water applied and $Y_i$ corresponds to yucca yield in gha$^{-1}$.

Yam producers

Consumption of yam in Sucre is pervasive and part of the essence of people’s gastronomic tradition. According to (DANE, 2015) data, there existed around 2000 ha of yam planted in six municipalities of this study area. A water productivity of 1.3 kg/m³ was found for the critical period (Mercado et al., 2014).

![Evolution of aquifer stock under optimal and status quo conditions for the first 50 years. Source: Author’s calculation](image)

permits analysis. Assuming a continuous extraction of groundwater for agricultural, domestic and industrial purposes, this differentiated declination is part of the mode how socio-physical interdependence in water consumption is made patent. More importantly, this spatial differentiation is crucial in understanding sustainability of groundwater resources. If equitable water distribution is intended by environmental authorities, extraction permits petitions by sparsely distributed water users, should be consistent with the users’ needs and their water accessibility.

According to Fig. 2, at 20th year in Sincelejo, water table declination velocity from the surface, would be 2 times quicker than the speed at which the saturated thickness is approached. This speed relationship is fewer in Morroa and Corozal since declination speed is half and a third respect to Sincelejo. For Sampues, Los Palmitos and Ovejas municipalities the relationships are different. The speed at which water table approaches the bottommost of the aquifer, is quicker than it gets distant from the surface.

Differences in declination speed have social implications as well. Water users are more interested in how many meters the aquifer static level is. The feasibility of water extraction depends on how much building, maintaining and operating a borehole cost. A water user might

be ignorant on different hydrogeological characteristics of the aquifer system; notwithstanding, the static level depth is uppermost in water users’ minds, because it is closer to the price per meter that he/she has paid to get waterwells built. In order to avoid observed steady declinations in aquifer stock and water tables in status quo situation, optimal extraction rates are suggested, especially to agricultural users. In Fig. 3 extraction paths for three staple crops are presented. Differences in optimal extraction rates are explained by the fact that different maximum efficiency of water use are obtained per crop.

Following (Mercado et al., 2014; Trout and De Jonge, 2017; Yao and Goué, 1992) maize gets a maximum at 4 m³ of water applied per hectare and at 108 m³ of water, yucca crops reach a maximum in water use efficiency. This is consistent with the fact cassava crops adapt well to water deficit (De Tafur et al., 1998) and contrarily, maize crops are sensitive to water stress (Steduto et al., 2012). Consequently, at the margin, yucca crops appear to be more nurtured with each water unit applied in comparison with maize crops.

Optimal extraction in m³/day/hectare for the first year for maize, yucca and yam producers correspond to 0.93 m³, 3.8 m³ and 3 m³ for yam producers, respectively. On a daily or monthly basis, this water volume might be unevenly distributed. In rainy seasons, less water would be abstracted from the underground while in the dry season, a greater volume could be extracted for irrigating crops. These water volumes per day per hectare might be used as policy instruments aimed at promoting efficiency extraction caps. Consequently, a serious institutional setting to progressively make this water abstraction caps, as part of sustainability action, shall be looked-for.

Municipalities and farms lying over the less deep saturated thickness zones are demanded to be more productive in terms of water use efficiency. Conversely, in case of business-as-usual scheme of water extractions continuing, some projections are made in terms the effect of simultaneous punches over the surface by the action of neighbor municipalities. Five steps are included in these projections as shown in Illustration 1.


2. Since population tend to increase and water table continue to decline, new or deeper punches are expected from different municipalities relying on Morroa Aquifer system. Corozal and Sincelejo are the ones suffering greater extractions since they concentrate most of departmental population.
**Fig. 2.** The evolution of water table declination index ($h_0/h_r$) for Sincelejo, Morroa, Sampués, Corozal, Ovejas and Los Palmitos.

**Conventions:**
- $h_0$ (surface to water table)
- $h_r$ (water table to saturated thickness)
- $h_0/h_r$

**Fig. 3.** Optimal extraction rates per year by type of agricultural users.

Source: Author’s elaboration
3. Water table declination, conformation of cones of depression would probably lead to punches made on close aquifer spots.

4. The evolution of water table is based on \[ h_t(S_t, W_t) = h_0 - \beta (S_t - \sum W_t) \]. Water stock \((S_t)\) incorporates the influence of multiple neighbor municipalities exercising extractions.

5. Extraction costs are projected for deepening water tables. Two municipalities are presented as an example for the way how additional extraction costs might spread over municipal water users, namely domestic and agricultural producers.

Alternatively, in case of prohibitive extraction costs as shown in Illustration 1, municipalities might start to think of distant water sources, such as other aquifers in Sucre Department. In this case, six municipalities (Sincelejo, Morroa, Corozal, Los Palmitos, Sampués and Ovejas) might need to invest financial resources to build new boreholes over Tolu Viejo Aquifer and Golfo de Morrosquillo in the north-west or La Mojana Aquifer in the south. However, these alternatives might result unfeasible for low income farmers and households since bringing water from 35 km or 43 km far (see Map 2), undoubtedly add transportation costs to extraction costs.

Instead of costly alternatives shown in Map 2, three scenarios are introduced to provide useful options for municipalities interested in finding sustainable options in managing scarcer groundwater, under the pressing forces of climate change. Different scenarios configure the research results. Gradual changes are incorporated in the presented alternatives, which are aimed at improving the efficiency of water supply and demand management. Large leaps in expected efficient supply-management enhancement, may result inconsistent within the contexts of developing countries, where many financial and cultural challenges in water conservation overflow. Climate variability would be driven by forecasted reductions in precipitations in the area of Sucre and the Caribbean (IDEAM et al., 2017) and consequently scant recharge rates are expected for all scenarios, consequently, reductions in water volumes extracted and efficient use is demanded.

4.1. Scenario 0. status quo: keeping water losses and increasing water stock efficiency gap

If water users may keep actual water consumption behaviors, water companies are asked to increase supply. More water wells are punched in order to match population increase and non-accounted water is taken as normal or part of the working social norms in place. Technical and commercial losses surround 50% of all water distributed from freshwater treatment plants. Reduced precipitations are assumed. Two key characteristics of this scenario are presented as follows:

- Non-accounted water losses surround 50%.
- Wastewater is discharged to different creeks without any previous treatment to reduce chemical or biological load.

Following Illustration 2, in this scenario a total extraction volume of 187.4 million m³ for next 20 years might be expected. Agricultural activities contribute with 43% while potable water production plants would extract more than 50% of this volume and 53% of the latter would get wasted due to technical and commercial losses. Circular analysis of water use in Sucre is limited since wastewater treatment plants are practically inexistent (see section 3.1 above).

In the status quo situation, for the next 5 years between 2021 and 2030 there is a potential of 67 million m³ of wastewater been generated. Business-as-usual, this volume, in turn would be discharged to different creeks that cross the municipalities. In circular economy terms this
4.2. Scenario 1. Audacious steps in the right direction: increasing water use efficiency

It focusses on maintaining the actual water supply capacity and progressive reductions of water losses. Groundwater outflows are carefully planned, and relevant hydrogeological variables are monitored. Water volume outflows are treated as a valuable resource object of a circular logic by design. Special attention is paid to the urgent need to guarantee Environmental Flow Requirements for ecosystems relying on surface water. More specifically, elements and assumptions, shaping scenario 1 are presented as follows: (see Illustrations 3 and 4)

- Steady reductions of water losses (between 5% and 10% per year for 10 years)
- Wastewater treatment plants are built and operated.
- A halt shall be made in collecting water from ponds and marshlands and surface water is left for Environmental Flow Requirement.
- Public–private investments in switching to more efficient irrigation techniques is demanded.
- Adaptation measures to tackle scarcity are put in place (e.g., rainwater harvesting, sharing excess of water among farmers).
67 million m³ of wastewater been generated in the status quo situation, might be put to beneficial use. A high potential in finding new sources of water for agricultural activities exists. Notwithstanding, this potential would not straightforwardly be achieved. Audacious efforts materialized in financial investments must be exerted. Political resolution is demanded as a prerequisite to get waste water treatment plants built and put under operation. Similarly, modifications in the distribution of municipal sewage water networks are needed, since in the actual design, the deployed ends of pipes, discharge sewage water in the different creeks crossing Sucre municipalities. Whether intended to circulation or not in the economy, waste water flowing different creeks, must get Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD) reduced to levels that do not get riparian ecosystems impaired.

4.3. Scenario 2. Stringent and feasible but urgent: efficiency + circularity

It entails a reduction in water volumes extracted from Morroa Aquifer and progressively, focuses on asking water users to reduce water consumption as much as possible to more efficient levels (see Illustration 4). This scenario specifically includes:

- Water treated in wastewater treatment plants circulated for agricultural purposes.
- Halting the collection of water from ponds and marshlands and surface water is left for EFR.
- Reuse and recirculate water treated at industrial plants.
- Adaptation measures to tackle scarcity are put in place (rainwater harvesting, sharing excess of water among farmers, switching to more efficient irrigation techniques).
- A serious water conservation policy is put in place.
- Autonomously devised cultural practices around CPR conservation, are embedded among different communities.

Respect to status quo situation a 22% of efficiency might be achieved in the next 20 years. If an efficient and circular management model is endeavored, multiple gains would be harvested for the benefit of water users and ecosystems relying on aquifers. Increased efficiency is mostly driven by 30 million m³ stemming from sewage water treatment. Water recirculated in agriculture would prevent aquifer extraction for agricultural activities.

5. Discussion

Actual models of water supply planning are based on isolated extraction activities by different water utilities and individual water users in the Caribbean region of Colombia. Since the intended or unintended competition for water resources is made patent in water table declination, this would not avoid egotistic attitudes in extractions to continue; therefore, public municipal water managers may play a key role in activating regional and interdependent water supply planning. For this aim, awareness on common-pool resource character of aquifer and hydrogeological conditions of shared aquifer systems are needed. CPR character is not overtly incorporated in existing hydro economic models such as (Pulido-Velazquez et al., 2016; Srinivasan et al., 2010; Zhu et al., 2015). Existing hydro-economic models incorporate utility, consumer, reservoirs, groundwater, tanker modules, from a systemic approach (Srinivasan et al., 2010); water conservation concern and options for extensions of infrastructure taking account of operational allocations under variable water availability (Rosenberg et al., 2008); water supply state along the river system and the water demands by the various sectors using water resource (Ringler et al., 2004). Notwithstanding the common-pool resource (CPR) nature of water resources, especially groundwater, are not observed in the extant analysis. I suggest that ignoring the CPR character of aquifer and surface water systems may put long-term water planning under risk, since one municipality might be confident of expected water stocks, while other competing municipalities and other users, may accelerate extractions and running aquifer water table far from feasible access. Thus, water supply planning for neighboring municipalities should no longer be performed in isolation but at a regional scale in which CPR character of water sources is incorporated.

Collective planning demands a shifting in status quo among planners and users. Extant model of water planners role dedicated to match supply with demand represent the Plan A. Conversely, a Plan B demands to introspective analysis in terms of how efficient the water consumption is. Key issue for efficiency analysis entails questioning to what extent the capacity of water applied to the agricultural and industrial processes is utilized to apprehend the maximum potential of water consumed.

Efficiency and circularity might be sound criteria for sustainable regional water management. For instance, given actual degenerative situation of extant waste water management, rooms for improvement exits for turning to regenerative-by-design waste water management. Waste water discharged to different surface water bodies do not fit into
the definition of efficiency. Efficient water use refers to reaping the maximum benefit of each cubic meter of water. Waste water has a continued potential in water applications to agricultural and industrial processes. However, waste water treatment plants deployed over Sucre are basically inexistent, and political resolution might be a must, since public goods such as water quality remains on public entities’ charge. Opportunities exist for associated water users endeavoring in investing in treatment plants as well to reduce the pressure on the aquifer. Morroa Aquifer demand special attention since declination speed is threatening the aquifer stocks for the future. New governance schemes led by extraction caps might help in groundwater conservation. An area that can affect both water demand and supply is conservation. Conservation can reduce demand for a particular use enabling the saved water to be allocated to other uses. In order to accomplish this, water conservation measures need to be less expensive than the cost of the water saved (Booker et al., 2012). Similarly, efficiency and common-pool rationale should replace actual independent water planning and the collective thinking should be sparked from dared entrepreneurs interested in conservation and limiting extractions.

An alternative governance scheme led by extraction caps, may be part of the urgent transition towards regenerative thinking and action and efficient water consumption, in groundwater dependent regions. Quantitative data on optimal extraction rates may support decision-making in extant institutional settings. Existing rules and institutions in groundwater governance systems, should open the door to utilizing quantitative inputs due to the declining and exhaustible nature of groundwater resources. However, due to different sources of uncertainty, the definition of optimal extraction rates should be cautiously prescribed as stated in Burt (1964); Noel and Howitt (1982); Provencher and Burt (1994a). This is, optimal extraction paths for long horizons such as 70, 80 or 90 years may result impractical due to that a lot of environmental alterations may occur and water users may shift extraction behaviors in the long term. Instead, cautious and iterative calibrations of optimal extraction levels might be implemented. We may refer to prescribing optimal rates for 35 or 50 years; without take no notice of future generations. A 50-years’ time horizon does not mean wittingly making aquifer depleted in 50 years. Instead, as new data on hydro-geological conditions influencing water stocks and flows are produced, updated optimal extraction rates might be calibrated for the subsequent 50 years. This iterative process should always be performed under the limits of state variables such as exploitable stocks and similarly, imposing constraints of abstractions to minimum stocks. Minimum levels of reserves may act as a precautionary principle. Long-term perspective is needed while devising cautious short-term water supply planning.

Since traditional water supply forecast use to simply match demand with supply, there exists an inertial supply management scheme in which water managers, just rush for satisfying the demand. In the politics of water planning, water managers are told to bring abundant water to all who demand it (Zetland, 2011). However, business-as-usual water demand projections data, tend to hide bad habits in water consumption, degenerative waste water management, inefficient water application to agricultural and industries and spendthrift attitudes. Instead, inefficient and damaging water consumption customs should be overtly recognized and disclosed. Once stakeholders become aware of caveats, risks, detrimental actions and opportunities, rooms for improvement should collectively be built, based on efficiency and circularity principles. Circular economy of water should be a compulsory criterion for water supply and demand forecast. In doing this, different users would use, reuse and recirculate water, which in turn would reduce water demanded. It does not only refer to an instrumental shift in water consumption; but an awareness-based shift towards sustainability. A long-term shift would imply a change in water use paradigm. Water should be utilized not as a simple input for agricultural, domestic or industrial activities but as a valuable natural entity serving nature as well.

A circular and efficient model would be a cost – effective strategy for climate variability adaptation. Otherwise, since declinations in precipitations are expected up to 2100 (IDEM et al., 2017), a deeper water table would place higher pressures on alternative water sources, unless water users are willing to collect water around 1 km deeper. Well-depths for differentiated water users will demand serious discussions on justice in water access. Rising water tables and rising energy costs would impose financial burdens on low income households and farmers. Conceivably, further water tables might trigger new reconfigurations of livelihoods location and new punches over surface would be developed. As trends on increasing urban sprawls have been observed, relocations in urban areas shall be convenient reasons for rethinking the prevailing water supply planning scheme. A new water governance deal led by extraction caps shall be needed. A Plan B water assessment applied to each municipalities and corresponding neighbors, would be needed as an integrative model aimed at providing inputs for water resources planning, in which the depletable and common-pool character of aquifers is incorporated.
6. Conclusion

This research was aimed at integrating the common – pool resource and depletable character of aquifers in municipal water supply planning. Efficiency and circularity of water in the economy were two criteria used for seek sustainable consumption of water. The term water productivity is kept when respective authors use it; however, the concept on water use efficiency is utilized in this research.

A hydro-economic model was built. It incorporates an optimization model aimed at calculating maximum efficiency in water applied to crops cultivated in the region of analysis. Optimal levels of extraction pretend to reap the maximum benefit of drops applied to three main crops namely, yuca, maize and yam. Optimal extraction was compared to status quo situation and an efficiency gap was found. In more stringent scenario for the conceivable future an efficiency gain of 22% in water saved for the economy. In actual situation there seems to be a degenerative-by-design waste water management since these waters are discharged directly to creeks crossing Sucre territory. Reducing water degenerative-by-design waste water management since these waters are water saved for the economy. In actual situation there seems to be a degenerative-by-design waste water management since these waters are discharged directly to creeks crossing Sucre territory. Reducing water degenerative-by-design waste water management since these waters are water saved for the economy. In actual situation there seems to be a degenerative-by-design waste water management since these waters are discharged directly to creeks crossing Sucre territory. Due to steady declinations of water tables, inevitably, water utilities and individual water users will be gradually forced to explore and exploit new water sources. Alternatively, instead of thinking of searching for new water sources, communities, water managers and individual water users, should make a halt in the inertial behavior of increasing consumption and instead, increase efficiency in consumption of current water supply sources will become more mandatory as the climate change exacerbates its effects on water sources. Similarly, a collective planning scheme might put to work since interdependent water extraction is made patent in the presence of externalities and every cubic meter extracted from one municipality may influence the extractions of neighbor municipalities and extraction costs of water as well. Consequently, water users located over more productive spots, might be hassle-free while others might experience stressful situation due to costly water supply because of rapid water table declination, especially in contexts of droughts.

However, referring to regional planning must be treated with caution, since the greater the regional scope of analysis, the more complex and entangled the analysis might be. Notwithstanding, water planners should make a halt in the inertial style of simply exploring how deep the waterwells could be exploited; instead, a reflexive interdisciplinary planning scheme might put to work since interdependent water extraction is made patent in the presence of externalities and every cubic meter extracted from one municipality may influence the extractions of neighbor municipalities and extraction costs of water as well. Consequently, water users located over more productive spots, might be hassle-free while others might experience stressful situation due to costly water supply because of rapid water table declination, especially in contexts of droughts.

Annexes.

Annex 1. A general overview of the region’s water resources

Glancing at the hydrologic map of Sucre (Colombia), we may have a mixed impression in terms of water distribution. Six watersheds encompass the whole department. Some basins are shared with environmental authorities of other regions different from Sucre. Northern basins correspond to different streams such as San Antonio, Matatigre, Emadio, Palmar, El Tigre, Cascoja y Pechilin; which mostly drain its waters to Caribbean Sea. These are mostly seasonal streams since they use to run water flows during rainy seasons lasting for less than 3 months a year. Listed streams run over municipalities of Sampués, Sincelejo, Morroa, Corozal, Los Palmitos and Ovejas. Another basin is distributed over the middle part of the department. It runs in direction northwest to southeast draining waters to some swamps and San Jorge River.

Available surface water supply in the shared watersheds in the northern part in rainy years correspond to 1714 million m$^3$ and it drops to 429 million
m$^3$ in drier years. For Low San Jorge – La Mojana watershed water supply is much higher since it sums up to 11,932 million m$^3$ for humid years and drops to 3068 million m$^3$ in dry seasons (Carsucre, 2018). However, most water supply in Sucre is provided by groundwater sources. Aquifer systems in Sucre are represented in Map 1.

Morroa Aquifer lays under the area of five municipalities (Sampués, Sincelejo, Corozal, Morroa, Los Palmitos and Ovejas). The aquifer encompasses an area of 60,964 ha. This aquifer is endowed with exploitable water stock estimated in 719,691,835 m$^3$ and 3,247,746,000 m$^3$ of stored reserves (Carsucre, 2003). The reserves have been used to serve freshwater provision for more than 70 years. In Sucre, 24 out of 26 municipal water companies have built boreholes to collect water, treat and distribute it through aqueduct pipes (data from IDEAM, 2014). In addition to this, up to 2011 individual households, farmers and industries have built more than 1,788 water wells which are all under operation and it is assumed that this figure has increased. 89% of farm owners is Sucre report having access to water for agricultural activities. The whole area of this six municipalities is composed by 9687 farms (DANE, 2015). Yucca, maize and yam are predominant crops planted in this portion of Sucre as shown in Fig. 4.

Agricultural activities in Corozal, Los Palmitos, Morroa and Ovejas are largely depended on groundwater, since in more than 75% of farms this is the reported water source. In Sincelejo and Sampués groundwater is used in 44% of farms and the rest of them use water from lagoons and marshes (DANE, 2015). 4233 built water wells are reported for farms located in the six listed municipalities (DANE, 2015).

Since last three decades the capital city Sincelejo and Corozal have been served by the same water company. 61,500 households are connected to the aqueduct grid in Sincelejo and 12,027 more in Corozal benefit of freshwater distribution. Both municipalities sum around 320,000 inhabitants. Sincelejo and Corozal aqueduct system are supplied by 25 boreholes punching over Morroa Aquifer. Currently, boreholes are subject to groundwater abstractions for up to 18 h/day and water flows from each water well fluctuate between 6 l/s and 105 l/s; this flow let the water company to abstract between 12,000 and 204,120 m$^3$/month. On 2018 water consumption by households totaled 6.5 million cubic meters and industries and commercial businesses added up half million cubic meters in the same year. Sampués is served by the municipal water unit, water provision in Morroa is organized in three private and community companies, and Los Palmitos and Ovejas water service are privatized.

Agricultural water users in Sucre contribute with higher figures to water abstractions. Every year almost 9700 farms (DANE, 2015) collect water for crops irrigation and cattle raising activities. Most important sources are boreholes and lagoons. The latter case is applicable for Sincelejo and Ovejas in which 16% and 31% of their farmers respectively, report using water from this type of ponds. On average 60% of farms in Sucre use groundwater to sustain agriculture. Morroa and Los Palmitos are above this average with 70% and 80% of farms dependent on this important source.

12 There exists an important difference in the type of aquifer reserves. Exploitable reserves is different from total reserves, elastic reserves and stored reserves (Carsucre, 2003).

13 1.713 waterwells reported in the jurisdiction of CarSucre and 75 wells in the area of Regional Environmental Corporation CorpoMojana.
Assuming a 4-h/day and an average of 0.2 l/s extraction pattern, agricultural sector abstract around 5.7 million m$^3$/year for the main three crops planted in the six municipalities.

In respect to waste water generated, the situation deserves especial attention due to shocking damaging practices to ecosystems. Sincelejo sewage system is drained directly to two sanitary districts, the first discharge 105.6 l/s to Colomuto Brook in the northern part of the city in San Miguel area (this represents 36% of total discharges) and the southern district discharges 182.8 l/s to Caimán Book (collecting 63.4% of total sewage generated) (Contraloría Municipal de Sincelejo, 2017). Sewage water in Ovejas is drained to Mancomojar Brook. Sampués Municipality pour out sewage water to different interconnected brooks in six discharge points. Main sewage receptor is Canoa Creek which is served by Zanjón Creek from the south, Pachotó and Pasatruza Creek from the north (Contraloría General Departamental de Sucre, 2014). Los Palmitos Municipality counts with oxidation ponds (Carsucre, 2018) and Ovejas discharge sewage water to Mancomojar Creek which is 58 km long (Carsucre, 2015, 2018). Municipal sewage water in Morroa are discharged in Morroa and La Muerte Creeks, which in turn affect Morroa Aquifer as well (Contraloría General Departamental de Sucre, 2013). Chemical Oxygen Demand and Biological Oxygen Demand surpass ambient water quality conditions for ecosystems.

Annex 2. Specification of economic expressions for different water users

Domestic users

Domestic consumers demand water for activities at home. They incur in energy costs for pumping. Then, the price for the consumption of water given by $p_m$ includes the private energy cost ($c_{en}$) along with groundwater license fees, given by $c_l$. This rate is regulated by the environmental authorities. Actual extraction fees sum $4.70/m^3$ for domestic users, while $c_{en}$ is the cost of water collection corresponding to the energy bill. The energy consumption required to lift 1 m$^3$ of water is about 0.0166 kWh (Chaitra and Chandrananth, 2005). Recently the average energy price totals $111$/KWh (ACOLGEN, 2017), which implies that extracting each cubic meter represents a private cost of $1.82/m^3$. Inverse demand curve for domestic users is based on (PNUD & DNP, 2008) for municipalities located below 1000 m above sea level, which is expressed as follows:

$$P(i) = \frac{(e^{3.59} \cdot p_{m}^{0.27} \cdot y^{0.05})^{3.85}}{(W_d(i))^{1.88}}$$

$N$ represents the household size in average five people and $Y$ refers to average family income given by a minimum salary. Demand curve is used to calculate marginal benefit of consumption according to the following expression:

$$\text{Benefit}_{\text{Consumption}} = \int_{W_1}^{W_2} W_i \cdot \bar{Y} \cdot \bar{N} dW_i$$

(BM$i$), the subsequent expression results:

$$BM(i) = 4.10^{6} e^{-0.438 W_i}$$

(A3)

Maize producers

Maize crops are sensitive to water stress and water productivity losses due to stress are difficult to compensate despite stress period is overcome with water applied through irrigation or precipitation (Steduto et al., 2012). Maize crop yields have increased since last 60 years. Despite yields in USA and France are above 9 ton/ha and reported yields in countries such as Argentina, China, South Africa and Brazil are between 1/3 and ½ of the former countries, in all of them a growing trend of yields is observed (Steduto et al., 2012). Sustaining irrigated agriculture and meeting future food demand of the rising global population will request increasing crop productivity per unit of water (Hoekstra, 2013; Trout and DeJonge, 2017). Maize crops in Colombia represent 29% of total crops in the country and this is part of the two types of crops contributing to 79% of green water footprint in agricultural sector (IDEAM, 2019). Water use efficiency in maize crops is based on (Trout and DeJonge, 2017) and is determined as follows:

$$M(W_a(i)) = 0.1 - 0.25W_a^{2} + 2W_m$$

(A4)

$W_m$ represents irrigation water applied in m$^3$ and $M(.)$ corresponds to maize yield in Mg ha$^{-1}$. At some high stress level, the plant would not be able to produce grain and harvest index would be zero (Trout and DeJonge, 2017).

Yucca producers

Cassava crops tolerate well the prolonged water deficit (De Tafur et al., 1998). The characteristic of tolerance to droughts and unfertile soils, underlie the increasing importance of the crop in dry and semiarid environments (DANE, 2016; De Tafur et al., 1998). Yucca is one of the most common sources of carbohydrates for human consumption in the Caribbean Colombian Region. Among the six municipalities of the study area there are almost 7000 ha of planted yucca crops, 50% concentrated in Ovejas Municipality. Annual production of this tuber sum up to 74000 tons in this group of municipalities and average crop yield correspond to 10.7 ton/ha (DANE, 2015). A water use efficiency study of cassava crops was performed by Yao and Gou (1992) in which relevant data were produced. Based on (Yao and Gou, 1992) laboratory results, a water use efficiency function is built as follows:

$$Y(W_f(i)) = -6 \times 10^{-3} W_f^{2} + 0.113 W_f - 1.643$$

(A5)

$W_f$ represents irrigation water applied and $Y(.)$ corresponds to yucca yield in gha$^{-1}$.

Roots of yucca in Colombia are mainly used as fresh tuber preparation in households; as an input for food industry and as a raw material for starch and animal food industry due to its high starch, sugar and protein contain (Agullera-Díaz, 2012; Vergel Cabrales, 1999).
Yam producers
Consumption of yam in Sucre is pervasive and part of the essence of people’s gastronomic tradition. According to (DANE, 2015) data, there existed around 2000 ha of yam planted in six municipalities of this study area. 50% of this area is located in Ovejas and another 25% of yam crops are planted in Sampues and Corozal. Yam harvests in Sucre are predominantly allocated to human consumption; despite this use, yam has high potential for pharmaceutical industry (Reina-Aranza, 2012). Average crop yields for this region correspond to 2 ton/ha (DANE, 2015) which is slightly higher than data from 2012 whose use efficiency was between 0.1 ton/ha in Los Palmitos, 1.1 ton/ha in Ovejas and 1.5 ton/ha in Morroa (Aguilera-Diaz, 2013).

Studies about water use efficiency for this crop are scarce. A specific analysis for yam productivity in Sucre is reported by Mercado et al. (2014). Different irrigation schemes were included in the authors’ experimental designs for two species of yam (irrigation in critical grow period, irrigation in the whole period and no irrigation). A water use efficiency of 1.3 kg/m² was found for the critical period (Mercado et al., 2014).

\[ Y_a(W_m(t)) = -0.25W_m^2 + 1.3W_m \]

(A6)

Annex 3. The maximization problem
Optimal intertemporal allocation of water should balance actual water stock between its use in the present and future use. An intertemporal social discount rate of \( r = 0 \) is used.

\[ \max_{w_s, w_r, w_m} V = \int_0^{\infty} e^{-rt} \left[ \sum_{r=0}^\infty \frac{W_r}{r!} + \sum_{r=1}^\infty \frac{W_r}{r!} \right] \]

(A7)

The last term pre-multiplied by \( \Omega \) represents the externalities arising from the water use by \( k = 1, 2, \ldots, K \) users and \( i \) - user through the time \( t \). \( \Omega \) represents the marginal return for all group of municipalities and farmers, for conserving the CPR. This is, for not depleting the aquifer stock. \( \Omega = $132/m^3 \); is the marginal return calculated as the avoided cost of withdrawing water from alternative sources such as surface water. Given the location of Sucre, “feasible” surface water sources may correspond to Magdalena, Cauca or San Jorge Rivers or groundwater from further locations.

State variable equations
1. \[ \dot{S}(t) = S_0 + R(t) - W_r(t) - W_m(t) - W_{yr}(t) - W_{ym}(t) \]
2. \[ S(0) = S_0, S(T) = S_{min} \]
3. \[ \dot{h}(S(t), W(t)) = h_y - \beta \left( S_t - \sum W_r \right) \]
4. \[ W_r(t), W_{yr}(t), W_{ym}(t) > 0 \]

The Hamiltonian function is presented as follows:

\[ H = \left( W_r(t) \right) + M \left( W_m(t) \right) + \left( W_{yr}(t) \right) + \left( W_{ym}(t) \right) - c_{max} \left[ \frac{h_y}{h_y} \right] W_m + \left( S_0 - \sum_{i=1}^N \left( W_{yr} - W_{ym} \right) \right) + \lambda_s(S_0 + R(t) - W_r(t) - W_{yr}(t) - W_{ym}(t)) \]

(A8)

\[ \dot{\lambda}_s, \dot{\mu}_s \] represent stock variable and height of aquifer shadow prices, respectively. The necessary conditions for an optimal solution with the application of the Maximum Principle, are as follows:

\[ \dot{S} = \frac{\partial H}{\partial \dot{S}} = S_0 + R(t) - W_r(t) - W_{yr}(t) - W_{ym}(t) \]

(A9)

The previous expression recovers the equation groundwater stock. Now we present co-state variable for the resource stock.

\[ \dot{\lambda}_s = r\lambda_s - \frac{\partial H}{\partial \dot{S}} = r\lambda_s - \dot{\lambda}_s + \mu \beta + \Omega \theta - \theta_t \]

(A10)

\[ S_t \geq S_{min}; \theta_t \geq 0; \theta_t(S_t - S_{min}) = 0h = \frac{\partial H}{\partial \mu_s} = h_y - \beta \left( S_t - \sum W_r \right) \]

(A11)

As in the previous case, the last equation allows to recover the second state variable. Now we present co-state variable for the evolution of water table.

15 This high productivity is related to the high density of yam seeds sowed. Density corresponds to 10000 plants/ha and traditional tillage was the plowing technique used.

16 Cost of hiring water lorries to distribute water to communities lacking freshwater.
\[ \mu_t = r \mu_t - \frac{\partial H}{\partial W_d} = r \mu_t + a W^*_{\text{ener}} \left[ \frac{h_d}{h} \right] \sum \frac{h_d}{h^2} - \mu_t \]  

(A12)

Now we proceed to develop the Maximum Principle for control variables.

\[ \frac{\partial \mathcal{H}}{\partial W_d} = 1.75 \times 10^6 e^{-0.04W_d} - c_{\text{ener}} \left[ \frac{h_d}{h} \right] - \lambda_t + \mu_t \beta \leq 0, \text{ si } W_d = 0 \]  

(A13)

The optimization condition for the water extraction for domestic consumption, basically introduces the demand function of water, which depends on the rate that is charged for the extraction and the costs of energy to do so. It is assumed that in the long term, the costs of equipment and other supplies for the extraction are smaller compared with the expenditures for energy consumption.

\[ \frac{\partial \mathcal{H}}{\partial W_m} = n_m^* p_m \left( 2 + 0.5 W_m(t) \right) - c_{\text{ener}} \left[ \frac{h_m}{h} \right] - \lambda_t + \mu_t \beta \leq 0, \text{ if } W_f = 0 \]  

(A14)

\[ \frac{\partial \mathcal{H}}{\partial W_y} = n_y^* p_y \left( 0, 113 - 12 \times 10^{-4} W_y(t) \right) - c_{\text{ener}} \left[ \frac{h_y}{h} \right] - \lambda_t + \mu_t \beta \leq 0, \text{ if } W_p = 0 \]  

(A15)

The first two terms of each of the last three expressions, represent the marginal effect by using water. This effect is given by the short-term marginal utility/benefit (BMG), understood as \( \frac{\partial \mathcal{H}}{\partial W_d}, \frac{\partial \mathcal{H}}{\partial W_f}, \frac{\partial \mathcal{H}}{\partial W_p} \), multiplied each case by market prices.

For the centralized situation, in last three expressions can be grouped in the following way.

\[ BMG - c_{\text{ener}} \left[ \frac{h_m}{h} \right] - \lambda_t + \mu_t \beta \leq 0 \]  

(A16)

From this expression, we obtain

\[ BMG = c_{\text{ener}} \left[ \frac{h_m}{h} \right] + \lambda_t - \mu_t \beta \leq 0 \]  

(A17)

Annex 4. Crops area in six municipalities of Sucre (Colombia)

Fig. 4. Crops area in six municipalities of Sucre (Colombia)
Source: author’s calculation based on (DANE, 2015)

Annex 5. Yucca crops area in six municipalities of Sucre (Colombia)
**Map 3.** Yucca crops location in Sucre up to 2018. Source: Author’s elaboration based on (DANE, 2015).

**References**


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