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| **What is the most sustainable way to distribute the excess fresh water from the Arenal Reservoir in light of climate change impacts in Costa Rica?** |
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| **Abstract:** Costa Rica uses less than 10% of its available water resources. Regardless of this supposed water abundance, some regions of the country regularly experience difficulties with droughts. The Distrito de Riego Arenal-Tempisque (DRAT) is currently Costa Rica’s largest irrigation project. Water from the Arenal Reservoir is piped through fields and used to support the agriculture-heavy region through periods of insufficient rainfall. Excess water from the Arenal Reservoir is generally released into the Tempisque River. This supports downstream towns and farmers but leads to many million litres of lost freshwater to salt water bodies. In light of future climate change expectations, this decision analysis offers a method for evaluating the most sustainable distribution method for the reservoir water. The paper reviews all the elements required for a robust decision, and recommends a package of alternatives. |

**INTRODUCTION**

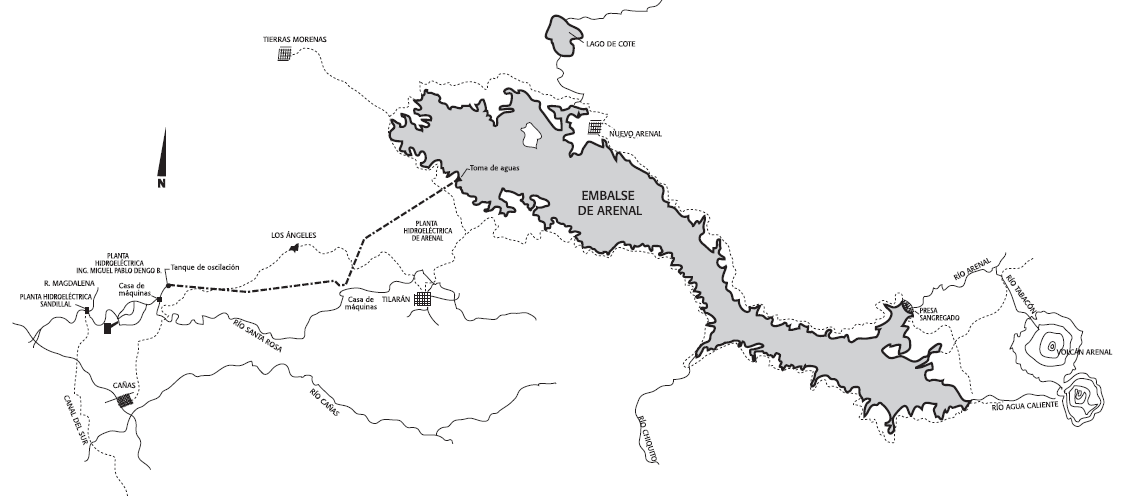
Costa Rica is a water-wealthy nation that uses only 5.8% of its available water resources (EarthTrends, 2003). However, the geomorphology of this tiny nation creates a large discrepancy in the spatial and temporal distribution of water resources. Specifically, Costa Rica is divided, from the north-west to the south-east, by three volcanic ranges that effectively result in the capture of moisture from the Atlantic trade winds and the direction of this water down the relatively gentle Atlantic slope. As a result, the Atlantic slope of Costa Rica experiences an only moderately variable climate with rainfall through the year and a more intense “rainy season” from May to December.

In contrast, the Pacific slope endures a long dry season from November to April, followed by an intense rainy season that delivers a similar amount of total annual precipitation (1,400−2,200 mm) to that received in some areas on the Atlantic slope throughout the entire year (CATIE, 2003). This relatively dry region with its average temperature of 28 degrees Celsius has very fertile soil, making it an important irrigation area (Vargas and Vargas, 2002). The human and ecological systems occupying the Pacific slope of Costa Rica, most of which fall within the province of Guanacaste, must cope with marked cyclical changes in water availability, from absolute scarcity to occasionally dangerous abundance (Nacion, 2007). The Guanacaste province has cloud forests as well as a rich biodiversity, which is in direct competition with urban developments, tourism, livestock and agriculture (Hope et al., 2005).

One of the ways in which Costa Ricans have adapted to this discrepancy in distribution is through large infrastructure projects. In the 1970s, a major project, the Lake Arenal Hydroelectric Project (Fig. 1), was initiated in the Northern region of Costa Rica in the Province of Guanacaste with the intent of satisfying several high priority objectives of the Costa Rican government. These were: increasing electricity generation for a growing, modernizing economy, and a massive-scale transfer of freshwater from the Atlantic to Pacific slope. These objectives were achieved by creating a large artificial reservoir, now known as Lake Arenal, high on the Atlantic side of the Cordillera Guanacaste, and then connecting this reservoir via a large tunnel (5.2 m in diameter, 6.5 km in length) through the continental divide to the Pacific slope. By directing a large volume (97.3 m3/s) (Grupoice, 2010a) of the abundant Atlantic resources westward, the Lake Arenal Hydroelectric project takes advantage of the large hydraulic potential created by the steep Pacific slope to generate “clean” energy at three sequential hydroelectric plants—Arenal, Miguel Pablo Dengo B., and Sandillal.

The Arenal project provides one third of Costa Rica’s electricity (Hope et al., 2005). After the Miguel Pablo Dengo B. plant, a portion of the water is directed into two large cement canals that carry it to the Arenal-Tempisque Irrigation District (Distrito de Riego Arenal-Tempisque, DRAT), where it is currently used to irrigate 28 000 hectares of farmland, bringing economic benefit to roughly 1,125 families, with the theorized capacity to one day irrigate 60,000 hectares, based on the available water (Ballestero et al. 2007). Beyond the irrigation district, the water supports fish farms (primarily Tilapia) and drains into the Palo Verde National Park. This wetland is vital for filtering the water before it enters one of the world’s most rich estuary ecosystems situated in the Gulf of Nicoya (Hope et al., 2005).

**Figure 1.** Lake Arenal Hydroelectric Project Area

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*Figure borrowed from the Instituto Costariccense de la Electricidad* (Grupoice, 2010b)

* River length: 3,405 km2
* 33% of Costa Rica’s total capacity and 50% of its dry season capacity (Hope et al., 2005)
* Irrigation system covers 18,000 hectares
* Annual average flow of 35 m3/s

This difference between the theorized and actual number of irrigated hectares has become an important topic in various management schemes aimed at improving water availability and furthering economic development in Guanacaste. At present, producers within the DRAT utilize only slightly more than half of the 97.3 m3/s of water that is delivered from the hydroelectric project; use varies seasonally from 60−65 m3/s during the dry season and 30−35 m3/s during the rainy season (Jimenez et al., 2001). The remainder of this water is released into the Tempisque and Santa Rosa Rivers.

This situation presents a question to all those concerned with water availability in Guanacaste: what is the most efficient and beneficial way to utilise the “wasted” water from the Arenal Hydroelectric Project? Costa Rica is very sensitive to changes in water management policies as well as temperature variations, leaving it vulnerable to long term changes (Amador, 2003). In the face of climate change, which is predicted to increase temperature in Guanacaste and disrupt the typical pattern of rainfall, this question is even more salient. Combined with the 13 million dollar investment to expand their irrigation system and farm an additional 8,800 hectares of land that the regional government has been considering since 2007, (Ballestero et al., 2007) the situation in Guanacaste is very suitable for this study.

Accordingly, this paper will examine three dimensions of water use and its associated benefits in Guanacaste and then use these dimensions to define objectives likely to be of importance to the various basin stakeholders. These objectives will subsequently be used to analyse nine different alternative water use strategies including the expansion of the irrigation project. Through a ranking of various objectives as well as a selection of objective weights, an overall ranking of the alternatives is created. After an additional review of three potential climate change scenarios, packages of alternatives are created to allow for the most sustainable use of water resources in the Costa Rican Province of Guanacaste.

**DECISION-MAKERS AND STAKEHOLDERS**

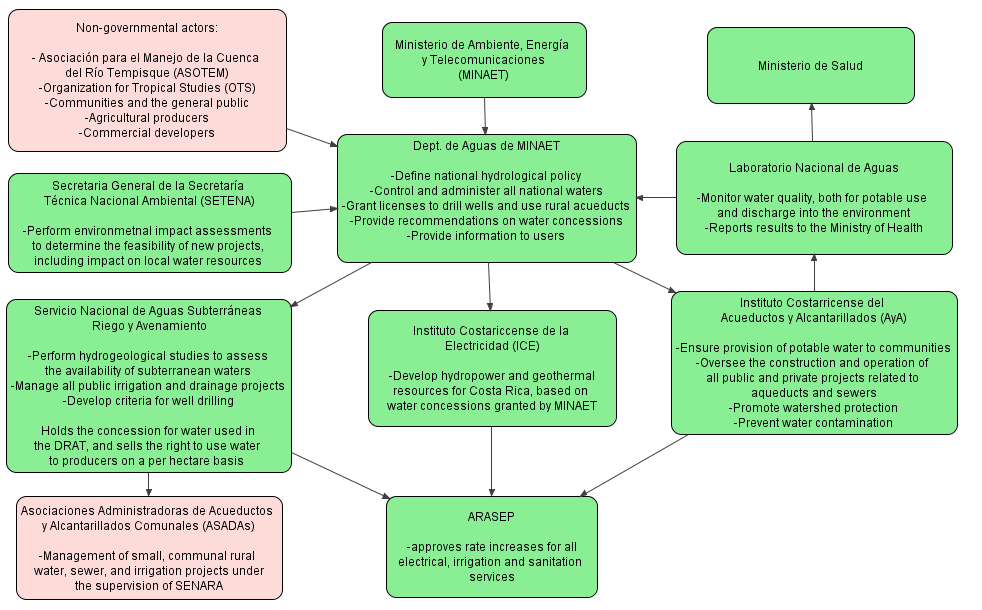
By far the most widespread criticism of Costa Rica’s water management efforts is the multiplicity of government agencies and institutions involved and the unclear delineation of their responsibilities (Fig. 2). As shown in Fig. 2, the ultimate power to grant or shift surface or groundwater concessions to other projects rests in the hands of the Departamento de Aguas MINAET; however, Aguas MINAET is dependent on other institutions, including SETENA, SENARA, and AyA for the collection and analysis of data necessary to make decisions and policies regarding water use. This constellation of interconnecting agencies is likely to change dramatically in the coming years as a result of the government’s stated intent to modernize MINAET and its related institutions (PNGIRH, 2009).

It is also important to note the Ministry of Health plays an important role in Costa Rican water policy where changes in water quality or quantity could be expected to jeopardize public health. Therefore, the objectives and alternatives selected for this decision context should also consider risks due to water-borne or water-related diseases (*e.g.,* contamination, creating habitat for disease vectors, *etc.*). Dengue is an example of an important irrigation-associated disease that can have a heavy impact on the health status of agricultural producers; this disease has been identified as a serious and under-researched health risk for Costa Ricans (Troyo et al., 2006).

In addition to the government agencies involved in water management, research and conservation activities are carried out by numerous foreign and domestic non-governmental organizations. One such organization of note in the Tempisque River Basin is the Organization for Tropical Studies (OTS), a group of 63 American and Latin American universities interested in understanding ecological flows that support ecosystems within the Tempisque River Basin, and the effects of upstream projects (reservoirs, dams, and canal systems) intended to support economic development (OTS, 2012). Other relevant organizations include the Tempisque River Management Association (Asociación para el Manejo de la Cuenca del Río Tempisque, ASOTEM) and the Asociaciones Operadoras de Sistemas de Acueductos y Alcantarillado Sanitario (ASADAS), which manage small, communal water, sewer and irrigation systems in a semi-independent fashion.

Finally, the role of the public in decision-making should not be ignored. In recent years, community input and protest have had powerful impacts on the development of projects perceived to threaten local water resources. This power derives in part from a strong social solidarity movement preserved within the Costa Rican government and the high levels of both engagement and awareness within the populace (Haglund and Gomez, 2006). Furthermore, Costa Rica’s long history of environmental legislation and conservation, and the subsequent “validation” of these strategies through increased tourism and economic benefits, has helped to establish the importance of ecosystems and environmental protection, so much so that the “fundamental right to healthy and ecologically balanced environment” is enshrined in Article 50 of the nation’s constitution. This right was a key factor in a recent Supreme Court case regarding the exploitation of the inland Sardinal aquifer to supply water to a large commercial infrastructure project in Guanacaste; by arguing that the development violated Article 50, local residents were able to halt development indefinitely. The project has since been eliminated (McDonald, 2010).

**Figure 2**. Governmental and non-governmental actors expected to be involved in water planning and policy in the Tempisque River Basin, Guanacaste



**PLANNING HORIZON**

Establishing a time horizon for the planning process is critical. It forms the basis for allocating resources and energies, as the realities of a problem vary depending on the time scale in which it is framed (Hoogstra and Schanz, 2009). Much debate exists regarding the appropriate timeframe for planning processes (Hoogstra and Schanz, 2009; Simons, Vansteenkiste, Lens, and Lacante, 2004; Wilby, Troni, Biot, Tedd, Hewitson, Smith and Sutton, 2009). It is generally agreed that the process should be long enough to allow objectives to be reached, but not so long that efforts are merely symbolic in nature (Hoogstra and Schanz, 2009; Simon et al., 2004). Simon et al. (2004), among others, state that 20-30 years is the maximum timeframe that should be considered if meaningful concern leading to concrete behavioural commitment is to be realized (Boniecki, 1980). This is due to the fact that the further in time a perceived goal is, the less it motivates action (Simon et al., 2004).

In Costa Rica, resource planning usually operates along the short-term, corresponding with the government changeover every four years (Ministry of National Planning and Economic Policy, 2010). The Ministry of National Planning and Economic Policy is working to develop longer term planning horizons on topics such as education, infrastructure, land, environment, health, and public safety among others (Ministry of National Planning and Economic Policy, 2010). Its focus has been on creating materials that develop policies, objectives, and actions over a 20-25 year time horizon (Ministry of National Planning and Economic Policy, 2010), a length of time mirroring what has been deemed appropriate in literature (Simon et al., 2004; Boniecki, 1980).

When considering climate change, a horizon of at least 30 years is preferable. Technical guidance has largely focused on scenarios for the end of the 21st century (Wilby et al., 2009; Carter, 2007; Mearns et al., 2003). This is not surprising considering that climate change involves change over relatively long time periods (Keenan et al., 2012). Although this trend is evolving and more attention is starting to focus on shorter term horizons, this has not been fully realized (Wilby et al., 2009). The most recent International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES), the central document informing the consideration of climate change scenarios in this paper, outlines expectations for the course of the 21st century. As such, this paper adopts a time horizon similar to the technical information available by focusing on the end of the 21st century while, where feasible, making considerations that reflect the shorter timeframe of planning in Costa Rica and the shift that is emerging in academic literature.

**THE DIMENSIONS OF THE STUDY**

***The Human Dimension***

The human dimension considers the water uses as well as current and potential water conflicts in the Guanacaste region. Guanacaste has approximately 7% of the total Costa Rican population (INEC, 2010). Although tertiary and secondary industry outweigh agriculture in terms of the total number of people employed, agriculture is by far the greatest user of water (important crops include sugar cane, rice, and fodder/pasture) and has been the source of numerous water-related conflicts within the Tempisque Basin (Ramirez Cover, 2008). A second important source of economic activity (and conflict) in Guanacaste is tourism, specifically the construction of large hotels, resorts, and condominiums, and associated facilities like golf courses. Between 1994 and 2000, the number of tourism-related building projects has more than doubled; not surprisingly, coastal regions have the greatest number of tourism water-related conflicts (Ramirez Cover, 2008). Currently, water use is distributed between the DRAT irrigation project as well as ground water extraction through the 1,800 legal wells and many unknown illegal wells in the underlying alluvial Tempisque aquifer (Jimenez et al., 2005). Oftentimes the surface water is also diverted for livestock. All these uses have lead to an occasional total cessation of river flow (Jimenez et al., 2005) suggesting that currently the water source is being overtaxed. Projections for water demand in 2020 are expected to increase from 5 to 35% of water supply (Ballestero et al., 2007).

***The Ecological Dimension***

Despite the emphasis placed on human users, the primary users of water flowing through the Tempisque River Basin are the biotic and abiotic components that make up the local ecosystem and provide, through their activities, a variety of ecosystem services upon which humans depend. Some of the ecosystem services that the Tempisque River Basin provides include: the degradation of contaminants that leach from cities and irrigation projects (including agrochemicals); nutrient cycling and retention (thus preventing eutrophication in the Gulf of Nicoya); and flood control, a particularly important feature given the marked seasonality in rainfall, and the likely exacerbation of this seasonality with climate change.

However, the ability of the Tempisque River Basin to continue providing these services is in doubt as a result of failure to maintain environmental flows. Environmental flows refer to the quantity (magnitude, duration, seasonality and frequency of flows) and quality of water required to maintain a desired level of health in the ecosystems. In 2005, a group of researchers working under the auspices of the Organization of Tropical Studies reported that, in the upper reaches of the river, 33% of the average natural flow is withdrawn, and the beginning of this historical trend coincided with the increased number of water concessions granted in the 1980s. The authors also concluded that the amount of water currently granted to users through concessions must be renegotiated to retain the minimum (not the optimum) environmental flow and prevent the degradation and fragmentation of key indicator species, such as crocodile and the guapote fish (Jimenez et al., 2005).

***The Geological Dimension***

As mentioned above, a large portion of the Tempisque River Basin is underlain by a large alluvial-colluvial deposit that is moderately to highly productive in terms of the amount of water it can provide per unit of time (estimated at 400 to 40,000 L/min by the US Army Core of Engineers). The Tempisque aquifer is one of the largest freshwater aquifers in Costa Rica. Currently, this aquifer is used extensively to provide drinking water to many small communities in the river basin, numerous agricultural producers who require water for livestock or irrigation, as well as to several coastal communities that have outstripped their own highly vulnerable or contaminated coastal aquifers—Playa Panama, Playa Hermosa, and Playa el Coco. As of 2008, withdrawals from the Tempisque aquifer were estimated to represent 75% of total recharge to the aquifer. However, this estimate was based on the number of registered wells; given the potentially large number of unregistered or illegal wells, actual usage may greatly exceed recharge (Zunhiga, 2008). These claims were at least partly confirmed by subsequent studies performed by the National Service of Groundwater, Irrigation and Drainage (Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento, SENARA, 2003). Currently, the Tempisque Basin and Aquifer are listed as resources at great risk under Costa Rica’s National Water Plan for the Integrated Management of Hydrological Resources (Plan Nacional de Gestión Integrada de Recursos Hídricos, PNGIRH, 2009).

**DEVELOPING THE OBJECTIVES HIERARCHY**

Based on the roles and identities of the decision-makers and stakeholders expected to participate in any long-term regional water planning decision, it is possible to identify a number of fundamental objectives in this decision context. Further structure is given to the objectives through the use of sustainability’s accepted triple-bottom-line (TBL) (Lundin and Morrison, 2002). Sustainability was publicized in 1987 through the presentation of *The Brundtland Report* by the United Nations World Commission on Environment and Development (WECD, 1987). In the report, sustainable progress was expressed as a concept that encompasses everyone on earth into the distant future. Through this, the TBL of environmental, economic and social issues were used to be able to integrate intergenerational and international justice as well as humanity’s inseparable dependence on the environment. A number of different means objectives are developed for the Tempisque river situation, connected to the fundamental objectives used for the decision-analysis, and arranged under the sustainability framework, shown in Figure 3.

Many decision-making situations, especially ones dealing with water-related issues, are very complex. To understand the context as well as make a sophisticated and analytical decision, problems are generally required to be decomposed into smaller components (Eiseman et al., 2011). The following objectives hierarchy has been created according to this theory from decision-analysis literature. As recommended by Keeney (1992), decision analysis should take place through the use of independent objectives that are compact in definition and together offer a complete but simplified image of the issue in question. In the selection of the fundamental objectives a great care is taken to avoid double measurements of a single issue, though ultimately factors are interconnected and interrelated. Multiple ends objectives are developed, though only a few fundamental objectives are selected to create a usable model (UNDPCSD, 1995).

The means objectives in this hierarchy are used to select performance indicators. For example, the fundamental or “end” objective of maintaining the ability to manage water resources in a flexible and adaptive way, is related to two things: 1) ensuring an increase in the total storage of water in the state (whether underground or superficial); and 2) avoiding large expenditures that would compromise the government’s future ability to spend on water planning (i.e., going into debt on a large project for which the future benefit cannot be adequately judged). Utilizing the objective of flexibility is necessary given Guanacaste’s uncertain future climate. Since climate change can be unpredictable in its speed and influence on the environment (Adger, 2003), flexibility must be measured to understand how an infrastructure system may react to potential changes. Similarly, this study uses the volume of water in storage as a natural measure for the performance of the infrastructure. In the case of the fundamental objective to provide Costa Ricans with a healthy and ecologically balanced environment, consistent with Article 50 of the Costa Rican Constitution, the conservation of wetlands appears to be an important factor in achieving other means objectives that satisfy this fundamental objective. Thus, “hectares of healthy wetlands” is a meaningful performance measure for the stated objective.

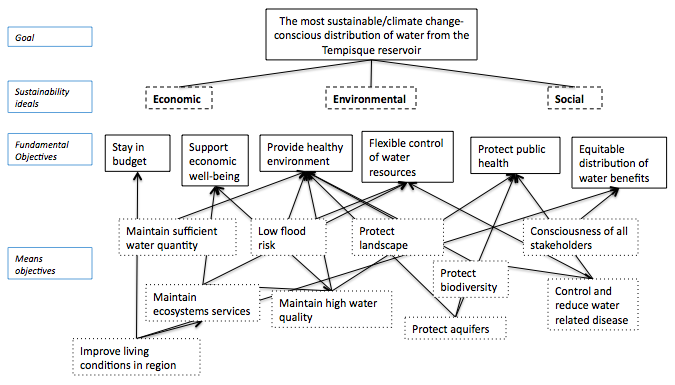
The livelihoods and economic well-being of the local population is measured through increased income. This fundamental objective is important to keep note of as it allows for an understanding of the economic benefits of the alternatives. The state of water systems and access to water is closely connected to economic well-being of a region and nation (Bdour, 2009) and so the changes in water use will have a direct and indirect influence on the livelihood of local people. The provision of clean water is vital for both the environment and the population. The health of these two entities is interlinked—a healthy environment provides vital ecosystem services for a healthy population. A project receives a high score for bringing positive changes to the environment through the measurement of hectares of healthy wetland. The health of people is measured through the incidence of water-related diseases or illnesses due to the fact that open water bodies provide locations for mosquitoes and other vectors of diseases (Vargas and Vargas, 2003). Studies have shown Dengue to be an irrigation-aggravated disease (Troyo et al., 2006).

The sustainability and success of the benefits of increased health as well as increased income should be accessible to as many people as possible. Projects can have substantially different beneficiaries, and many projects help one group while damaging others. For example, the irrigation system brings many millions of dollars of benefits to plantation owners. It also gives jobs to local people. With the land being used for agriculture, the region has fewer opportunities to benefit from tourism, and down-stream water users suffer from water polluted by pesticides and erosion sediment. This objective, crucial to the study of sustainability and its holistic ideals, is measured through the number of people receiving direct water use benefits.

***Keeping costs low***

For this study the costs are measured by reviewing the potential implementation costs of the various projects. Staying within budget and having inexpensive projects is vital for the sustainable functioning of the system. Considering the recent surface reservoir project that needed to be cancelled due to an inability to cover the start-up costs this is determined to be an appropriate measure as budgets are limited and various borrowing and international funding is not secure. This fundamental objective is also measured using the -2 to +2 scale. The +2 is used for the alternative “do nothing,” as there is an implementation cost of zero dollars and so +2 expresses the least expensive option. Then -2 is used for the creation of the surface reservoir, which has a predicted value ranging between 20 and 100 million dollars (Central America Data, 2008; The Costa Rican News, 2010) and is the most expensive alternative. The estimated implementation costs of the various projects are then fit into the five-point scale.

**Figure 3.** The objectives hierarchy created for this decision-making context



**The weights of fundamental objectives**

With the inclusion of sustainable development in Costa Rican policies, economic, environmental, and social goals have all become central to national decision-making (CR Constitution, 2012). Though the fundamental objectives selected for this study have comparable levels of importance, a review of the Costa Rican constitution, water laws and water resource management literature, informs a selection of varied weights aimed to reflect a local government perspective. The addition of weights allows for a multi-faceted discussion of what are believed to be inevitable trade-offs (Brunner and Starkl, 2004).

The highest ranked objectives are the two connected to finances. Sustainable decisions should be mindful of society and the environment; however they should also be financially viable “with costs not exceeding benefits” (Balkema et al., 2002). The Costa Rican constitution mirrors this ideal (CR Constitution, 2012). Ultimately, projects must be financially feasible in order to be implemented (Brunner and Starkl, 2004). There are many restrictions and regulations that must be abided by, but there are also subsidies and various incentives promoting tourism and cash-crop agriculture (Barrantes-Reynolds, 2010). With tourism and connected service industries being central to the Costa Rican economy (CIA-CR, 2012), it is clear that the government is an advocate of their development.

Environmental and public health are given similar weights because in the national policy they are recognized as interconnected goals. Public health is weighed higher because the importance of environmental health is connected to its influence on public health. Furthermore, the Costa Rican government recognizes its role in the protection of the nation’s “natural beauty” (CR Constitution, 2012, Article 69). Costa Rica is a world-wide leader in conservation and sustainable ecological policy-making (Campbell, 2002). It is, however, still clear that these objectives have a slightly lower ranking than the objectives of financial success. Cruise tourism, a recent development that accounts for over 15 % of tourist arrivals, has developed without any major environmental impact assessments (Durham et al., 2010). Recently, there have even been discussions to encroach on a National Protected Area in order to make way for tourism infrastructure (Barrantes-Reynolds, 2010).

Fair distribution of benefits is next in the ranking of the fundamental objectives. Equal distribution is expressed in the Costa Rican constitution as well as national water laws. The regulations call for the destruction of infrastructure that causes suffering or inequality within society. Additionally, over the last 20 years income inequality has risen significantly (Gasparini et al., 2009) in light of structural adjustment policies (Edelman, 1999). Due to tourism, prices have increased to reflect demand, leaving many activities and experiences inaccessible to the local population (Campbell, 2002; Himmelgreen et al., 2007).

The objective focused on system flexibility has the lowest ranking in this decision-making study. Flexibility has been considered one of the most significant objectives in an attempt to fulfill sustainability ideals in water management (Berndtsson and Jinno, 2006), especially in light of climate change predictions (Smith et al., 2000). There are various water policies that express an interest in planning for climate-change and being appropriately adaptable; however so far there is very little implementation (ALM, 2009). The Costa Rican constitution and the national water laws show little direct indication of a commitment to flexible systems. Therefore, balancing the general ideals in regulations with action, the flexibility objective is the lowest ranked.

**The challenge with the fundamental objectives**

Achieving an equitable distribution of water benefits may present the greatest challenge to attain in combination with other objectives. To do so would require a strategy that effectively increases income for all sectors while maintaining healthy wetlands and ensuring equal water access for all. Agricultural pursuits, such as the encouragement of cash-crops like pineapple, require large amounts of water and land (Neubert, et al., 2008). This would leave little water to be used elsewhere, limiting local water access, opportunities for growth in other sectors, and ability to improve environmental health. Similarly, if the focus was on equal water use benefits for everyone the reality of already overcommitted well rights (Servicio Nacional de Aguas Subterráneas, Riego y Avenamiento, SENARA, 2003) would inevitably leave no water for improving ecological conditions. Providing Costa Ricans with a healthy and ecologically balanced environment may also be difficult to achieve in combination with the objective of promoting livelihood and economic well-being of local communities. In a similar manner, allocating the excess water to increase the area of healthy wetlands appears to be in competition with local agricultural and traditional tourism pursuits. If local economic development in the area focused more on eco-tourism this conflict would be less of a concern, as wetlands would be beneficial to such an endeavour. However, an eco-tourism focus would require fundamental changes to regional development. Considering alternative options that help overcome these challenges is central to a solution that achieves the desired objectives.

**ALTERNATIVES: SIGNIFICANT TRADEOFFS AND COSTS**

Using the objectives outlined in Figure 3, we select a number of possible water use strategies and identify their benefits and associated tradeoffs, risks and costs. The primary risks and benefits are discussed below and additional considerations are listed in Table 1. We then compare these alternatives with respect to the degree to which they satisfy the fundamental objectives identified above.

***Commit the water to the upper reaches of the Tempisque River***

As described in the section examining the ecological dimensions of water use, the Tempisque River Basin appears to be under stress, which may result in the failure of this system to provide certain ecological services, such as water purification, nutrient cycling, and flood regulation. It is important to note that this stress is apparent even with the very significant input of “excess” water coming from the DRAT. Thus, removing this flow from the river could be expected to further exacerbate habitat fragmentation, wetland loss, and loss of the least robust species, particularly in the face of future water stress brought on by climate change. One option to ease pressure on the entire river would be to re-allocate some portion of the “excess” flow to the upper river basin, which is the most stressed (Jimenez et al., 2005). This would simultaneously support the lower reaches. However, because the existing surface water concessions already far exceed the actual flow in the upper reaches; such a strategy could only be successful if surface water concessions are curtailed or renegotiated.

***Expand the irrigation canal system***

Another option for the “extra” water flowing from the Arenal Hydroelectric Project is to continue with the long-standing “irrigation and drainage ethic” that first gave rise to the DRAT in the late 1970s. Further expansion of large-scale irrigation projects like the DRAT would support the livelihoods of producers currently constrained by water shortages. Increasing the supply of water may allow these farmers to move into more valuable water-intensive crops, like pineapple and melon, and would thus support economic development in the region.However, expansion of the irrigation networks has been associated with increases in water-related diseases, particularly those transmitted by insect vectors. In other tropical regions, physical proximity to irrigated fields and orchards was associated with increased dengue infection (Vanwambeke et al., 2006). On a global scale, both irrigation projects and large dams have been identified as risks for malaria infection (Keiser et al., 2005). Thus, increasing the irrigated area of the Tempisque and the subsequent creation of standing-water habitat for mosquitoes may be a concern for public health.

A second issue with expanding irrigated agriculture is the potential increase in the contamination of the Tempisque River, both through an increase in overall agrochemical use on irrigated land, and the connecting of these lands to waterways via concrete canals. In 2008, the Agricultural Development Institute (Instituto de Desarrollo Agrario, IDA) and SENARA were ordered to pay $6 million in damages to Palo Verde due to the influx of pesticides from the draining canal waters and the subsequent wetland loss (Costaricapages, 2008). Irrigation expansion may further threaten scientifically and socially valued environments like Palo Verde and become a source of conflict.

The other alternatives were developed from discussion of expanding the DRAT to cover 8,800 more hectares of agricultural land (Ballestero et al., 2007). Though the regional agricultural developments would have great economic benefits, the erosion, intensified by tree-free regions, would have considerable negative influences on local flora and fauna.

***Create additional surface reservoirs***

The storage of water in traditional surface reservoirs is a long-standing practice with several benefits. Such reservoirs can be relatively simple to build (*e.g.,* a concrete-lined pit) and can be scaled according to storage needs. In addition, unlined surface reservoirs can be used to increase local groundwater infiltration (in which case the structure may be referred to as a “seep-away”), which increases underground storage and at least partially alleviates groundwater over-exploitation. However, this option can be relatively expensive to implement and, as with irrigation canals, the presence of a warm, standing body of water (as in a dam or reservoir) provides a suitable habitat for vector-borne disease (Keiser et al., 2005). In 2008, there was a plan to create a new 800 hectare surface reservoir for the Guanacaste region, Rio Piedras dam. This new surface water storage would have provided increased water for urban centers as well as for irrigation. It was, however, found to be too expensive to be implemented (The Costa Rican News, 2010).

***Aquifer storage and recovery***

Aquifer storage and recovery (ASR) refers to the practice in which “excess” water, typically derived from high surface flows during the wet season, is collected, purified, and pumped into underground formations at high pressure. This practice essentially creates an underground reservoir that can be later extracted and used to support human activities (drinking water, irrigation, *etc.*) or to support environmental flows in stressed aquatic ecosystems. ASR is preferable to traditional surface reservoirs in that they protect the stored water from contamination and evaporation. The most important benefits of ASR are that it: 1) increases the total store of water (although at increased cost); and 2) can be used to relieve pressure on stressed alluvial aquifers (like the Tempisque) and thus avoid future problems with compaction and reduced storage. Currently, aquifers supply 88% of Costa Rica’s ‘consumptive water demand’ (Ballestero et al., 2007), making them a very important water source. The Tempisque aquifer in particular is in danger of being over-exploited as its use rate of 50-100 litres per second is higher than its natural recharge rate (Page and Redclift, 2002).

Although ASR is usually practiced using an aquifer that will not allow the stored water to leak away, there is also benefit to injecting water into an open system. First, this kind of subterranean distribution supports groundwater-dependent ecosystems like the Tempisque River and associated wetlands through the restoration of natural discharge areas. Furthermore, in cases where groundwater contamination has occurred (*e.g.,* seepage of wastewater or agrochemicals into the aquifer), AS(no-R) can be used to create a “flushing flow” to drive contaminants out of the formation. Studies using hydro-geological modelling and GIS have indicated that groundwater formations in Guanacaste are susceptible to contamination (Fallas, 2002; Mende et al., 2007). Thus, planning to reduce the incidence of contamination and remediate the aquifer may be required. The majority of aquifer pollution comes from untreated sewage as well as agricultural and industrial chemicals.

In terms of cost, ASR can be an expensive option depending on the quality of water to be stored (*i.e.,* the need for prior purification) and the number of installations required. Finally, ASR involves “double pumping” costs, in that energy is required to inject water and to later recover it for use. Extraction costs may also limit access to injected water for those with limited financial resources, decreasing the “equitability” of this option. Some other studies in Latin America have shown the cost of artificial aquifer recharge to be up to 1,700 dollars per hectare (Ringler et al., 2000). If a similar amount of space is used as is planned for the 8,800 hectare DRAT expansion, then the costs would be over $12 million.

***Support urban centers***

Although Guanacaste maintains only a small percentage of the population of Costa Rica, much of this population is concentrated in urban centers, consistent with the shift from a primarily agricultural to a service-oriented economy (Ramirez Cover, 2008). Several studies have examined the effects of urbanization in Guanacaste, and one of the primary criticisms is that it occurs without planning and without the appropriate water and sanitation services (Calvo, 1990). The most rapidly urbanizing areas of Guanacaste include Nicoya, Playa Tamarindo, and Liberia. Throughout Costa Rica, over 97% (Ballestero and Reyes, 2006) of the population has a water connection into their homes, however in Guanacaste it is still under 80% (UNGA, 2009). With increasing urban populations, increased efforts towards water connectivity will contribute to supporting the livelihoods of the local population.

Notably, piping water to urban centers and thus relieving pressure on the aquifer is beneficial in that it would allow the aquifers to recharge. However, there is the danger of liberating demand and increasing water use as a result of increasing supply. In any case, further urban growth without a marked decrease in per capita use would ultimately result in increased total water use.

***Support commercial development***

The final option here, and one that follows with Costa’ Rica’s long-standing economic development plan, is to pipeline the “excess” water from the Arenal Hydroelectric Project directly to the “zona hotelera” on the Pacific coast. As of 2005, only 0.4% of all federally granted well licenses were held by facilities intended for tourism (Ballestero et al., 2007). These licenses are often linked to concessions for relatively large volumes of water meant to satisfy tourism-related facilities, such as golf courses and swimming pools. The discrepancy between the volume of water consumed by tourism and that consumed by locals was a key sticking point for plaintiffs involved in the Sardinal Aqueduct case, which eventually reached the Supreme Court. In this case, water withdrawn for the purposes of commercial development would have exceeded that of the local community by at least 10 times (Baxter-Neal, 2008). The project was subsequently halted, leaving many uncertain as to how tourism will develop along the coast without water. Given that most or all of the coastal aquifers are currently under stress, some form of water transfer is an attractive option.

***Reforestation***

Costa Rica experienced severe issues with deforestation between the 1950s and 1980s. With the government support and subsidization of cattle farming, much of the forested land was removed (Quesada and Stoner, 2004). Regions with fertile soil were the most tempting for these industries. The tropical dry forest of the Guanacaste region is one of the most threatened and climate sensitive ecosystems in the world (Bawa and Seidler, 1998). Over the last 30 years, however, there has been a decline in the cattle industry as well as major changes in forest policies with the government promoting the re-growth of tropical dry forest (MINAE, 2002; Abizaid and Coomes, 2004). In the Guanacaste region, forest coverage has increased to 47.9% (Sanchez-Azofeifa et al., 2006). Increasing re-forestation would not only require the planting of trees but it would also require the purchasing of land and/or further subsidies to encourage private land owners to convert their land to forested area (Calvo-Alvarado, 2009). It would require increased subsidies to give incentive to preserve the forests. In the 1990s the Costa Rican government instilled a sustainable forestry and tree replanting subsidy, with a payment of 150 dollars per hectare per year for a five year time period. The subsequent support of forest protection is about 221 dollars per hector. This amount is insignificant compared to the benefits of other land uses (Calvo-Alvarado, 2009).

Tree planting supports the natural environment, increasing the soil quality, as well as reducing erosion. More forest means more habitats for animals, larger areas acting as CO2 sinks (Oelbermann et al, 2004), and increased space for eco-tourism. The greater job opportunities in the service industry shift the local economy further away from agriculture, taking land away from agricultural practices and threatening the potential profits from cash crops and farm animals. The benefits of tree planting from land value increase, tourism, and other ecosystems services would be gained gradually over a 5 -20 year time period as the trees grow to their full potential (Harrison and Herbohn, 2001). Repayment from the agriculture sector would be much more immediate.

***Do not change water distribution but invest in water use efficiency***

The implementation of this alternative would require no changes in the distribution system. It could still, however, lead to major changes for the environment and for the local people. In general, the irrigation of crops flushes out important nutrients and increases the speed of soil erosion (Barbier and Bishop, 1995). Assisting and encouraging farmers’ adoption of resource conserving technologies, changes in crops/livestock, and use of farm systems that incorporate trees can help increase the sustainability and success of farm land (Pretty et al., 2006). Local urban water users also overuse the water through legal and illegal access to wells (Ballestero et al., 2007). To increase water use efficiency would require long term investments into education. It may also lead to long term benefits as people become more aware of their resources and their responsibility towards the environment and to others. More financial effort would need to be directed towards educating tourists to be more careful with their water use.

***Do nothing***

A ‘do nothing’ option is important for a decision analysis study as it brings the current situation into focus. This alternative allows us to compare alternatives to current performance. The current system distributes water to 18,000 hectares of irrigated land with an annual average flow of 35 m3 per second (Jimenez et al., 2001). The remaining water from the reservoir is released into the Tempisque river, meaning that many millions of litres of fresh water are lost to salt-water bodies every year. The current water distribution allows the river water level to support fisheries downstream as well as allow downstream towns to make use of the water from the Tempisque aquifer. Continuing with the current ‘business-as-usual’ distribution system, would be the best alternative for a regional government reviewing a short time-line and focusing primarily on the budget. However, in the long term, ‘do nothing’ is not the best option as it does not prepare the region for climate change issues or potential fluxes in tourism and population.

**Table 1.** Risks and benefits of the proposed alternative uses for water from the Arenal Hydroelectric Project

|  |  |  |
| --- | --- | --- |
| **Alternative** | **Benefits** | **Tradeoffs, costs, and risks** |
| Commit flows to the upper Tempisque River | -Supports the production of ecosystem services enjoyed by humans, including flood regulation and the production of commercially and ecologically important species.  -Equitably beneficial. | -May result in the unintentional “reclamation” of drained wetlands currently used for agriculture.  -Without better control over or re-negotiation of concessions allowing withdrawals from the river, may ultimately increase total water use. |
| Expand irrigation projects | -Supports livelihoods of agricultural producers.  -Relieves pressure on the Tempisque River in terms of the deviation of superficial flows. | -Benefits only a few families connected to the system.  -Creates habitat for vector-borne disease.  -Expanding cultivated area and increasing connectivity between fields and waterways via concrete channels may develop agrochemical, organic, and sediment contamination of the Tempisque River. |
| Create additional surface reservoirs | -Increases localized infiltration to the aquifer.  -Easy to access stored water. | -Results in loss of water through evaporation.  -Creates habitat for vector-borne disease.  -Possibly produces methane gas. |
| Aquifer Recovery and Storage | - Relieves pressure on the Tempisque aquifer and avoids future problems with compaction and reduced storage.  - Avoids evaporative waste.  - In the dry season, stream-flow exhibits a continuous recession and is highly predictable. In the wet season, there is both a predictable component (increased base-flow and, presumably, groundwater elevation and the extent of saturated soils) and an unpredictable component involving the timing and magnitude of individual stormslong-term storage.  - Supports groundwater-dependent ecosystems like the Tempisque River and associated wetlands through the restoration of natural discharge areas.  - Equitably beneficial in the sense that ASR increases a common pool resource. | - Increases cost in terms of equipment, pre-injection water purification, and pumping.  - The amount of water that can be stored is constrained by the characteristics of the available formations (conductivity, connectivity to other formations).  -Sustainable use is dependent on the equitable and controlled access to groundwater through MINAET concessions. |
| Support urban centers | -Benefits many.  -Relieves pressure on aquifers, allows recharge, and supports discharge to groundwater-dependent ecosystems. | -Only a temporary solution if Guanacaste’s cities continue to grow. |
| Reforestation | -Benefits many in the long run.  -Supports the environment.  -Provides natural water cleansing. | - Takes land away from people and agriculture. |
| Water use efficiency | -Allows people to make better use of their resources.  -Facilitates a stronger community bond through conservation ethic. | - Re-education is time consuming and difficult.  - Pipe repair on a large scale is a decade long project that will disrupt people’s lives. |
| Support commercial development | -Provides indirect economic benefits to those living in tourist areas. | -Direct water use benefits fewer people.  -By promoting further coastal development, total water use will increase with no increase in storage. |
| Do nothing | - Results in zero initial costs.  -Allows budgets to go towards other important issues and infrastructure. | - Risk long-term costs of not making appropriate changes in the system.  -Risk being unprepared for future droughts. |

Table 2, below show the relative score given to each alternative based on the benefits and tradeoffs described in Table 1, above. Relative scores range on a simple scale from -2 to +2 as described in the objectives listed above. Table 3, below compares ranking alternatives with and without weights. The relative even distribution of weights does little to reorganize the order in which the alternatives are ranked, but provides a tie-breaker for the three ‘mid-ranked’ alternatives which will be useful in creating a strategic combination of alternatives in the future.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Objectives**  **……………**  **…………… Alternatives** | **Ability to manage water in flexible and adaptive manner** | **Support livelihoods and economic well-being** | **Provide 'healthy and ecologically balanced' environment** | **Protect public health** | **Equitable distribution of benefits** | **Project costs** | **Total score** | **Weighted score** |
| **-** | 0.11 | 0.2 | 0.16 | 0.17 | 0.14 | 0.22 | 1 | - |
| **Flow to upper Tempisque** | some infiltration, most lost to sea | increase fishing and ecotourism | direct wetland support | water purification | river inhabitants | minor change | 7 | 1.16 |
|  | 1 | 1 | 2 | 1 | 1 | 1 |
| **Expand irrigation** | some infiltration, most lost to sea | increase agriculture | contamination to wetland | chemicals and vectors | farmers | develop network | -2 | -0.43 |
|  | 1 | 1 | -2 | -2 | 1 | -1 |
| **Surface reservoirs** | some infiltration, most evaporated | increase agriculture | small disjointed wetland | vectors and unprotected | locals | most expensive | 1 | 0 |
|  | 1 | 1 | 1 | -1 | 1 | -2 |
| **Aquifer storage & recovery** | high infiltration loss to natural cycles | increase agriculture, tourism, fishing | discharge supports wetland | clean storage | everyone and future | artificial aquifer creation | 8 | 1.18 |
|  | 2 | 2 | 1 | 2 | 2 | -1 |
| **Support urban centers** | high level of control | increase urban quality of life | wetland contamination | water access | urbanites | develop network | 2 | 0.24 |
|  | 1 | 1 | -1 | 1 | 1 | -1 |
| **Support tourism** | no storage opportunities | increase tourism | wetland contamination | water access | tourists | develop network | -1 | -0.09 |
|  | -2 | 1 | -1 | 1 | 1 | -1 |
| **Reforestation** | plant trees along tributaries | more ecotourism | supports wetland | no direct public | locals/tourists/nature | tree planting | 4 | 0.61 |
|  | 1 | 1 | 1 | 0 | 1 | 0 |
| **Water use efficiency** | high level of control | support all users | same use for environment | efficiency/ high quality | same distribution | re-piping/re-education | 4 | 0.57 |
|  | 2 | 2 | 0 | 1 | 0 | -1 |
| **Do nothing** | lost to river and some irrigation | supporting agriculture | contamination/ wetland support | contamination of river | farmers | no changes cheapest | 4 | 0.74 |
|  | 0 | 0 | 1 | 0 | 1 | 2 |

**Table 2.** Quantitative evaluation and weighting of alternatives

**Table 3.** Alternative rankings with and without weighting considered

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Ranking** | **Alternative** |  | **Ranking** | **Alternatives + Weights** |
|  |  |  |  |
| 1 | Aquifer storage & recovery | 1 | Aquifer storage & recovery |
|  |  |  |  |
| 2 | Commit flows to upper Tempisque | 2 | Commit flows to upper Tempisque |
|  |  |  |  |
| 3 | Reforestation | 3 | Do nothing |
|  |  |  |  |
| 3 | Do nothing | 4 | Reforestation |
|  |  |  |  |
| 3 | Water use efficiency | 5 | Water use efficiency |
|  |  |  |  |
| 4 | Support urban centers | 6 | Support urban centers |
|  |  |  |  |
| 5 | Surface reservoir | 7 | Surface reservoir |
|  |  |  |  |
| 6 | Support tourism | 8 | Support tourism |
|  |  |  |  |
| 7 | Expand irrigation | 9 | Expand irrigation |
|  |  |  |  |

The appreciation and comparison of trade-offs is considered a vital component of sustainable development studies (Cash et al., 2003). The extent to which the alternatives are exclusive or able to be achieved in combination with one another varies greatly. Alternatives can be packaged together based on several criteria related to timing, resources, and anticipated changes in the environment. Perhaps one of the most crucial changes to consider is climate. Before determining potential packaging options it is important to consider how climate change will impact the order in which alternatives could be implemented.

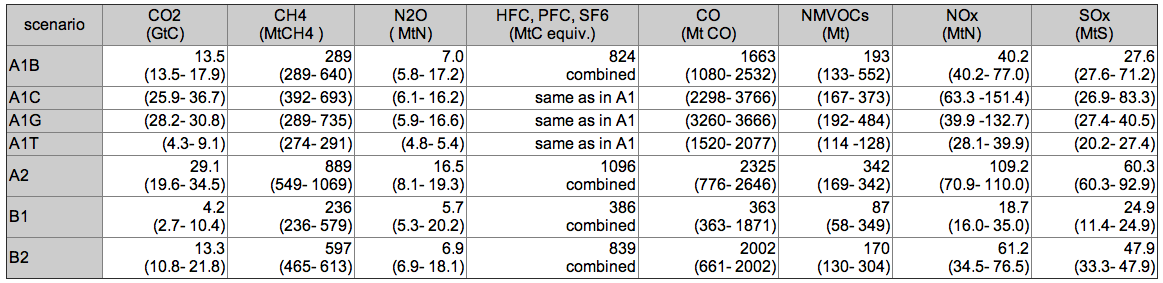
**CLIMATE CHANGE SCENARIOS**

**Global Context**

The International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) describes the diverse and numerous drivers of climate change, and how they may affect different climate futures. The report discusses interactions between factors such as socioeconomic development, population growth, greenhouse gas (GHG) sources, GHG sinks, and land use changes. Since the trajectories of the forces driving climate change are uncertain, the SRES projects varying scenarios, representing a possible range of futures associated with differing quantities of GHG emissions released into the atmosphere over time.

There are four main scenarios detailed by the SRES, categorized as A1, A2, B1, and B2. These scenarios illustrate how different interactions between climate change drivers may evolve through the 21st century and their associated global implications. In scenario A1, the future is marked by rapid, globalized economic growth, a mid-century global population peak, as well as swift technological change supporting energy efficiency. Scenario A2 is characterized by regional wealth accumulation, slow regional convergence, and constant population increase. In scenario B1, the world globalizes in a more equitable fashion than in A1 and A2, global population peaks mid-century (as in A1), and there is an emphasis on technological efficiency. Scenario B2 is marked by localized climate change and sustainability solutions, with constant population growth (lower than scenario A2), medium levels of economic development, and less swift but more varied technological evolution than A1 or B1.

**Table 4.** Overview of GHGs, ozone precursors, and sulfur emissions for the SRES scenario groups.

**Note:** Numbers are for the four markers and (in brackets) for the range across all scenarios from the same scenario group (standardized emissions).

**Source:** Environmental Software and Services Meteorological and Climate Modeling. Climate Change Scenarios. Retrieved June 10, 2012: <http://www.ess.co.at/METEO/CCS.html>.

**Costa Rica Relevance**

The IPCC SRES climate change scenarios A1, A2, B1, and B2 all reference population growth, the state of the world economy, the global energy system, and land use change—connected forces driving climate change. However, to isolate the variable of greenhouse gas emissions (GHG), and their specific implications to Costa Rica, we use the following categories: no climate change (a baseline with no associated IPCC scenario), moderate climate change (IPCC A2, B2), and extreme climate change (IPCC A1, B1).

**Scenario 1: No Climate Change (Baseline)**

A scenario of no climate change—while very implausible—is useful to consider as a baseline from which to compare other scenarios. Without climate change, ostensibly the hydrological cycle would remain relatively constant on average over time, without a trend toward more intense precipitation in shorter time periods. However, the annual freshwater withdrawals of 2.7 billion cubic meters per year (World Bank, 2012) would likely slowly increase with annual average population increase of 1.5% (World Bank, 2012). Without climate change, freshwater withdrawals each year could remain at 53% for agriculture, 29% for domestic and 17% for industry, consistent with 2009 statistics (World Bank, 2012)—depending on other economic changes and policy choices. Finally, in the absence of climate change, the total renewable internal freshwater resources could remain at 24,484 cubic meters per capita (World Bank, 2012).

**Scenario 2: Moderate Climate Change**

A scenario of moderate climate change is based on regional and localized climate change impacts, consistent with IPCC scenarios A2 and B2. Costa Rica’s 2000 and 2009 communications to the United Nations Framework Convention on Climate Change (UNFCCC) outline several key climate change vulnerabilities. These include: costal sea-level rise, negatively impacted agricultural efficiency and productivity, and a reduction in forest canopy coverage (GFDRR, 2011). Over the last 40 years, Costa Rica has experienced growing intensity in its hydrological cycle: greater quantities of rain fall in shorter episodes, a trend projected to continue (GFDRR, 2011). The future result will likely be more frequent and intense flooding and drought events, affecting crop production, forests and soils, as well as water availability (GFDRR, 2011).

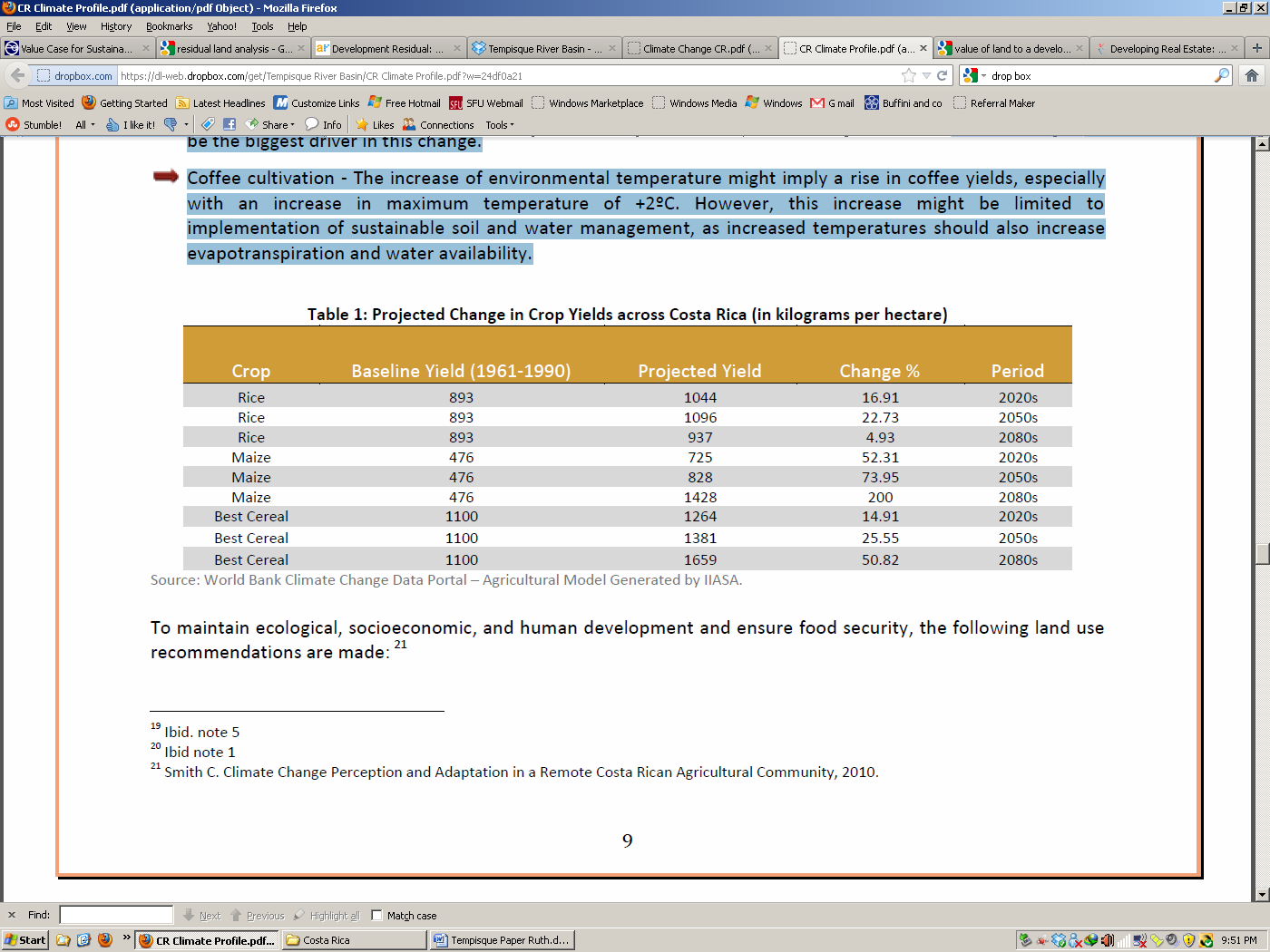
***Impacts on Water Resources***

Freshwater availability is expected to become a growing concern in the future. The problem of uncoordinated water management policies is seen to exacerbate climate change impacts. For example, climate change triggered floods could risk lowering the Costa Rican population that receives potable water below the current level of 76% (GFDRR, 2011). An imbalance in potable water supply is projected to occur in Costa Rica’s Central Valley by 2022, given interactions between climate change and population growth trends (GFDRR, 2011).

***Impacts on Agriculture***

Climate change is also expected to bring major changes to Costa Rica’s agricultural sector, which makes up 14% of the country’s employment (GFDRR, 2011). The main economic drivers of Costa Rica’s agricultural sector are exports of bananas, sugar, coffee and beef. Coffee cultivation generates the most employment and contributes most, relative to these other crop exports, to Costa Rica’s GDP (GFDRR, 2011). The following table shows the World Bank’s projections of crop yield changes due to climate change.

**Table 5.** Projected Change in Crop Yields across Costa Rica (in kilograms per hectare)



**Scenario 3: Extreme Climate Change**

A scenario of extreme climate change is based on rapid, globalized economic growth and greenhouse gas emissions, consistent with IPCC scenarios A1 and B1. The key climate change vulnerabilities identified in the moderate climate change scenario—costal sea level rise, negatively impacted agricultural efficiency and productivity, and a reduction in forest canopy coverage—would likely be experienced sooner and with greater intensity. In particular, climate change related floods and water scarcity issues would even further exacerbate social equity problems with access to potable water. The drivers within the agricultural sector would likely become those that are the least energy and water intensive (e.g. coffee industry would grow, while beef farming may become less of an economic driver).

**PACKAGING ALTERNATIVES**

By its very nature, the ‘do nothing’ option is a completely exclusive alternative that cannot be realized in combination with any other option. On the contrary, *reforestation* is an extremely flexible alternative that could be combined to varying extents with each of the other alternatives listed. Investing in water use efficiency is another alternative that can be realized in combination with other alternatives. By providing the opportunity to increase the efficiency of the current system, it may also contribute to added benefits if coupled with other alternatives. For example, improving water use efficiency would improve the results realized from committing the excess water to the upper reaches of the river basin. Less water would be required for flows to reach the lower basin and existing irrigation systems as a result of the mitigation of water loss. This could decrease the portion of water that would need to be allocated to higher reaches for the same benefits to be realized with the current, less efficient, system. Other alternatives, such as aquifer storage and recovery and creating additional surface reservoirs, are more difficult to achieve together due to the similar water demands and relatively high costs associated with each.

**Short-term – No climate change**

Provided the region plans for no climate change, planning decisions will continue to be made in a short-term time frame, as is the norm throughout the country and an similar contexts. In this instance the *do nothing* option may be the most viable. It ranks high on both the weighted, and non-weighted alternatives lists, largely due to the low costs. If fresh water supply remains constant, and demand slowly increases in correlation with population, doing nothing in the short-term presents little risk of impeding the defined and most valued objectives. Taking no immediate steps towards redistributing the excess flows of the Tempisque allows resources to be utilized elsewhere. This could be in the form of addressing current water management issues in the basin, such as infrastructure quality or water governance fragmentation. This may be useful in the long-term to the basin as both of these options set the stage for better future decision-making around the excess water in the Tempisque. Resources may also be used to better explore the alternatives, detailed cost-benefit, feasibility, and environmental impact studies would be necessary if more complicated alternatives (such as aquifer storage and recovery) are implemented in the future.

**Table 6.** Package Option I

|  |  |
| --- | --- |
| Short-term (0-20 years) | *Do nothing* with the excess flows and commit resources to current issues in the Tempisque, especially those that will impact future decision-making processes (e.g. governance restructuring) (requires no commitment of flow). |
| Conduct feasibility, cost-benefit, and environmental impact studies for: *commit flows* and *aquifer recovery* alternatives (requires no commitment of flows). |
| Monitor climate, water supply, and demand on an ongoing basis. Revise projects as necessary and appropriate. |

**Short- to long-term – Moderate climate change**

Though Costa Rica generally plans on a short-term scale, climate change and large fluctuations in historical average precipitation and temperature provide good reason to extend planning beyond the short-term. Fluctuations in water supply are increasingly outside of the historical ranges that are used for planning. Coupled with projected shifts in demand, it is clear that there is a growing level of uncertainty around future availability.

Provided the region plans for moderate climate change in the short- to medium-term time scale, *do nothing* no longer seems to be a viable option. However, having that baseline as part of the process enables decision-makers to consider the advantages of it, and create ways in which those advantages can be incorporated into a plan that better considers the uncertainty of the future. For example, the cost-saving component of doing nothing, could allow the region to address current issues while creating a more thoughtful implementation strategy for the high-ranked complex alternatives. However, with the acceptance of imminent climate change, it is no longer responsible to do nothing in the short- or medium-term. To keep the advantages of Package I, while dealing with the risks identified in the Package II scenario, simpler, highly-ranked options could potentially be combined in the short-term. Choosing alternatives that have a lower ranking to start with may seem counter intuitive, but ‘low-hanging fruit’ is a good way to bring focus. Issues and projects that take a long time to reach the benefits stage should begin early. For these reasons the second package option includes the *water use efficiency* and *reforestation* alternatives as outlined in Table 7 below.

**Table 7.** Package Option II

|  |  |
| --- | --- |
| Short-term (0-20 years) | Conduct feasibility, cost-benefit, and environmental impact studies for: *commit flows* and *aquifer recovery* alternatives (requires no commitment of flows). |
| Implement *water use efficiency* education programs, focusing resources specifically in the most wasteful locales and sectors. Conduct related pilot programs and demonstration projects where they will prove to be most useful (requires no commitment of flows). |
| Develop strategic plan to participate in *reforestation* programs. Collaborate with reforestation programs working independently and offer assistance in providing water supply from the excess flows of the Tempisque to support the reforestation where possible (requires a commitment of flows; should be limited only by demand projections for higher ranked alternatives to be implemented in the future). |
| Using results from initial studies, implement pilot or demonstration projects for *commit flows* and *aquifer recovery* alternatives, monitor and evaluate success and design larger scale implementation (requires partial commitment of flows). |
| Monitor climate, water supply, and demand on an ongoing basis. Revise projects as necessary and appropriate. |
| Medium-term (20-40 years) | Implement *commit flows* and/or *aquifer recovery* alternatives on a larger scale as appropriate (requires commitment of remaining flows of water, ideally sufficient to meet future demand projections based on moderate climate change projections). |
| Continue and expand *water use efficiency* education programs. |
| Continue and expand *reforestation* programs where appropriate. |
| Monitor climate, water supply, and demand on an ongoing basis. Revise projects as necessary and appropriate. |
| Long-term (60-80 years) | Continue and expand *water use efficiency* education programs. |
| Continue and expand *reforestation* programs where appropriate. |
| The results of the *water use efficiency* and *reforestation* programs may begin to become apparent and lead to a lesser need to *commit flows to the upper Tempisque*. Once *aquifer storage* is met and use properly managed, a reevaluation of other alternatives may be conducted, starting with *support urban centers.* |

**Short- to long-term – Extreme climate change**

Should the region choose to plan for the extreme climate change scenario, the package will likely be different and focus on large scale impacts associated with extreme changes. As the impacts are projected to occur sooner, measures to mitigate the risk might be implemented quickly without pre-project studies or committing resources to other problems in the region.

Extreme climate change poses the risk of abrupt potable water shortages. Using solely this analysis, *aquifer storage and recovery* is the highest ranked alternative and would likely be implemented immediately in this scenario.

**Table 8.** Package Option III

|  |  |
| --- | --- |
| Short-term (0-20 years) | Implement *aquifer recovery* alternative on a large scale (requires high commitment of flows of water, ideally sufficient to meet future demand projections based on extreme climate change projections). |
| Implement *water use efficiency* education programs, focusing resources specifically in the most wasteful locales and sectors. The high cost of immediate implementation of the *aquifer recovery* alternative will likely leave few resources for pilot programs and demonstration (requires no commitment of flows). |
| Develop strategic plan to participate in *reforestation* programs. Collaborate with reforestation programs working independently and offer assistance in providing water supply from the excess flows of the Tempisque to support the reforestation where possible (requires a commitment of flows; will be highly limited by demand projections and related flow commitments to *aquifer storage*). |
| Monitor climate, water supply, and demand on an ongoing basis. Revise projects as necessary and appropriate. |
| Medium-term (20-60 years) | Continue and expand *water use efficiency* education programs. |
| Continue and expand *reforestation* programs where appropriate. |
| Monitor climate, water supply, and demand on an ongoing basis. Revise projects as necessary and appropriate. |
| Evaluate regional, national, and global economy and food supply, redirect flows to locales and sectors in need. |
| Long-term (60-80 years) | Continue and expand *water use efficiency* education programs. |
| Continue and expand *reforestation* programs where appropriate. |
| Evaluate regional, national, and global economy and food supply, redirect flows to locales and sectors in need. |

**DISCUSSION**

Choosing among the three packaged options requires an analysis of the uncertainty associated with each climate change scenario to which they are tied. As well, the decision makers will want to weigh the probability of risk against the benefits of the outcome. A full water resource analysis in the Guanacaste Province would require a more holistic review of the not just the water but also the wastewater and its potential for reuse. While a full technical evaluation of each of these factors is beyond the scope of this paper, the following logic may guide an evaluation of the packaged options:

First, in choosing the climate change scenario, it is safest to use the precautionary principle, that is, decision-makers ought to plan to be able to mitigate the greatest impacts. That is not to say that Package Option III will automatically be deemed most suitable, but rather that the components of Package Option III that mitigate the greatest impacts of extreme climate change in the region (storage of potable water, and long-term consideration of economy and food supply) must not be ignored. This effectively rules out Package Option I.

Second, decision-makers will want to choose alternatives that provide the greatest benefit, regardless of the climate change scenario that ultimately occurs. Package Option III may immediately deal with the risk of extreme climate change, but it requires resources from other problems in the region, which may result in problems that ultimately impact the implementation of the desired alternative. Furthermore, this option eliminates the ability to implement other highly ranked alternatives that may ultimately contribute to climate mitigation in the long term (such as *committing flows to the upper Tempisque*). This effectively rules out Package Option III.

Package Option II provides the most flexibility to deal with the uncertainty of climate change. It allows for the implementation of multiple high-ranked alternatives, without hastily committing resources to ill-defined projects. It should be noted that monitoring and evaluation should take place at every stage. Indeed, flexibility is incorporated so that changes can be made should extreme shifts occur.

**CONCLUSION**

The unique problem of excess water from the Arenal Project provides an opportunity for resilience-focused forward thinking in watershed management. This is particularly important in the Guanacaste region which will be especially sensitive to uncertain climate change due to its susceptible hydrologic features and predictions of rainfall reduction (Daniels and Cumming, 2008). The decision-making methodology used in this paper provides a sound objective evaluation of how to best use that water based on regional and national values. However, not all costs and benefits were ranked and weighted, though many were considered in discussion, and the evaluation remains relatively high-level. Though not detailed enough to influence policy, this analysis can serve as a useful tool in starting a dialogue with decision-makers and stakeholders. The background information, identified values, and overall methodology can be used in strategic planning for the region, especially through the lens of climate change planning and the building of natural, social, and economic adaptive capacity.

Costa Rica will need to be strategic in planning for water resources especially in the face of near and distant climate change projections. Human activities have significantly degraded ecosystem services (Pizarro and Marchena, 2008) due to short term economic-focused thinking. Local and national governance organizations must develop an in depth analyses and a thorough understanding of the Guanacaste water bodies and their influences on natural and social capital. This understanding will prove to be pertinent in decision-making that will provide the least short-term disruptions and the most sustainable future.

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