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Article

Social Investment for Sustainability of Groundwater: A Revealed Preference Approach

Edna Loehman

Department of Agricultural Economics, Purdue University, West Lafayette, IN 47907-4773, USA; E-Mail: loehman@purdue.edu; Tel.:+1-720-989-8042

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Abstract: Groundwater is a form of natural capital that is valued for the goods it provides, including ecosystem health, water quality, and water consumption. Degradation of groundwater could be alleviated through social investment such as for water reuse and desalination to reduce the need for withdrawals from groundwater. This paper develops a participatory planning process—based on combining revealed preference with economic optimization—to choose a desired future for sustaining groundwater. Generation of potential groundwater futures is based on an optimal control model with investment and withdrawal from groundwater as control variables. In this model, groundwater stock and aquatic health are included as inter-temporal public goods. The social discount rate expressing time preference—an important parameter that drives optimization—is revealed through the participatory planning process. To implement the chosen future, a new method of inter-temporal pricing is presented to finance investment and supply costs. Furthermore, it is shown that the desired social outcome could be achieved by a form of privatization in which the pricing method, the appropriate discount rate, and the planning period are contractually specified.

Keywords: groundwater; sustainability; optimal control; revealed preference; social investment; privatization; water pricing; public participation; planning process; backcasting

1. Introduction

The importance of groundwater for drinking water supply is well-recognized. In the U.S., about 78% of the 55,000 Community Water Systems identified by U.S. EPA and about 30% of the U.S. population use groundwater as a drinking water source (U.S. EPA, 2008) [1]. In the world at large, groundwater provides about 50% of drinking supplies (United Nations, 2003) [2]. It is especially important in rural areas where wells supply water needs (Water Science and Technology Board, 2002) [3]. Groundwater provides about 40% of irrigation water used in the western U.S. (Feinerman and Knapp, 1983) [4]. And, groundwater is increasingly important for agriculture as a substitute for surface water when there is drought (Llamas and Martinez-Santos, 2005) [5]. Recently, it has been found to be a potentially important source of irrigation water in Sub-Saharan Africa (Villholth, 2013) [6], especially in the face of climate change.

However, around the world, groundwater sustainability is being threatened by overdraft, salinization, and pollution [7]. Foster and Chilton (2003) [9] describe the major pathways for aquifer degradation and state that "little of the economic benefit of resource development has been reinvested in groundwater management" (p. 1957).

Groundwater is stored in aquifers that are underground layers of rock containing trapped water. Many unconfined or leaky aquifers are replenished by infiltration of rainwater, thus are renewable in the terminology of resource economics, but those with "fossil water" are non-renewable. Even when groundwater is rechargeable, its recharge rate may be small relative to withdrawal, particularly in areas of low rainfall and high urbanization. Therefore, an aquifer can be damaged by over-pumping which may cause containing rock layers to collapse, thus reducing water storage capacity and in some areas causing salt water intrusion (van der Gun and Lipponen, 2010) [10]. Van der Gun and Lipponen also point out that defining a rate of pumping that provides a "sustainable yield" is not so simple and is actually controversial among hydrologists.

A groundwater system is a form of natural capital. First, there is water storage provided by nature that would otherwise require fiscal capital. Also, groundwater can be of higher water quality than surface water because of natural filtration. Furthermore, groundwater is like a form of insurance, since it can be pumped in times of drought when rain and surface water are scarce, and water can be recharged by rainfall. Also, groundwater is now recognized as being connected to surface water (Kendy and Bredehoeft, 2006; Howe, 2002) [11,12]; a study by U.S. Geological Survey for 54 streams over a 30 year period found that an average of 52% of stream flow is contributed by groundwater (van der Gun and Lipponen, 2010) [10].

Finally, through its connection to surface phenomena, groundwater is important for sustaining aquatic ecosystems (Wohl, 2013) [13] (pp. 51, 269). Ecosystems that depend on groundwater include terrestrial flora and fauna, wetlands, estuaries, and near-shore ecosystems. The recognition of the linkage of groundwater to ecosystems has recently been studied empirically in an economic optimization context by Duarte *et al*. (2010) [14] and Esteban and Albiac (2011) [15].

To address groundwater problems, a variety of policies have been suggested, such as defining property rights, pricing, regulation of pumping, and introducing a market in groundwater rights. There are many articles discussing alternative policies and institutions. Notable reviews of groundwater management methods are presented by Orr and Colby (2004) [16] for innovative methods in Arizona, by Koundouri and Groom (2002) [17] for a world view, and by Blomquist (1992) [18] for an emphasis on local self-governance methods. A recent book reviewing Arizona water policy (Colby and Jacobs, 2007) [19] states that "One of the most important lessons to emerge from the history related here is the ultimate importance of institutions and institutional arrangements in managing water resources (p. xiv)."

Social investment for groundwater and how to achieve it is the focus here. The term "social investment" was first coined by Kenneth Arrow (1965) [20] with reference to United States' experience with investment in water resources. Arrow stated that "all users will receive the benefits over the lifetime of the investment" [20] (p. 3), and he specified social investment as yielding benefits that accrue to a wide class of individuals who cannot be excluded from resulting benefits [21]. Because of its collective nature, Arrow recognized that market pricing cannot be used to finance such investments.

1.1. Social Investment in Groundwater Systems

Investment could improve groundwater sustainability by making available technologies that could augment or substitute for withdrawal from groundwater. For example, technologies such as re-cycling and desalination can substitute for groundwater use. Aquifer storage of treated wastewater can directly recharge groundwater stock, either through percolation or deep well injection. In coastal areas, injected water may also be used as a buffer to prevent saltwater intrusion.

Investment in water technologies can be expensive (Bick and Oron, 2000) [22]. For example, the Orange County Water District built a large scale plant (70 million gallons per day) that converts waste-water into near-distilled quality which is injected into the underground supply, at a construction cost of about $480 million with operating costs of $1.61 per 1000 gals [23]. An example of desalination of brackish water is the city of El Paso's construction in 2007 of the largest non-coastal plant to supply 27.5 million gallons at a construction cost of about $87 million and operating costs of about $1.65 per 1000 gallons [24,25]. These operating costs compare favorably to a U.S. national average cost of potable water of $2 per 1000 gallons (this average includes both surface and groundwater sources; surface water sources generally have higher costs due to water treatment for drinking quality) [26]. Investment for agricultural groundwater use can be highly effective because of large worldwide agricultural groundwater use; about 60% of world groundwater withdrawal is for agriculture, and the rest is equally divided between domestic and industrial sectors [27]. Israel provides a demonstration of the benefits of investment for improved irrigation and for the use of recycled urban wastewater (Kislev, 2002) [28]. Per capita water for agriculture has been cut in half—compared to 1960—by replacing 90% of irrigation by drip irrigation, at the same time that agricultural production per capita has risen by at least 150 per cent. Thirty percent of the water provided to agriculture is recycled, and 60 percent of urban wastewater is sent to agriculture. Israel's use of recycled water—mainly for non-edible crops—is probably the highest in the world, and it has required large investments in water treatment and infrastructure (OECD, 2012) [29] (pp. 149–150).

To complement the need for more investment to sustain groundwater, there are questions of how investment decisions should be made, and how water supply should be produced and managed. Regarding investment decisions, benefit-cost analysis (BCA) has historically been used to make investment decisions about water, usually carried out by a government agency because large scale water investments have most often been financed and constructed by governments. (See Appendix 1 for a brief review of BCA and the discount rate.) In actuality, considering possibilities of level and timing of investment as well as possible levels and timing of water consumption/withdrawal, there would be infinite possibilities for alternative groundwater outcomes. However with BCA, only a limited set of alternative investments would be analyzed, so that BCA would only accidently result in finding the *optimum* investment, and it would not include determination of an optimal time path for consumption/withdrawal. Here, the purpose of optimization is to reduce the effort to find the desired solution among many alternatives when timing of consumption/withdrawal is included among the alternatives.

Government agencies and for-profit utilities ("privatization") are two alternative organization entities to perform investment and water supply management. Supporters of privatization believe that for-profit industry may be better able to provide for the large financial needs of investment than government or public utilities. Privatization has been suggested as a way to achieve needed investment particularly for less-advantaged communities. In practice, privatization of water supply has been controversial because there have been delays in making needed investments, corruption, and poor management (Bakker, 2010 [30]; Committee on Privatization of Water Services in the United States, 2002 [31]). However, Bakker also describes drawbacks of government water supply. A government agency would not necessarily minimize water production costs and may not produce the desired water-related outcomes.

Voluntary or cooperative approaches to finance social investment are also possible. The cooperative finance of public investments such as for construction of public utilities was addressed by Loehman and Whinston (1971) [32] based on the Shapley Value, a cooperative game theory method of cost allocation. This cooperative game approach was applied by Esteban and Dinar (2012) [33] for groundwater management with environmental externalities for aquifers in Spain. Generally, game theoretic cost allocation procedures require definition of weights that determine cost shares; these weights can be either subjectively or axiomatically determined. Instead of a cooperative game approach, this paper presents the idea of a voluntary pricing method to cover investment cost. By "voluntary" is meant that water users agree ex ante to a pricing scheme to cover the cost of achieving their desired sustainability outcome.

To respond to those who may question whether water users would voluntarily "tax" themselves to provide for the future, there are cases of voluntary payment for water programs, including groundwater. Christchurch, New Zealand provides one example of willingness to pay for groundwater improvement; there, increased use of a high-quality aquifer is leading to concerns about sustainability. A questionnaire study of Christchurch residents resulted in a mean willingness to pay of $416 per household per year to maintain river flows, and avoid restrictions on water use, more than adequate to pay for augmentation of the groundwater supply (Kerr, Sharp, and White, 2003) [34].

One method of voluntary payment on utility bills is called Check Box for Water-for-Environment (see Megdal, Bate, and Schwartz, 2009 [35]). In Bend, Oregon, water consumers in the Blue Water Program have voluntarily agreed to automatic donations on each month's water bill—with four possible donation levels of $1.60 to $6.40 per month—to support environmental flows in the Deschutes River. San Antonio, Texas provides an example of voluntary funding of groundwater protection via a bond measure funded by an increased sales tax of one-eighth percent; the money is used for land acquisition for greenways to protect the Edwards Aquifer from contamination (Greenwalt and McGrath, 2009) [36].

Lurie *et al*. (2012) [37] proposed that water utilities could be potential "drivers" to manage a marketplace in watershed and related ecosystem services. A review of relative success of methods of payments for watershed services by water utilities (including drinking water, wastewater, and electric utilities) is given by Bennett *et al*. (2014) [38]. Clearly, there is promise for methods of voluntary payment for water and ecosystem protection administered through water utilities.

1.2. Contributions of This Paper

Sustainability can be described as a level of a resource stock that could be maintained at a constant level, or a near-constant level allowing small perturbations, over a long period of time. The "steady state"—a term used for a stationary outcome in dynamic systems in physics, economics, and engineering—is used here to denote a possible sustainable future. But, it is important for this paper to note that groundwater stock and aquatic ecosystem health could be sustained at either a high or a low level: the point is to choose the desired steady state, *i.e*., whether the desired state has high or low ecosystem health and groundwater stock.

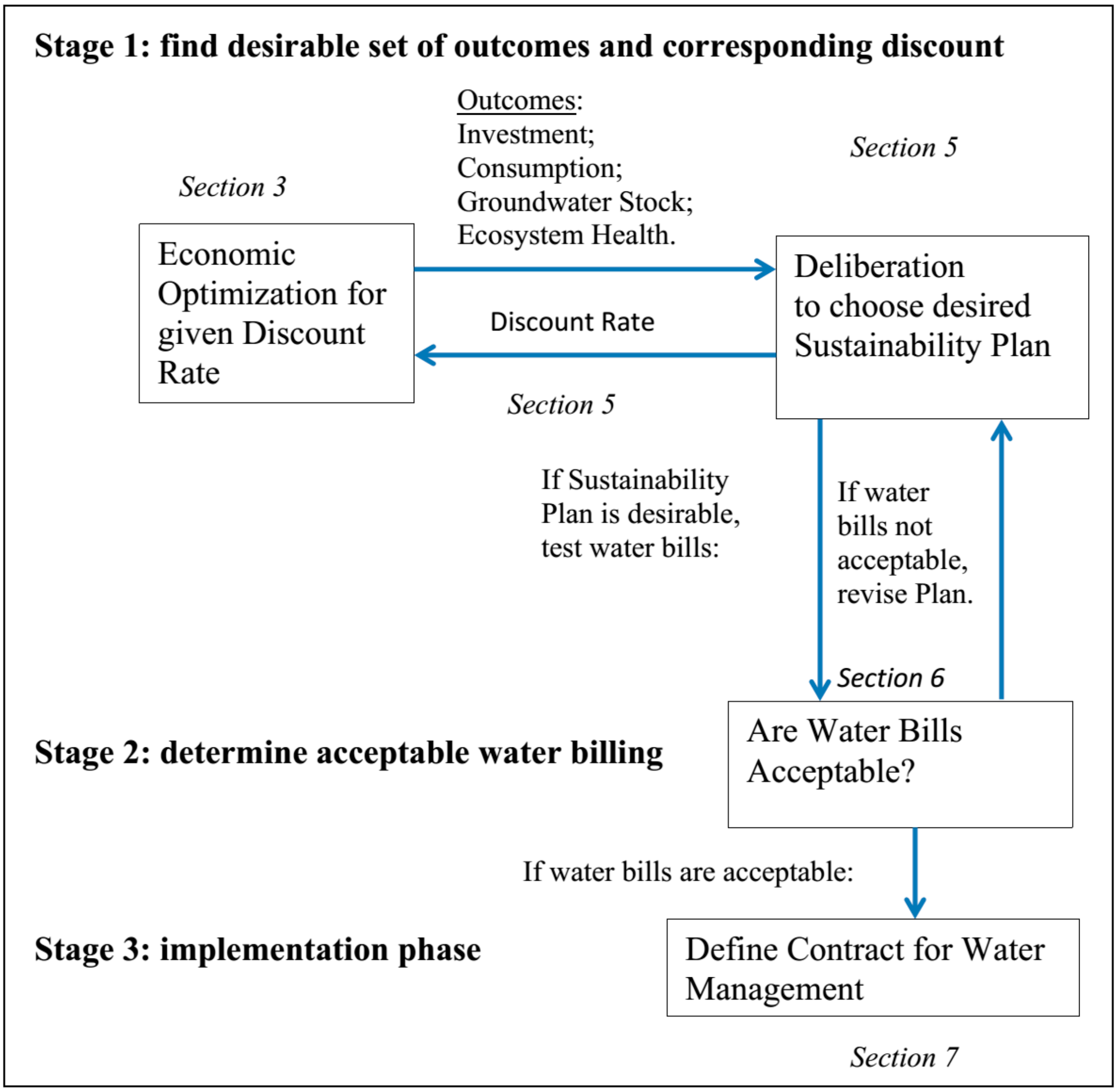
The method of this paper helps to differentiate among the concepts of equity, sustainability, and efficiency. Equity and sustainability concepts have a long history and have often been confounded in economics literature [39]. Here, the steady state is a sustainable future outcome, whereas equity has to do with the choice of a path to the desired future. Efficiency—as usual in economics—is defined in terms of satisfying optimality conditions; as shown for the optimization model here, there are many possible efficient paths that can be differentiated on the basis of equity.

Social investment is explored here as an instrument to make possible the achievement of the desired sustainable, equitable, and efficient future. To date, social investment as an instrument for sustaining groundwater has not yet been examined. One thesis of this paper is that, given current conditions of groundwater degradation and depletion, there should be increased social investment to support a higher level sustainability of groundwater systems and aquatic ecosystems. By "social", is meant the collective determination of what the groundwater future should look, like together with collective willingness to finance the desired investment. A related thesis is that the desired sustainability outcome should be a matter of local choice relevant for local conditions, including the nature of water supply, socio-economic conditions such as water demand and income, and the nature of environmental/ecosystem concerns.

The participatory unit for planning here will be called a hydro-geologic-economic (HGE) community [43]. In defining the appropriate geographical boundaries for investment planning, a complication is that societal and physical boundaries may not coincide. The nature of the underlying aquifer(s), the relationship of ground and surface waters, geologic formations, and economic and political interrelationships are all relevant aspects. Thus, the designation of the appropriate boundaries can itself be a complicated matter of social choice.

A Social Investment Planning and Implementation (SIPI) process is proposed here for a HGE community to determine the desired sustainability outcome for groundwater, together with needed social investment, and how to achieve it. The design of this process integrates roles for a community desiring an improvement in the status of groundwater, a government water management agency, and a for-profit water management enterprise. Figure 1 illustrates the SIPI process, to be explained in more detail in this paper [44]. The design of each stage of this process is based on underlying economic theory. Figure 1 indicates relevant sections of this paper describing each stage.

Figure 1. The social investment, planning, and implementation process.



Here the desired sustainability outcome for a groundwater system is modeled in terms of economic optimization of net benefits over time, with benefits including environmental services as well as water consumption. Investment and groundwater withdrawal are control variables, and groundwater stock and aquatic ecosystem health are state variables. However, prescriptive optimization is deemed inadequate in light of issues about the discount rate. The innovation here—based on a theoretical result—is to determine the social discount rate from the desired sustainability outcome, which is to be revealed through the planning process. (See Appendix 1 for alternative concepts of the discount rate and related ethical issues.)

In general, an advantage of economic optimization—besides reducing the effort of finding a solution for the future—is to provide pricing signals that can be used to "decentralize" consumption decisions. Similarly here, a unique pricing method is derived from optimization; it serves to recover full costs of investment and water supply in addition to performing the usual water rationing function of pricing. Moreover, the pricing method in intended to be a voluntary—rather than a market-based [46]—approach to finance social investment. It is envisioned that water users would voluntarily agree to the pricing method to achieve the desired sustainability outcome.

In addition to the investment planning and finance contributions, novel economic theory results are obtained here concerning optimal investment for a renewable resource. It is shown that the well-known Hotelling and Hartman rules do not apply to the groundwater situation when groundwater is renewable and has public good aspects as well as providing for water consumption.

Another theoretical result is that the desired sustainability outcome could be accomplished through a contractual arrangement with a for-profit water management enterprise. This water management arrangement provides an alternative to government production or pure privatization. The contract must specify the pricing rule, the appropriate discount rate, and the planning period. The appropriate social discount rate—here revealed through the planning process—must be specified for this contractual arrangement to produce the desired sustainability outcome.

Thus, the overarching contribution of this paper is to link economic theory, public participation, and institutional design for the purpose of planning and implementing social investment for sustaining groundwater and related aquatic ecosystems.

1.3. Roadmap for this Paper

The following sections of this paper provide background, theoretical results, and suggestions for implementation of the steps in Figure 1:

- Section 2 discusses equity and sustainability concepts for optimal growth models and rules for social investment found in the literature.
- Section 3 presents the basic economic optimal control model.
- Section 4 presents economic theory results derived from the optimal control model.
- Section 5 applies theory to develop the revealed preference approach for Stage 1 of the planning process to choose the desired groundwater future. The overall process is described in more detail than above.
- Section 6 presents inter-temporal pricing for full cost recovery, to be used for Stage 2.
- Section 7 develops the proposed organizational arrangement and the nature of the contract for Stage 3.
- Section 8 comments briefly on participatory application methods.

1.4. Embedded Ethical Assumptions

The revealed preference approach here—to choose the discount rate and the desired path to the steady state—embodies three underlying ethical assumptions: (1) the appropriateness of revealed preference in planning; (2) the appropriateness for a current generation to make decisions about sustainability for future generations; (3) the requirement of choice consistency for inter-temporal choice.

In a-temporal situations, the principle of revealed preference has been used to infer preference (*i.e.*, demand) parameters from observed (market) consumption choices; an observed choice is taken to be revealed to be preferred to all other feasible choices (see for example Mendelsohn and Brown, 1983 [48]). Here this principle is extended to determine the discount rate through choice among alternative sustainable outcomes, with choice generated within the planning process rather than from market data.

In a planning process, members of a current generation make decisions about the future. Since the life of a water project such as a desalination project may extend over multiple generations, not all relevant preference holders are present at the time of investment decision. However, a current generation may appropriately represent the interests of future generations, e.g., when parents make decisions concerning interests of children and grandchildren. For example, parents may sacrifice consumption in the present to save for education for their children, and similarly parents may be willing to invest in the healthy future of their children and grandchildren. Since children in one time period become parents in a future period, "iterated altruism" arises from the connectivity or overlap of preferences over a time span.

Choice consistency means that the choices made by a current generation for future periods should be the same as those that would be made by a future generation for those same periods, if such choices were possible. Optimization of the discounted sum of utilities with a constant discount rate over generations satisfies this consistency criterion (Heal, 1973) [49], provided that preferences for all generations have the same representation.

2. Sustainability, Equity, and Investment in Economic Literature

Below, a brief review is given of economic literature concerning sustainability, equity, and investment. A more complete review can be found in Pezzey and Toman (2002) [40].

2.1. Optimal Growth Models

Early inter-temporal optimization modeling of resource allocation and investment explicitly included equity concerns. Capital theorists in the 1960s such as Cass (1966) [50] and Dorfman (1969) [51] used optimal control to investigate desirable consumption-investment paths. That per capita consumption should be constant over time is a prominent economics notion of equity in this literature. From Solow (1974) [52], "...the max-min [equity] principle requires that consumption per head be constant through time (p. 30)." The "golden rule path" was identified as an investment path that would maintain maximum constant flow of consumption per capita. Furthermore, Solow thought that if capital assets could offset natural resources in producing consumption goods, then consumption sustainability could be consistent with depletion of a natural resource stock.

Chichilnisky *et al*. (1995) [53] extended classical growth modeling to include an environmental aspect that is degraded by consumption; they proposed the "Green Golden Rule" to determine a growth path that is both equitable and sustainable in terms of the environmental good. The "green golden rule" gives the highest maintainable level of utility when environmental goods are valued. However, capital in their model was solely for the purpose of producing consumption, not for investment to maintain a renewable resource.

2.2. Other Sustainability and Equity Concepts

Since capital assets usually generally cannot substitute for natural capital beyond some level, some ecological economists have suggested the steady state requirement that both natural capital and physical capital should be kept constant at a steady state (see Gatto, 1995 [54]), emphasizing non-destruction of natural systems as a standard for sustainability. Similarly, Bromley (1989) [55] suggested the ethical requirement of endowing future generations with undiminished stocks of natural resources and environmental quality to ensure inter-generational justice.

That ecosystem and environmental outcomes associated with excessive human development are inherently uncertain was recognized by Howarth (1997) [56]. Because of uncertainties in management of resources, Howarth proposed another criterion of sustainability: the *opportunity* to provide "future generations with a set of life opportunities that is undiminished relative to the present (p. 576)."

Some economists have defined sustainability in terms of utility or welfare: "A requirement of sustainablity entails that no generation should allow itself a level of utility that cannot also be shared by all future generations" (Withagen and Asheim (WA) 1998, [57], p. 159). The WA definition of equity implies that welfare for each generation should be non-decreasing; this criterion is also known as "weak sustainability" (Howarth, 1997) [56].

Pezzey (1989, 1997) [58,59] supported the WA criterion, and he suggested that to ensure equity, a formal constraint should be added to optimization that utility be non-declining. However, Endress *et al*. (2005) [60] (p. 527) state that an "optimal growth path [can be] sustainable without the contrivance of a sustainability constraint," and that adding a formal constraint may make the optimization problem unsolvable.

Here, sustainability is differentiated from equity in a unique way: sustainability has to do with the optimal steady state in terms of physical and economic parameters, while equity has to do with the welfare along a path to arrive at this steady state. Revealed preference determines the path to the desired steady state. Thus, revealed path preference allows testing whether or not the WA definition of equity—non-decreasing welfare over time—would be supported by the HGE community, avoiding use of a mathematical sustainability constraint. At the same time, the approach allows testing whether the community would support or wish to avoid a resource depletion outcome.

2.3. Hartwick's Investment Rule

Hartwick (1977, 1978, 1997) [61–63] introduced a reasonable investment rule for a non-renewable resource: the rule is that the value of investment should be the amount needed to replace the value of withdrawal from the resource stock. This rule was termed "zero net investment". This rule was not obtained from an optimization model; instead, its purpose was to fully distribute the value of total production among current consumption, investment, and extraction costs. With the assumption that capital is used only for production, Hartwick used a special case of production function (homogeneous of degree one) and assumed the Hotelling rule (Hotelling, 1931) [64,65] for equilibrium in the asset market. He then showed that under this investment rule, per capita consumption would be constant, thus satisfying Solow's (1974) [52] definition of inter-generational equity.

The theoretical results here obtained from the optimization model do not result in the Hartwick rule, and also the Hotelling rule is shown not be valid for the situation here for a renewable resource with public good aspects.

3. Model of Optimal Investment for a Groundwater System

Many resource economics papers specify an optimal control model with a very important parameter—the discount rate—to indicate time preference for returns to investment (see Appendix 1 discussion). Usually such papers end with a phase diagram describing a steady state and the nature of paths to it depending on initial conditions. Examples of optimal control modeling for environmental and natural resources include Smith (1968) [66], Plourde (1970) [67] and Conrad (1999) [68] for resources such as fish, water, and timber; for renewable resources, these studies show the nature of optimal paths of resource use towards a steady state outcome. A common finding in such resource economics applications is that the optimal solution for resource extraction may result in stock depletion, and the larger the discount rate, the faster the rate of depletion (Conrad and Clark, 1987 [69]). However, Conrad and Clark also suggested—since society does not choose to cash out a resource such as the blue whale—that the consumption values for such resources do not correctly reflect their value to society.

The approach here goes beyond the typical optimal control modeling in that the optimal control model is to be used as a tool within a participatory planning process to indicate how the discount rate and other parameters can be adjusted to reflect the desired future for local groundwater.

For a groundwater management area—a HGE community—in which consumption and investment paths are being planned, the paradigm of resource economics portrays optimal investment and water consumption as maximizing net social welfare over a time period, with social welfare represented by the discount-weighted sum of utilities for water users in the HGE area. (See Appendix 2 for background on early groundwater optimization models without investment.)

In traditional resource models such as Plourde (1970) [67], welfare derives only from consumption produced with the resource as an input. If capital for investment is modeled at all, previous resource economic models of optimal investment have only considered capital and resources to be substitute inputs for production of private consumption goods. Solow (1974) [52], Rausser (1974) [70], Smith (1974) [71], and Burt and Cummings (1970) [72] modeled investment in a general model, but operational rules for investment were not derived. The model here differs in two ways: (1) the groundwater resource provides for public goods such as water quality and aquatic ecosystem health as well as for water consumption; (2) investment can directly augment the stock of the resource.

Here, groundwater stock enters in the expression of net social welfare as a public good [73]. The rationale for including groundwater stock directly in the objective function is that it provides several public goods. First, groundwater stock acts as insurance against drought in low rainfall years. Second, a higher groundwater stock—through its relationship to surface water—provides for a higher quality of ecosystem health. Finally, maintaining groundwater stock provides for the interests of both current and future generations. Altruism is allowed by including stock in the preferences of all generations.

3.1. Specification of Model of Optimal Investment

Here the planning period is a set period T consistent with the life of potential investments. Rather than the infinite time framework commonly used in resource economics optimization models, we use a finite time period for planning. One reason for the finite time period is to provide consistency with a benefit-cost framework which uses the life of water projects as a planning period. A more important reason is the lack of realism of an infinite time frame. The infinite time period commonly used in resource economics optimization models is for ease of solution rather than realism. Considering Gould's "punctuated equilibrium" theory that abrupt unanticipated changes can occur (Gould, 2007) [75], a steady state over an infinite time horizon—as commonly studied in resource economic models—is not realistic.

Following Burt and Cummings (1970) [72] who used a discrete time framework, the social optimization problem for groundwater employs difference equations rather than differential equations. The difference equation to describe groundwater stock in a hydro-geologic region is a simplified physical model of stock balance in a leaky aquifer:

$$S^t - S^{t-1} = -w^t + f(K^t) + h(S^t) + \alpha\rho^t \tag{1}$$

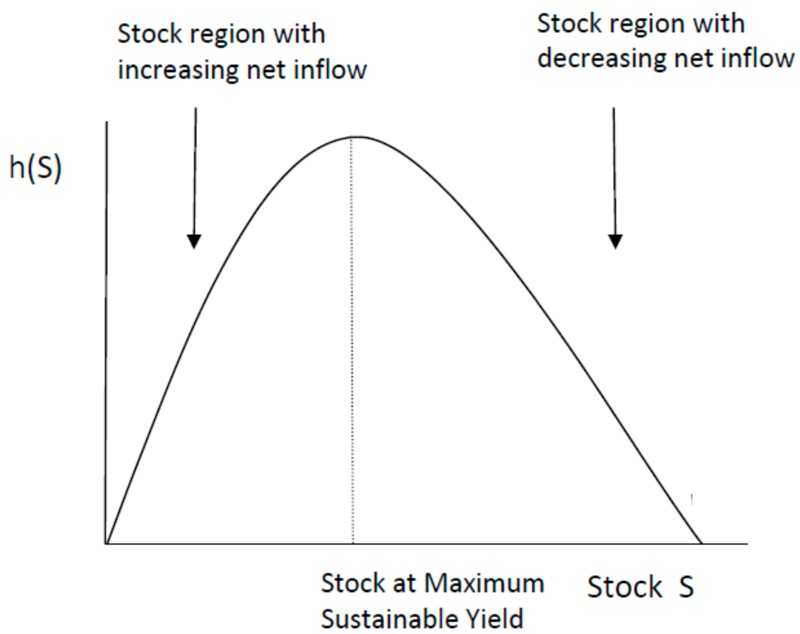
where the ρ^t term represents the direct effect on stock due to rainfall, adjusted for permeability and other physical effects; the pattern of rainfall over time is here considered to be known *ex ante,* such as from historical data. (Rainfall effects could be lagged without effecting the form of economic conditions [76–78].) Appendix 3 discusses application of the model when varying rainfall is not known *ex ante.*

Total withdrawal w^t is removed by pumping from groundwater stock each period; this supply will satisfy the sum of water demand volumes w_i^t over all water users i. $h(S^t)$ represents net inflow to the aquifer due to stock—apart from direct rainfall effects—including lateral flow, leakage, and potential subsidence effects; it can be positive or negative depending on the level of stock S. As is common in models of renewable resources (Conrad and Clark, 1987) [69], $h(S)$ is assumed to be quadratic and concave (see Figure 2); *i.e.*, it can exhibit both positive and negative slopes with $h_{SS} \leq 0$. From Equation (1), it can be seen that the maximum sustainable yield for withdrawal from stock is where the derivative of $h(S^t)$ is zero. As Plourde (1970) [67] describes for a general natural resource, this maximum sustainable yield need not be the same as the economic optimum, especially here when capital can substitute in part for withdrawal from stock.

Below, an assumption needed for mathematical reasons is that the derivative of $h(S^t)$ be negative at the optimum. Then from Figure 2, optimal groundwater stock at a steady state will be greater than that corresponding to the maximum sustainable yield [79]. This assumption is reasonable considering that groundwater stock is needed both to sustain natural systems and to supply human use.

The amount of stock substitution provided by investment in capital K is indicated by the capital production function $f(K)$ [82]. As is usual for production functions, we assume $f_K > 0$ and $f_{KK} < 0$. The relation between groundwater stock and capital investment is modeled as continuous for simplicity: the greater the capital, the greater the stock augmentation or substitution effect, with diminishing returns to scale. For example, the volume of water obtained from shallow well desalination would depend on the size of capital investment; a larger facility with greater cost would provide for more desalination.

Figure 2. Representation of groundwater net inflow h(S).



C(*w*, *S*, *Q*) denotes recurring water supply costs for pumping and water treatment. Pumping cost is related to volume of withdrawal *w*; more pumped means higher cost, e.g., for energy to pump, and it is also affected by groundwater stock, with pumping costs increasing as stock decreases (Burt, 1964) [83]. Water quality can also affect cost: for example, drinking water treatment cost is less with better raw water quality. Also, there could be remedial construction costs, for example to restore stream banks to improve aquatic eco-system health.

The investment planning model for the water community is represented as [84,85,87]:

$$\begin{aligned} &\operatorname*{Max}_{w_i, I} \sum_{t=0}^{T} \sum_{i} \frac{u^i(x_i^t, w_i^t, S^t, Q^t)}{(1+r)^t} + \frac{V(S^T, K^T, Q^T)}{(1+r)^T} \\ &\text{s.t.} \quad \sum_i x_i^t \le M^t - C(w^t, S^t, Q) - iK^t \\ &S^t - S^{t-1} \le -w^t + f(K^t) + h(S^t) + \alpha\rho^t \\ &Q^t \le g(S^t) \\ &K^t \le K^{t-1}(1-d) + I^t \\ &\sum_i w_i^t \le w^t \end{aligned} \tag{2}$$

In the terminology of optimal control theory, groundwater stock *S*, quality *Q*, capital *K*, and all other goods x_i are state variables, while investment *I* and total water withdrawal *w* are control variables. The control variables determine the status of the state variables.

For the HGE community each period, each water consumer (*i*) has individual preferences that depend on water consumption w_i, stock of water *S*, eco-system and water quality aspects *Q*, and expenditure for all other goods x_i. Preferences for heterogeneous water users in the community over water consumption, stock, quality, and all other goods are represented by utility functions u^i. Groundwater stock and quality enter into preferences as public goods. Social benefit each period is expressed by the sum of discounted utilities over all community water consumers representing preferences for water and all other goods, for a social discount rate r such that $(1 + r)$ is positive.

Aquatic eco-system and water quality effects of groundwater stock are represented by $Q = g(S)$, where the derivative g_S with respect to S is positive to indicate that increasing groundwater stock increases eco-system and water quality.

The first constraint is the community financial feasibility constraint: each period the community must pay for total water system cost from its financial resources: total water system cost is the sum of operating supply cost $C(w^t, S^t, Q^t)$ plus the cost of capital K^t borrowed at market rate of interest i. Here, the market rate for borrowing is not necessarily the same as the social rate of time preference. The market rate i is constant over time, and the finance charge each period at this interest rate is applied to the total capital stock each period. Prices of non-water consumption goods and water supply costs are given from outside the HGE community. The community will pay for water costs from local resources. M^t represents the total community economic resources each period (exogenous) to cover water costs and costs of all other goods x_i^t.

Following the assumption of "free disposal" in Kuhn-Tucker theory (Takayama, 1985 [88]), the stock equation is written as an inequality; the interpretation is that that the stock of groundwater can be no greater than the previous stock, minus total withdrawal, plus rainfall and recharge effects, plus effects of capital investment.

The level of capital after depreciation and investment is also expressed as an inequality. For the capital constraint, the capital value of technology K^t for groundwater sustainability depreciates at a rate d. I^t denotes annual investment in infrastructure; it can offset depreciation but also add to augmentation or substitution of stock. Investment is required to be non-negative, *i.e.*, there can be no decline in capital except through depreciation.

The terminal time, or length of the planning period, is denoted by T. Salvage value for remaining capital, stock, and ecosystem quality has a terminal value denoted by V. Terminal constraints, such as reaching a certain level of consumption or stock by a certain time, are not included.

3.2. Money Metric Re-Formulation

For implementation purposes, the optimal control problem (2) is reconstituted to be in money metric terms by assuming that preferences are of the quasi-linear utility form:

$$u^i(x_i^t, w_i^t, S^t, Q^t) \equiv x_i^t + B^i(w_i^t) + N^i(S^t) + E^i(Q^t) \tag{3}$$

i.e., preferences are separable in terms of private good consumption and water-related commodities and are expressed in monetary terms. B^i represents water consumption benefits, N^i represents non-consumption and insurance benefits of existence of groundwater stock, and E^i represents environmental quality benefits. Note that this form embodies the assumption that the same benefit functions apply over time, *i.e.*, that the form of preference is the same over generations [89–91].

To obtain the optimal control problem (4) below from the optimal control problem (2), for quasi-linear utility the financial constraint can be substituted for the sum of private good consumption. (The community income resource total is not present in the objective function since it is exogenous and not relevant for optimization.) Also, total water withdrawal is replaced by the sum of water demands; these should be equal. The resulting reformulation is:

$$\begin{aligned} &\underset{w_i, I}{\text{Max}} \sum_{t=0}^{T} \frac{B^i(w_i^t) + N^i(S^t) + E^i(Q^t) - C(\sum w_i^t, S^t, Q^t) - iK^t}{(1+r)^t} + \frac{V(S^T, K^T, Q^T)}{(1+r)^T} \\ &\text{s.t.} \quad S^t - S^{t-1} \le -\sum_i w_i^t + f(K^t) + h(S^t) + \alpha\rho^t \\ &Q^t \le g(S^t) \\ &K^t \le K^{t-1}(1-d) + I^t \end{aligned} \tag{4}$$

An interior solution of the optimal control problem (4) satisfies the first order necessary conditions for the optimal control problem (2). However, in addition to the first order necessary conditions, the community financial feasibility constraint for the optimal control problem (2) must also be satisfied for a full solution (Takayama, 1985) [88]. A later section of this paper shows how to satisfy the community financial feasibility constraint through appropriately specified water pricing. The next section provides the first order necessary conditions—together with their implications—for investment and water consumption.

4. Economic Theory Results: Necessary Conditions for Optimal Investment

Necessary conditions for optimality are given below. These necessary conditions are used later in the paper to develop investment and pricing rules. Among theoretical results, it is shown that the Hotelling and Hartwick rules do not apply here, because groundwater is considered here to be a renewable resource and has public good as well as consumption aspects. In addition, different assumptions are made about the role of capital in substituting for resource stock.

Necessary optimality conditions [94] are described as follows, denoting accounting prices for stock and quality (shadow prices for the corresponding constraints) by μ and τ. In conditions given below, B_w^{it} denotes marginal benefit of water consumption at time t, E_Q^{it} denotes the marginal benefit of quality, and N_S^{it} denotes marginal benefit of increased stock at time period t for water user i. Marginal costs with respect to total groundwater withdrawal, stock and quality are similarly notated as C_w, C_S, C_Q. Necessary conditions for optimal water consumption, groundwater stock, investment, and ecosystem quality for each time period t are expressed as follows:

(i) $B_w^{it} - C_w^{\ t} = \mu^t(1+r)^t$

(ii) $i = \mu^t(1+r)^t f_K(K^t)$

(iii) $\sum_i N_S^{it} - C_S^{\ t} + g_S(S^t)(\sum_i E_Q^{it} - C_Q^{\ t}) + h_S(S^t)\mu^t(1+r)^t = (\mu^t - \mu^{t+1})(1+r)^t$

(iv) $V_S^{\ T} + g_S^{\ T} V_Q^{\ T} = \mu^T(1+r)^T$

(v) $V_K^{\ T} = \mu(1+r)^T f_K(K^T)$

For convenience, define the "spot value" of withdrawal from stock—the current value of raw water—to be the "forward value" of the accounting price for stock: $\lambda^t \equiv \mu^t(1+r)^t$. From:

$$(\mu^t - \mu^{t+1})(1+r)^t = \lambda^t - \frac{\lambda^{t+1}}{1+r} \tag{5}$$

the following result expresses optimal water consumption, groundwater stock, and investment in terms of the spot value.

Result 1: Each period, optimal groundwater withdrawal, capital investment, and stock must satisfy a set of necessary conditions in terms of spot price:

(a) For each water user *i*, the marginal net benefit of water consumption is equal to the spot value:

$$NB_w^{\ it} \equiv (B_w^{\ it} - C_w^{\ t}) = \lambda^t \tag{6}$$

(b) The optimal investment path must be related to the spot value as follows:

$$i = \lambda^t f_K(K^t) \tag{7}$$

(c) The net marginal benefit of increasing stock should satisfy the following relationship to spot value:

$$NB_S^{\ t} \equiv \sum_i N_S^{\ it} + g_S^{\ t} \sum_i E_Q^{\ it} - (C_S^{\ t} + g_S C_Q^{\ t}) = \lambda^t - \frac{\lambda^{t+1}}{1+r} - \lambda^t h_S^{\ t} \tag{8}$$

Conditions (1a) and (1b) are similar to a-temporal efficiency conditions. From (1a), the spot price is equal to the net marginal net value of water consumption. Note as usual that water users can have difference preferences, but for each, their marginal valuation is set equal to the spot price plus the marginal supply cost. From (1b), the marginal value product of investment in stock augmentation is set equal to the interest rate for borrowing.

Condition (1c) is an inter-temporal public good condition: the total marginal benefit of increasing stock—summing individual water user benefits over all beneficiaries—should be equal to the marginal social cost of an increase in stock. Again, preferences of individual water users can differ, and as such, they are summed to express public good benefits. Here, the marginal social cost consists of four parts: marginal production cost (pumping and quality effects) as related to stock level, plus the value of foregone consumption, minus the present value of consumption for the next period, minus the value of stock-related physical effects. The net marginal benefit of increasing stock (NB_S^t) should be non-negative on the optimal path; if not, a decrease in stock would increase total net benefits, negating optimality. Therefore, important for results below: the right hand side of Eqution (8) should be non-negative.

Re-writing Equation (8) in terms of the difference in spot values gives Equation (9) to replace Hotelling's Rule here. Equation (9) differs from Hotelling's Rule because of the public good effect of stock and the physical stock effect, not present in Hotellings's non-renewable resource case.

Corollary 1: The equation of motion for optimal spot value is:

$$\frac{\lambda^{t+1} - \lambda^t}{\lambda^t} = r - \frac{(NB_S^{\ t} + \lambda^t h_S^{\ t})}{\lambda^t / (1+r)} \tag{9}$$

Corollary 2 generalizes the so-called Ramsey condition (Dasgupta and Heal, 1974 [95]) about the consumption rate of change as related to the rate of price change on the optimal path. Here, the relation of optimal consumption to investment is also given, for $w = \Sigma w^i$.

Corollary 2: Along the optimal path: the rate of change in consumption should be opposite in sign to the change in spot price and change in net investment; change in net investment should have the same sign as the change in spot value (to simplify notation, using "dots" to denote time derivatives):

$$-1/\varepsilon \frac{\dot{w}}{w} = \frac{\dot{\lambda}}{\lambda^t} = 1/\eta \frac{\dot{K}}{K} \tag{10}$$

where ε is the elasticity of demand and η is the output price elasticity for capital.

This result is obtained by differentiating Equations (6) and (7) in terms of the spot price change. Reasonably, this result says that when spot price is increasing, optimal consumption should be decreasing. Also, it would not be optimal for consumption to be increasing when capital investment is increasing, because of cost.

Example: For $f_K(K) = k_1 K^\alpha$ where $\alpha < 0$, then $f_{KK}(K) = k_1 \alpha K^{\alpha-1}$. For the marginal benefit (inverse demand) function for each water user of the form $NB^i{}_w(w^i) = k_2 w^{i\ \beta}$, then $NB^i{}_{ww}(w^i) = k_2\beta\ w^{i\ \beta-1}$ for $-1 < \beta < 0$. Applying the above corollary,

$$\frac{\dot{w}}{w} = -\alpha / \beta \frac{\dot{K}}{K}$$

Corollary 3: The optimal investment each period can be determined recursively from that period's raw water spot value, the marginal product of capital, and past capital investment [96]:

$$I^t = f_K{}^{-1}(i/\lambda^t) - (1-d)K^{t-1} \tag{11}$$

Inserting the expression for change in capital and implicitly solving Equation (7) give this expression.

Example: For $f(K) = k_1/(\alpha+1)\ K^{\alpha+1}$ and $f_K(K) = k_1 K^\alpha$, with $\alpha < 0$, from Equation (8): $i/\lambda^t = k_1 (K^t)^\alpha$. Substituting for capital stock to solve recursively for optimal investment:

$$I^t = (i/(k_1\lambda^t))^{1/\alpha} - (1-d)K^{t-1}$$

5. Relating the Steady State to the Social Discount Rate and Design of the SIPI Process

Here, a theory foundation is given for the SIPI process integrating optimization and public participation as illustrated in Figure 1. Equation (17) below is the key to relate the discount rate to the optimal steady state: by choosing a desired steady state, the implied social discount rate is revealed by the water community.

The phase diagrams below indicate that there is a panoply of possible optimal paths leading to a chosen steady state, each path corresponding to a specific set of initial conditions (starting point of the path) while satisfying first order conditions (efficiency). It is explained why there is a degree of freedom to allow choice of the initial condition. Choosing among these potential paths reveals a community's notion of equity. Furthermore, a potential depletion outcome can be avoided, either by re-selecting the discount rate or by redefining initial water consumption. Adjustment procedures are explained below with illustrating diagrams.

Thus, revealed preference enters the SIPI process in three ways: first, to reveal the discount rate; second, to choose the path to the steady state; and finally, to impose any constraints that might be necessary to avoid depletion.

5.1. Determination of Optimal Steady State

Sustainability here is represented as being a "steady state," which is a stationary outcome to be attained by the end of the planning period. A steady state solution may not be possible for given initial and physical conditions and discount rate. If one exists, the optimal steady state satisfies zero change for dynamic conditions as well as the necessary conditions for optimality. Here, the optimal steady state is denoted by "*" for state variables (S^*, Q^*, K^*), control variables (I^*, w^*), and spot value λ^*.

The steady state solution for groundwater investment and total withdrawal satisfies the following simultaneous system of first order *conditions*:

(1) From Equation (6), the steady state spot price sets marginal net benefit for the steady state water consumption to the spot price, for each water user's water consumption:

$$\lambda^* = NB_w^{\,i}(w_i^*) \tag{12}$$

(2) From Equation (9), the steady state optimal stock S^* is related to spot price λ^* as follows:

$$NB_S^{\ *} = (\frac{r}{1+r} - h_S^{\ *})\lambda^* \tag{13}$$

From Equation (13), $(\frac{r}{1+r} - h_S^{\ *})$ must be positive, because both $NB_S^{\ *}$ and λ^* are non-negative (important for the phase diagram below). With the assumption that $h_S^{\ *}$ is non-positive, r can be zero, or even negative.

(3) K^* is determined in terms of λ^* and the market interest rate i; from Equation (8), it satisfies

$$i = \lambda^* f_K(K^*) \tag{14}$$

(4) Total consumption is equal to total withdrawal from groundwater: $\sum_i w_i^{\ *} = w^*$.

(5) From Equation (1), the steady state stock satisfies:

$$0 = -w^* + f(K^*) + h(S^*) + \alpha\rho \tag{15}$$

(The time superscript is omitted for rainfall, because there could be no steady state with varying rainfall. See Appendix 3 for a suggestion regarding how to deal with uncertain rainfall.)

Result 2: If it exists, the optimal steady state for stock, total withdrawal, consumption, capital, and spot price is determined by the simultaneous system (12)–(15).

The following comparative statics result shows the effect of the discount rate on the steady state, for example a decrease in r means an increase in S^* and an increase in λ^*. To simplify, rather than individual demands, aggregate demand is used; w^* denotes total pumping withdrawal—equal to total consumption—and NB_w and NB_{ww} indicate derivatives of the inverse aggregate water demand function, found by summing the individual demands.

Result 3: Steady state stock, withdrawal, capital, and spot price are affected by the discount rate as follows:

$$\frac{dS^*}{dr} = -\frac{\lambda}{(1+r)^2}\frac{(NB_{ww}f_K{}^2 + \lambda f_{KK})}{D} \leq 0$$
$$\frac{d\lambda^*}{dr} = -\frac{\lambda^2 h_S}{(1+r)^2}\frac{f_{KK}NB_{ww}}{D} \leq 0$$
$$\frac{dK^*}{dr} = \frac{\lambda}{(1+r)^2} h_S f_K NB_{ww} / D \leq 0 \qquad (16)$$
$$\frac{dw^*}{dr} = -\frac{\lambda}{(1+r)^2}\frac{\lambda f_{KK} h_S}{D} \geq 0$$

for $h_S \leq 0$, where $D = -(NB_{SS} + \lambda h_{SS})(NB_{ww}f_K{}^2 + \lambda f_{KK}) - NB_{ww}(h_S{}^2)\lambda f_{KK} \leq 0$.

This comparative statics relationship is key to describe adjustment of the discount rate during the planning process. For example, if a potential steady state stock is less than desirable, then the discount rate should be decreased. Or, if a potential steady state total consumption is less than desired, then the discount rate should be increased.

The reverse relationship is given in Equation (17) below, implying that selection of the desired steady state can be used to infer the corresponding discount rate. This result is obtained by rewriting Equation (13) and substituting Equation (12). Note that r^* could be positive or negative.

Result 4. Suppose the water community desires a steady state stock level S^* and a steady state total consumption w^* (which corresponds to the steady state spot price λ^*). Then the corresponding discount rate r^* is determined:

$$r^* = \frac{NB_S{}^* + \lambda^* h_S{}^*}{NB_w{}^* - (NB_S{}^* + \lambda^* h_S{}^*)} \qquad (17)$$

Figure 3a [97] gives the phase diagram for S and λ in terms of the two loci $\Delta S = 0$ and $\Delta\lambda = 0$, for the assumption that h_S is negative at a solution (from Equation (19), h_S cannot be zero). The locus of S and λ satisfying $\Delta\lambda = 0$ has a negative slope, obtained by solving for $dS/d\lambda$ from Equation (13):

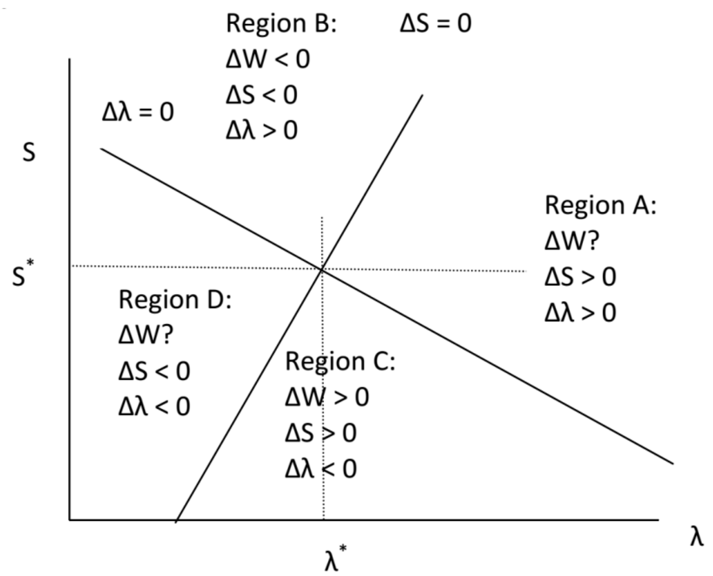
$$\frac{dS}{d\lambda} = \frac{[r/(1+r) - h_S]}{(NB_{SS} + \lambda h_{SS})} \qquad (18)$$

because $(\frac{r}{1+r} - h_S{}^*)$ is positive from (13), and the denominator is negative from second order conditions. A positively sloped line describes the locus $\Delta S = 0$; this is obtained, for negative h_S, by solving for $dS/d\lambda$ from Equation (15) and substituting for $dK/d\lambda$ and $dw/d\lambda$ from the first order conditions (12) and (14):

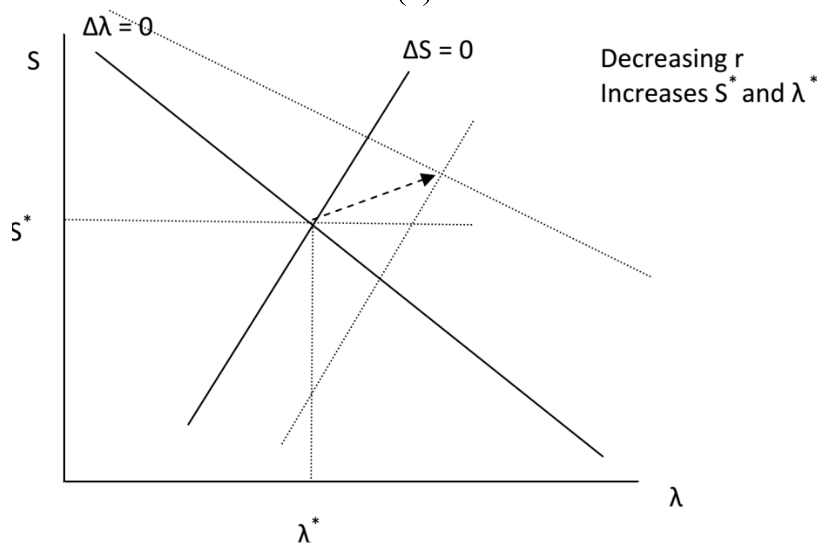
$$\frac{dS}{d\lambda} = \frac{\frac{1}{NB_{ww}} + \frac{f_K{}^2}{\lambda f_{KK}}}{h_S} \qquad (19)$$

The opposite slopes in Equations (18) and (19) ensure there is a solution for the steady state S^* and λ^* at the intersection of these two loci, as shown in Figure 3a.

Figure 3. (**a**) Phase diagram; (**b**) Effect of changing the discount rate.



(**a**)



(**b**)

In addition to illustrating the steady state, Figure 3a indicates the direction of movement of stock and spot price in each region depending on initial conditions. Convergence to the steady state occurs for initial conditions in Regions C or B. For initial conditions in Region D, there is movement toward depletion of stock, while Region A has movement toward maximum stock and declining water consumption.

Figure 3b illustrates how the steady state is affected by the discount rate. From the comparative static results above, the locus $\Delta\lambda = 0$ must shift to the right as r decreases, and the locus $\Delta S = 0$ must also shift to the right; thus Region C shifts upward and outward.

5.2. Welfare along Paths to the Steady State

Initial points in different regions of Figure 3a produce optimal paths with different welfare effects. Welfare along a path in the phase diagram is determined by its combination of water consumption, stock, and quality at each point in time. To examine welfare for an optimal path to the steady state, consider the expression for un-discounted welfare W^t at a point in time along an optimal path:

$$W^t(w_i^t, S, Q) = \sum_i [B^i(w_i^t) + N^i(S^t) + E^i(Q^t)] - C(\sum w_i^t, S^t, Q^t) - iK^t \tag{20}$$

Taking the derivative with respect to *t*, change in welfare along an optimal path is:

$$\frac{dW}{dt} = \sum_i (B_w{}^i - C_w)\frac{dw_i}{dt} + (\sum_i N_S{}^i - C_S)\frac{dS}{dt} + (\sum_i E_Q{}^i - C_Q)g_S\frac{dS}{dt} - i\frac{dK}{dt} \tag{21}$$

An optimal path must of course satisfy the necessary conditions (6)–(8) at each point in time. Substituting from Equations (6)–(8) and solving for time derivatives for w^i and K in terms of λ:

$$\begin{aligned}\frac{dW^t}{dt} &= \lambda^t \sum_i \frac{dw_i^t}{dt} + NB_S{}^t\frac{dS}{dt} + i\frac{dK}{dt} \\ &= \frac{d\lambda}{dt}[\sum_i \frac{\lambda^t}{NB_{ww}{}^{it}} + \frac{(f_K{}^t)^2}{f_{KK}{}^t}] + NB_S{}^t\frac{dS}{dt}\end{aligned} \tag{22}$$

The bracketed coefficient of λ "dot" is negative under the assumed second order conditions. The net benefit of stock should be non-negative because of optimality. Therefore, a sufficient condition for welfare improvement along an optimal path—to satisfy WA and Pezzy's ethical criterion described in Section 2—is decreasing spot price and increasing stock. A necessary condition for welfare improvement is that either the spot price must be decreasing (implying increasing water consumption) as in Region D, or the stock must be increasing (Region A).

Accordingly, starting points in Region C in Figure 3a result in increasing welfare over time, while decreasing welfare over time occurs for increasing spot price and decreasing stock, found in Region B. To be consistent with altruism, Region B should be avoided on decreasing welfare grounds. Considering alternative possible paths with either increasing or decreasing welfare over time, revealed preference by the current generation for a time path with non-decreasing welfare over generations would indicate a preference for altruism.

5.3. Choosing a Path to the Steady State

Here, adjustments in discount rate and/or spot price are suggested when considered outcomes are deemed undesirable. The following discussion refers to aggregate consumption rather than individual consumption. From Equation (6), there is a spot price corresponding to any level of aggregate consumption.

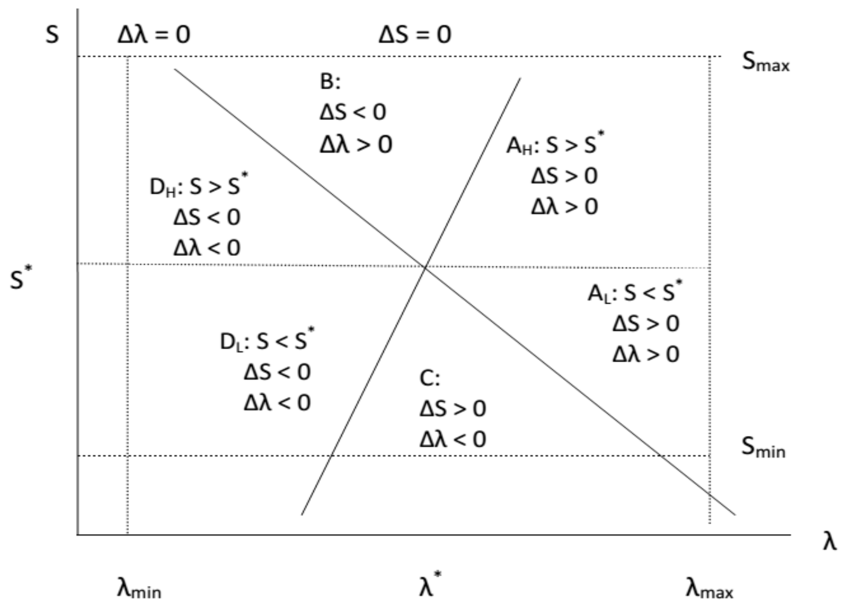
Two "degrees of freedom" can be utilized to locate a preferred path when one potential path is not desirable. First, the initial point can be changed to provide a path in a different region. Although initial groundwater stock is a physical parameter determined by hydro-geologic conditions, initial water consumption (water consumption at the start of the planning period) does not have to be taken as given, *i.e.*, a different starting point for initial consumption can be chosen to produce a preferable situation. For example, suppose the "actual" initial conditions for a water community are a low stock and high water consumption (corresponding to a low spot price), corresponding to Region D_L. The water community may provide for a better future by setting the initial spot price such that the initial consumption is less than the existing situation. So, the initial spot price can be chosen such that the optimal path will lie in Region C with increasing welfare over time. Or, given past consumption corresponding to an initial point in Region B, the initial spot price can be set such that the starting consumption is set to be in Region D_H.

Second, if no desirable path can be found for a given discount rate, the discount rate can be changed to obtain a different steady state, with a potentially more desirable path to it. For example, if a starting point is in Region A_L with ambiguous welfare change and without convergence to a steady state, the discount rate could be decreased to put the starting point in a new Region C, providing a path with increasing welfare toward a new steady state. Similarly, for an initial point in Region D_L the discount rate could be increased to put the path in a new Region C.

Alternatively for starting points in Region D, if stock depletion is not desired, a boundary condition can be set as a limit to avoid depletion. A minimum stock level (S_{min}) could be designated based on ecological concerns or on avoidance of aquifer collapse. Another boundary condition could be based on a physical maximum stock level (S_{max}) based on the hydro-geological situation; there would be no need for further capital investment beyond this limit. Furthermore, minimum and maximum water consumption levels (w_{min} and w_{max}) could be specified: minimum water consumption is the least that could be tolerated for human health reasons; for a maximum, there is limit to the volume from the size of the physical water distribution system. See Figure 4a for a phase diagram with limits.

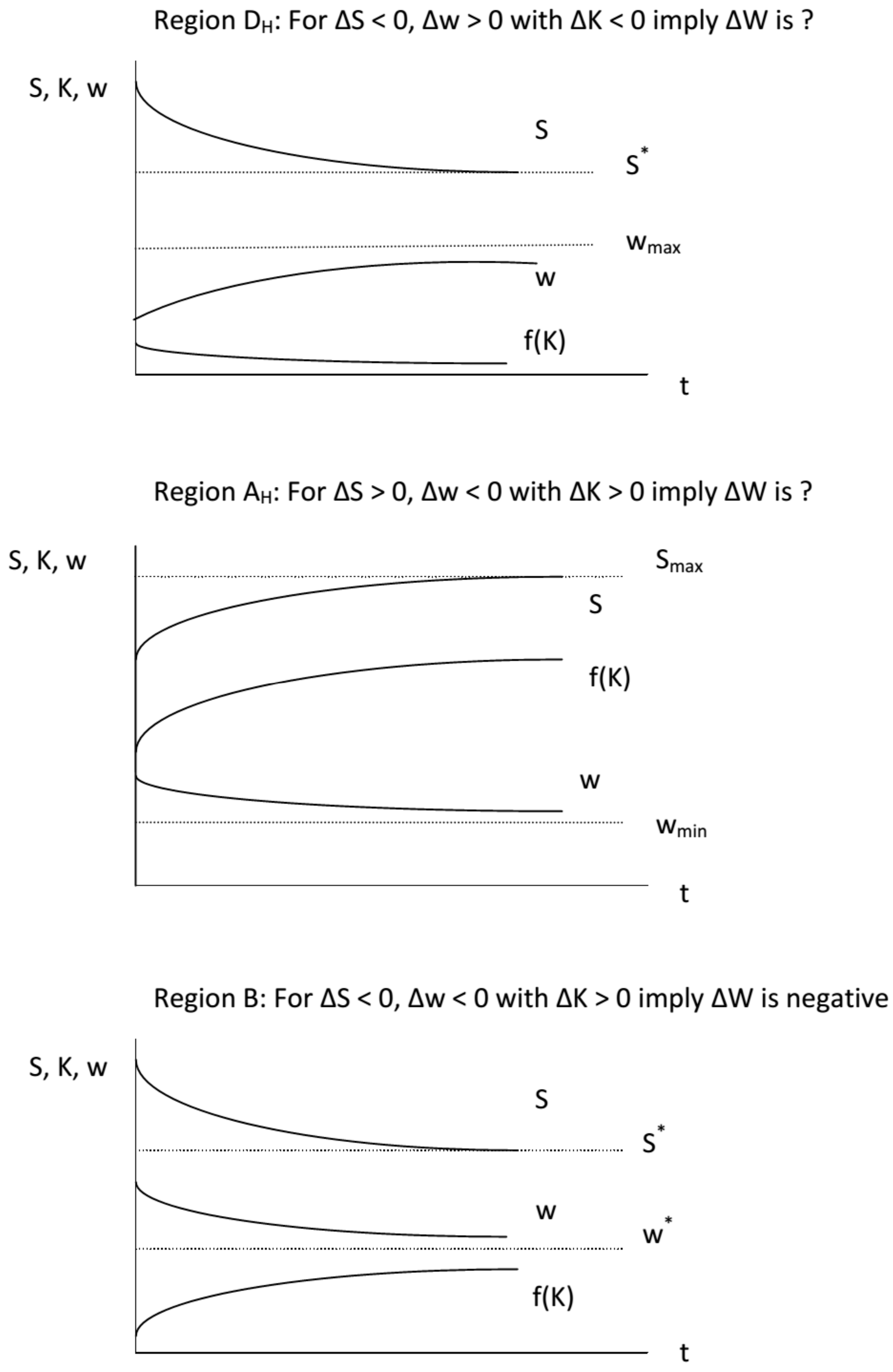
With boundary conditions, any trajectory would end at a boundary once it is reached. Since a boundary-terminated path would no longer satisfy first order conditions for an interior solution, there would be a social cost of imposing a boundary condition [98]. Still, this "non-optimality" cost could be more agreeable to the water community than depletion. See Figure 4b,c to illustrate turnpikes with such boundaries for high and low initial stock levels.

Figure 4. (**a**) Phase diagram regions with boundaries for S and λ; (**b**) Shapes of potential turnpikes for regions in Figure 3a with S_0 greater than S^*; (**c**) Shapes of potential turnpikes for regions in Figure 3a with S_0 less than S^*.



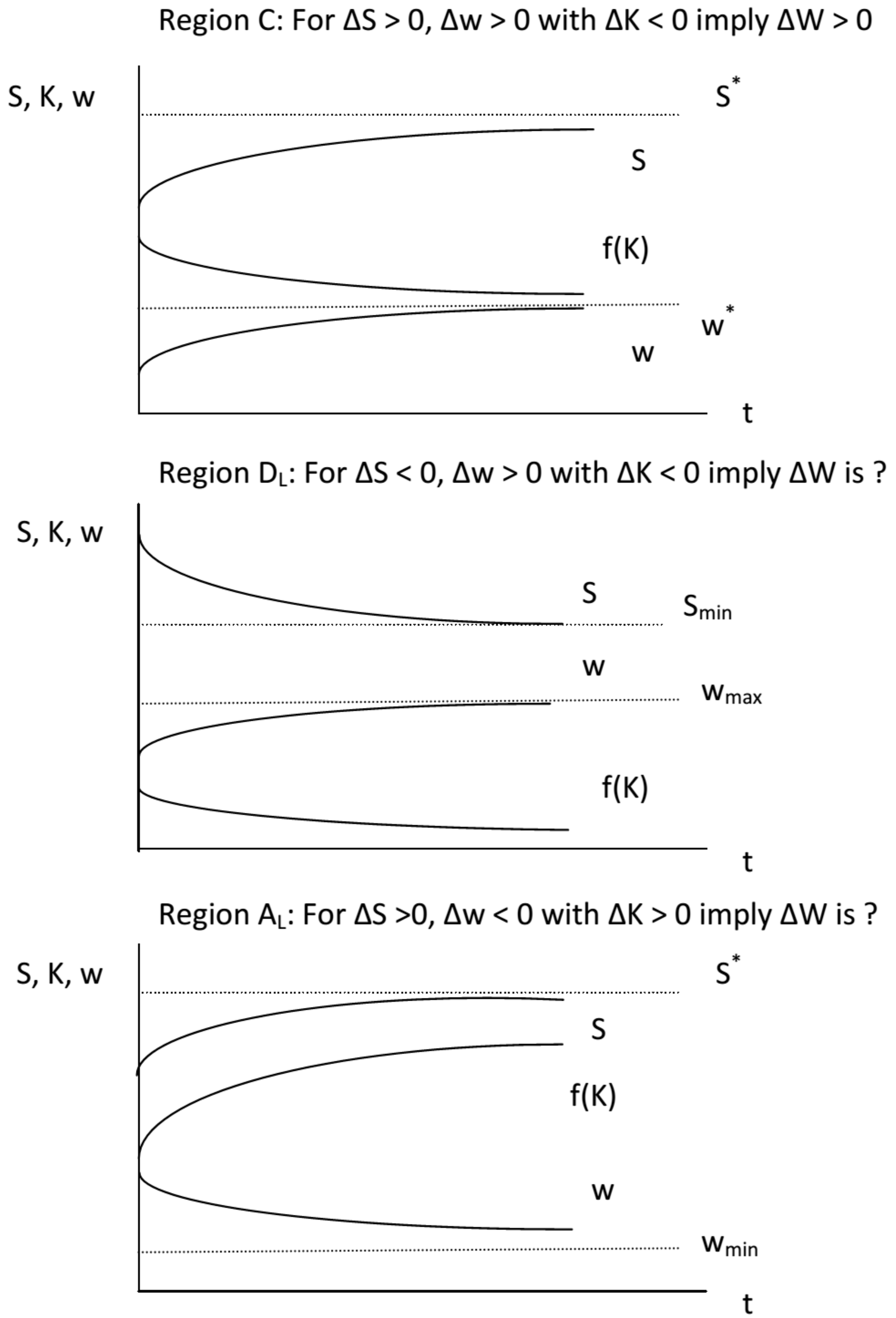
(**a**)

Figure 4. *Cont.*



(**b**)

Figure 4. *Cont.*



(c)

5.4. Application to Stages 1and 2 of the Participatory Planning Process

The above results provide the foundation for structuring the SIPI process. The description below corresponds to Stage 1 and Stage 2 for the SIPI process. The foundation for Stage 3 is described in Sections 6 and 7 below.

Summarizing the phase diagram discussion above, steps in the planning process are as follows:

(1) Identify a target steady state, thus implying a corresponding discount rate.
(2) For the given discount rate, identify potential paths to the target steady state and their associated welfare effects. Check acceptability of potential paths.
(3) If no desirable path can be identified, change the initial spot price/water consumption and/or the discount rate, and repeat Step 2.
(4) Once the desired future—the steady state and path to it—are identified, determine the associated water bills for water users (see pricing details below). Check with water users to see if these water bills are acceptable to the current generation, who also represent future generations.
(5) If water bills corresponding to the desired steady state and path are not acceptable, re-specify the target steady state and repeat the process.

Because satisfying necessary optimality conditions does not ensure that water user budget constraints will be satisfied, explicitly checking water bill acceptability in step (4) is needed. Section 6 describes how to determine the water user bills to cover operating and investment costs for water supply.

To carry out these steps, the proposed blueprint for planning in a HGE community implies the following participatory roles:

- citizens to reveal preferences to choose the desired future satisfying relevant physical and economic constraints;
- physical scientists, engineers, and mathematicians to provide scientific and technical information and computational methods for modeling;
- social scientists to work with preference elicitation and measurement of economic relationships, such as benefits, costs, and pricing.
- a government water agency to manage the planning process; if relevant, also to have oversight over a contractual arrangement with a water management enterprise.

To successfully accomplish the SIPI process, also needed will be information tools to translate physical and social sciences into layman's terms.

6. Pricing for Full Cost Recovery and Optimality

One common interpretation of economic optimal control modeling is that the optimal steady state would be determined and implemented by a social planner. A more "decentralized" planning approach is for the planner to use optimization results to set appropriate prices. A common procedure is to set price equal to the marginal social cost of consumption (the spot price plus marginal supply cost) to correspond to optimality (here, condition (6)); see for example Roumasset and Wada (2010) [99] for a groundwater application.

This pricing approach is inadequate here. There are two reasons. First, full solution of the social optimality problem (2) requires covering full costs of investment and water supply, whereas covering costs is not a part of the monetized optimization problem. If price were set equal to marginal social cost of consumption, this would not necessarily cover investment and other costs, especially when costs are non-linear and there are fixed costs [100]. Second, in addition to the necessary marginal cost condition (6), the public good necessary condition for stock and ecosystem health in Equation (8) must also be satisfied.

This section describes a pricing method to cover full cost of water supply each period, including the amortized investment cost, from payments by water users throughout all time periods of the investment life. And, it satisfies both the consumption and public good necessary conditions. Thus, the pricing method provides demand management [103], because water consumers each time period make consumption choices that correspond to the social optimum.

The proposed method for inter-temporal cost recovery—"Inter-temporal Variable Unit Pricing—extends the "Variable Unit Pricing" method for covering full water supply costs in an a-temporal setting that was described and applied in Loehman (2004, 2008) [101,102]. Similar to the a-temporal situation, the inter-temporal method constructs a multi-part water charge function such that the sum of charges over water users each period covers supply and investment costs for that period. Here the public good condition for stock and ecosystem health is also used to specify the charge function.

Consider the following nonlinear charge function specifying the total water charge for a water consumer i with consumption w_i^t at time t:

$$R^{it}(w_i^t, S^t) = (a^t + b_i^t w_i^t) w_i^t + c_i^t (S^t - S_o) \tag{23}$$

where S_o is the initial stock and S^t is a stock higher than the initial stock. That is, there is a volumetric charge per unit of water consumption (a^t + b_i^t w_i^t) as well as a charge c_i^t per unit improvement in groundwater stock [105]. The volumetric charge is further sub-divided into the per unit base charge a^t and the per unit demand charge b_i^t w_i^t. It is not necessary to include ecosystem quality Q in the charge since quality is directly related to stock.

Given this charge function, each period each water consumer would choose water consumption to maximize net benefit subject to the consumer budget constraint [106]:

$$\begin{aligned} \text{Max} \quad & x_i^t + B^i(w_i^t) + N^i(S^t) + E^i(Q^t) \\ & x_i^t + R^{it}(w_i^t, S^t) \le M_i^t \\ & Q^t \le g(S^t) \end{aligned} \tag{24}$$

Optimization results in the consumer setting marginal benefit equal to the marginal charge, for both consumption and stock.

The parameters a^t, b_i^t, and c_i^t are specified to satisfy first order conditions (6) and (8) and cost recovery. To determine the parameters for this charge function:

(1) To correspond to Equation (6), where C^t is the operating cost evaluated at the optimum values for total withdrawal, capital, and stock, water users should set marginal benefit of consumption equal to marginal consumption cost, with the marginal opportunity cost represented by the spot price:

$$B_w^{\ i} = R_w^{\ i} = a^t + 2b_i^{\ t} w_i^{\ t} = C_w^{\ t} + \lambda^t \equiv MC_w \tag{25}$$

Since the right hand side of Equation (25) is the same for each water consumer, a reference consumer *m* can be chosen. From Eqution (25),

$$b_i^{\ t} w_i^{\ t} = b_m^{\ t} w_m^{\ t} \tag{26}$$

so that the "demand charge" and volumetric charge per unit water consumption are the same for all water consumers.

(2) Each period, the sum of charges must cover the total cost, which is the sum of three components: the operating cost $C^{t,}$ plus the investment cost iK^t amortized at the market rate of interest *i*, plus any water management fee F^t. Summing water charges over all consumers to equal total cost:

$$\sum_i [a^t + b_i^{\ t} w_i^{\ t}] w_i^{\ t} + \sum_i c_i^{\ t} (S^t - S_o)^t = C^t + iK^t + F^t \tag{27}$$

Substituting Equation (26) in Equation (27):

$$\begin{aligned} \sum_i [a^t + b_i^{\ t} w_i^{\ t}] w_i^{\ t} &= \sum_i [a^t + b_m^{\ t} w_m^{\ t}] w_i^{\ t} \\ &= C^t + iK^t + F^t - (S^t - S_o) \sum_i c_i^{\ t} \end{aligned} \tag{28}$$

Thus, the volumetric charge per unit for the representative consumer must satisfy:

$$[a^t + b_m^{\ t} w_m^{\ t}] = \frac{C^t + iK^t + F^t - (S^t - S_o) \sum_i c_i^{\ t}}{\sum_i w_i} \equiv AC \tag{29}$$

Combining Equations (25), (26), and (29) above gives two simultaneous equations each period in the two unknown parameters a^t and $b_m^{\ t}\ w_m^{\ t}$

$$a^t + 2b_m^{\ t} w_m^{\ t} = MC_w^{\ t} \tag{30}$$

$$a^t + b_m^{\ t} w_m^{\ t} = AC^t \tag{31}$$

Average demand can be used to specify $w_{m.}^{\ t}$ Then, base and demand charge parameters each period can be obtained by solving Equations (30) and (31) simultaneously, given AC^t and $MC_W^{\ t}$ (average and marginal cost evaluated at the optimal solution for that period for capital, stock, quality, and total withdrawal).

(3) From the first order necessary condition (8) for optimal stock as a public good, the sum of stock marginal benefits over water users should be equal to the marginal social stock cost. To satisfy this, the sum of water consumer marginal charges for stock $c_i^{\ t}$ should satisfy:

$$\sum_i c_i^{\ t} = (C_S + g_S^{\ t} C_Q^{\ t}) + \lambda^t - \frac{\lambda^{t+1}}{1+r} - \lambda^t h(S^t) \tag{32}$$

Recall from Equation (8) that the right hand side of Equation (32) must be non-negative.

Result 5 below summarizes these results:

Result 5: Inter-temporal Variable Unit Pricing covers costs of investment and supply each period and provides appropriate inter-temporal water use incentives if pricing parameters a^t, b_i^t, and c_i^t satisfy:

$$
\begin{aligned}
b_i^t w_i^t &= MC_w^{\ t} - AC^t \\
a^t &= 2AC^t - MC_w^{\ t} \\
\sum_i c_i^{\ t} &= (C_S + g_S^{\ t} C_Q^{\ t}) + \lambda^t - \frac{\lambda^{t+1}}{1+r} - \lambda^t h(S^t)
\end{aligned}
\tag{33}
$$

for spot value and costs each period evaluated along the optimal path for capital, stock, quality and total withdrawal.

The above result does not fully specify the allocations $c_i^{\ t}$ since only their sum is specified. The allocation of the total stock charge among water users can be made in many ways as long as the individual charges are set independently of water consumption levels, so that first order conditions are not affected. Equal shares or shares proportional to income are two potential distribution methods that would not affect first order conditions.

If investment and other costs were to be subsidized from government grants, parameter determination is modified by subtracting subsidies from the full costs to be covered, and again pricing parameters to cover the remaining costs could then be determined as indicated above.

7. Organization for Optimality

Here, to support Stage 3 of the SIPI process, we show that a for-profit water enterprise—with the appropriate contractual arrangement—could provide a solution of the inter-temporal groundwater optimality problem. The reasoning is similar to the First Theorem of welfare economics (Takayama, 1985 [88]) for the a-temporal private consumption, stating that price in a market (a decentralized solution) can produce the social optimum. Decentralized decision-making by consumers and producers is generally preferred by economists to centralized planning because of reduced information and enforcement costs (Hurwicz, 1973 [107]). Here this reasoning is extended to an inter-temporal setting with non-linear pricing [108].

The proposed economic organization for HGE water management consists of: water users; a public water planning agency; and a profit-maximizing water enterprise. This structure is "decentralized" in the sense of "incentivized" consumption and production decisions. The planning agency will specify the nonlinear pricing rule $R^i(w_i^t, S^t)$—the charge function described above—for each water user's total bill, with revenues to be received by the water enterprise. A government agency to specify the form of the pricing rule is not too different from a government agency setting a rate of return (ROR) on investment for for-profit water supply, with the purpose of limiting monopoly returns.

The water management enterprise will receive revenue according to the pricing rule and pay for all water system costs from the proceeds. This contractual arrangement should also include a management fee F for the enterprise managing investment and water production. The fixed fee for management is necessary because the pricing rule gives zero profit; without such a fee, there would be no incentive for the enterprise to manage water. This fee should be independent of the volume of water withdrawal for optimization reasons.

The management fee would increase supply costs and should be added to supply cost for the social optimizations (2) and (4). Note that it is usual in economics to consider cost of management as part of the economic cost of production. The management fee would of course be subject to mutual agreement, and there should be competitive bidding among potential water managing companies to minimize this fee [110].

Mathematical description of this water management organization is as follows:

(1) The public agency sets the charge functions $R^i(w_i^t, S^t)$ for water consumers each period. Parameters for the charge functions are specified as above to satisfy cost recovery including the finance charge for investment and the management fee:

$$\sum_i R^i(w_i^t; S^t) = C(\sum w_i; S^t, Q^t) + iK^t + F^t \quad (34)$$

By construction, this pricing rule results in community financial feasibility:

$$\sum_i M_i^t = \sum_i [x_i^t + R^i(w_i^t, S^t)] = \sum_i [x_i^t + C(\sum w_i, S^t, Q) + iK^t + F^t] \quad (35)$$

(2) Given the charge functions, water consumers determine their water demands from Equation (24).

(3) Receiving revenue from the specified charge functions and management fee F, the water enterprise chooses investment and withdrawal to maximize present value of net profit for discount rate σ subject to supply constraints:

$$\begin{gathered} \text{Max} \sum_t \frac{F^t + \sum_i R^i(w_i^t, S^t) - C(\sum w_i^t, S^t, Q^t) - iK^t}{(1+\sigma)^t} + \frac{V(K^T, S^T, Q^T)}{(1+\sigma)^T} \\ S^t - S^{t-1} = -w^t + f(K^t) + h(S^t) + \alpha\rho^t \\ Q^t \le g(S^t) \\ K^t = K^{t-1}(1-d) + I^t \\ \sum_i w_i^t \le w^t \end{gathered} \quad (36)$$

Note that the water enterprise has the stock condition (1) included in its optimization problem (36).

First order conditions for profit maximization for the water enterprise are:

$$\begin{aligned} & R_w^{it} = C_w^t + \hat{\lambda}^t \\ & \sum_i R_S^{it} - (C_S + g_S^t C_Q^t) = \hat{\lambda}^t - \frac{\hat{\lambda}^{t+1}}{1+r} - \hat{\lambda}^t h_S^t \\ & i = \hat{\lambda}^t f_K(K^t) \\ & V_S^T + g_S^t V_Q^T = \hat{\lambda}^T \\ & V_K^T = \hat{\lambda}^T f_K(K^T) \end{aligned} \quad (37)$$

where $\hat{\lambda}^t$ denotes the spot prices for the optimal control problem (36). The first condition above is the familiar profit condition that marginal revenue must equal marginal cost, here including the spot price.

The joint solution of this set of "decentralized" decisions (if it exists) gives an equilibrium for this organization in the sense that no party could be better off by any party changing its decision from the equilibrium outcome. We seek an equilibrium of this system that corresponds to the social optimum. The above pricing rule and this organization of decisions are specified to achieve this correspondence. The optimal control problem (2) is satisfied by an equilibrium of the system because: (i) the combination of first order conditions for the water users and the water supplier satisfies the first order conditions for social optimality, including the public good condition, provided that the discount rate used by the supplier is the same as the social rate; (ii) financial feasibility is satisfied by the form of the pricing rule.

Result 6: A profit-maximizing water enterprise—given a contract specifying a fixed management fee, the method of inter-temporal variable unit pricing, the appropriate social discount rate, and the planning period—can satisfy the social optimality problem (2).

These contract requirements are not trivial. A for-profit water provider would tend to base decisions on a desired market rate of return rather than the social rate of discount, and the provider may have a shorter time horizon T for return on investment than the social planning horizon. Without the correspondence of the discount rate and planning horizon to social preferences, the desired sustainability outcome will not be achieved by a for-profit water management enterprise.

8. Implementation Considerations: The Backcasting and Planning Approaches

The proposed SIPI process—the HGE community identifying the desired steady state and then choosing the path to achieve it—is consistent with the idea of backcasting described below. Because to date there are more than 7000 citations to backcasting work on the internet, applying the SIPI process within a backcasting context may provide for successful implementation. Experience with backcasting and other planning methods can add to the development of the SIPI approach.

For backcasting, a desired target outcome is first identified, followed by consideration of how to determine a feasible path to this desired outcome. If no feasible path is found for a targeted future, then the target is re-cast, and deliberation continues. For the purpose of futures planning, backcasting was developed as an alternative to forecasting, which is a planning method based on trends extrapolated from past actions and technologies; it is unlikely to be pertinent for developing a new future with new behaviors and technologies.

The idea of backcasting was developed initially for use by professional water planners (Gleick, 1998 [111]). Recognizing the inherent interests of multiple stakeholders in futures planning, Robinson (2003) [112] proposed participatory backcasting: rather than a plan or set of plans being determined by experts and then brought forward for public approval, participatory backcasting has back-and-forth interchanges among stakeholders and planners regarding possibilities and tradeoffs in determining how to achieve the desired future. Applications of participatory backcasting involving citizens, scientists, and planners has been tested for water concerns in Canada by Robinson (2003) [112], Brooks, Brandes, and Gurman (2011) [113], and Brooks and Brandes (2011) [114]. Robinson *et al*. (2011) [115], Quist (2007) [116], and Vergragt and Quist (2011) [117] review applications for contexts other than water.

Decision makers need to have some understanding of the likely outcomes of their choices in order to make good decisions. However, choosing a desirable future for a groundwater system presents difficulties because of the complexities and uncertainties of physical, ecological, and social systems and their interactions.

Another difficulty is reaching a common agreement in a HGE community if there are widely differing individual preferences and values. As described by Brooks and Brandes (2011) [114] in a backcasting context, “The best way to achieve a sustainable future for fresh water is to develop decision-making processes, institutions, and technologies that emphasize both efficiency and conservation. These two terms are commonly treated as synonyms, but, respectively they reflect anthropogenic and ecological bases for making decisions (p. 315).” It is likely that stakeholder groups (e.g., conservationists, agriculturalists, industrialists, health practioners, *etc*.) may have differing values about efficiency, conservation, and other pertinent characteristics of alternative plans. Little attention in the backcasting literature has been given regarding how–when there are stakeholders with differing interests or values–agreement about the desired sustainable future and the path to it would come about. However, focusing on a desired future−before seeking acceptable means for change−may improve the likelihood of agreement among groups with different values.

Because of such difficulties, backcasting cannot be a “stand-alone” methodology. For example, Swart, Raskin and Robinson (SRR) (2004) [118] have suggested combining backcasting with scenario analysis for problems of sustainability. “...scenarios may be thought of as coherent and plausible stores, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems.... The characterization of the nature of human and environmental response under contrasting future conditions is key in scenario formulation (p. 139).” SRR also recognized the importance of involving “a sufficiently large and diverse group of participants” including experts from different disciplines and stakeholders with different interests (p. 144).

Multi-criteria decision-making methodologies should be combined with backcasting to address finding agreement for stakeholders with different interests. Relevant group decision procedures that should be explored include: (1) deliberative processes for environmental applications; for example, see Depoe *et al*. (2004) [119] and Forester (2001) [120]; (2) Delphi techniques to help find agreement (Zimmermann, Darkow, and Gracht, 2012 [121]); (3) Analytic Hierarchy Process to rank alternatives for multi-criteria water planning in a group context (Bosch, Pease, *et al*. 2012 [122]).

9. Conclusions

Hermans *et al*. 2008 [123] (p. 51) stated that: “Collaborative public participation is increasingly the norm in environmental decision-making and management in the United States. The *process* by which multiple stakeholders are involved, more than any other aspect of the project of decision activity, can dictate the success of the endeavor.” Unfortunately, planning literature is frequently devoid of economic reasoning and likewise, economic literature frequently avoids issues of implementation.

Here, planning procedures and economic reasoning are combined in the proposed SIPI process with pricing, contract rules, and organization designed to achieve an identified desired sustainability future for groundwater in a HGE community. The SIPI process described here provides a step-by-step structure for public participation based on economic theory. During the process, the HGE community identifies the desired steady state for groundwater stock, aquatic ecosystem health, and water consumption, and this in turn determines the social discount rate required for implementation of water pricing and contractual water management arrangements. The desired path toward this steady state—for investment, groundwater stock, and water consumption over time—is also a matter of water community choice, and the chosen path choice reveals the nature of community altruism. Depletion—a possible outcome under optimal control modeling—can be avoided by the HGE community by re-specifying the discount rate and/or initial water consumption, and if necessary, applying a sustainability constraint.

Then, the combination of decentralized decisions by water consumers and a for-profit water managing enterprise can achieve the desired sustainability outcome for the contractual arrangement described here. Although water management can be privatized through the contractual arrangement, there is still a major role for a government water agency to oversee the planning process and water management.

The described SIPI process seems complex, and there may be high transactions costs to implement such a system. However for groundwater, "business as usual" has resulted in an inadequate investment and non-sustainable consumption levels, and privatization has been "no panacea". It should be recognized that there are also transactions costs for an unsustainable situation when ameliorative actions must be taken *ex post*. It is an empirical question how such transactions costs might compare to the welfare gains from achieving sustainability.

More work is undoubtedly required to make operational the concepts presented here and to "flesh out" planning procedures. Clearly, measurement of economic and physical relationships and heuristics will be needed. Given the world-wide situation of threats to groundwater sustainability, there should be ample opportunities for application along the lines suggested in this paper.

If successful, the methods suggested in this paper may be applied to other dynamic resource problems with the possibility of renewal/restoration through social investment. For non-renewable resources such as "fossil" water, there is no steady state. However, social investment in alternative technologies can still prolong the use of the resource and help to mitigate negative environmental impacts. Without a steady state, the social discount rate may be less directly discoverable, but the idea is still relevant for public participation to choose the path to the future through social investment and appropriate pricing.

Appendix 1: Discount Rate and Benefit-Cost Analysis

The money-metric optimization specification (4) is reminiscent of benefit-cost analysis in its use of the sum of discounted net benefits for the objective function. Benefit-cost analysis (BCA) has been useful for making water investment decisions (see Maas, 1966 [124]; Prest and Turvey, 1965 [125]), and at the same time there has been much controversy about its limitations (De Alessi, 1969 [126]; Wildavsky, 1966 [127]). In traditional BCA, discounted net social benefit is the metric used to make yes-no decisions among a limited set of pre-specified alternative proposals.

The selection of a discount rate has always been an issue for benefit-cost analysis. For example for the Cross Florida Barge Canal proposed by the U.S. Army Corps of Engineers in the 1970s, controversies concerning the discount rate helped to overturn this potential development: Roberts (1976) [128] showed that if a high enough rate were used, negative net benefits would support rejection of the project.

Some economists have suggested that the discount rate be set at the market rate of interest to reflect market opportunity cost. Using a lower rate could result in making an investment decision that is less productive than market opportunities (Toth, 2000 [129]; Howarth and Norgaard, 2004 [130]). In contrast, for water investments, the rate is congressionally prescribed at a lower than market rate to reflect that society would prefer longer-lived projects, which by nature would not be provided in a market setting.

Controversies about the discount rate issue can in part be explained as confounding several different concepts, namely: rate of time preference, investment productivity, opportunity cost, and rate of return on capital (borrowing cost); see Toth (2000) [129] for a comparison and discussion of these different concepts. The idea of a social rate of discount was presented by Marglin (1963) [131]. He suggested that there should be a difference in the way we view savings *versus* consumption decisions for collective goods in comparison to individual consumption decisions. He also explicitly recognized that investment for such goods would provide benefits for future generations as well as the current generation.

For any positive rate, discounting implies weights on the distant future that are effectively zero for catastrophic events such as climate change. Consequently, equity over generations has been a concern for BCA. A zero discount rate (Dasgupta, 1982 [132])—or equivalently equal weights on the net benefits of each generation—has been suggested to express equity concerns. Negative discount rates have even been suggested to reflect a preference for increasing welfare over time. Recent psychology experiments regarding observed preferences for future consumption/income over present consumption/income support a negative discount rate (Lowenstein and Prelec, 1992 [133]; Frederick and Loewenstein, 2002 [134]). Moreover, the discount rate may also vary over time, as with hyperbolic rates (Heal, 2000 [135]).

Appendix 2: Optimal Control Models for Groundwater Based on Height of the Water Table

Most papers applying optimal control for groundwater concerns have focused on agricultural pumping externalities, with a "single-cell or "bath-tub" unconfined aquifer model based on the height of the water table. When there is increased pumping by any person in the basin, the associated externality is that pumping costs increase for everyone as the water table falls. Gisser and Sanchez (1980) [136] used this type of model and empirical relationships from New Mexico for agricultural returns from groundwater extraction and the externality effect of extraction on pumping cost; they obtained the conclusion that regulated management of an aquifer brings negligible returns compared to "free market" decisions.

To revisit this conclusion, Burness and Brill (2001) [137] focus a similar model but add the relation between investment in irrigation capital and water conservation. Investment in irrigation increases efficiency of water use, thus ameliorating the pumping cost externality. In the optimal control model, net revenue is maximized over a fixed time period, and they compared this objective empirically for a planning solution *versus* a competitive (myopic independent agricultural producer) situation; data from a county in New Mexico was used. Over-pumping is shown to result from under-investment in irrigation. By the end of the planning period (200 years), the outcome under both regimes is nearly the same in terms of water use. However, net revenue from the planning solution surpasses the competitive solution after about fifteen years, and is clearly superior after forty years.

The conclusion that there would be only small gains from groundwater regulation was questioned by Esteban and Albiac (2011) [15] because the above agricultural models excluded effects on aquatic ecosystems that are dependent on aquifers. They estimated an empirical agricultural model for Spain, with ecosystem values included, and used it to compare three regimes: free market (non-cooperative) with myopic pumping, full cooperation (or joint management), and partial cooperation. Partial cooperation accounts only for the extraction externality, whereas full cooperation includes both environmental and pumping externalities. Free market decisions result in massive depletion, whereas full cooperation results in initial extraction reduction followed by rapid recovery of the water table and about 50% higher social welfare compared to the free market outcome. The partial cooperation solution is nearly as good as the full solution in terms of welfare and water stock at the end of the period. How cooperation would be organized was not addressed.

Roumasset and Wada (2010) [99] addressed groundwater management for the urban setting of Oahu, Hawaii; they studied optimal pumping when there is a backstop technology (desalinization) that can substitute for pumping; they assumed that desalinization has a linear cost. From optimality conditions, they defined a pricing rule for the purpose of demand management. A main point of their work is to show the inappropriateness of "maximum sustainable yield" as a rule for groundwater management.

Appendix 3: Adjustment Procedure for Uncertain Rainfall

The optimization problems (2) and (4) were specified in terms of *ex ante* known rainfall patterns. However, especially with climate change rainfall patterns are not known *a priori*. This appendix indicates how the investment planning process can still be applied in terms of social preferences, even in the face of varying and uncertain rainfall.

Burt (1967) [138] suggested one approach to deal with rainfall risk: maximize expected net benefits using expected rainfall ($\bar{\rho}$) to give a "stochastic equilibrium which is always approached but rarely experienced (p. 46)." Following Burt's suggestion, an expected steady state and corresponding paths could be determined from optimization in terms of expected rainfall; *i.e.*, the planning process for making investment and pricing decisions can be based on the expected conditions or a guess about anticipated conditions.

For a constant reference expected rainfall $\bar{\rho}$, the "reference" optimization with this expected rainfall provides a reference steady state S_r^* and reference investment K_r^*; the reference steady state total withdrawal w_r^* will satisfy:

$$w_r^* = f(K_r^*) + h(S_r^*) + \alpha\bar{\rho} \tag{A1}$$

where reference water user consumption paths will satisfy $w_r^t = \sum w_{ri}^t$.

Define consumption shares at the steady state: $\gamma_i = \dfrac{w_{ri}^*}{w_r^*}$. Then, *ex post* consumption could be determined by actual rainfall conditions, as follows. After actual rainfall ρ^t is observed, consumption w_i^t can be allocated according to these same shares:

$$w_i^t = w_{ri}^t + \gamma_i \alpha \; (\rho^t - \bar{\rho}) \tag{A2}$$

That is, *ex post* water consumption would exceed the reference withdrawal when actual rainfall exceeds average rainfall, and conversely. Taking expected values, the total *ex post* consumption each period will equal the reference total withdrawal w_r^t. These *ex post* allocations will also satisfy the steady state stock condition for the reference steady state stock, capital, and total withdrawal:

$$\dot{S} = -\sum w_i^* + h(S_r^*) + f(K_r^*) + \alpha\rho^t = -w_r^* - \alpha(\rho^t - \bar{\rho}) + h(S_r^*) + f(K_r^*) + \alpha\rho^t = 0 \quad \text{(A3)}$$

Thus, this adjustment procedure has the good property that *ex post,* there is a steady state that is consistent with the *ex ante* optimal plan.

Of course, for pricing purposes spot prices can be re-specified to match *ex post* allocations. However, a problem is that the first order necessary conditions for optimization—specified in terms of reference spot prices—will not hold for *ex post* water consumption so specified. Still, the acceptability of this *ex post* allocation method can be tested as part of the SIPI process.

Conflicts of Interest

The author declares no conflict of interest.

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76. In contrast, the groundwater physical model in many economic optimal control models is in terms of the hydraulic head related to pumping costs for a well. See Feinerman and Knapp (1983) [4] for an example. Other examples are given in Appendix 2.
77. Many geographic areas combine surface and groundwater for water supply. In such cases, conjunctive management of ground and surface water should be a part of conservation measures. However, here groundwater is modeled as the only water source.
78. The direct addition to stock due to rainfall would undoubtedly have some time delay that would depend on the hydro-geologic conditions in an area.
79. That the steady state should be at a stock that is greater than the maximum sustainable yield is consistent with bioeconomic models of fisheries and forestry. See for example Berck (1979) [80] and Bjomdal (1988) [81]. (Thanks for this note to one reviewer.)
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82. Time superscripts sometimes are omitted for simplicity and are understood in context.
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84. Note that this resource economics problem has two control variables, investment and total withdrawal. Most resource economics models have only one control variable, usually the rate of resource extraction.
85. In optimization models for "overlapping generations", the objective function still has the form of discounted summed utility over time; see for example Jouvet *et al.* (2000) [86].
86. Jouvet, P.-A.; Michel, P.; Vidal, J.-P. Intergenerational Altruism and the Environment. *Scand. J. Econ.* **2000**, *102*, 135–150.

87. Population and income growth are ignored here to simplify development; optimal social investment should be greater with income and population growth. The analysis of income and population growth effects on optimal investment can be obtained from the author by writing loehman@purdue.edu.
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89. This additive form embodies the assumption that water consumption and ecosystem values are perfectly substitutable in terms of preferences, which may not be true. However, this form is consistent with benefit-cost analysis. The analysis could have been carried out strictly in utility terms with similar results.
90. This utility formulation could include agricultural and industrial users as well as households. If so, their preferences would be represented by profit functions.
91. Money-metric benefits for water consumption can be measured by demand functions, whereas ecosystem values can be measured in terms of payment for ecosystem services. There are many relevant studies of ecosystem value measurement. For example, Layman, Boyce, and Criddle (1996) [92] measure the value of chinook salmon in Alaska with the travel cost method. For social investment, it seems appropriate to measure collective values of non-consumption goods in a deliberative context; methods have been developed by Howarth and Wilson (2006) [93].
92. Layman, R.C.; Boyce, J.R.; Criddle, K.R. Economic Valuation of the Chinook Salmon Sport Fishery of the Gulkana River, Alaska under Current and Alternative Management Plans. *Land Econ*. **1996**, *72*, 113–128.
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96. This result clearly differs from Hartwick's rule which here would imply that investment each period should equal that period's spot price times the total water withdrawal that period.
97. The phase diagram is drawn with linear curves, but there is no reason why these relationships should be linear except the limitations of the graphics package.
98. If a community chooses to hold consumption constant after reaching an imposed boundary, the spot price at the boundary becomes the terminating spot value. The difference between the "optimal" spot value and the terminating spot value is the per unit social cost of imposing the boundary. But this social cost would be offset by the social value of avoiding depletion.
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104. Baumann, D.D.; Boland, J.; Hanemann, W.M. *Urban Water Demand Management and Planning*; McGraw Hill Companies, Inc.: Burr Ridge, IL, USA, 1997.
105. The charge per unit of stock improvement is like a Pigouvian tax, as used in welfare economics, which creates incentives for private decisions to correspond to the social optimum.
106. If there are agricultural water users, a charge for use of groundwater is similar to a "pump fee" which has been suggested for groundwater regions with over-pumping (Howe, 2002 [12]), similar to a public agency setting a Pigouvian tax for an externality.
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108. The First Theorem has been extended by Dasgupta and Mitra (1988) [109] to the inter-temporal case for a multi-sector growth model with discounted welfare with infinite time; they show conditions for which competitive programs are optimal. Since our problem has a finite time period, the usual concavity assumptions are enough to ensure optimality of our decentralized program.
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