Optimal Investment in Research and Development

Regarding a Backstop Technology

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Abstract

We examine the role of investment opportunities on the marginal cost of a backstop technology and the resulting implications for optimal depletion of a non-renewable resource. We consider the case in which two economic agents (individuals, cities, or nations) compete for a non-renewable resource, and investments in research and development will reduce the marginal cost of a backstop technology. We examine the problem in both social optimization and game theory frameworks. We consider three scenarios: 1) The social planner's problem in which the sum of net benefits earned by the two agents (players) is maximized, 2) A scenario in which two players compete for the limited resource, while making investments jointly, and 3) A scenario in which the players compete for the resource and they choose investment levels independently. We examine, in particular, the case of groundwater withdrawals from an aquifer with a very small rate of natural recharge. The backstop technology is desalination. Results describe the optimal paths of investments in knowledge, as the original stock of groundwater is depleted. Groundwater is extracted over a longer interval, and the sum of investments in knowledge is smallest, in the social planner's scenario.

1. Introduction

The concept of a backstop technology was developed in conjunction with the economic theory of non-renewable resources. In brief, a backstop technology is a substitute for a non-renewable resource (Herfindahl, 1967; Nordhaus, 1973; Goeller and Weinberg, 1976). The supply of a backstop technology, by definition, is not limited, but the marginal cost of provision is higher than the marginal cost of extracting the non-renewable resource. Hence, it is socially optimal to extract all of the non-renewable resource before switching to the backstop technology. Optimization requires also that the supply of the non-renewable resource is exhausted precisely at the time that the marginal cost of extraction reaches the higher, but constant, marginal cost of the backstop technology (Dasgupta and Heal, 1979; Fisher, 1981). Classic examples of backstop technologies include solar energy, nuclear fusion, and desalination of seawater.

Reductions in the marginal cost of a backstop technology will extend the time during which the non-renewable resource is extracted, while reducing the scarcity rents earned by owners of the resource, *ceteris paribus*. If the marginal cost of a using a backstop technology can be reduced or if new backstop technologies can be discovered through investments in research and development, then society might benefit from implementing an optimal program of investments in research and development. Private firms investing in research and development also may benefit if they are able to obtain patents for the improvements they make in backstop technologies (Dasgupta and Heal, 1979). The optimal program of investments in research and development likely will begin during the period in which the non-renewable resource is being consumed.

The conceptual framework in which a discrete switch occurs from the use of a non-renewable resource to a backstop technology does not describe all empirical situations. There are many cases in which both a non-renewable resource and a backstop technology provide products and services to consumers. For example, many consumers derive energy services from a mix of fossil fuels and solar energy sources. Recent developments in groundwater pumping technology enable farmers to use solar energy to power their pumps. Some farmers adopting the new technology retain their connection to the electricity grid system, to enable the use of that energy source when necessary. In the automobile industry, some new cars are powered by a hydrogen fuel cell, while others are powered by a mixture of gasoline and "renewable" electricity that is generated while the gasoline engine is running.

The potential benefits from investments in research and development in backstop technologies may be substantial in regions where non-renewable resources are diminishing rapidly and where the supply of a renewable resource is insufficient to satisfy increasing demands. For example, a city or region that depends on a non-renewable groundwater supply for drinking water might benefit from timely investments in research and development regarding desalination technology. Similar benefits might accrue to an urban area where the surface water supply or the natural rate of recharge to an aquifer is insufficient to satisfy increasing municipal and industrial water demands.

In this paper, we examine investment policies regarding research and development (R&D) in backstop technologies, from both optimization and strategic perspectives. The technology chosen for analysis is desalination of water for use in municipal and industrial applications. Desalination of seawater and brackish groundwater will provide larger portions of municipal water supplies in many regions of the world, as the demand for high-quality water continues to increase with rising populations and income levels. In some areas, desalination will enable cities and nations to replace water supplies that once were obtained from non-renewable groundwater sources. In other areas, desalination will be one of several sources of water supply that may include groundwater, surface water, and wastewater treatment.

2. Desalination as a Backstop Technology

Two types of technologies have been developed for removing salts from water: thermal processes and membrane technologies. Thermal processes include multistage flash methods (MSF), multiple effect evaporation (MEE), and mechanical vapor compression (MVC). Membrane technologies include reverse osmosis (RO) and electrodialysis (ED). The energy cost of MSF operation is approximately three times as high as the RO system (Darwish, 2001). Worldwide, multistage flash and reverse osmosis account for 44% and 42%, respectively, of the installed capacity of desalination technology (Fiorenza et al., 2003). Thermal processes are more appropriate than membrane technologies for desalinating seawater. The multistage flash method accounts for 70% of seawater desalination capacity.

The initial cost of installing a desalination plant can be substantial, particularly if it is located some distance from the source of saline or brackish water. The high costs of technical components and of operating and maintaining a desalination facility have limited the installation of desalination plants to regions with notable effective demand for high-quality drinking water, such as some of the wealthier nations in the Persian Gulf Region. At present, desalination provides more than 40% of municipal water supplies in Bahrain, Kuwait, Qatar, and Saudi Arabia (Al-Sahlawi, 1999; Bremere et al., 2001; Darwish, 2001; Hamoda, 2001). Desalination plants in Oman provided 42 million m^3 of water in 1996, or about 53% of that country's potable water supply (Al-Ismaily and Probert, 1998). Desalination provides smaller portions of national water supplies in several other nations where the demand for water is increasing. Cyprus began operating desalination plants in 1997, with the goal of someday producing 40 million m^3 of water per year, or about 17% of its current water demand (Tsiourtis, 2001).

Estimates of the current cost of desalination range from \$0.20 to \$0.35 per m^3 (\$247 to \$432 per acre-foot) for brackish water and from \$0.70 to \$1.20 per m^3 (\$864 to \$1,481 per acre-foot) for seawater (Bremere et al., 2001). Seawater desalination in coastal areas of the Gaza Strip and Israel might cost \$0.70 per m^3 (Haddad and Lindner, 2001), while the average cost of water produced at desalination plants on the island of Cyprus ranges from \$0.42 to \$0.54 per m^3 (Kalogirou, 2001). The average cost of seawater desalination using the multistage flash method in Abu Dhabi is \$1.08 per m^3, but transmission and distribution require an additional expenditure of \$0.95 per m^3 (Abu Qdais and Al Nassay, 2001). The estimated cost of desalination at a new facility constructed by the city of Tampa, Florida ranges from \$0.46 to \$0.55 per m^3 (Lokiec and Kronenberg, 2001; Wilf and Klinko, 2001). The source of water is Tampa Bay, which is less saline than the ocean, due to inflows from surface water sources.

Some reviewers may suggest that desalination is not a true backstop technology, given its reliance on fossil fuel energy sources in most of its industrial applications. Three considerations seem pertinent regarding that consideration: 1) The backstop terminology applies to the water resource, rather than the energy resource, 2) The energy cost, per unit of water produced by desalination has declined substantially in recent decades, with advances in technology, and 3) Desalination facilities can be powered by solar and nuclear energy sources. The use of solar and nuclear energy to desalinate water may increase, over time, with developments in technology and with increases in demand for desalination, particularly in regions with limited or expensive supplies of fossil fuels (Ahmad and Schmid, 2002; Bouchekima, 2003; Fiorenza et al., 2003; Nisan et al., 2003).

3. Conceptual Framework

Previous work regarding the optimal pattern of investment in research and development regarding backstop technologies is limited. Dasgupta and Heal (1979) show that from a social perspective, the optimal research and development program will vary with the size of the stock of a non-renewable resource. They describe also how private firms are motivated to invest in research and development by the prospect of profits they might earn if awarded patents for new discoveries. In fully competitive conditions, non-renewable resources and backstop technologies will be used sequentially, rather than at the same time. However, in some cases, private firms can increase their profits by choosing investment and marketing strategies to influence the time at which the switch occurs from a non-renewable resource to a backstop technology. The possibility of strategic behavior and the uncertainty inherent in searches for substitutes lead to the conclusion that some research and development should be undertaken by public agencies.

Tsur and Zemel (2000, 2003) provide a model in which both a traditional resource and a backstop technology can be used at the same time, and investments in research and development reduce the marginal cost of the backstop technology. The authors demonstrate that the optimal transition from the traditional resource to the backstop technology is smooth, rather than discrete. Use of the backstop technology increases gradually, as its marginal cost declines, and as the remaining stock of the non-renewable resource diminishes.

We extend the model of Tsur and Zemel (2000, 2003) in two ways: 1) including adjustment costs, and 2) examining dynamic game scenarios. Adjustment costs include costs associated with purchasing and installing new equipment, removing old equipment, and training labor to use the use the new equipment. Dynamic game scenarios are examined to determine the potential gains from cooperation if two municipalities in an arid region combine their efforts to invest in research and development activities. Two scenarios are examined in which the two cities compete for water from an aquifer that has a limited rate of natural recharge. In the first scenario, the cities agree to cooperate in making investments and implementing the backstop technology. In the second scenario, each city invests in its own desalination plant and operates it individually, to provide water only for its residents.

3.1 Joint Maximization of Net Benefits

A dynamic optimization model of investments in research and development (R&D) is formulated as a discrete time, infinite horizon dynamic programming problem. The social planner's model is formulated as the joint maximization of net benefits for two cities, $p = a,b$. The benefit function is specified as $B(w^p + z^p)$, where w^p is the amount of groundwater consumed and z^p is the amount of desalinated water consumed. The source of water is unknown to consumers, and so the marginal benefits of w^p and z^p are identical and they are assumed to be positive (i.e. B_w^p , $B_z^p \geq 0$). The cost of providing groundwater, $C(w^p, s)$, is a function of the amount of water withdrawn, w^p, and the remaining stock of groundwater, s. The cost function $C(w^p, s)$ is such that $C_w > 0$ and $C_s < 0$. Following Tsur and Zemel (2000, 2003) the marginal cost of providing desalinated water is assumed to be a function of accumulated knowledge, k. In particular, the marginal cost of desalination decreases as k increases. The total cost of providing desalinated water is $D(k)z^p$, where $D(k)$ represents the desalination cost function.

Investments, y^p, can be made to increase knowledge regarding desalination technology, which will lower the marginal cost of providing desalinated water in the future. Investment is assumed to be made from the net benefit (net revenue) earned in each period, thus excluding the possibility of external funding. As the technology improves, the cities need to upgrade their technology to benefit from the lower marginal cost of desalination. That process generates the cost of adjustment, $F(y^p)$. We assume that the marginal cost of adjustment increases as a larger sum is invested in research and development.

There are two state variables in the model. One is the remaining stock of groundwater, *s*, that the two cities share. The transition equation for this stock is:

$$s_{t+1} = s_t - \sum_{p=1}^{2} w_t^p + R \ , \tag{1}$$

where *R* represents a constant recharge rate. Assuming the identical players, the steady state pumping amount is *R/2* for each player. The other state variable is the accumulated knowledge regarding desalination technology, *k*. The transition equation for the accumulated knowledge is:

$$k_{t+1} = \left(k_t + \beta \sum_{p=1}^{2} y_t^p \right)^{\gamma} , \quad k_0 < 1, \qquad 0 < \gamma < 1. \tag{2}$$

The Bellman equation for the joint maximization of net benefits, subject to non-negativity constraints on all the control variables, becomes:

$$V(s,k) = \max_{w^p, z^p, y^p} \left(\sum_p \begin{Bmatrix} B(w^p + z^p) - C(w^p, s) - D(k)z^p - y^p - F(y^p) \\ + \theta_1 w^p + \theta_2 z^p + \theta_3 y^p \end{Bmatrix} + \delta V(\hat{s}, \hat{k}) \right) \tag{3}$$

Note that $\hat{s}$ and $\hat{k}$ represent the values of state variables in the next time period and $\delta = \frac{1}{1+r}$, where r is the discount rate.

Let $\frac{\partial V}{\partial s} = \lambda$ and $\frac{\partial V}{\partial k} = \mu$, then the Euler conditions for equation (3) are:

(4) $B_{w^p} - C_{w^p} - \delta\lambda + \theta_1 = 0 \qquad w^p \geq 0 \qquad \theta_1 w^p = 0$

(5) $B_{z^p} - D(k) + \theta_2 = 0 \qquad z^p \geq 0 \qquad \theta_2 z^p = 0$

(6) $-1 - F_{y^p} + \delta\mu\hat{k}_{y^p} + \theta_3 = 0 \qquad y^p \geq 0 \qquad \theta_3 y^p = 0$

(7) $\lambda = -C_s + \delta\lambda$

(8) $\mu = -D_k + \delta\mu\hat{k}_k$,

where $\hat{k}_{y^p} = \gamma\beta\left(k + \sum_p y^p\right)^{\gamma-1}$, $\qquad \hat{k}_k = \gamma\left(k + \sum_p y^p\right)^{\gamma-1}$

Equation (4) indicates that when $w^p > 0$, the amount of w^p should be chosen so that the benefit from the last unit of groundwater taken today is equal to the sum of the marginal cost of pumping and the marginal user cost of groundwater. If the marginal benefit is less than the sum of marginal costs, no groundwater will be withdrawn. There is no limit to the amount of available for desalination. Hence, when $z^p > 0$, we need only to equate the marginal cost of producing desalinated water with its marginal benefit (equation (5)). If the marginal benefit is less than the marginal cost of desalination (for example, when there is little accumulated knowledge), water will be taken only from groundwater. Equation (6) suggests that along the optimal path, a municipal water manager should choose the amount of investment so that the sum of the direct cost of investment, *1*, and the marginal adjustment cost, F_y^p is equal to the discounted value of the investment. Investments in R&D will not be optimal if the marginal benefit from the accumulated knowledge is less than the marginal cost of investments.

Equation (4) and (5) provide interesting information. Both w^p and z^p are positive only when $C_{w^p} + \delta\lambda = D(k)$. When the marginal cost of desalination is higher than the sum of the marginal cost of providing groundwater and the marginal user cost of groundwater, water is provided only from groundwater. So, $w^p>0$ and $z^p=0$, when $B_w = C_{w^p} + \delta\lambda < D(k)$. Similarly, $w^p=0$ and $z^p>0$, when knowledge regarding desalination technology accumulates to a point such that $C_{w^p} + \delta\lambda < D(k) = B_w$ is true.

Assuming that an internal steady state exists, manipulations of equations (4) through (8) produce two golden rules. Let $MNB_{w^p} = B_{w^p} - C_{w^p}$, which is the marginal net revenue from groundwater consumption, and $MC_{y^p} = 1 + F_{y^p}$. Also using the relation $\hat{k}_{y^p} = \beta\hat{k}_k$, the golden rules become:

(9) $$r = \frac{-C_s}{MNB_{w^p}}$$

(10) $$r = \hat{k}_k\left(1 - \frac{\beta D_k}{MC_{y^p}}\right) - 1.$$

The right-hand-side of equation (9) is the ratio of the marginal value of groundwater stock and the marginal net value of groundwater withdrawal. The optimal, steady-state values of w^p and s should be chosen so that the ratio of those two terms is equal to the discount rate. Similarly, the steady state values of y^p and k should be chosen so that the discount rate is equal to the right-hand-side of equation (10).

3.2 Competition for Groundwater, with Joint Investment (Game 2)

In this model, the cities compete for limited groundwater, but they cooperate in making investments in R&D regarding desalination technology. The cities also agree to operate the desalination activity in a cooperative manner. This framework involves only one variable describing accumulated knowledge, *k*, as in the case of maximizing the sum of net benefits. Although the two cities invest in R&D jointly, each city determines its own level of investment. Therefore, the new transition equations for city *a* become:

(21) $$s_{t+1} = s_t - w_t^a - w_t^b(s_t, k_t) + R$$

(22) $$k_{t+1} = \left(k_t + \beta\left(y_t^a + y_t^b(s_t, k_t)\right)\right)^{\gamma}, \qquad k_0 < 1, \qquad 0 < \gamma < 1$$

.

The steady-state pumping amount for each player is *R/2*.

The Bellman equation for city *a* becomes:

(23) $$V^a(s,k) = \max_{w^a, z^a, y^a} \left\{ \begin{aligned} & B(w^a + z^a) - C(w^a, s) - D(k)z^a - y^a - F(y^a) \\ & + \delta V^a(\hat{s}, \hat{k}) + \theta_1 w^a + \theta_2 z^a + \theta_3 y^a. \end{aligned} \right\}.$$

The Euler conditions for this model differ from those described above for the optimal solution to the social planner's model.

3.3 Competition for Groundwater, with Independent Investments (Game 2)

In this model, two cities compete for a limited groundwater resource, while each city invests in R&D regarding desalination technology independently. The independent investments in R&D are denoted as k_p for $p = a$ and b. For clarity, the superscripts a and b are used to denote the two cities. The new transition equations for remaining groundwater stock and accumulated knowledge for one of the cities (a) become:

(11) $$s_{t+1} = s_t - w_t^a - w_t^b(s_t, k_t^b) + R$$

(12) $$k_{t+1}^a = \left(k_t^a + \beta y_t^a\right)^\gamma, \qquad k_t^a < 1, \qquad 0 < \gamma < 1$$

Assuming identical players, the steady-state pumping amounts for each player are *R/2* in this model, just as in the social planner's model.

Given the new transition equations, the Bellman equation for city a becomes:

(13) $$V^a(s,k^a) = \max_{w^a, z^a, y^a} \left\{ \begin{array}{l} B(w^a + z^a) - C(w^a, s) - D(k^a)z^a - y^a - F(y^a) \\ + \delta V^a(\hat{s}, \hat{k}^a) + \theta_1 w^a + \theta_2 z^a + \theta_3 y^a. \end{array} \right\}.$$

4. Empirical Analysis

4.1. Solution Method

We use numerical methods to obtain optimal solutions for all three models. In particular, we use collocation methods that involve solving for unknown coefficients of approximating functions, as described in Miranda and Fackler (2002).

4.2. Functions and Parameter Values

The benefits of water consumption are defined by the following function:

$$B(w^p + z^p) = \frac{a}{1-b}\left(w^p + z^p\right)^{(1-b)}$$

The costs of groundwater pumping, are defined as a function of the volume of water withdrawn each year and the remaining groundwater stock, as follows:

$$C(w^p, s) = e\left(h_{\max} - \frac{s}{area - sy}\right)w^p w^p$$

The annual cost of desalination increases with the volume desalinated, while the per-unit cost declines with accumulated knowledge:

$$D(k)z^p = \frac{d}{k^{0.5}} z^p$$

Adjustment costs are represented by a quadratic term involving the amount of funds invested each year:

$$F(y^p) = qy^p y^p$$

The following constraints are imposed on the state and control variables:

$$0 \le w_t^p \le s_t, \quad 0 \le z_t^p, \qquad 0 \le y_t^p \le NB_t^p$$

$0 \le s \le 100$, $\quad 0.1 \le k \le 40$, or $0.1 \le k^p \le 40$

Initial values: $s_0 = 100$, $k_0 = 0.1$

Parameter values are shown in Table 1.

Table 1: Parameter Values

Parameters	Values	Parameters	Values
a	5	*d*	2
b	0.8	*q*	1
e	0.025	*β*	0.1
hmax	12	*γ*	0.9
area	100	*r*	0.05
sy	0.1	*δ*	1/(1+r)

5. Results

5.1. Optimal Response Functions

The optimal level of groundwater pumping declines with reductions in the stock of groundwater available, but is not very responsive to changes in accumulated knowledge. The optimal response function is very similar in both of the game scenarios, while the social planner's scenario depicts a slightly greater responsiveness to the level of accumulated knowledge (Figure 1).

The optimal response functions for desalination also depict limited responsiveness to changes in groundwater availability or the stock of accumulated knowledge (Figure 2). Because the maximum level of accumulated knowledge is limited, the maximum amount of desalination also is limited in all scenarios. Differences among the models are observed in the location of the demarcation lines that divide zero desalination from positive amounts of desalination. In the social planner's scenario, desalination begins when the remaining groundwater is less than *40* units, provided that the accumulated knowledge is close to its maximum level.

The shapes of the optimal investment policy functions are consistent with economic intuition (Figure 3). In all models, the response surfaces suggest that more money is invested in research and development when both the remaining groundwater stock and accumulated knowledge are small. A comparison between Figure 3a (the social planner's scenario) and 3d (the game with joint investment) reveals the shirking behavior of players. In both scenarios, investments are made jointly and the parameter values are identical. However, while investment becomes positive when the remaining groundwater is *40* units in the social planner's scenario, investment remains at zero until the remaining groundwater is *20* units in the game with joint investment. The largest investment amount is observed in the game with independent investments. This is because players do not receive external benefits generated by the investments of other players, as they do in both the social planner's scenario and in the game with joint investments.

5.2. Optimal Paths of States and Controls

Further insight regarding the results can be gained from graphs of the optimal time paths for the state and control variables. In all graphs, we show the time path for only one of the two players in the game scenarios because we assume that the players are identical. The optimal paths of groundwater extraction are very similar in both of the game scenarios, and those paths lie above the optimal path for the social planner's model, through the first ten years (Figure 4). Groundwater pumping diminishes quickly beyond year 10 in the game scenarios, while it diminishes more slowly in the social planner's scenario. Groundwater is depleted by year 13 in the game scenarios, while depletion occurs in year 17 in the social planner's scenario. The time paths depicted in Figure 4 are consistent with expectations. Groundwater is depleted more quickly when players compete for the limited resource, than when a social planner chooses extraction rates to maximize the sum of net benefits.

Investments in knowledge begin in year 7 in the social planner's scenario and they continue through year 15 (Figure 5). Hence, it is socially optimal to begin investing in knowledge while groundwater is still available, and to stop investing just before the switch from groundwater to desalination is completed. When the players compete for groundwater, but they invest jointly in knowledge, investments do not begin until year 9 of the pertinent scenario, and they continue through year 17 (Figure 5). The sum of investments appears to be similar in the social planner's scenario and in the game scenario in which the players make joint investments. The nominal sum of investments also appears to be similar, although we have not yet computed the areas under the curves depicted in Figure 5. Investment begins much earlier in the scenario in which players compete for groundwater and they make investments independently. Investments are larger in at least two of the years in this scenario and investment ends at about the same time as in the other scenarios (Figure 5). Hence, the nominal sum of investments is largest in this scenario. One explanation for this result might be that when players compete for groundwater and they make investments independently, they must begin making investments earlier and they must invest a larger sum to achieve the desired reductions in the marginal cost of desalination. In addition, the players in this game do not receive external benefits generated by the investments of the other players, as they do in both the social planner's scenario and in the game with joint investments.

The optimal investment paths depicted in Figure 5 generate the optimal paths of knowledge accumulation shown in Figure 6. The optimal paths for all three scenarios begin rising about the path depicting the exogenous rate of increase in knowledge at some time between year 6 and year 11. The optimal paths for the social planner's model and the game in which player make independent investments decisions are very similar, while the path for the game in which players make joint investments in knowledge begins rising above the exogenous path at a later date. That delay is consistent with the delayed investments in knowledge in that scenario (Figure 5).

The switch from groundwater to desalinated water occurs more gradually in the social planner's scenario than in either of the game scenarios (Figure 7). The steady-state amount of desalination is the same in all scenarios, but that level is reached about six years later in the social planner's scenario than in the other scenarios. This result is consistent with the sharper decline in groundwater pumping in the game scenarios, as compared with the more gradual decline in the social planner's scenario (Figure 4).

Beyond year 17, desalination is the major source of water in all scenarios. The initial stock of groundwater has been depleted and the rate of annual recharge is quite small. The steady-state level of knowledge and desalination are the same in all scenarios, due largely to the constraint on the total amount of knowledge that can be achieved in all scenarios. That constraint causes the marginal cost of desalination to be the same in the steady-state solution for all scenarios. The benefit functions also are the same in all scenarios and, hence, the optimal amount of desalination is the same in the steady-state solutions.

The time paths of total water consumption (groundwater plus desalinated water) are very similar for all scenarios in the early years, when the players are extracting large amounts of groundwater (Figure 8). As groundwater is depleted, the marginal cost of pumping increases and players begin making investments in knowledge. Total water consumption declines until the players begin using desalinated water. Interestingly, the time path of total water consumption for the social planner's scenario lies below the time paths for the other scenarios until desalination reaches its optimal level. However, nominal annual net benefits are higher in the social planner's scenario, during the transition from groundwater to desalinated water, than in either of the game scenarios (Figure 9).

The time paths of annual net benefits for the three scenarios differ substantially during the period in which the transition is made from groundwater to desalinated water. The annual net benefits are similar during the early years of the scenarios, but they begin declining more sharply for the game with independent investments in about year 6 (Figure 9). The annual net benefits for both game scenarios are small than the net benefits in the social planner's scenario from year 10 through year 17. Annual net benefits are the same in all scenarios, once the steady-state solutions have been achieved. As expected, the present value sum of net benefits is highest in the social planner's scenario, given the number of years in which the annual net benefits exceed those in both of the game scenarios.

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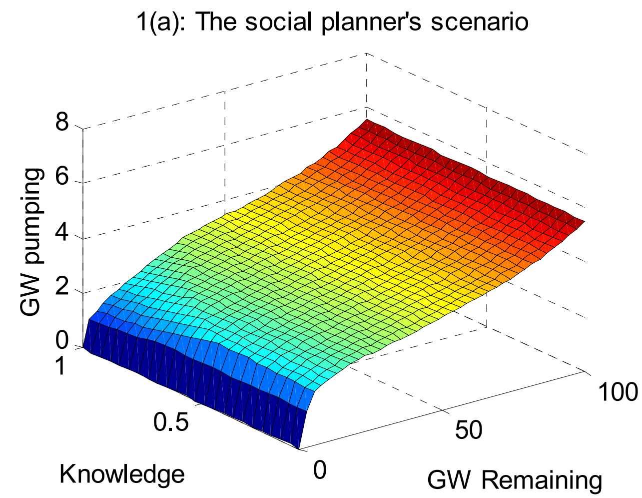
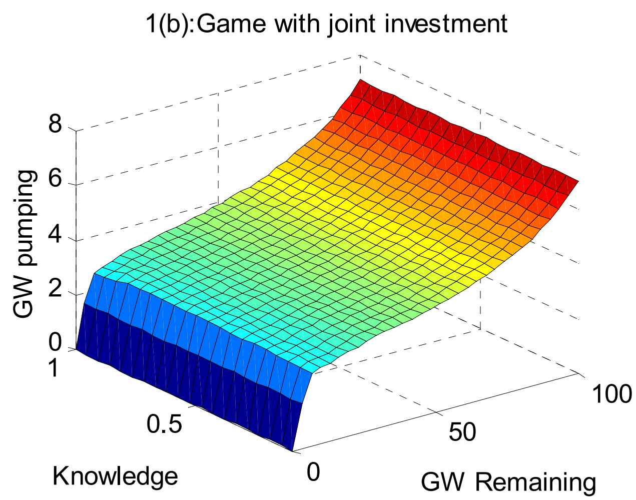
Figure 1.

Optimal annual groundwater Pumping,
as a function of groundwater remaining and
accumulated knowledge





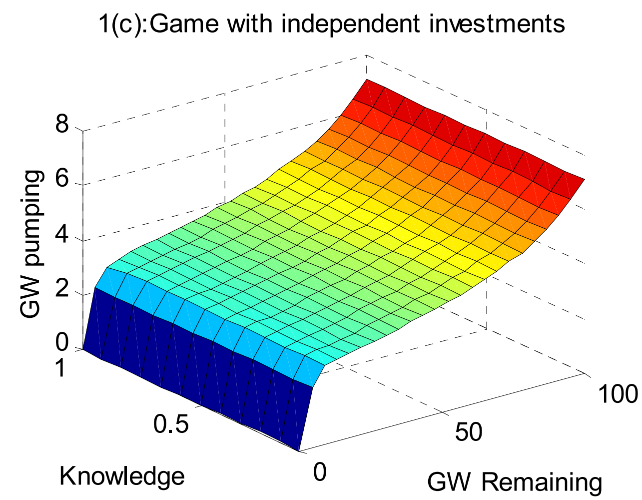
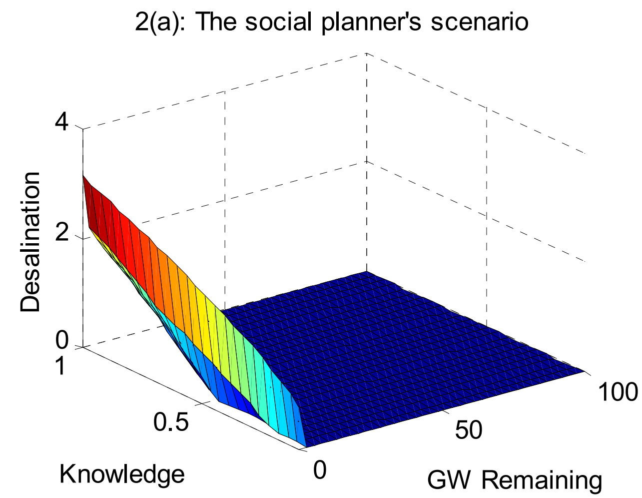
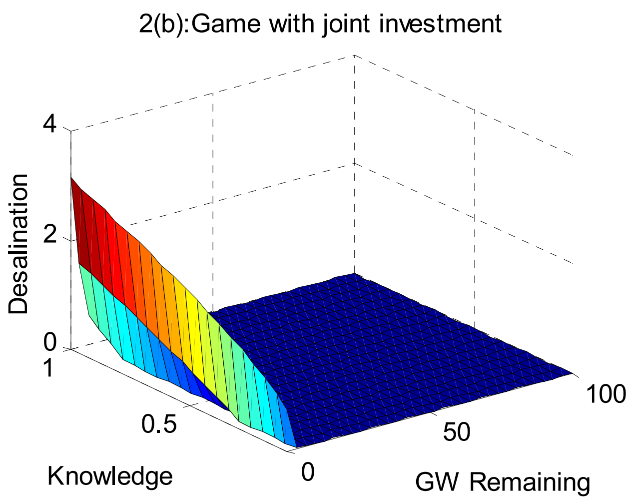


Figure 2.

Optimal annual desalination,
as a function of groundwater remaining and
accumulated knowledge





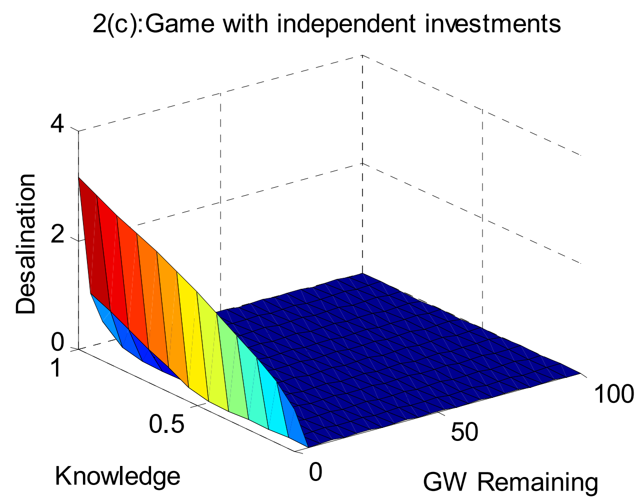


Figure 3.

Optimal investment,
as a function of groundwater remaining and accumulated knowledge

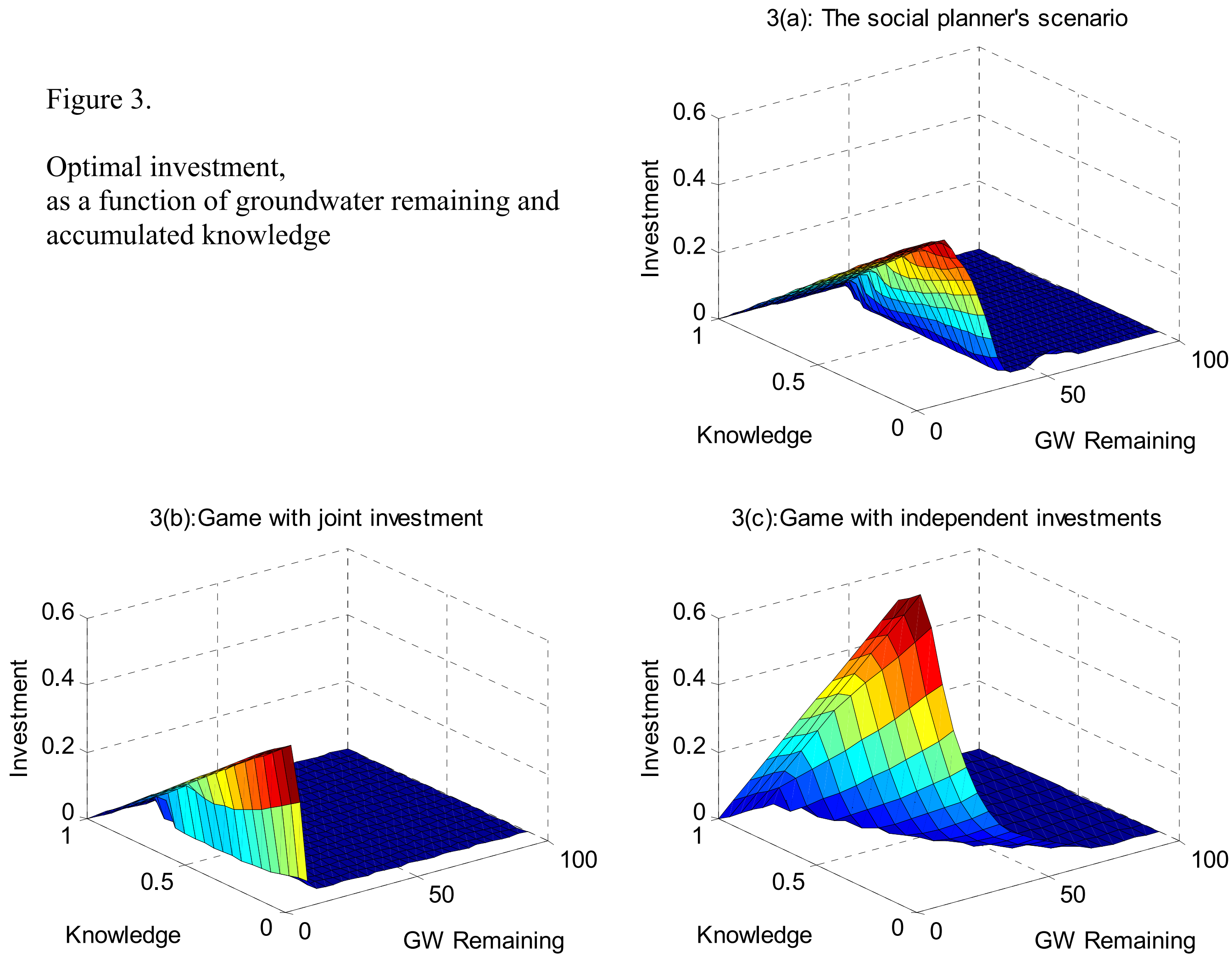


Figure 4. Optimal time paths of groundwater withfrawals

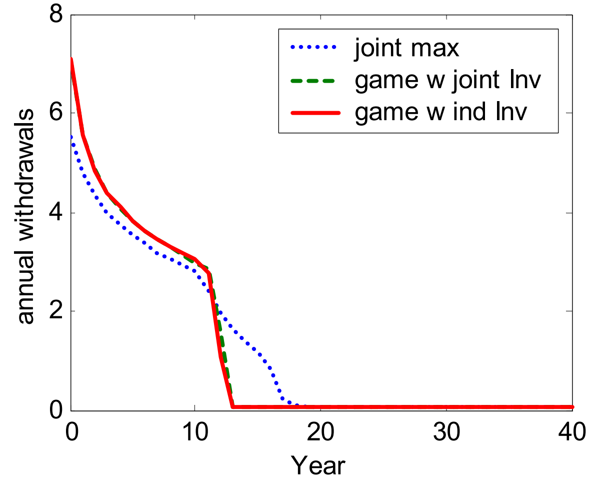


Figure 5. Optimal time paths of investments

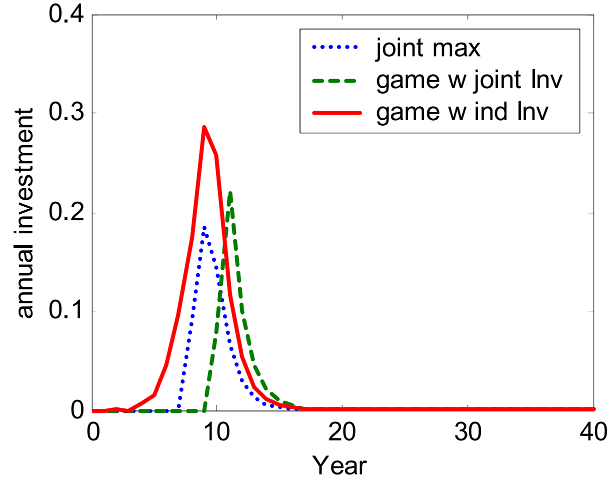


Figure 6. Optimal time paths of knowledge accumulation

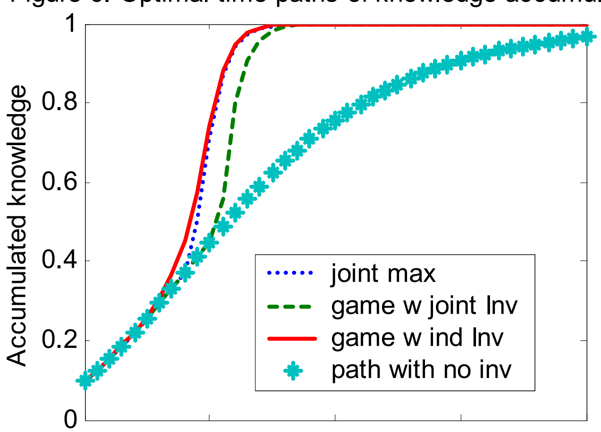


Figure 7: Optimal time paths of desalination

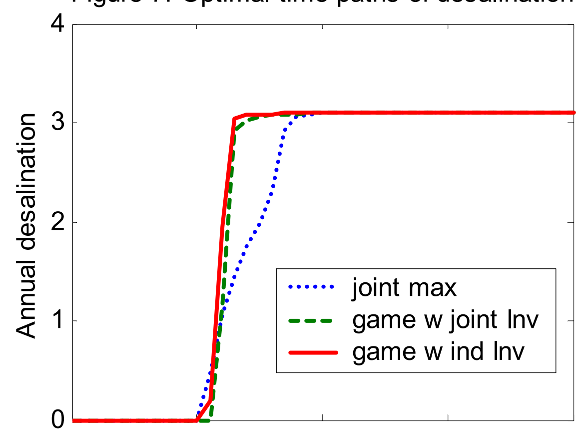


Figure 8. Optimal time paths of total water consumption

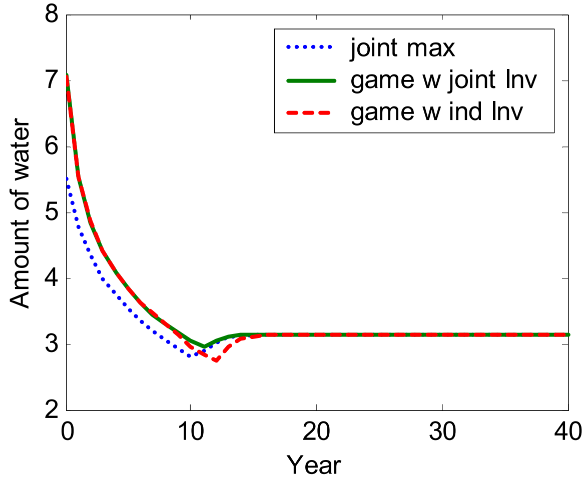


Figure 9. Optimal time paths of annual net benefits