Staff Paper

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RURAL WATER SUPPLY AND THE ECONOMIC COST OF GROUNDWATER CONTAMINATION: THE CASE OF NITRATES

Groundwater contamination is a significant threat to the water supply of rural communities. This paper develops a framework for estimating the economic damages due to water supply contamination. Applied to the case of groundwater contamination by nitrates, typical economic damages range $105 to $140 per household per year.

Rural Water Supply and the Economic Cost of Groundwater Contamination: The Case of Nitrates

Groundwater provides the primary water supply for 95 percent of rural households (Pye et al, 1983). Recent research suggests that a significant portion of this water supply may be subject to contamination (Nielson and Lee, 1986; Rajagopal and Talcott, 1983). In several areas of the nation, more than twenty-five percent of wells sampled fail to meet Federal drinking water standards (Nielson and Lee, 1986). Nitrate fertilizers and agricultural pesticides are potentially important contributors to this water supply contamination problem (ESCOP, 1985; Hallberg, 1987).

An informed response to groundwater contamination requires some knowledge of the relative benefits and costs of alternative policy responses. In this paper we develop a framework for estimating the economic damages of groundwater contamination when water treatment--removal of the contaminant from water used for human consumption--is chosen as the remedial policy response. The framework uses the concepts of water supply and demand to identify an appropriate economic damage measure.

Groundwater contamination is shown to increase the marginal cost of providing water that meets Federal standards. With a contamination induced increase in marginal costs, both the supplier and consumer of water lose economic surplus. This loss in economic surplus measures the economic damages experienced by a community due to groundwater contamination. Our measure of net damages would be added to ecological and existence values (Randall, 1987) to obtain an overall estimate of economic damages.

The paper is divided into three sections. The first section develops a conceptual framework for measuring the economic damages of groundwater contamination. The second section applies the framework to measuring the economic damages of nitrate contamination of groundwater. The third section reviews the estimated economic damages caused by nitrate contamination of a groundwater supply.

A Framework for Measuring the Economic Damages of Contamination

The framework developed for measuring residential damages is based on the economic concepts of demand and supply. Before a contamination event occurs, demand and supply of residential water determine initial water costs and water consumption benefits. After groundwater contamination occurs, additional water treatment is required and additional supply costs are incurred. These additional supply costs lead to an increase in water prices and a reduction in the net benefits of residential water consumption. This section shows how this loss in net benefits can be measured.

Residential Water Demand

Economic demand measures consumers' marginal willingness to pay for successive quantities of a good or service. A residential water demand function summarizes the relation between a community's willingness to pay for water and the successive quantities of water that the community is willing to purchase.

Residential water demand is a function of water, community, and climatic characteristics. This functional relation is

(1) p = f[water quantity consumed per household (c), water quality (q), average household income (y), precipitation (r)].

where p is the price that households are willing to pay for successive units of water and where $dp/dc<0$, $dp/dq>0$, $dp/dy>0$, and $dp/dr<0$.

Residential Water Supply

The economic supply of a good is the marginal cost of a good or service. A water supply function measures a water system's cost of providing successive quantities of water.

The marginal cost of providing water arises due to the resources used in the development, treatment, and delivery of potable water. A water supply function represents these costs as

(2) mc = g(water quantity consumed per household, input water quality, service area size, capital equipment prices, input prices)

where mc represent marginal costs. Marginal costs may either increase or decrease with the quantity of water provided to households. A decline in input water quality tends to increase marginal costs since additional treatment and processing are required in order to maintain a consistent output water quality. Marginal costs may either increase or decrease with the number of households within a service area. Marginal costs tend to increase with capital and input prices such as wages and energy prices.

The Economic Benefits of Water Consumption

The interaction of water demand and supply are basic forces that guide the provision of water within a community. Households are willing to pay for additional units of water as long as their demand price is not less than the market price. Over the long run, it pays a water system to increase the quantity of water supplied until the marginal cost of the last unit of water sold is equal to the market price. Water demand and supply tend to equilibrate at a point where the price that households are willing to pay equals the marginal cost of water supply.

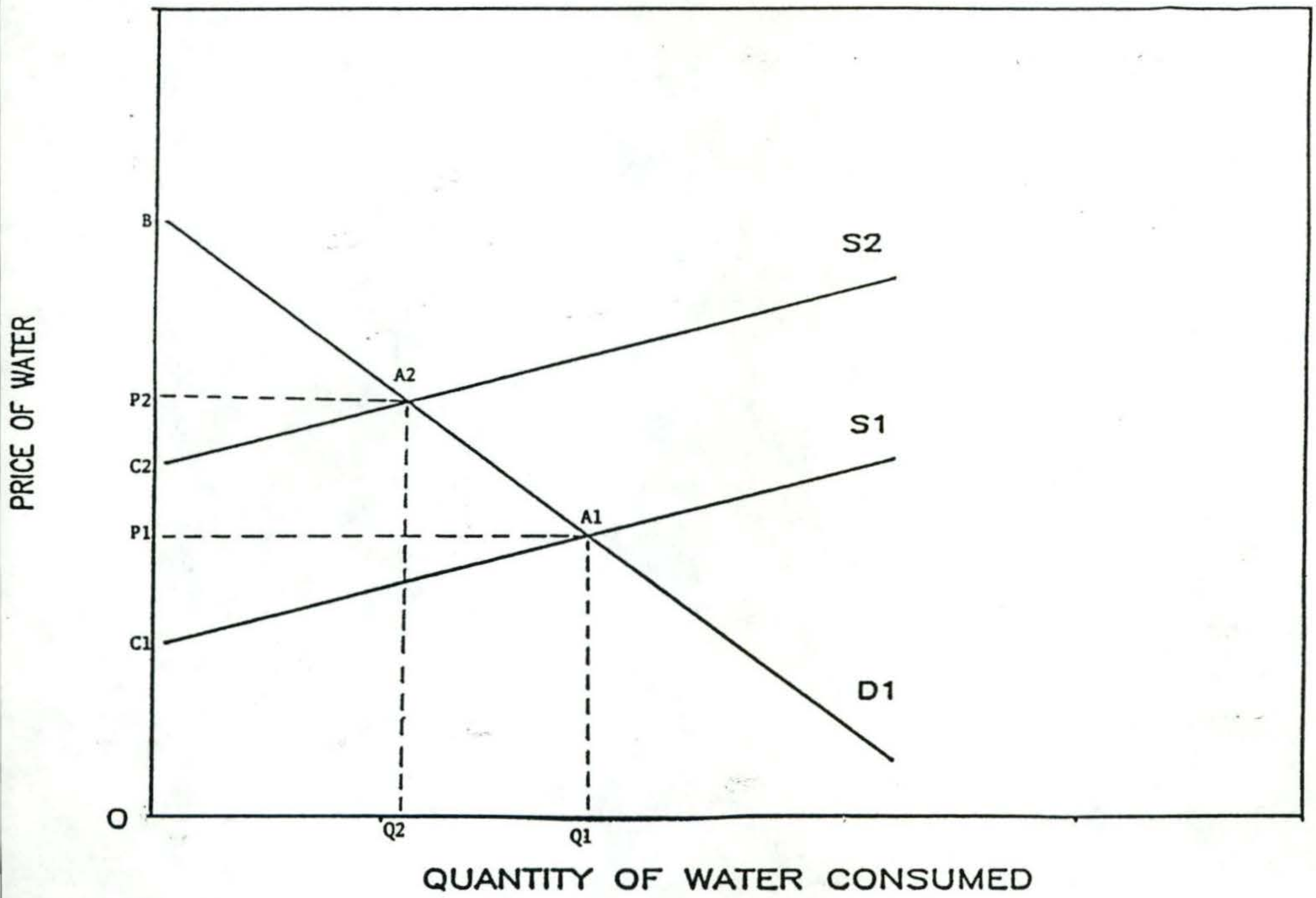
Figure 1 illustrates one possible price and quantity equilibrium. With the supply curve S1 and demand curve D1, demand price and marginal cost are equal at point A1. The economic benefit of a community water supply is the households' total willingness to pay for water quantity Q1 minus the total cost of supplying this quantity.1 This economic benefit is the area underneath the demand curve between points zero and Q1 minus the area underneath the supply curve between zero and Q1. Economic benefit is therefore the triangular area connecting points B, A1, and C1.

The Economic Damages of Groundwater Contamination

Public water systems that provide drinking water to households are required by law to maintain nitrate concentrations below ten milligrams per liter (mgl) of water (CFR, 1985). If nitrate concentrations in groundwater rise above ten mgl, the system must either find a source of uncontaminated water or add on additional treatment facilities to remove the contaminant before water is actually distributed to households. Either action increases the system's marginal costs.

FIGURE 1

BENEFITS OF WATER CONSUMPTION



The contamination induced increase in marginal costs reduces the economic benefit of water consumption. Where contaminants are removed by treatment, this reduction in benefits represents the economic damages imposed on residential users by groundwater contamination.

Figure 1 illustrates economic damages for a representative case of groundwater contamination. As discussed above, the initial economic benefit of the community water system is the area of triangle BA1C1.

After contamination occurs, the marginal cost of providing water shifts upward from S1 to S2. After contamination, the marginal cost of providing Q1 units of water is greater than households' marginal willingness to pay for Q1. Given marginal costs S2, households are willing to purchase no more than water quantity Q2. After the contamination event the system provides quantity Q2 and households pay a price of P2 dollars per unit of water. Due to the increase in marginal costs, water quantity consumed is lower and the water price is higher after contamination occurs.

The economic benefit of water consumption after the contamination event is the difference between households' total willingness to pay for water quantity Q2 minus the total cost of providing this quantity. Therefore, after the contamination event, the economic benefit of consumption is the triangular area connecting points B, A2, and C2.

The economic damage caused by groundwater contamination is the difference between the economic benefits of water consumption before and after the contamination event. This difference, the economic damage due to contamination, is the quadrilateral area connecting points A2, A1, C1, and C2.

Measuring the Economic Damages Due to Nitrate Contamination

This section uses the general damage framework to develop an empirical model for estimating the economic damages of groundwater contamination by nitrates. The model is based upon the assumption that nitrates are removed from the water supplied to households using a centralized, ion exchange treatment facility (see Gumerman et al, 1984).

There are three functions that are necessary for applying the damage estimation framework: a residential water demand function, a pre-contamination supply function, and a post-contamination supply function. Once these functions are identified, they are combined in a manner analogous to Figure 1 to create a economic damage simulator for nitrates.

A Water Demand Function

There have been at least fifteen different studies of residential water demand in the United States during the last twenty years. All but three of these studies are specific to particular cities or regions. Of the three national studies, only a study by Foster and Beattie (1979) allows adjustments for regional variations in water demand.

The form of the Foster and Beattie (FB) demand estimate parallels equation (1). However, the FB demand function also includes several zero-one shift variables to account for regional differences in demand that are not explained by the four independent variables in equation (1). These regional adjustments result in a single demand function that compares very favorably with the estimates obtained in twelve regional demand studies (Libby et al, 1986). Since it accurately represents many different regions, the FB estimates are used to represent residential water demand in the empirical model of economic damages.

Pre-Contamination Water Supply

The pre-contamination water supply function represents the marginal cost of providing water before contamination occurs. Pre-contamination marginal cost is assumed to be constant in both per household water consumption and and service area size. Capital and input prices are assumed to be constant. Under these assumptions, the pre-contamination supply function is

$$S1 = b \tag{3}$$

where b is a constant. In implementing the model of economic damages, b represents the initial equilibrium price of water. This initial price may be different for different water systems.

Post-Contamination Water Supply

The post-contamination water supply function represents the marginal cost of providing water after nitrate contamination of groundwater occurs. Analytically, post-contamination marginal cost is the sum of two quantities: (1) pre-contamination marginal cost and (2) the additional marginal cost of removing excess nitrates.

A centralized ion exchange system is used in estimating the additional costs of removing excess nitrates. With centralized treatment all water delivered to households is treated at a central processing facility to remove nitrates. With centralized removal of nitrates, post-contamination marginal costs are

$$(5) \qquad S2 = S1 + mc_C$$

where mc_C represents the marginal costs of centralized treatment. Marginal costs for centralized systems were estimated using an engineering model developed by the U.S. Environmental Protection Agency (Gumerman et al, 1984).

An Economic Damage Simulator

To estimate economic damages with centralized treatment, a computerized simulation algorithm was developed to carry out the calculations implied by Figure 1 and the general damage estimation framework. To produce a set of damage estimates using the simulator, one first describes a set of baseline conditions. Baseline conditions allow for six community-specific characteristics; nitrate concentration in the system intake water, average household income of the population served by the water system, the water system's service area size, initial water price, annual precipitation, and annual evaporation.

Given the baseline data, the simulator computes economic damages in a five step process. The damage simulator 1) Finds the initial quantity of water consumed by the community, 2) Computes initial economic benefits for the water system, 3) Finds the price and quantity of water consumed after the contamination induced shift in the water supply function from S1 to S2, 4) Computes post-contamination economic benefits and 5) Computes economic damages as the difference between economic benefits before contamination and economic benefits after contamination.

Economic Damage Estimates

The research developed two alternative ways to generate economic damage estimates when centralized treatment is used to remove nitrates. The first approach is to use the damage simulator directly. With this approach, a set of baseline conditions are entered into a computer program and damage estimates are produced within seconds. The second approach uses a summary damage equation. This summary damage equation was derived by running a large number of treatment scenarios through the damage simulator and then using statistical methods to estimate the algebraic relation between the baseline conditions and the resulting damage estimates. Use of the summary equation is slightly less accurate than the cost simulator but it requires only a pocket calculator to produce an initial set of damage estimates.

To illustrate results, the damage simulator was set up to estimate the economic damages associated with a contamination event that requires the removal of ten milligrams of nitrate per liter. It was assumed that contamination results in an intake concentration of fifteen milligrams (mg) per liter and the system management invests in equipment to bring the output water quality down to five mg of nitrate per liter. Five mg per liter allows a margin of safety below the Federal standard of ten mg per liter.

Other baseline conditions included the following. The initial water price was set at one dollar per thousand gallons. Average annual household income in the community was $14,000. The number of households served by the water system was 1,000. Annual precipitation was 20 inches and annual evaporation was 15 inches.

Table 1 reviews the output of the economic damage simulator. After contamination occurs, the price of water within the community doubles from one dollar to two dollars per thousand gallons of water. Given the increase in water prices, average household water consumption drops from 135 gallons per day (gpd) to 112 gpd.

Annual economic benefits of water consumption are initially $275 per household but drop to only $175 per household after contamination. Nitrate contamination of groundwater at a concentration of fifteen mg per liter therefore imposes an annual economic damage of $100 per household or $100,000 across the community as a whole.

A change in baseline conditions changes the level of economic damages. To illustrate this, the damage simulator was run for two communities. The first community had an average household income of $15,000 per year and the second an average income of $35,000 per year. In each community, the initial water price was assumed to be two dollars per thousand gallons, the number of households serviced was 500, annual precipitation was 20 inches, and annual evaporation was 15 inches. Both communities remove ten mg of nitrate per liter from the system intake water.

Table 2 gives results for both communities. Though initial prices are the same in both communities, the higher income community consumes more water. Subsequent to contamination, the increase in water price in the higher income community is fifty percent larger than in the lower income community. The larger price increase causes higher income households to cut back on water

Table 1. Annual Economic Damages Due to Nitrate Contamination

Variable	Initial Situation	10 MGL Removed
Price of Water ($/1000 gallons)	1.00	2.00
Household Water Consumption (gpd)	135	112
Annual Economic Benefits ($/hsld)	275	175
Annual Economic Damages ($/hsld)	–	100

Table 2. Annual Economic Damages Due to Nitrate Contamination by Income

Variable	Income = $15,000		Income = $35,000	
	Initial	Post-Event	Initial	Post-Event
Price of Water	$2.0	$3.4	$2.0	$3.6
Water Consumption (gpd)	110	85	180	150
Annual Benefits / Hsld	225	120	370	230
Annual Damages / Hsld	–	105	–	140

consumption by thirty gallons per day. The lower income community cuts back on water consumption by twenty-five gallons per day.

Both the benefits of water consumption as well as the damages of groundwater contamination are larger in the higher income community than in the lower income community. This is apparently due to greater water consumption in the higher income community. Annual economic damages per household ranged from \$105 to \$140 depending on the income level of the community.

The effect of baseline conditions is clearly evident in the structure of the summary damage equation.[2] The summary damage equation is

$$\ln ED = 3.5 + .118\ln(\text{Nitrate Concentration}) - .152\ln(\text{Initial Price})^{*} + .383\ln(\text{Average Household Income}) - .340\ln(\text{Service Area Size}) - .016\ln(\text{Precipitation}) - .092\ln(\text{Evaporation}) \quad (6)$$

where ED is economic damages sustained per household. The positive signs on nitrate concentration and average household income indicate that economic damages increase with increases in either of these variables. The negative signs on initial price, service area size, precipitation, and evaporation indicate that economic damages decrease with increases in these variables.

Conclusions

This paper has described a framework for estimating the economic damages of groundwater contamination. This study is different from most studies concerning contamination events in that it estimates not the simple costs of increased treatment but the economic costs which are the surplus losses. The water cost simulator is unique in that it used an engineering water treatment

* Price in dollars per thousand cubic feet.

model to estimate the post-contamination supply function. Using the supply functions with the Foster and Beattie demand function, the simulator can estimate the economic damages that result from equilibrium changes when treatment costs increase due to a contamination event.

Endnotes

1. We measure willingness to pay in terms of a Marshallian surplus. Willig shows that Marshallian surplus provides a very close approximation to either the Hicksian compensating or Hicksian equivalent measures of welfare change.

2. The summary damage equation was derived to fit the following conditions: nitrate concentrations ranging from zero to 100 mg per liter; services areas of up to 5000 households; evaporation rates from 5 to 100 inches per year. Dollar terms are at the 1983 price level.

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