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ESTIMATING THE ECONOMIC DAMAGES OF GROUNDWATER CONTAMINATION BY NITRATE

By

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ABSTRACT

ESTIMATING THE ECONOMIC DAMAGES OF GROUNDWATER CONTAMINATION BY NITRATE

By

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Groundwater is an important source of high quality, low cost water for residential water systems. In the United States, fifty percent of the water used for residential purposes is obtained from groundwater.

Contamination of groundwater by chemicals is of increasing concern. Agriculture fertilizer is part of the problem, with nitrate commonly being found in many rural groundwater supplies.

This thesis estimates the economic damages imposed on residential users of groundwater due to the treatment cost of returning nitrate contaminated water to its former state. The damage estimation framework is based upon the economic concepts of water demand and supply. Previous research and engineering data are used to empirically implement the framework in the form of a computerized economic damage simulator. The simulator is applied to estimating the economic damages of groundwater contamination by nitrate.

Nitrate removal imposes an annual net surplus loss ranging from $67 to $169 per household.

I dedicate this thesis to my Dad and Mom, to my wonderful wife Hirae whose love and support helped me in so many ways, and to my Lord and Savior Jesus.

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I greatly appreciate all the help that my advisor, Dr. John Hoehn provided. His advice was valuable beyond measure. I also appreciate the helpful comments of Dr. Allan Schmid and Dr. Milton Steinmuller.

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Nitrate Contamination of Groundwater and Public Policy

Introduction

Groundwater provides an important source of high quality, low cost water in many regions of the United States. In Michigan, approximately 15 billion gallons of water are withdrawn from all water sources per day. Approximately four percent of the total or 530 million gallons of groundwater is withdrawn each day in Michigan. However, 28 percent of Michigan's households rely entirely on groundwater for residential water uses and 100 percent of the water used by inland public water systems in Michigan is groundwater (Libby et al, 1986).

Nitrate contamination of groundwater appears to be an increasingly common public health problem. Routine ingestion of water containing more than 10 milligrams per liter (mgl) may cause methemoglobinemia, a condition that impairs the oxygen carrying capacity of blood (National Academy of Sciences, 1981). Infants are particularly sensitive to methemoglobinemia. Due to the health threats of water-borne nitrates, Federal regulations require public water systems to maintain nitrate levels below 10 mgl (Code of Federal Regulations, 1985).

In several parts of the country, raw groundwater does not meet the maximum contaminant level (mcl) posed by Federal regulations. In irrigated regions of Arizona and

Illinois, 112 mgl of nitrate is common in well water. In Iowa, 16 to 20 percent of private drinking water wells exceed the Federal mcl for public systems (Rajagopal and Carmack, 1983). In southern Michigan, a 1984 survey revealed that 34 percent of 191 rural drinking water wells tested exceeded 10 mgl (Vitosh, 1985).

There are several ways for dealing with the problem of nitrate contamination of drinking water supplies. First, the source of contamination may be controlled or eliminated. Second, an alternative source of water may be sought out or a well may be relocated. Third, chemical processes may be used to remove nitrates from groundwater withdrawals that are used for drinking water (EPA, 1983).

The choice of a strategy for dealing with nitrate contamination of drinking water depends in part upon the relative economic benefits and costs associated with the alternative approaches. The objective of this thesis is to take a first step toward estimating the benefits and costs of alternative policy instruments. Specifically, this thesis examines the benefits and costs associated with a single treatment option: the removal of nitrates by a public water system through the use of a central processing facility. Measured appropriately, these treatment cost estimates help to quantify one dimension of the economic damages associated with nitrate contamination. The economic damages of groundwater contamination is estimated while holding the output water quality constant. This implies that demand for residential water supplies is not directly affected by changes in the quality of input water supplies.

Nitrate Contamination of Water Supplies

Nitrate is a negatively charged particle. Each particle consists of one molecule of nitrogen and three molecules of oxygen. Nitrates occur naturally in the environment and can be introduced into the environment via human activities. Nitrates can occur in rainfall, for instance, when nitrogen oxides from automobile exhaust combine with moisture in the air to produce what is commonly called acid precipitation. Nitrate contamination of surface or groundwater may also occur from sources of contamination such as sewage disposal into rivers, surface lagoons, septic tanks, or cesspools (Meints and Vitosh, 1986). Agricultural fertilizers are an important source of nitrates in rural areas (Meints and Vitosh, 1986).

Several factors influence the concentration of nitrates in groundwater. The first factor includes the transformations of nitrogen which take place in the soil profile (Bailey and Swank, 1983). Second, soil characteristics and aquifer depth affect the quantity of nitrates that reach groundwater (Rajagopal and Carmack, 1983). Third, the geohydrological attributes of the aquifer affect the nitrate concentrations in groundwater. Relevant geohydrological attributes include the volume of the aquifer and the recharge rate to the aquifer (Sharefkin et al, 1984). Finally, the quantity of organic nitrogen released into the environment plays a key role in affecting the nitrate concentrations in water supplies (Vitosh, 1985).

Nitrates are being detected in groundwater across the United States. In parts of California, well water contains high levels of nitrate (Resource Losses, 1980). At McFarland, California, the McFarland Mutual Water Company installed an anion exchange system to remove nitrates from their well water since the contamination level exceeded the maximum contaminant levels (Lauch and Guter, 1984). Also, in the city of Redlands, California, the wells of the public water supply had nitrate levels of 18 and 30 milligrams per liter respectively, due to nitrogen fertilizer (Resource Losses, 1980). In Texas and Kansas, surveys show that 60 rural Texas and Kansas municipal water supplies exceed the Federal mcl as do many rural Texas domestic water supplies (Hartman, 1982).

Nitrate contamination in groundwater has been documented in a number of Midwestern states. In southern Illinois, farm supply wells had a median nitrate concentration of 145 mgl (Mirvish, 1983). Levels of nitrate exceeding 33 mgl occured in more than 25 percent of tested well water samples in Missouri and Wisconsin (Mirvish, 1983). It appears that in South Dakota, 30 percent of domestic wells have nitrate levels above 10 mgl (Meyer, 1986). In Kansas and Nebraska, 41 and 22 community drinking water supplies respectively, exceeded the mcl (Rajagopal and Carmack, 1983).

Parts of Michigan are also experiencing nitrate contamination of water supplies. For example, 22 percent of rural drinking water wells in the eight southern townships of Van Buren county exceeded the maximum contaminant level (D'Itri et al, 1983). Also, approximately 11 percent of 1,212 water wells sampled at the Old Mission Peninsula of Michigan exceeded the mcl (Ellis, 1982).

Regulation and the Public Health Impacts of Nitrate

According to Federal Regulations, the maximum allowable contaminant level (mcl) for nitrates in publicly supplied drinking water is 10 milligrams per liter (Code of Federal Regulations, 1985). The mcl for nitrate is applicable to community and noncommunity water systems, both of which are considered public water systems. A community water system is that which serves at least 15 service connections used by year-round residents or regularly serves at least 25 year-round residents. A noncommunity water system means a public water system which is not a community water system (Code of Federal Regulations, 1985).

At the discretion of the state, nitrate levels not to exceed 20 mgl may be allowed in a noncommunity water system if the supplier of water demonstrates to the satisfaction of the state that: (1) such water will not be available to children under six months of age; (2) that there will be

continuous posting of the fact that nitrate levels exceed 10 mgl and the potential health effects of exposure;
(3) that local and State public health authorities will be notified annually of nitrate levels that exceed 10 mgl; and
(4) no adverse health effects shall result (Code of Federal Regulations, 1985).

The health impacts of ingesting well water that is contaminated with nitrates are not entirely clear. Nevertheless, nitrate ingestion has been associated with a disease called methemoglobinemia. In addition, some research suggests that nitrates may play a role in the development of cancers (National Academy of the Sciences, 1981).

Methemoglobinemia, also known as the blue baby syndrome, is caused by decreased oxygen in circulating blood (National Academy of the Sciences, 1981). Infants are at greatest risk of developing methemoglobinemia from excessive intake of nitrate (National Academy of Sciences, 1981). This risk is due to a number of physiological factors. Several other categories of individuals with altered physiological states or with hereditary or acquired diseases may also be predisposed to the development of nitrite or nitrate induced methemoglobinemia. Pregnant women are included in the high risk group (National Academy of the Sciences, 1981).

Mild cases of methemoglobinemia can be treated with oral doses of ascorbic acid (Vitamin C). In extreme cases, injection of methylene blue quickly reverses the methemoglobinemia (National Academy of the Sciences, 1981).

There were approximately 2,000 documented cases of methemoglobinemia in the United States and Europe between 1945 and 1971 (National Academy of the Sciences, 1981). In the United States, from 1939 to 1950, there were reports of approximately 320 cases of methemoglobinemia in infants who ingested nitrate rich well water (National Academy of the Sciences, 1981). From 1956 to 1986, 80 cases of methemoglobinemia were reported in the counties of the Big Sioux River Basin of eastern South Dakota (Meyer, 1986). In June of 1986, methemoglobinemia was suspected in the death of a 2 month-old girl (Meyer, 1986). According to Michael Meyer of the Office of Water Quality, South Dakota Department of Natural Resources: "Methemoglobinemia appears to be poorly reported and many cases probably occur which are not documented and the widespread nitrate contamination of a significant percent of the nation's domestic wells continues to make methemoglobinemia a very real health hazard" (Meyer, 1986).

Water borne nitrates have not been established as being carcinogens in laboratory testing. Nevertheless, nitrate ingestion has been associated with the development of gastric cancer in a number of epidemiological and associated studies (Hartman, 1983). Some studies have shown geographic correlations of stomach cancer incidence with nitrate content of drinking water (National Academy of the Sciences, 1981). A study in England found a positive correlation between stomach cancer mortality rates and the nitrate content of drinking water (National Academy of the Sciences, 1981). Further research is needed to establish a link between ingestion of nitrate and development of certain cancers (National Academy of the Sciences, 1981).

An important area of research would be to determine the health effects of long-term ingestion of small amounts of nitrates. Researchers in this area admit that the long-range impact of persistent methemoglobinemia on human health, if any, remains relatively unstudied (Hartman, 1982). Consistently decreased levels of oxygen in the blood during infancy may cause reduced mental capabalities. Mental retardation has been observed in only some cases of clinical congenital methemoglobinemia, but even these are not well understood (Hartman, 1982). Hartman, 1982, states: "Therefore, no extrapolation can be made to the much more prevalent instances of subclinical but significantly elevated methemoglobin content, and minor effects on mental health could be easily missed."

Strategies for Reducing Nitrate Levels in Drinking Water Supplies

Three general approaches are possible in dealing with groundwater contaminated by nitrates. First, the pollutant source may be controlled. Second, alternative sources of water may be substituted for the contaminated wells. Third, chemical processes may be used to remove nitrates from that portion of the groundwater withdrawn for drinking water purposes. Selection of a strategy for dealing with groundwater contamination depends upon the hydrological characteristics of an aquifer, political feasibility, and the economic benefits and costs of alternative approaches.

Methods for pollutant control involve local and state governments choosing among alternative regulatory actions. One possible pollutant control include land zoning, which could be used to restrict land uses that contribute to contamination of groundwater. Another pollutant control involves the protection of various quality features of groundwater such as protecting sensitive groundwater recharge areas (Libby et al, 1986).

Nontreatment methods substitute alternative sources of water for at least a portion of the contaminated water. For instance, in many cases, nitrate contamination decreases with the depth of an aquifer (Rajagopal and Carmack, 1983) and a user group may be able to find an uncontaminated source by simply drilling deeper. In some areas, however, nitrate levels may actually increase with well depth (Lauch and Guter, 1984).

Additional nontreatment options include the development of a new field in a different location or the importing of water from a different locale. In either case, water of high and lower nitrate concentrations may be blended to achieve an overall supply of water that meets public health standards. The cost and feasibility of such nontreatment approaches are likely to be highly specific to the water resource endowment of a particular locality.

Treatment options use chemical or physical processes to remove nitrate contamination from water withdrawn from an aquifer. Treatment systems may be either point-of-use systems or central processing systems.

Point-of-use treatment, also referred to as a decentralized system, is treatment that occurs at the individual household. Conversely, centralized treatment is performed on a larger scale at a single location. The advantage of point-of-use treatment over centralized treatment include (1) small capital investment relative to centralized treatment and (2) a smaller volume of water to be treated, since only water used for drinking and food preparation is treated. The disadvantages of point-of-use are (1) high operation and maintenance costs relative to a centralized system, (2) potential difficulties in servicing point-of-use systems, and (3) inability to allow for process optimization (Gumerman et al, 1984).

This study examines the costs associated with centralized treatment and removal of nitrates. Currently, there are available two types of centralized treatment system that may used to remove nitrates from drinking water. One system is an anion exchange treatment system that selectively removes nitrate ions from water. Anion exchange systems use equipment and technologies similar to those used for home water softeners. The other treatment system is a reverse osmosis system that uses semipermeable membranes to remove pollutants. Reverse osmosis systems presently are not being used by public water systems for removing nitrates due to its prohibitive costs of use (EPA, 1983).

Measuring the effects of treatment costs is important. It allows one to estimate the impact that contamination of drinking water supplies has upon the public. The costs and benefits of treatment can be compared to other policy options such as pollutant control methods. Estimation of treatment costs also allows one to measure the distributional impacts of contamination across different groups.

Objectives

The goal of this thesis is to estimate the economic damages sustained by consumers and producers when treatment costs increase due to the contamination of drinking water supplies by nitrate. Economic damages are estimated by the loss in consumer surplus and producer surplus. These damages are incurred due to the increase in treatment costs associated with the removal of nitrates by a centralized anion exchange system.

To accomplish the above task, the objective of Chapter II is to develop a conceptual framework which can be used to to measure the surplus losses due to removing contaminants from drinking water supplies. This framework is based on the economic concepts of water demand and supply.

The objective of Chapter III is to use the conceptual framework of Chapter II to develop an empirical cost simulator for small scale public water systems. This cost simulator is composed of aggregate residential water demand and supply curves. A pre-contamination and post-contamination water demand and supply equilibrium is estimated. A change in the equilibrium due to increased treatment costs results in consumer and producer surplus losses. These surplus losses measure the economic damages of groundwater contamination.

The objective of Chapter IV is to discuss the empirical results obtained using the water cost simulator. These results include estimates of the economic damages associated with various levels of nitrate contamination in drinking water supplies.

Finally, Chapter V provides research and policy implications concerning the water cost model and its results. Contamination of drinking water supplies can impose large surplus losses, depending on certain baseline conditions such as concentration of nitrates in the water supply and the number of households served by the public water system.

Chapter II

Conceptual Framework for Estimating the Costs of Drinking Water Contamination

Introduction

In this Chapter, a conceptual framework is developed to identify the economic damages associated with the contamination of drinking water supplies. Economic damages are measured by the loss in consumer and producer surplus after a contamination event occurs. The sum of consumer and producer surplus is referred to as net surplus. Economists use these surplus concepts to estimate the change in well-being associated with an environmental or policy change.

The Chapter begins by describing the demand for and supply of residential water. The quantity of water purchased by households and the cost or price of providing this water are shown to depend on both demand and supply conditions. Generally, one expects there to be a single price at which the quantity that consumers are willing to purchase is equal to the quantity that a supplier is willing to provide. This price and quantity combination is known as an economic or market equilibrium. The equilibrium concept is used to show how net surplus changes with the rate of nitrate contamination.

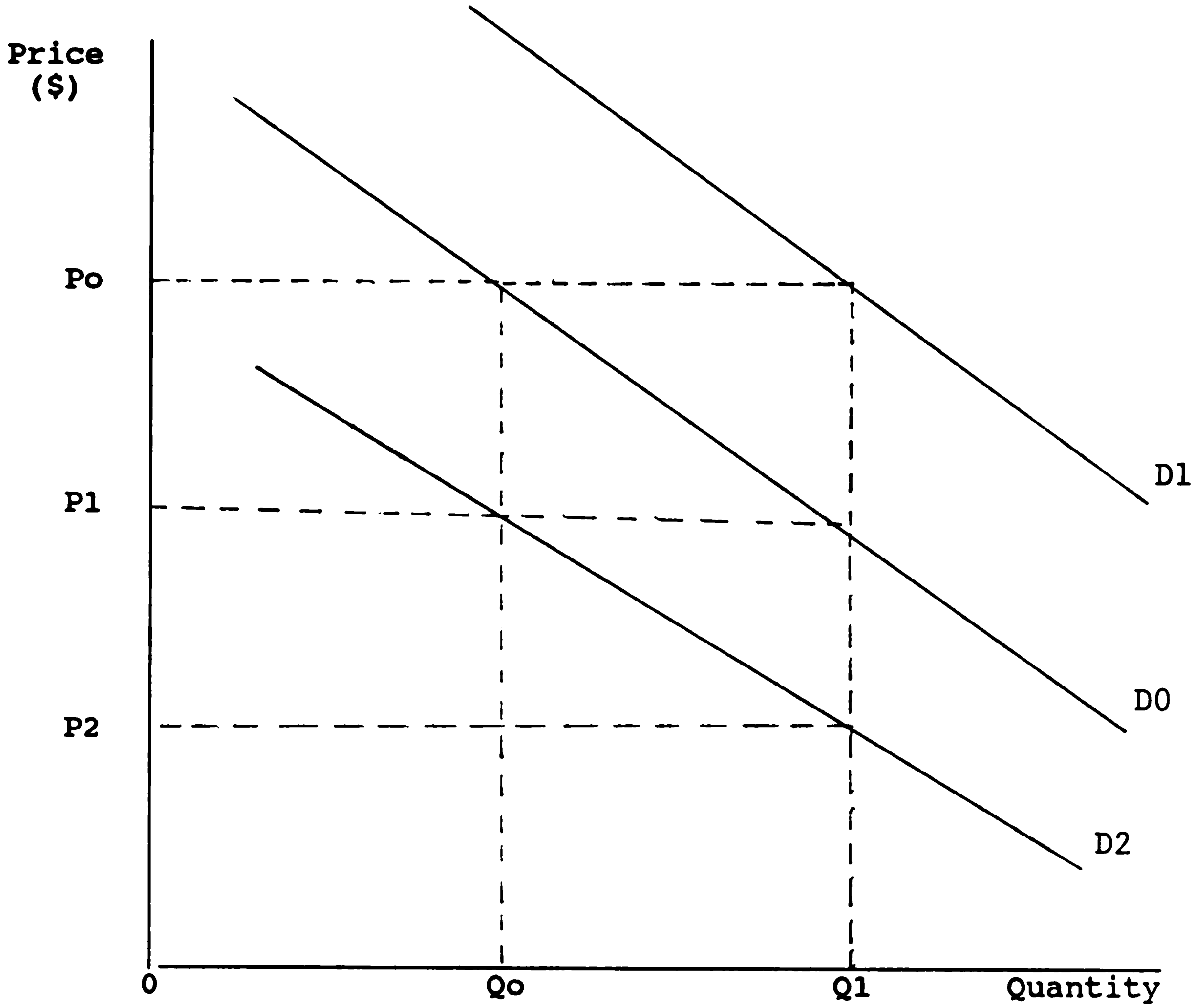
The Demand for Residential Water

Economic demand measures a consumer's marginal willingness to pay for a good or service. Demand is a relationship between an individual's willingness to pay and quantities that an individual is willing to purchase and consume. Economists expect an inverse relationship between willingness to pay and the quantity that an individual purchases: as an individual purchases and uses a larger quantity of a good, his/her marginal willingness to pay declines. For instance, in the case of water, a consumer may be willing to pay a great deal for the first few quarts of water. These first few units of water are essential for biological survival. As greater quantities of water become available, water is used in successively lower valued uses such as washing, waste disposal, and garden and lawn irrigation. These latter uses of water have a lower value than biological survival. Thus, the typical water demand curves slopes downward.

A representative demand curve is shown in Figure 2-1. Dollars are represented on the vertical axis and water quantities are represented on the horizontal axis. The water demand curve slopes downward due to the decreasing marginal willingness to pay for greater quantities of water. For example, the demand curve Do shows that a consumer would be willing to pay Po for a quantity Qo. However, for the larger quantity Q1, consumers are willing to pay only P1 for the marginal unit of water.

Figure 2-1

Demand for Residential Water



Several factors may cause the consumer's water demand curve to shift to the right or left in the price quantity space. These factors include income, rainfall, water quality, and population (Morgan and Smolen, 1976, Howe and Linaweaver, 1967, Gardner and Schick, 1964, and Foster and Beattie, 1979).

Higher income households are more likely to engage in more water using activities than low income households. These activities may include using dishwashers and washing machines, washing automobiles, irrigating lawns and gardens, and filling of swimming pools. Given these likely activities, an increase in household income is likely to be associated with an increase in water use. This increase in use would shift a household's demand curve to the right. In Figure 2-1, this rightward shift is illustrated as the movement from Do to D1. Initially, at demand Do, a household was willing to pay P1 for quantity Q1 of water. With an increase in income the demand curve shifts rightward to D1 and the household is now willing to pay Po for a quantity Q1. The rightward shift in demand represents an increase in value of water.

Demand for water is likely to be inversely related to precipitation. An increase in precipitation is likely to result in a reduction of water use activities such as lawn and garden irrigation. As illustrated in Figure 2-1, increased precipitation would shift water demand to the left from Do to D2. The leftward shift of the demand curve to D2 results in a new willingness to pay for water. At quantity Q1, marginal willingness to pay falls from P1 to P2. Therefore, the value of water decreases with a leftward shift of the demand curve.

A change in water quality may increase or decrease the demand for water. There is no available study of water demand as a function of quality, therefore, uncertainty prevails as to the effect of water quality on water demand. Nevertheless, it should be expected that a decrease in water quality would decrease the demand for water.

Population is also included as a shift parameter of water demand curves. The overall market demand for water is the sum of individual household demands. Thus, an increase in population increases the demand for water. In Figure 2-1, an increase in population would shift the demand curve from Do to D1.

A change in the price of water does not cause a shift of the demand curve but a movement of demand along the demand curve. Using the demand curve Do, an increase in market price from P1 to Po decreases the quantity of water that households are willing to purchase from Q1 to Qo.

The demand relation for the quantity of water purchased, D is:

(2-1) $D = D(Y,H,R,P)$

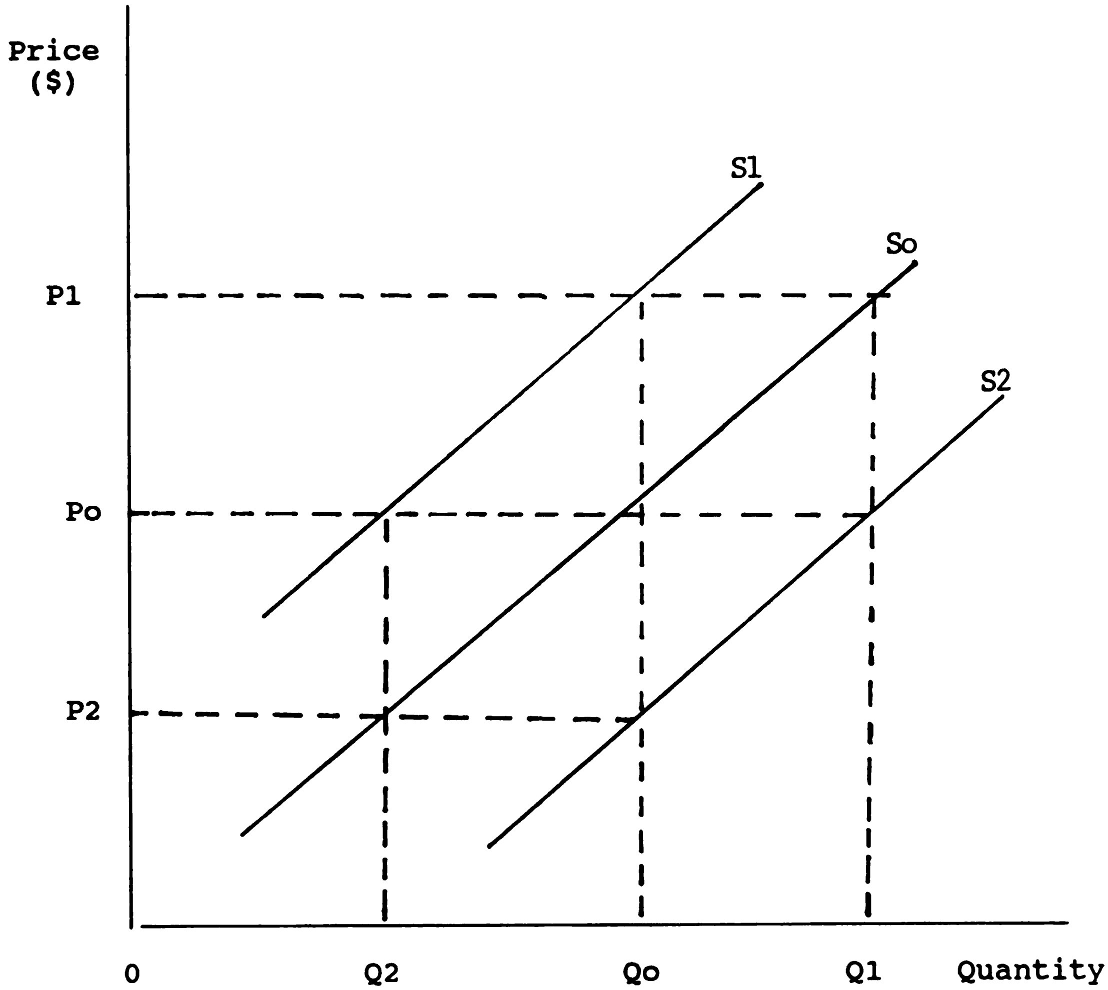
where Y is household income, H is population, R is rainfall, and P is price for water. An increase in Y or H shifts the demand curve to the right and a decrease in Y or H shifts the demand curve to the left. An increase in R shifts the demand curve to the left and a decrease in R shifts the demand curve to the right. An increase in P reduces the quantity of water demanded and a decrease in P increases the quantity of water demanded. Water quality is not explicitly included in the demand formulation given by equation 2-1. First, there have been no water demand studies which considered water demand as a function of water quality, thus no estimates of a water quality dependent demand function are available in the literature. Second, as a first approximation, it seems reasonable to assume that residential water demand is not significantly affected by water quality levels that meet federal guidelines. Since the objective of this study is to examine the cost of meeting Federal standards for nitrates, demand effects due to quality levels that meets Federal guidelines are likely to be negligible.

Residential Water Supply

The economic supply of a good or service represents the marginal cost of a good or service. Marginal cost is the increase in the total costs of production resulting from an additional increment in output (Silberberg, 1978). In Figure 2-2, the supply curve So sketches out the marginal

Figure 2-2

Supply of Residential Water



costs of producing some good or service. The supply curve is positively sloped since additional units of output are obtained at successively higher unit costs.

The economic supply of water should not be confused with the geologic supply. The economic supply of water is a relationship between water quantities and the marginal cost of providing the quantities. The geologic supply of water is that quantity of water that physically exists. In this study, "supply" refers to the economic concept of supply.

The economic supply of water--the costs of supplying water--arise due to the resources used in the development, treatment, and delivery of potable water. Resources used for development (including maintenance and operation of a public water system) include labor, capital, and materials such as concrete and wood. Resources used for treatment of potable water include chemicals used to remove contaminants from water and disposal systems for holding or transporting the removed contaminants. Resources used to deliver potable water include such items as pipeline and pumps. A water supply curve represents the incremental resource costs of developing, treating, and delivering potable water to residential communities.

An increase in the costs of developing, treating, or delivering potable water causes a leftward shift in the water supply curve. In Figure 2-2, this leftward shift is illustrated as the change from So to S1. Along So, a producer requires a price of Po to supply a quantity Qo.

The leftward shift of the supply curve to S1 represents the increased cost of supplying water. Therefore, for water supply S1, production of quantity Qo requires a higher price P1.

A rightward shift of the supply curve So to S2 represents an increase in the economic supply of water. An increase in the economic supply of water results from a decrease in the costs of producing water. Initially, to induce the producer to supply Qo amount of water required a price Po but at the new supply curve S2 a lower price of P2 is required for the producer to supply quantity Qo of water.

A change in the price of water does not cause a shift of the supply curve but a movement along the supply curve. For example, as illustrated in Figure 2-2, for the supply curve So, an increase in price from Po to P1 results in the producer supplying a greater quantity of water Q1 instead of Qo. A decreased water price from Po to P2 results in less water supplied--quantity Q2 instead of Qo.

Input water quality may shift the water supply curve. If the water supply system is required to meet Federal standards, a change in input water quality results in a change in the marginal costs of treatment. For example, suppose that input water quality exceeds the Federal mcl for nitrate. The water system must therefore remove the nitrates or shut down. Additional treatment, however, increases the marginal cost of providing a given quantity of water. This increase in cost shifts the water supply curve to the left. Overall a decrease in input water quality shifts the water supply curve to the left and an increase in input water quality shifts the supply curve to the right.

The supply relation for the quantity of water produced, S is:

(2-2) S = S(DC,DLC,TC,P)

where DC is development costs, DLC is delivery costs, TC is treatment costs, and P is the price for water. An increase in DC, DLC or TC shifts the supply curve to the left and a decrease in DC, DLC or TC shifts the supply curve to the right. An increase in P increases the quantity of water supplied and a decrease in P decreases the quantity of water supplied.

Benefits of a Safe Water Supply

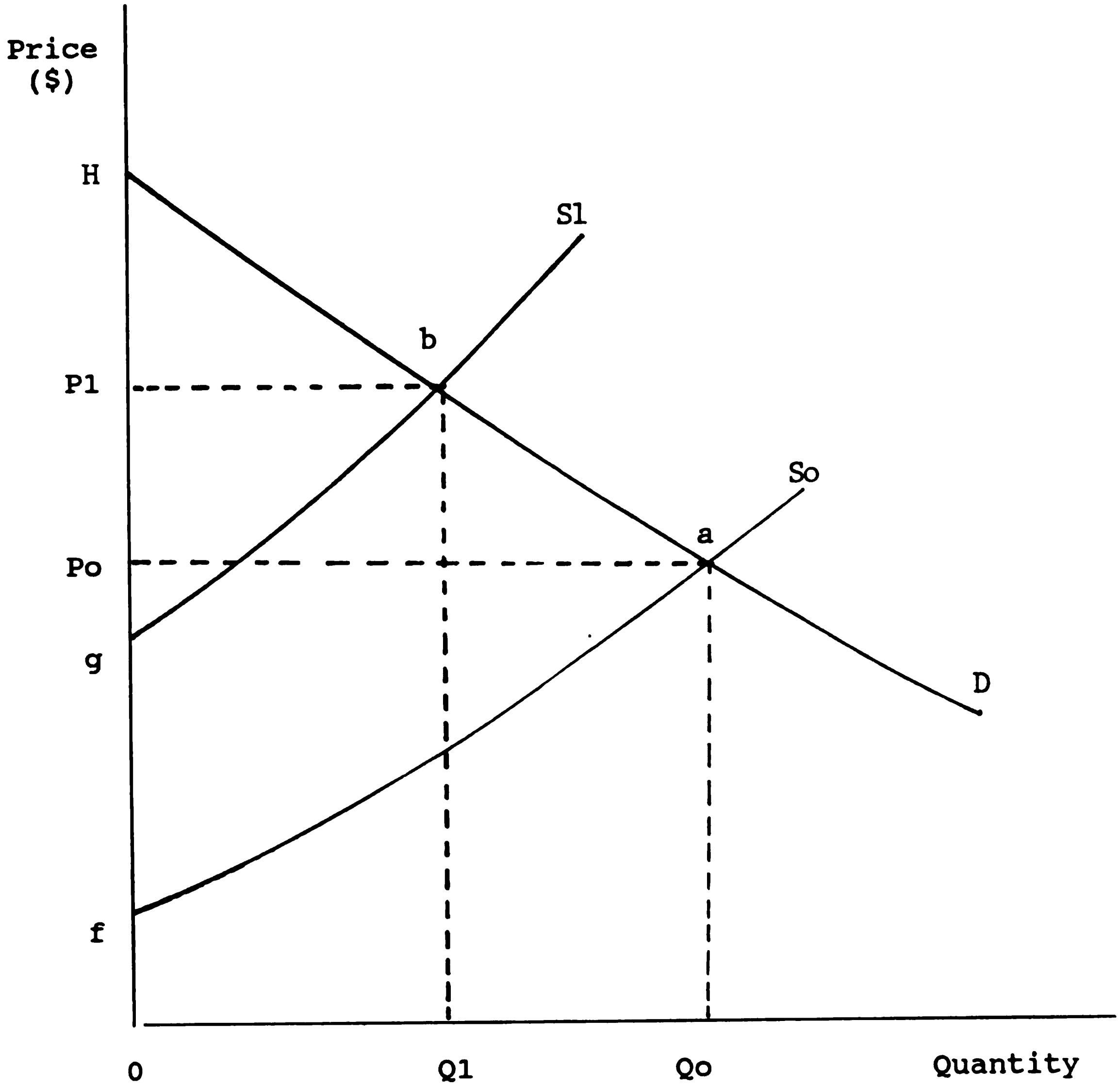
The demand and supply for residential water typically operate within a market setting. In this water market, price acts as a signal for equilibrating the demand and supply for water. An individual is willing to pay for additional units of water as long as the value the individual places upon the last unit of water consumed is just equal to or greater than the price of the water. An individual will consume increasing units of water up to the point where the value of an additional unit of water is just equal to the market price.

The public water system is assumed to increase the quantity of water supplied until the marginal cost of the last unit of water sold is equal to the market price. At the point where marginal cost of production is equal to the consumer's marginal willingness to pay, there is no excess supply and no excess demand: the quantity of water purchased is just equal to the quantity of water supplied. The prices and quantities that yield an equality between quantities demanded and supplied are termed "equilibrium" prices and quantities.

Figure 2-3 illustrates two possible price and quantity equilibria. With the supply curve So, the equilibrium market price of water is Po. The equilibrium water quantity is Qo. At point a, the consumer is willing to pay P^o for the quantity Qo. The producer is willing to sell Qo units of water. At price Po, marginal costs of production for the last increment of output is just equal to this market price.

If input water quality decreases, the marginal costs of treatment increase. Higher treatment costs increase the marginal cost of water supply and shift the supply curve from So to S1 as shown in Figure 2-3. This shift in the water supply curve results in a new price-quantity equilibrium at point b. At the new equilibrium price P1, a consumer is only willing to consume Q1 amount of water and a producer is only willing to produce Q1 units of water. For

Figure 2-3
Demand and Supply Equilibrium



any quantity of water greater than Q1, the consumer's marginal willingness to pay for more water is less than the market price. Also, for any water quantity greater than Q1, the marginal costs of production is greater than the market price. Therefore, at the price-quantity equilibrium at point b, the consumer's marginal willingess to pay for an extra unit of water is just equal to the producer's minimum selling price for supplying an extra unit of water.

In summary, an equilibrium of demand and supply for water occurs when the market price of water is equal (1) to the consumer's marginal willingness to pay for an extra unit of water and (2) to the producer's marginal cost of producing an extra unit of water. An equilibrium is altered when the supply curve or demand curve shifts due to a change in one of its shift parameters.

The benefits of a safe water supply are measured by net surplus. Net surplus is the sum of producer surplus and consumer surplus. Producer surplus is the difference between the market revenue received by producing a given good or service and the minimum cost of producing that good or service (Boadway and Wildasin, 1984). At the initial equilibrium point a in Figure 2-3, market revenue for each unit of water sold is Po and the minumum unit cost of production is given by the supply curve So. Total revenue from the sale of Qo is the area QoOPoa and the overall minimum cost of production is the area under the supply curve between the origin and Qo; that is, the area QoOfa.

Producer surplus is therefore the difference between the area QoOPoa and the area QoOfa, or the triangular area connecting the points Po, a, f.

Consumer surplus is the difference between the maximum amount that an individual would be willing to pay and the amount that is actually paid (Camm, 1983). At the initial equilibrium point a in Figure 2-3, the total payment for each unit of water bought by a consumer is the area PoaQoO. The total willingness to pay for quantity Qo at equilibrium point a is the area under the demand curve from O to Qo; that is, the area HaQoO. Consumer surplus is therefore the difference between the area PoaQoO and the area HaQoO or the triangular area connecting the points H, a, Po.

For the initial equilibrium, net surplus is the sum of producer and consumer surplus. This sum is the triangular area connecting the points F, a, H. Net surplus is therefore, a measure of total benefits for consuming and producing Qo units of water when the equilibrium market price is Po.

The Economic Damages due to Groundwater Contamination

A procedure for estimating the economic damages due to groundwater contamination is developed using the concepts of market equilibrium and net surplus. As discussed above, groundwater contamination increases treatment costs resulting in increased marginal costs of providing potable drinking water. This is illustrated above in Figure 2-3 by the leftward shift of the supply curve from So to S1. This shift in supply increases the price of water and reduces net surplus--the net benefit--of water supply. This change in net surplus measures the economic damages imposed on residential water users by groundwater contamination.

Suppose at initial equilibrium point a in Figure 2-3, the mcl for nitrate in residential drinking water quality is met. Suppose input water quality then declines due to local nitrate contamination. Contamination requires increased treatment so as to meet Federal regulations concerning water quality. Increased treatment costs shift the supply curve So left to S1. This shift causes the marginal costs of producing a safe water supply to increase. The shift of the supply curve results in a new price-quantity equilibrium at point b as illustrated in Figure 2-3. At equilibrium point b, a consumer's marginal willingness to pay for Q1 units of water is equal to the producer's marginal cost for producing Q1 units of water. This change in equilibrium results in net surplus losses.

Producer surplus, initially represented by area Poaf for equilibrium point a is reduced when the supply curve shifts left resulting in a new equilibrium at point b. At the new equilibrium point b, total market revenue from the sale of Q1 units of water is area P1bQ10 and the overall minimum cost of production is the area underneath the supply curve between the origin and Q1; that is, the area gbQ10. Producer surplus is therefore the difference between the area P1bQ10 and the area gbQ10; that is, the triangular area connecting the points P1, b, g. Therefore, a shift of the supply curve from So to S1 causes producer surplus to decline from area Poaf to area P1bg.

Consumer surplus at the initial equilibrium point a in Figure 2-3 was represented by area PoaH. With increased treatment costs the supply curve shifts left resulting in a new equilibrium at point b. At the new equilibrium the total willingness of a consumer to pay for Q1 units of water is area Q1bH0. The actual amount the consumer paid for Q1 units of water is P1bQ10. Consumer surplus is the difference in the area Q1bH0 and area P1bQ10, or triangular area connecting the points P1, b, H. Therefore, a shift of the supply curve from So to S1 causes a reduction in consumer surplus from area PoaH to area P1bH.

Net surplus for the new equilibruim point b is the sum of producer and consumer surplus. This sum is the area gbH. The area gbH measures the total benefit of producing and consuming Q1 units of water when the equilibrium market price is P1. Total economic damages due to contamination of public drinking water supplies is the difference of initial net surplus faH and new net surplus gbH. This difference is the area connecting the points f, g, b, a. Thus, an increase in treatment costs due to nitrates exceeding Federal standards in public water supplies causes the total benefit of producing and consuming water to decrease. This decrease in benefit is represented by area fgba.

Summary

The economic damages of groundwater contamination are measured by a change in net surplus. Changes in net surplus are estimated in four steps. First, two quantities are needed for estimating net surplus. One quantity is demand, which is a consumer's marginal willingness to pay for a good or service. The other quantity is supply, which is the marginal cost of producing water.

Second, using the notion of a price-quantity equilibrium, net benefits of water consumption can be computed. Net benefits are measured by net surplus at equilibrium.

Third, groundwater contamination causes increased treatment costs thereby reducing the economic supply of water. A declining economic supply of water results in increased marginal costs of production as well as increased market prices for a given quantity of water. Finally, the increase in market price leads to changes in net surplus. The change in net surplus represents the economic damages imposed on residential water users by groundwater contamination.

Chapter III

Formulation of a Water Economic Damage Simulation Model

Introduction

In the United States, Federal regulations set standards for the maximum level of contaminants in drinking water. By these regulations, the concentration of nitrates may not exceed ten milligrams per liter. If water taken into a system contains more than ten milligrams per liter, water used for drinking must be treated to bring the concentration under the ten milligram limit.

This chapter uses the general damage framework of Chapter II to develop an empirical model for estimating the economic damages of groundwater contamination by nitrates. There are three functions that are necessary for applying the general 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 2-3 to create an economic damage simulation model for nitrates.

An Empirical Model of Demand

The water demand function used in this study was originally estimated by Foster and Beattie (1979). The Foster and Beattie (FB) demand function is used because it allows adjustments for regional variations. The section begins by describing the structure of the FB demand function. Following this, the elasticity coefficients of the independent parameters in FB demand function are examined. Finally, the FB demand function is compared to water demand functions estimated in other studies.

Foster and Beattie's Household Water Demand Function

The household water demand function estimated by FB is as follows:

$$(3\text{-}1) \qquad Q = Bk * e^{BpP} * Y^{By} * R^{Br} * N^{Bn}$$

where Q is the quantity of water demanded per household in thousands cubic feet per year, P is the average price of water per thousand cubic feet in 1960 dollars, Y is median annual household income measured in 1960 dollars, R is rainfall in inches, and N is the average number of persons per water service meter.[1]

Table 3-1 gives the FB parameter estimates for the independent variables in equation 3-1 for six regions within the United States.[2] The size of the estimated coefficents for income (By), rainfall (Br), and persons per water service meter (Bn) are identical for the six regions. They are identical because FB estimated, using statistical procedures, that there is no signifcant differences in the six regions for the effects of income, rainfall, and persons per water service meter on the demand for water. However, the effects of price on water demand were estimated by FB to be significantly different for the six regions.

The algebraic signs on the FB coefficients for the parameters are consistent with the discussion in Chapter II. For example, the FB estimated income elasticity is .6274. This elasticity implies that the demand for water is income inelastic. Income inelastic means that the percentage change in the quantity of water demanded is smaller than the percentage change in income. If income increases by 10 percent, demand for water increases by only 6.274 percent.

Table 3-1

Foster and Beattie's Estimated Parameters[a]

Region	Bk	Bp	By	Br	Bn
1. New England and Northern Atlantic	.04307	-.1180	.6274	-.0403	.3026
2. Midwest	.03558	-.0804	.6274	-.0403	.3026
3. South	.04303	-.0928	.6274	-.0403	.3026
4. Plains and Rocky mountains	.08858	-.2261	.6274	-.0403	.3026
5. Southwest	.08121	-.1223	.6274	-.0403	.3026
6. Northern California and Pacific North-West	.09416	-.2686	.6274	-.0403	.3026

[a] From Foster and Beattie, 1979

The FB rate of change price coefficient (Bp) has a negative sign for all regions. The negative sign implies that as the price of water increases the quantity of water demanded decreases. A price coefficient of -0.25 implies that if the price of water increases by one dollar the quantity of water demanded decreases by 25 percent. To estimate a price elasticity, one would multiply the price coefficient (Bp) by the price of water (P).

The negative sign on Br, the rainfall elasticity coefficient, implies that as rainfall increases the demand for water decreases. For example, the FB rainfall elasticity is -.0403. If annual rainfall increases by 10 percent, demand for water decreases by 0.403 percent.

Finally, the positive sign on the elasticity coefficient for the average number of persons per water service meter Bn, implies that as the number of persons per water service meter increases demand for water increases. For example, the FB water service meter elasticity is .3026. This means that if the average number of persons per water service meter increase by 10 percent, demand for water increases by 3 percent.

FB compared their price elasticity estimates to those of four other water studies as seen in Table 3-2. The FB price elasticity estimate is obtained by multiplying the appropriate price coefficient Bp by the price of water for the selected area of study. The Bp data comes from Table 3-1 and the average price of water for the city of interest was obtained from 1960 American Water Works Association data (1960). The cities used by FB for comparison of price elasticity was based on available 1960 AWWA data and closeness of the city to the site of the other studies.

Each of the four studies estimated price elasticities in a different area of the United States. The earlier studies specified price in log-linear form implying a constant price elasticity.

Table 3-2

Comparison of Elasticity Estimates[a]

Previous Models			Foster and Beattie's Model			
Author	Year	Price Elas.	Similiar City	Average Price[b] (P)	Bp	Price Elas.
Gottlieb (Kansas)	1957	-.69	Great Bend	2.97	-.2261	-.67
Wong(Chicago Suburbs)	1961	-.26 to -.82	Calumet City	3.45	-.0804	-.27
			Kankakee	7.52	-.0804	-.60
Gardner-Schick (Utah)	1964	-.77	Colorado Springs	3.37	-.2261	-.76
Ware-North (Georgia)	1965	-.61	Anniston[c]	3.76	-.0928	-.35
			Huntsville	4.76	-.0928	-.44

[a]From Foster and Beattie, 1979
[b]The price is in dollars per one thousand cubic feet of water.
[c]The new estimates for Anniston and Huntsville are -.65 and -.55 respectively.

The FB price elasticity varies directly with price, that is, price elasticity equals $B_p P$. Therefore, the comparisons presented in Table 3-2 are the constant elasticity estimates from earlier studies versus elasticity estimates from the appropriate regional model of FB.

As seen in Table 3-2, Gottlieb estimated that the water price elasticity in the State of Kansas is -0.69 Gottlieb, 1963). The FB price elasticity of -0.67 is very similiar to Gottlieb's. Also, FB price elasticity estimates compares favorably to that estimated by Wong and by Gardner and Schick (Wong, 1972).

The FB price elasticity estimates are dissimiliar to the estimates of Ware and North, 1966. FB computed price elasticity estimates for Anniston and Huntsville, Georgia. FB price elasticity estimates for the two cities were -0.35 and -0.44. According to FB, use of 1965 data by Ware and North implies that underlying factors could have changed the price elasticity from 1960 to 1965. Therefore, FB made additional estimates of price elasticity based on 1970 AWWA data (Foster and Beattie, 1978). The revised estimates were -0.65 for Anniston and -0.55 for Huntsville.

FB price elasticity estimates were compared to a larger number of water demand studies by Libby et al, 1986. The price elasticities estimated from the other water demand studies represents most areas within the United States. The FB price elasticity estimates compared quite favorably to the other studies.

Since the FB demand function accurately represents many different regions, the FB estimates are used to represent residential water demand in the empirical model of economic damages.

An Empirical Model of Water Supply

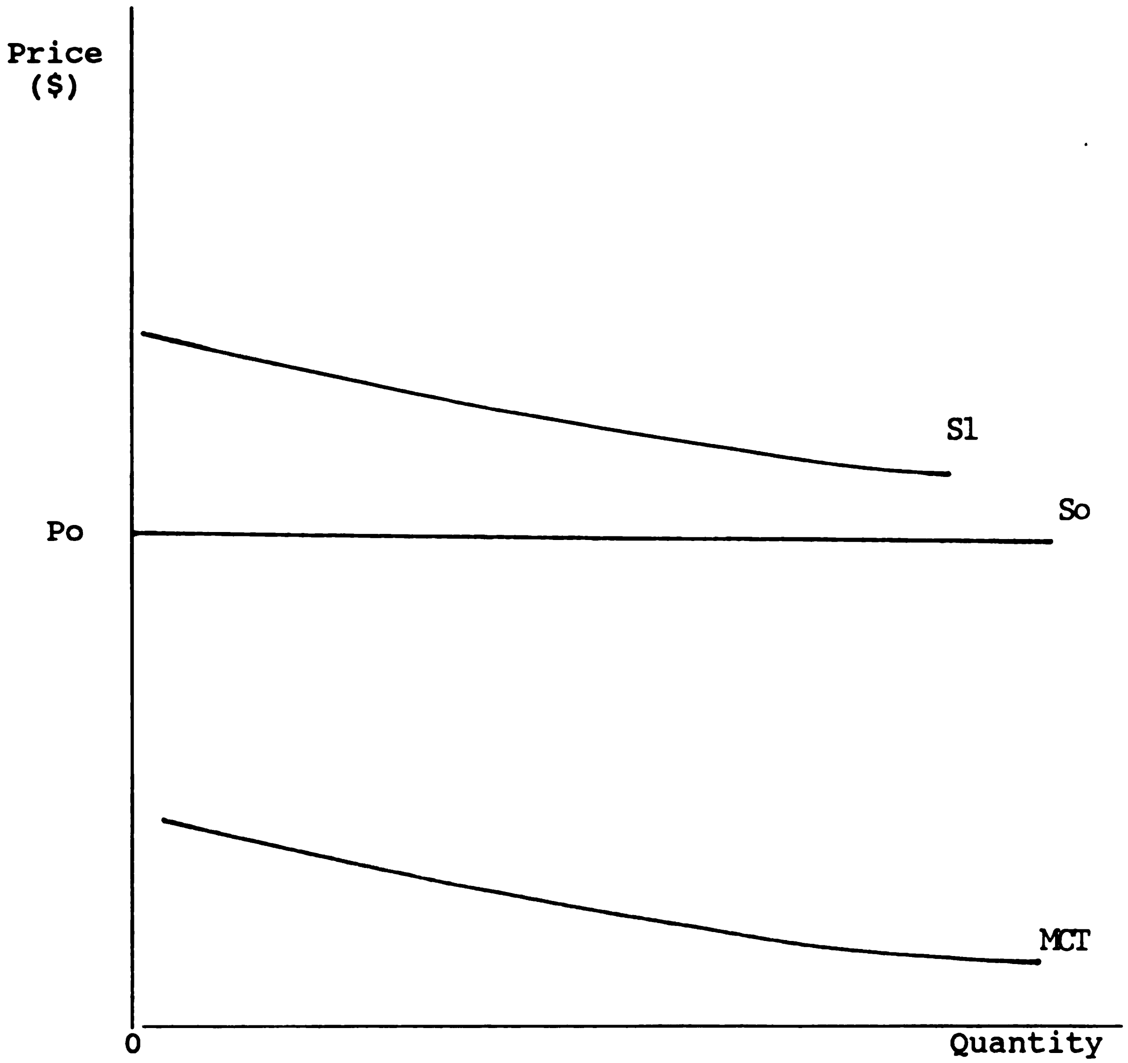
This section begins by describing a pre-contamination water supply function. Second, a post-contamination water supply function is estimated. The post-contamination supply function is the sum of the pre-contamination water supply function and the marginal costs of treatment (removing nitrates from the water supply). The post-contamination supply function represents the marginal costs of supplying water after a contamination event occurs.

A Pre-Contamination Water Supply Function

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 the quantity of water consumed per household and service area size. Capital and input prices are also assumed to be constant. Constant marginal costs imply that the cost of supplying an extra unit of water is constant over all quantities. Constant cost pricing results in a horizontal supply curve (So) as illustrated in Figure 3-1. Constant cost pricing implies that the unit price of water charged by a water utility is the same regardless of

Figure 3-1

Pre and Post Contamination Supply Curves



the quantity purchased. Approximately twenty five percent of all Michigan water utilities price at constant costs (Michigan AWWA, 1980). Another twelve percent of Michigan utilities use a flat rate schedule. The remaining sixty three percent use either increasing or decreasing step rates. The constant cost pricing assumption is therefore descriptive of about twenty five percent of Michigan utilities. In addition, the constant cost assumption simplifies the development of an initial model. Given the constant cost assumption, this model may be viewed as a first step in the development of a more general framework.

Under these assumptions the pre-contamination water supply function is estimated simply as

(3-2) $So = b$

where So represents the pre-contamination water supply function and b is a constant. In implementing the model of economic damages, b represents the initial equilibrium price of water. The initial price may be different for different water systems.

A Post-Contamination Water Supply Function

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 So and (2) the additional marginal cost of removing excess nitrates.

This subsection follows a step by step process for estimating a post-contamination water supply function. First, the treatment costs of removing excess nitrates from the water supply by a centralized ion exchange treatment system is estimated by using an engineering model developed by the United States Environmental Protection Agency (Gumerman et al, 1984). A treatment cost equation is estimated by running a number of contamination scenarios (baseline conditions) through the E.P.A. model and then using statistical methods to estimate the algebraic relation between the baseline conditions and the resulting treatment costs.

Second, using simple differentiation, a marginal treatment cost equation is derived from the treatment cost equation.

Finally, the pre-contamination water supply function -- b -- is added to the marginal cost equation resulting in the post-contamination water supply function.

Figure 3-1 graphically illustrates the process of obtaining a post-contamination water supply curve. The pre-contamination water supply function previously described is represented by the water supply curve So. The marginal costs of treatment (removing nitrate from the public water supply) is represented by the curve MCT. The post-contamination water supply function S1 is obtained by summing the marginal costs of treatment, MCT, with the pre-contamination supply function So. S1 represents the marginal costs of supplying water after a contamination event occurs.

An engineering computer program developed by Gumerman et al (1984) was used to estimate treatment costs. The principal purpose of the Gumerman et al study was to develop construction, operation and maintenance cost data for centralized and point-of-use water treatment systems. The Gumerman program is flexible enough to estimate the costs of removing a wide range of contaminants. This study, however, focuses on the removal of nitrates.

The Gumerman et al model estimates the costs of nitrate removal by either an anion exchange treatment system or a reverse osmosis treatment system. This study used an anion exchange system to estimate the costs of removing nitrates from water. The anion exchange system was selected due to the generally higher capital and maintenance costs of a reverse osmosis system (Gumerman, 1984).

There are three major costs involved in the use of an anion exchange treatment system. The first major cost includes the capital costs of an anion exchange system. These costs include such items as materials, labor and land.

The second major cost arises from the maintenance and operation of an anion exchange system. The use of salt to remove nitrates from the intake water supplies makes up a large percentage of the operational and maintenance costs.

The third major cost is the removal and storage of waste water resulting from treatment. The use of salt to remove nitrate from drinking water supplies results in brine waste water. The volume of brine waste water is equal to approximately 4 to 6 percent of the total amount of water treated. For this study, it is assumed that brine waste water is pumped into evaporation lagoons, a common disposal method. Lagoons are large enough to evaporate a year's brine waste flow. The brine evaporation lagoons are built with liners so as to prevent seepage of salt water to groundwater. The size of the brine lagoon is dependent upon the evaporation rate and the flow of wastewater. With a constant brine waste water flow, a higher evaporation rate would translate into a smaller brine evaporation lagoon.

The Gumerman model encompasses capital, operational, maintenance, and waste removal and storage costs. The annualized capital costs of constructing an anion exchange system are a function of the quantity of water that is treated. The operational and maintenance costs are a funtion of the quantity of water treated as well as the concentration of nitrates in the water supply. The waste water removal and storage cost is a function of the quantity of water treated as well as the evaporation rate.

A summary water treatment cost equation was estimated using cost data generated by the Gumerman et al model. Three variables are entered into the Gumerman model so as to estimate the treatment costs of removing nitrate from public water supplies. The three variables include nitrate concentration in the intake water supply, quantity of water treated, and the evaporation rate. The size of these three variables are allowed to vary so as to represent different nitrate contamination scenarios. Each scenario results in a different treatment cost. Treatment costs are then regressed on the three variables. The resulting treatment cost equation is used to estimate the costs of removing nitrate from a public system's water supply.

Each of the three variables used to estimate the treatment cost equation can take on one of six possible values in the contamination scenarios.

For the contamination scenarios, a nitrate concentration of 12 milligrams per liter (mg/l) of water was chosen to represent the minimum concentration of nitrate in the intake water supply. 100 mg/l of water represents the maximum concentration of nitrate in the contamination scenario. 12 mg/l represents a low nitrate concentration that just exceeds Federal standards for nitrate removal. 100 mg/l of nitrate represents the maximum concentration of nitrate that an anion exchange system can efficiently remove from water supplies. Since it is not known if there is a linear relationship between treatment costs and nitrate concentrations, midpoint values were included for the estimation of the treatment cost equation. Nitrate concentrations in the water supply for the treatment scenarios were set at a level of 12, 20, 33, 55, 90, or 100 milligrams per liter of water, where 20, 33, 55, and 90 mg/l of nitrate simply represent nitrate concentrations between the minimum and maximum concentrations.

The quantity of water treated per day is used to estimate the size of the anion exchange system that is constructed, the size of brine lagoon and partially the quantity of salt used. The minumum size anion exchange system used by a public water system would approximately treat 8,000 gallons per day. The maximum size anion exchange system built can efficiently treat approximately 729,000 gallons per day. Therefore, the two extreme levels included in the water treatment scenarios are 8,000 and 729,000 gallons of water treated per day. Four additional quantities of water treated were selected between the two extremes. These four quantities were chosen since it is not known if there is a linear relationship between treatment cost and the quantity of water treated. The six levels of treated water were 8,000, 22,000, 60,000, 163,000, 442,000, and 729,000 gallons per day.

Evaporation rate determines the appropriate size of the evaporation lagoon that is constructed. Holding the quantity of waste water that results from treatment constant, a higher evaporation rate means a smaller lagoon is constructed. The treatment cost scenarios include a very low evaporation rate of 5 inches per year and a high evaporation rate of 100 inches per year. The evaporation rates for most areas within the continential United States fall between the extreme values. Four additional evaporation rates were selected to represent points between the two extreme values since it is not known if there is a linear relationship between treatment cost and the evaporation rate. The six selected evaporation rates were 5, 15, 25, 55, 75, and 100 inches per year.

With three variables and six different levels or values for each variable, there are 216 different treatment scenarios. A random sample of treatment scenarios reduced the time and costs of estimating the treatment cost equation. Therefore, this study used a random sample of 50 different treatment scenarios so as to estimate a treatment cost equation.

The treatment cost equation was estimated in log form

$$\text{(3-3)} \quad Ln(TC) = Ln(A') + (a+1)Ln(y) + bLn(q) + cLn(E)$$

where Ln is the natural log, TC is treatment costs in 1983 dollars, y is the amount of water treated in thousands of cubic feet per day, q is water quality or nitrate concentration (milligrams per liter of water), and E is the evaporation rate in inches per year. This equation estimates the cost of treating water given the quantity of treated per day, the concentration of nitrate in the water supply and the annual evaporation rate. The estimated elasticity coefficients for equation 3-3 are

$$A' = 9.837672 \qquad b = 0.12649\ (0.0267)$$

$$(a+1) = 0.62797\ (0.0142) \qquad c = -0.30615\ (0.0217)$$

where standard errors for each coefficient are in parentheses. The R-squared for the estimated treatment cost equation is 0.978.

The positive elasticity coefficient (a+1) implies that as the quantity of water treated increases, the costs of treatment increase. A 10 percent increase in the quantity of water treated increases treatment costs by 6.28 percent.

The positive elasiticity coefficient b implies that as the nitrate concentration increases in the water supply, the cost of treatment increases. If nitrate concentrations increase by 10 percent then treatment costs increases by 1.26 percent.

The negative sign on the elasticity coefficient c for the evaporation rate implies that as the evaporation rate increases the cost of treatment decreases. If the evaporation rate increases by 10 percent, the costs of treatment decrease by 3.06 percent.

The derivative of treatment cost is marginal treatment cost. Therefore, differentiating equation 3-3 with respect to y, the marginal treatment cost of removing nitrate is

$$(3\text{-}4) \quad MC = (a+1)*A'y^{a}*q^{b}*E^{c}$$

where MC is the marginal cost of removing nitrate from water supplies, and the other coefficients and variables are the same as for equation 3-3. This equation estimates the marginal costs of removing nitrate from water given the quantity of water treated per day, the concentration of nitrates in the water supply, and the annual evaporation rate.

The post-contamination supply function is the sum of the pre-contamination supply function (equation 3-2) and the marginal costs of removing nitrates (equation 3-4). This sum is

$$(3\text{-}5) \qquad S1 = b + (a+1)*A'*y^{a}*q^{b}*E^{c}$$

where S1 represents the post-contamination supply function, b is the pre-contamination price of water, and the other variables and coefficients are the same as in equation 3-3.

As discussed in Chapter II, the water supply function represents the marginal cost of producing some quantity of water. Equation 3-5 therefore represents the marginal cost of producing a quantity of water after the removal of nitrate from intake drinking water supplies.

Summary

This chapter developed an empirical water cost model for estimating the economic damages sustained by consumers and producers due to increased treatment costs. The model is based on demand for and supply of residential water. An appropriate demand function, a pre-contamination supply function and an estimated post-contamination supply function were described. Consequently, this model can estimate the loss in benefits (damages) with a change in the water demand and supply equilibrium.

Endnotes

1. A water service meter measures the quantity of water used by the occupants of a home, apartment complex or nursing home.
2. See FB, 1979 for a description of the regional classifications.
3. See FB, 1979 for a complete description of the estimation of their demand function.

Chapter IV

Empirical Results of the Water Cost Simulation Model

Introduction

This chapter examines the empirical results derived from the water cost simulation model. The empirical results are estimates of the economic damages inflicted upon residential users of public drinking water supplies as a consequence of nitrate contamination of the public drinking water supplies.

There are two ways that the model is used to estimate the economic damages of groundwater contamination. First, the economic damages are estimated directly from the water cost simulation model. Secondly, economic damages are estimated by equations that approximate the structure of the water cost model. The results given by these equations are less exact than those obtained from the water cost model. However, the equations are simple to use, requires no computer programming, and provide initial estimates of the economic damages associated with nitrate contamination.

The first section of this chapter derives economic damage estimates directly from the water cost simulation model. It is shown that removing nitrates from drinking water supplies results in higher water prices, reduced water consumption, and a loss in net surplus.

The second section examines post-contamination equations that are estimated from the water cost simulation model. The equations summarize the structure of the general water cost model. The post-contamination equations include the change in the price of water from the pre-contamination price and the annual per household change from the pre-contamination level for the quantity of water consumed and for net surplus.

The last section uses the post-contamination equations to derive estimates of the economic damages inflicted upon consumers and producers due to a nitrate contamination event.

Representative Results of the Water Cost Simulation Model

Table 4-1 illustrates the economic damages associated with the removal of 15 milligrams of nitrate from a public system's water supplies. The economic damages are estimated by the general water cost model as described in Chapter III. Due to the nature of the post-contamination supply function, economic damages are estimated using a computerized simulation algorithm. The algorithm was developed to carry out the calculations implied by Figure 2-3 and the water cost model framework. The water cost simulation model in this example is based on an annual household income of $13,726, a water service area size of 1,000 households, annual rainfall of 20 inches, yearly evaporation rate of 15 inches, 2.7 persons per household,

Table 4.1: Annual Economic Damages of Drinking Water Contamination for a 1000 Household Population[a]

Variable	Nitrates removed from a water supply (milligrams of nitrate per liter) 0 mg/l	15 mg/l	Change due to contamination
1. Price of water (dollars per thousand cubic feet)	7.5	15.0	+7.50
2. Water consumption per household (cubic feet per year)	6,600	5,500	-1,100
3. Producer surplus per household (dollars per year)	0	-56	-56
4. Consumer surplus per household (dollars per year)	275	230	-45
5. Net surplus per household (dollars per year)	275	174	-101

[a] Water cost model was based on a yearly household income of $13726, a yearly rainfall of 20 inches, a yearly evaporation rate of 15 inches, and a pre-treatment water price of $7.5 per thousand cubic feet of water. Prices and income are in 1983 dollars. There are 2.7 persons per household.

and a pre-contamination water price of $7.5 per thousand cubic feet of water. All dollar figures are in 1983 price levels. Given this baseline data, the water cost model computes economic damages in a five step process. The cost model

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.
4. Computes post-contamination economic benefits.
5. Computes economic damages as the difference between economic benefits before contamination and economic benefits after contamination.

In Table 4-1, column one includes the variables that are affected by a contamination event. Column two represents the pre-contamination levels of the variables. Column three represents the post-contamination level of the variables, that is, the level of the variables after treatment costs increase due to the removal of nitrate from the water supply. The anion exchange system reduces the nitrate level to approximately 5 milligrams of nitrate per liter of water. If the nitrate contamination level in the water supply is 20 milligrams per liter, the anion exchange systems removes 15 milligrams of the nitrate per liter. Finally, column four represents the annual per household change in the variables from the pre-contamination level or the difference between column two and column three.

As shown in column one of Table 4-1, the pre-contamination price of water is $7.5 per thousand cubic feet. The post-contamination price of water increases to $15.0 per thousand cubic feet. Removing 15 milligrams of nitrate per liter of water from public drinking water supplies causes the price of water to increase by $7.5 per thousand cubic feet.

The pre-contamination annual consumption of water per household is 6,600 cubic feet. After nitrate removal, water consumption decreases to 5,500 cubic feet per household per year. Yearly household water consumption decreases by 1,100 cubic feet. The reason for the decrease in water consumption is due to the increase in the post-contamination price of water.

Annual producer surplus decreases by $56 per household. This decrease is due to the fact that the public water system sell its water at a price less than its marginal cost of production.

Annual consumer surplus decreases by $45 per household. Consumer surplus decreased due to the increase in the price of water and subsequent reduction in the quantity of water demanded.

Annual economic damages per household due to increased treatment costs are represented by the change in net surplus. The annual loss in net surplus is the sum of (1) the loss in producer surplus and (2) the loss in consumer surplus. As illustrated in Table 4-1, annual net surplus decreases by $101 per household. The economic damage sustained due to the removal 15 mg/l of nitrate is $101 per household.

Post-Contamination Economic Damage Equations

Instead of operating the water cost simulation model each time for a different set of pre-contamination baseline conditions, this section summarizes the water cost model by introducing equations that can estimate results analagous to those of Table 4-1.

To summarize the structure of the water cost model, post-contamination equations were estimated for each of the variables listed in Table 4-1. The post-contamination economic damage equations were derived by running 100 treatment scenarios--baseline conditions--through the water cost model and then using statistical methods to estimate the algebraic relation between the baseline conditions and the resulting damage estimates. Use of the post-contamination damage equations is slightly less accurate than the cost simulator but it requires only a pocket calculator to produce an initial set of damage estimates.

Table 4-2 includes the post-contamination equations for the increase in the initial price of water in dollars per thousand cubic feet, the annual reduction in water consumption per household, the annual per household loss in consumer and producer surplus, and the annual loss in net surplus per household. These five variables were regressed on six independent variables including the concentration of nitrates (water quality) in milligrams per liter of water, the yearly evaporation rate in inches, annual rainfall in inches per year, number of households served by public water system, the per capita income per household for the water system service area in dollars, and the initial or pre-contamination price of water in dollars per thousand cubic feet. The post-contamination equations were estimated in log-linear form so that the coefficients on the independent variables are elasticities.

Table 4-2 indicates that the increase in the price of water is positively related to nitrate concentration, rainfall, and the initial price of water. The increase in the price of water is negatively related to the evaporation rate, household income, and number of households served by the public water system. The income elasticity coefficient is -0.334. This implies that as household income increases by 10 percent the price increase is 3.34 percent lower. The price increase is smaller with higher income households because the marginal treatment cost per unit of water decreases as the quantity of water treated increases.

Table 4.2: Post-Contamination Equations

Dependent Variable	Constant	Elasticity Estimates[a]						
		nitrate concentration	evaporation	income	rainfall	# of hh	initial price	R-Square
1. Increase in the price of water (dollars per thousand cubic feet)	7.342	0.136 (22.3)[b]	-0.334 (-66.7)	-0.234 (-2.9)	0.010 (1.4)	-0.401 (-112.2)	0.093 (25.6)	0.956
2. Reduction in Water Consumption per household (thousand cubic feet per year)	-0.193	0.129 (14.9)	-0.298 (-40.2)	0.368 (28.1)	-0.016 (-1.5)	-0.366 (-69.1)	-0.147 (-27.2)	0.991
3. Loss in Producer Surplus per household (dollars per year)	2.318	0.111 (11.3)	0.048 (5.6)	0.395 (26.4)	-0.017 (-1.4)	-0.322 (-53.4)	-0.158 (-25.6)	0.983
4. Loss in Consumer Surplus per household (dollars per year)	3.541	0.129 (14.9)	-0.298 (-40.0)	0.368 (28.0)	-0.016 (-1.5)	-0.366 (-68.8)	-0.147 (-27.1)	0.991
5. Loss in Net surplus per household (dollars per year)	3.500	0.118 (13.1)	-0.092 (-11.7)	0.383 (27.7)	-0.016 (-1.4)	-0.340 (-60.9)	-0.152 (-26.7)	0.987

[a] Water quality is milligrams of nitrate per liter of water, evaporation is inches of water evaporated per year, income is the yearly household income, rainfall is inches per year, # of hh is the number of households served by the public water system, price is the price of water per thousand cubic feet before treatment. Prices and income are in 1983 dollars. There are 2.7 persons per household. Equations were estimated in log-linear form so the estimated coefficients are elasticities.

b Student's t-value in parentheses.

The second equation in Table 4-2 measures the annual per household reduction in water consumption. The reduction in water consumption is positively related to water quality and income. This positive relationship means that as the nitrate level increases in the water supply or as household income increases, the annual reduction in water consumption per household increases. For example, the elasticity coefficient on household income is 0.368. This means that as household income increases by 10 percent, the reduction in per household annual water consumption increases by 3.68 percent. On the other hand, the negative relationship of annual water consumption to evaporation, rainfall, number of households and initial price means that as these independent parameters increase, the reduction in water consumption decreases. For example, the elasticity coefficient on price is -0.147, meaning that as the pre-contamination price of water increases by 10 percent, the annual reduction in water consumption per household decreases by 1.47 percent.

The loss in net surplus is positively related to nitrate concentrations and household income. For example, if nitrate concentrations increase by 10 percent, net surplus losses increase by 1.18 percent. Also, if household income increase by 10 percent, net surplus losses increase by 3.83 percent. The loss in net surplus is negatively related to the evaporation rate, annual rainfall, number of households served by the public water system, and the initial price of water. For example, if the initial price of water increases 10 percent, the loss in net surplus decreases by 1.52 percent.

Included in Table 4-2 are the Student's t-value (in parentheses) for each elasticity coefficient estimate of the independent parameters. Also included in the last column is the R-squared value for the estimated equation.

As an example of using the post-contamination equations, assume that the nitrate concentration level is 20 milligrams per liter of water, the annual evaporation rate is 20 inches, the average income per household for the water service area is $20,0000, annual rainfall is 20 inches, the water service serves 500 households, and the pre-contamination price of water is $10 per thousand cubic feet. To estimate the loss in net surplus, variable five in Table 4-2, the baseline data is entered into the equation and net surplus is estimated as follows

$$\mathrm{Ln(net\ surplus)} = 3.500 + 0.118*\mathrm{Ln}(20) - 0.092*\mathrm{Ln}(20) + 0.383*\mathrm{Ln}(20000) - 0.016*\mathrm{Ln}(30) - 0.340*\mathrm{Ln}(500) - 0.152*\mathrm{Ln}(10).$$

The other post-contamination equations are used in an analogous fashion.

The Economic Damages of a Contamination Event

In this section the economic damages sustained by consumers and producers due to contamination of drinking water supplies are examined using the post-contamination damage equations.

Given baseline conditions one can estimate the initial or pre-contamination benefits of consuming water by use of the Foster and Beattie demand function. To estimate the quantity of water consumed per household (q) one merely enters the baseline conditions into the FB demand function.

With constant marginal cost pricing, producer surplus is zero. To estimate consumer surplus requires integrating underneath the FB demand function from the price p to the price where demand equals zero. Net surplus is estimated in the same manner as consumer surplus.

Table 4-3 contains the pre-contamination benefits of consuming water for two public water service areas. Benefits are estimated for a water service area that provides water to 500 households or to 2000 households. For both water service areas, average annual per household incomes are assumed to be either $15,000, $25,000, or $35,000. It is assumed that annual rainfall is 25 inches. The pre-contamination price of water is $14.96 dollars per thousand cubic feet. It is assumed there are 2.7 persons per household. Finally, the pre-contamination concentration of nitrates in the water supply is equal to or less than 10 milligrams per liter, therefore requiring no removal of nitrate.

Given the baseline conditions the annual household consumption of water is 5,400 cubic feet, 7,200 cubic feet,

Table 4.3: Pre-Contamination Equilibria for a 500 and 2000 Household Population[a]

	500 Households			2000 Households		
	Income			Income		
Variables	$15000	$25000	$35000	$15000	$25000	$35000
1. Water consumption per households (thousand cubic feet per year)	5.40 (40.0)[b]	7.20 (54.0)	8.70 (65.0)	5.40 (40.0)	7.20 (54.0)	8.70 (65.0)
2. Producer surplus per household (dollars per year)	0.0	0.0	0.0	0.0	0.0	0.0
3. Consumer surplus per household (dollars per year)	226	303	367	226	303	367
4. Net surplus per household (dollars per year)	226	303	367	226	303	367

[a] Estimations are based on 25 inches of rainfall during the growing season and a water nitrate content of less than 10 milligrams per liter. There are 2.7 persons per household. The price of water is $14.96 per thousand cubic feet or $2 per thousand gallons. Water price and incomes are in 1983 prices. Some rounding off of number occurs for convenience.

[b] Water consumption per household in thousands of gallons per year.

and 8,700 cubic feet for an average annual household income equilibrium of $15,000, $25,000,and $35,000. Since water is a normal good, demand for water increases as income increases. Household water consumption for both service areas is the same for the given average annual per household income. This occurs because the price of water is the same per unit, regardless of total quantity of water consumed.

Pre-contamination producer surplus is zero for both water service areas and all income levels because of constant marginal costs and marginal cost pricing. Marginal cost pricing with constant marginal costs implies that the public water system receives exactly the amount of money needed to pay for resource costs.

Table 4-3 shows that consumer surplus is positive and increasing as income increases. This is true for both water service areas. Consumer surplus increases with income because willingness to pay for water increases as income increases.

Net surplus, the measure of total benefits to producers and consumers for producing and consuming some quantity of water at a price of $14.96 per thousand cubic feet, is positive and increasing as income increases. This is true for both water service areas. Consuming 5,400 thousand cubic feet of water per year at a price of $14.96 per thousand cubic feet results in a net benefit of $226 per year per household at an income level of $15,000. Net benefit increases with income. Households with an annual income of $35,000 gain a net benefit of $367 per year. The next section illustrates how benefits change when nitrate contaminates the public water supply.

Post-Contamination Economic Damages

Tables 4-4 and 4-5 contain the damages associated with a contamination event for two different scenarios. In the first scenario, the public water system removes 10 milligrams of nitrate per liter of water. In the second scenario, the water system removes 40 milligrams of nitrate per liter of water. Table 4-4 describes post-contamination damages for a public water service system supplying water to 500 households. Table 4-5 describes the post-contamination damages for a public water service system serving 2000 households. Parentheses indicate the percentage change of the variables from pre-contamination levels (as illustrated in Table 4-3).

In Table 4-4, two separate contamination events are described. In the first, 10 milligrams of nitrate per liter of water are removed. In the second, 40 milligrams of nitrate per liter of water are removed. Included in Table 4-4 are three different average household incomes levels. These income levels are either $15,000, $25,000 or $35,000 per household. As in Table 4-3, it is assumed that annual rainfall is 25 inches, the pre-contamination price of water is $14.96 per thousand cubic feet of water, there are 2.7

Table 4.4: Post-Contamination Damages for a 500 Household Population[a]

	milligrams of nitrate removed					
	10 mg/l			40 mg/l		
	household income			household income		
	15000	25000	35000	15000	25000	35000
1. Increase in the pre-treatment price of water (dollars per thousand cubic feet)	10.50 (70)[b]	9.30 (62)	8.60 (57)	12.10 (81)	10.80 (72)	10.00 (67)
2. Reduction in water consumption per household (thousand cubic feet per year)	1.20 (22)	1.40 (20)	1.60 (19)	1.40 (25)	1.60 (23)	1.90 (21)
3. Loss in producer surplus per household (dollars per year)	58	71	81	66	80	92
4. Loss in consumer surplus per household (dollars per year)	49 (22)	60 (20)	67 (18)	57 (25)	69 (23)	78 (21)
5. Loss in net surplus per household (dollars per year)	107 (47)	131 (43)	148 (41)	123 (54)	149 (49)	169 (46)

[a] Estimates are based on 25 inches of rainfall during the growing season and a yearly evaporation rate of 15 inches per year. Pre-treatment price is $14.96 per thousand cubic feet or $2.00 per thousand gallons. There are 2.7 persons per household. Income and prices are in 1983 terms.

[b] The percentage change in the variable from the pre-treatment equilibrium is in parentheses.

Table 4.5: Post-Contamination Damages for a 2000 Household Population[a]

	milligrams of nitrate removed					
	10 mg/l			40 mg/l		
	household income			household income		
	15000	25000	35000	15000	25000	35000
1. Increase in the pre-treatment price of water (dollars per thousand cubic feet)	6.00 (40)[b]	5.30 (36)	4.90 (33)	7.00 (47)	6.20 (41)	5.70 (38)
2. Reduction in water consumption per household (thousand cubic feet per year)	0.70 (13)	0.90 (12)	1.00 (11)	0.80 (15)	1.00 (14)	1.10 (13)
3. Loss in producer surplus per household (dollars per year)	37	46	52	42	51	59
4. Loss in consumer surplus per household (dollars per year)	30 (13)	36 (12)	41 (11)	34 (15)	41 (14)	47 (13)
5. Loss in net surplus per household (dollars per year)	67 (30)	82 (27)	93 (25)	76 (34)	92 (31)	106 (29)

[a] Estimates are based on 25 inches of rainfall during the growing season and a yearly evaporation rate of 15 inches per year. Pre-treatment price is $14.96 per thousand cubic feet or $2.00 per thousand gallons. There are 2.7 persons per household. Income and prices are in 1983 terms.

[b] The percentage change in the variable from the pre-treatment equilibrium is in parentheses.

persons per household, plus the annual evaporation rate is 15 inches.

In Table 4-4 it can be seen that when 10 milligrams of nitrate is removed, the increase in the price of water is $10.50, $9.30, and $8.60 per thousand cubic feet, respectively, for $15,000, $25,000 and $35,000 per household incomes. This represents, respectively, a 70 percent, 62 percent and 57 percent increase in price from the pre-contamination price level. The price increase is smaller for the higher income groups because the marginal costs of treating water decreases as the quantity of water treated increases. The per unit cost of treatment for a higher average household income community is lower since a larger quantity of water is treated.

Table 4-4 shows that the removal of 40 milligrams of nitrate increases water prices by about 10 percent more than the removal of 10 milligrams, regardless of household income.

The annual reduction in water consumption per household increases as income increases. For example, the removal of 10 milligrams of nitrate per liter when average household income is $15,000, results in an annual reduction in water consumption of 1.20 thousand cubic feet. For an average household income of $35,000, the annual reduction in water consumption is 1.60 thousand cubic feet. Even though the price increase was smaller for higher incomes, their water consumption decreased to a greater extent. This anamoly can be explained by noting that a higher income community initially consumes more water. This implies that even though their decrease in consumption was larger, on an absolute basis, a higher income community still consumes more than a lower income community.

It can be also be seen in Table 4-4 that if 40 milligrams of nitrate is removed, the reduction in water consumption is greater than in the 10 milligram case. This is due to the larger price increase that occurs in the 40 milligram case. Consistent with theory, a larger price increase brings about a greater reduction in water consumption.

The loss in net surplus measures the economic damages of removing nitrate from a public system drinking water supplies. As seen in Table 4-4, when 10 milligrams of nitrate per liter is removed from the water supply, the annual loss in net surplus is $107, $131, and $148 per household as average household income increases. Higher income communities experience larger losses on an absolute basis but not on a percentage basis. When 10 milligrams of nitrate is removed, a $15,000 average household income has a 47 percent loss in net surplus whereas a $35,000 average household income only has a 41 percent loss of net benefits.

Removing 40 milligrams of nitrate increases net surplus losses. These net surplus losses range from $123 per household to $169 per household, depending on income level.

The net surplus losses decrease as income increases. This is due to the fact that higher income households have smaller water price increases. Net surplus losses could also be estimated by summing up the loss of producer surplus with the loss in consumer surplus.

Before comparing Table 4-4 to Table 4-5 an important point should be covered. That is, the loss in producer surplus in Table 4-4 represents the loss the firm suffers each time it sells water after removing nitrate. In other words, the firm is selling water at a price below its marginal cost of production. Removing 10 milligrams of nitrate for an average household income of $15,000 results in a producer surplus loss of $49 per household. This means that the water supplier doesn't cover the costs of supplying water by $49 per household. The $49 dollars is the difference between revenues received per household and the marginal costs of supplying water per household. This loss occurs because water pricing is based on marginal costs. With decreasing marginal costs in the post-contamination situation, average costs are greater than marginal costs; the firm losses money for each unit of water produced at marginal cost. Possible approaches to cover these losses include average cost pricing, tax subsidies, and regionalization. Note that these alternatives would generally increase net damages and lead to inefficiencies. These approaches are discussed in depth in Chapter V.

In Table 4-5, the increase in the price of water for all income levels and both nitrate concentration levels is smaller than in Table 4-4. This is due to the fact that the marginal costs of treating water decreases as the quantity of water treated increases. The quantity of water treated increases due to the fact that 2000 households instead of 500 households are served by the public water system. For example, as shown in Table 4-5, the percentage increase in the price of water from the pre-contamination level was 33 to 40 percent for the case of removing 10 milligrams of nitrate per liter. This compares to a percentage increase in price of 57 to 70 percent for the removal of 10 milligrams of nitrate per liter as seen in Table 4-4. This is due to greater marginal costs of treatment for the 500 household community.

The decrease in water consumption is smaller for the 2,000 household service area than for the 500 household service area due to the smaller increase in the price of water. Removing 40 milligrams of nitrate reduces annual water consumption by 0.80, 1.00, and 1.10 thousand cubic feet for income levels of $15,000, $25,000, and $35,000. For the identical case in Table 4-4, the annual reduction in water consumption was 1.40, 1.60, and 1.90 thousand cubic feet.

The net surplus losses that occur when 10 milligrams of nitrate is removed are $67, $82, and $93 per household. For the identical situation in Table 4-4, the losses were $107,

$131, and $148 per household as income increases. These greater losses are due to higher water prices. In fact, the net surplus losses when 40 milligrams of nitrate is removed is smaller for the 2,000 household service area than when 10 milligrams of nitrate is removed for the 500 household service area. These results are due to the decreasing marginal costs of removing nitrate. Decreasing marginal costs reduces the price increase. These results have some important consequences that are dicussed in Chapter V.

Chapter V

Conclusions

Introduction

This study derived a conceptual framework for estimating the economic damages of nitrate contamination of groundwater. The framework is based on the economic concepts of supply and demand. These are simple yet powerful concepts. The water demand function represents the total willingness of consumers to pay for various quantities of water. The water supply curve represents the total willingness of producers to provide water for various prices and quantities.

The conceptual framework was operationalized using a demand function and a pre- and post-contamination supply function. The demand function used was estimated by Foster and Beattie. The pre-contamination supply function represents the marginal costs of supplying potable water before contamination occurs. The post-contamination supply function was estimated using an engineering model of water treatment.

The water cost simulation model was used to identify the economic damages of a contamination event. The initial effect of groundwater contamination is to increase water treatment costs and water supply prices. Higher prices lead to a reduction in water purchased by households.

Higher costs and lower water consumption imposes economic damages on both water suppliers and consumers. These economic damages were measured by the loss in net surplus.

Advantages and Limitations of the Model

There are a number of advantages to using the water cost model in measuring economic damages. First, economic damage estimates can be easily calculated using the post-contamination equations. These equations require only a pocket calculator to produce an initial set of damage estimates. Baseline conditions are simply entered into the equations and the appropriate arithmetic calculations are carried out.

Second, economic damages can be estimated for different community sizes and for various average per capita household incomes of the community.

Third, economic damages can be estimated for various environmental conditions such as annual rainfall and evaporation rates. For example, damages can be estimated for dry summers versus wet summers in Michigan.

Finally, economic damages can be estimated for various concentration levels of nitrate in the intake water supply.

The limitations of the model deal mainly with the use of consumer surplus to measure the benefits and costs of residential consumption of potable groundwater. One problem encountered with using consumer surplus is that of path dependency (Boadway and Bruce, 1984). That is, consumer surplus estimates will change as prices of substitutes and complements change.

Another problem is aggregation of consumer surplus over many individuals (Boadway and Bruce, 1984). The consumer surplus benefits of consuming potable groundwater by a wealthy individual may be much higher than that for a poor individual. Therefore, if a flat tax is levied on all individuals to pay for treatment costs, a poor individual will be paying the same tax as the rich individual even though he places a lower value on the consumption of potable groundwater.

Finally, how one measures consumer surplus can present a problem. That is, should one estimate consumer surplus by willingness to sell or willingness to pay (Tresch, 1981)? Depending on wealth effects, these two measures may not be equal (Schmid, 1987).

Research Implications

There are a number of refinements future researchers may want include in the water cost model. First, the model is constrained to estimating the economic damages of nitrate contamination by the increased treatment cost of installing and operating a centralized treatment system. It may be the case that a different treatment or nontreatment system may more accurately estimate the economic damages of contamination in certain situations.

One alternative to the centralized treatment system is a point-of-use treatment system. Hoehn and Walker (1987) suggest that point-of-use water treatment systems may be less expensive than centralized treatment for communities composed of less than 50 households.

Second, the assumption of constant marginal costs of producing water could be relaxed. Using constant marginal costs of production simplified the setup of the water cost model. The water cost model could be modified by replacing the assumption of contant marginal cost production by either actually estimating the marginal costs of supplying water or using a previously estimated water supply curve. One could estimate a pre-contamination supply function by using the Gumerman engineering model. The estimated pre-contamination supply function would have decreasing, increasing, or possibly constant marginal costs of production.

To estimate the post-contamination supply function, the pre-contamination supply function that was estimated using Gumerman's model is added to the marginal cost of removing nitrate from the water supply. The assumption of marginal costs is not unrealistic but it may not be the typical case. Therefore, it may be more reasonable to actually estimate a pre-contamination water supply function or use a previously estimated water supply function.

Third, the water cost model could be generalized to estimate the economic damages of public water contamination by other nonorganic as well as organic substances. For example, baseline engineering data can be entered into Gumerman et al's computer model so as to estimate the marginal treatment costs of removing a contaminant (other than nitrate) from the water supply. This estimated marginal cost of treatment is added to the pre-contamination marginal cost of supplying water. This sum is the post-contamination water supply function. This post-contamination water supply function replaces the post-nitrate contamination water supply function in the water cost simulation model.

Finally, a researcher may want to relax the assumption of marginal cost pricing. As a first approximation, marginal cost pricing is a suitable pricing mechanism. However, using marginal cost pricing might not be possible in many cases. This may occur due to a lack of knowledge of a firms' cost structure. Therefore, flexibility in the pricing scheme may be more realistic.

Policy Implications

This section discusses a number of policy implications. These implications involve the results obtained from the model as well as the model structure.

Many socioeconomic factors affect the distribution of economic damages inflicted upon residential users of a public water system by groundwater contamination. Therefore, a policy analyst may want to take into account these socio-economic factors when estimating the impact of groundwater contamination.

One socio-economic factor that affects the size and distribution of economic damages is the size of the community served by the public water system. It was demonstrated that smaller size communities suffer greater damages per household from groundwater contamination as compared to larger size communities, everything else equal.

Income also affects the distribution and size of economic damages due to groundwater contamination. As shown in Chapter IV, as the per capita income of the community increases the economic damages per household decreases.

An important result of the model is that marginal cost pricing leads to firm losses when the firm has decreasing marginal costs of producing potable drinking water. With decreasing marginal costs, average costs of production are greater. Therefore, with marginal cost pricing the firm has a loss on each unit of water sold. The loss is the difference between average cost and marginal cost.

With the firm losing money on each unit of water sold, it may be desirable to have a second best policy. By second best we mean that it may be more reasonable to have a policy that allows the firm to cover its losses while simultaneously minimizing damages (George and Shorey, 1978). Marginal cost pricing results in the smallest economic damages, however, this pricing mechanism results in firm losses that must be covered by some method (George and Shorey, 1978).

One method to cover firm losses is for the local governmental unit to subsidize the firm for pricing at marginal costs. This method, however, has many drawbacks. First, the government may need to raise taxes to pay for the subsidy. Raising taxes would increase economic damages in the economy unless of course the taxes could be raised in a lump sum manner (Diamond and McFadden, 1974). However, since water consumption is relatively price inelastic, a government tax on water consumption may only cause small economic damages. The economic damages due to taxation may also depend upon the administrative costs of collecting and dispersing the tax revenues back to the firm.

Second, subsidizing a firm may reduce firm efficiency. Subsidizing firm losses may cause managers to be lax in their job causing increased firm losses (George and Shorey, 1978).

A second method which could be used to reduce or eliminate firm losses is to allow the firm to price at average costs. Average cost pricing may cause smaller economic damages than subsidization (George and Shorey, 1978). Nevertheless, the type of pricing mechanism to be used by the water system is an important area of research.

Another implication of the study is that groundwater contamination can cause substantial economic damages. This implies that policy analysts may want to find alternative methods for dealing with groundwater contamination that reduces the level of economic damages. However, estimating economic damages is one element of policy for dealing with groundwater contamination. For example, policy analysts may want to estimate the costs of preventing groundwater contamination. Alternatively, the policy analyst could estimate economic damages using alternative treatment and nontreatment methods.

Summary

This research has shown that nitrate contamination can lead to substantial economic damages. This may require public agencies to find solutions to reducing or eliminating the economic damages associated with groundwater contamination of public water supplies. Public agencies need to look at the efficiency and distributional effects of groundwater contamination. Therefore, future research is needed to estimate the economic costs and benefits of other groundwater management policies. For any given contamination event, the various management policies could be compared so as to chose the policy scheme that results in the lowest costs and highest benefits. Such research would shed much light on the problem of groundwater contamination.

APPENDIX

APPENDIX

An Algebraic Description of Economic Damages

In this appendix, pre- and post-contamination equilibria are described algebraically.

Marginal costs are

(3-8) $MC = b$ if $q < qo$

(3-9) $MC = b + A'(a+1)*y^{a}*q^{b}*E^{c}$ if $q \geq qo$

where MC is marginal cost, b is the pre-contamination price of water, q is the quality of water as measured by the concentration of nitrates in milligrams per liter of water, qo is the water quality standard in milligrams of nitrate per liter of water, and the other variables and coefficients are the same as described above for equation 3-3.

Expenditures on water are

(3-6) $E = b * Q$ if $q < qo$

(3-7) $E = P1 * Q$ if $q \geq qo$

where E is expenditures on water, b is the pre-contamination price of water, Q represents the FB water demand function, and P1 is the post-contamination price of water.

Resource costs are

$$(3\text{-}10) \quad C = b * y \qquad \text{if } q < qo$$

$$(3\text{-}11) \quad C = b * y + (a+1) * A' * y^{a} * q^{b} * E^{c} \qquad \text{if } q \geq qo$$

where C is resource costs, y is quantity of water demanded, and the coefficients and variables are the same as discussed above.

Consumer surplus is

$$(3\text{-}12) \quad CS = \int_{b}^{d} Gdp \qquad \text{if } q < qo$$

$$(3\text{-}13) \quad CS = \int_{P1}^{d} Ddp \qquad \text{if } q \geq qo$$

where CS is consumer surplus, G represents the FB demand function, b is the pre-contamination price of water, P1 is the post-contamination price of water, and d is the price of water at the vertical intercept of the demand curve.

Producer surplus is

$$(3\text{-}14) \quad PS = 0 \qquad \text{if } q < qo$$

$$(3\text{-}15) \quad PS = - \int_{P1}^{C} MCdp \qquad \text{if } q \geq qo$$

where PS is producer surplus, MC is marginal costs of treatment, and C is the price of water at the vertical intercept of the post-contamination supply curve.

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