Statistical Analysis of Drinking Water Treatment Plant Costs, Source Water Quality, and Land Cover Characteristics

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Abstract

Revisiting an earlier study conducted by The Trust for Public Land in 2004, this research brings new data and methodologies to offer insight on the impact of the decline of forest cover and the increase of agriculture or urban land cover in a drinking water source drainage area on the water quality for that drinking water source and the drinking water treatment costs. The statistical analyses showed that there were significant relationships among percent land cover, source water quality, and drinking water treatment costs. The data exhibited high variability indicating possibly unaccounted constraining factors – such as the differences in water treatment plant practices/processes and hydrological, geological, and regional differences, which remain as future considerations.

I. Project Summary

This study considers the impacts of declining forest cover on drinking water treatment costs. Even though research exists on land cover's impact on water quality, little is known on the associated impact on drinking water treatment costs. The Trust for Public Land (TPL) began studying this subject in 2004. The preliminary study suggested that costs of treatment for utilities using surface water supplies varied depending on forest cover in the source area. Specifically, the less forest in a source water drainage area, the higher the water treatment costs. Therefore, it is of interest to examine whether the percent of forest cover[1] in a source water watershed is negatively related to drinking water treatment costs, i.e., as forest cover decreases, drinking water treatment costs increase. The analyses were conducted in two phases: 1) first analysis investigates

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[1] The forest land use class does not distinguish between protected forests or actively managed forests. Literature suggests that undisturbed forests generally create very little erosion while certain forestry-related activities such as road construction, movement of logs, and site preparation can have an impact on erosion (Binkley and Brown 1993; Brown and Binkley 1994; Dissmeyer 2000). Best management practices can, however, mitigate much of the disturbance of forestry practices. The forested Quabbin watershed that serves as Boston's water supply, for example, is actively managed. Its forestry practices have been certified sustainable by the Rainforest Alliance SmartWood and forestry management occurs parallel to drinking water management (Barten, Kyker-Snowman et al. 1998).

whether water quality decreases as percent forest cover decreases; and 2) second analysis investigates whether treatment costs increase as water quality decreases.

This round of research and analysis included extensive data collection, advanced data processing, and statistical analyses of additional variables to examine how source water quality, drinking water treatment cost, and land cover characteristics are related to one another. In addition to evaluating the percent forest cover of the entire source water watershed, this study considered urban land cover, agricultural land cover, and non-forest vegetation cover. The relationship of a 100-ft and 300-ft buffer of the waterbodies in the source water watershed was tested separately. The study also included testing of three different variables to represent water quality, one of them is an index that takes into account multiple parameters, such as TOC, alkalinity, and turbidity.

Overall, this study found that there were significant relationships among source water quality, percent land cover, and drinking water treatment cost. Increased percent agriculture and urban cover were significantly related to decreased water quality, while decreased forest land cover was significantly related to decreased water quality. Further, low water quality was related to higher treatment cost. High percent land cover by non-forest vegetation was significantly related to low treatment cost, while high percent land cover by urban area was related to high treatment cost.

Section II provides a review of relevant literature, Section III present the study methodology, and Section IV describes statistical findings. Finally, Section V presents concluding remarks including observations and recommendations for future study.

II. Literature Review and Background on Study Subjects and Assumptions

Numerous reports make a narrative case linking forests to drinking water quality or treatment costs. However, these reports rarely include data-supported research and statistical studies. Notable narrative references include: *Land Use Effects on Streamflow and Water Quality in the Northeastern United States* (de la Cretaz and Barten, 2007), which provides an exhaustive review of the literature regarding the link from forests to water quality and the effects from converting forests to agriculture or development; *Liquid Assets: the Critical Need to Safeguard Freshwater Ecosystems* (Postel, 2005), a World Watch paper relating the history of human influence on water sources, which includes case studies of watershed-based actions that reduced treatment costs and policy recommendations; *Running Pure: The Importance of Protected Areas to Drinking Water* (Dudley and Stolton, 2003), a World Wildlife Fund/World Bank report, which finds that 33% of the world's 100 largest cities obtain their drinking water primarily from forested watersheds; and *Drinking Water from Forests and Grasslands: a Synthesis of the Scientific Literature* (Dissmeyer, 2000), a Forest Service literature synthesis.

The closest research objective and methodology to this study is a series of economic studies relating turbidity levels to drinking water treatment costs (explored in detail in Section II(E)). But first, there is research focused on interconnected themes that offer useful background information for this study: the relationship between forest land and water volume, velocity, and pollutants; the impact of forest conversion on development; and the implicit relationship between forests and drinking water. Later in this section, background information is provided on drinking water treatment processes, changing drinking water quality treatment standards, and common examples of treatments plants that have avoided filtration costs with watershed conservation.

A. The relationship between forest lands and water volume, velocity, and pollutants

One of the basic relationships between forests and water concerns forests' ability to infiltrate water, slowing and reducing the volume of storm flows. In an undisturbed forest, there is increased soil infiltration of water because of the leaf litter layer and the pore spaces in the organic soil horizon (Sartz, 1969; from de la Cretaz and Barten, 2007). As forests slow down water, the velocity of storm flow and peak discharge decreases. The scouring effect of high velocity water also diminishes and thus, sediments and the pollutants that are carried by sediment are reduced (Phillips and Lewis, 1995; Weiss, 1995; from Dissmeyer, 2000).

Forests can also trap pollutants attached to sediments in the forest litter layer. This forest layer "protect[s] the soil from raindrop impact particle dislodging, promotes maximum infiltration of water into the soil and slows downslope water movement by myriad barriers of leaves, twigs and debris" (Dudley and Stolton 2003, p.60). Decreasing sediments by both trapping them in the sediment layer and reducing storm event channel scouring is important for water quality because "sediment-related discharges contribute about 98 percent of total suspended solids, 52 percent of 5-day BOD, 88% of total nitrogen, and 86% of total phosphorous in the nation's waterways" (Gianessi, Peskin et al. 1986; from Holmes 1988, p.360). The forests buffering streams, called riparian forests, are especially efficient in trapping sediments and an 80% retention is normal (Uusi-Kamppa, Turtola et al. 1997; Lee, Isenhart et al. 2000; from de la Cretaz and Barten 2007).

Also, forests keep pollutants out of water through uptake by plants and microbes in the soil (de la Cretaz and Barten 2007, p.50). Forests cycle nutrients from food source, to storage in plant matter, to nutrient release during decay, and back into plant uptake(Likens, Bormann et al. 1967; Likens, Bormann et al. 1977; from de la Cretaz and Barten 2007). Very little of the nutrients are exported to water bodies unless there is excess input of nutrients from agricultural fertilization or air deposition from power plants and vehicle emissions. In these instances, forests are "saturated" as atmospheric deposition of nitrogen exceeds their uptake capacity (Murdoch and Stoddard 1992; Magill, Downs et al. 1996; from Barten, Kyker-Snowman et al. 1998; USGS 1999; Paerl, Dennis et al. 2002; from de la Cretaz and Barten 2007). One study found that up to 25% of the nitrogen in the Chesapeake Bay has been linked to atmospheric deposition (Fisher and Oppenheimer 1991; Nixon, Ammerman et al. 1996; from de la Cretaz and Barten 2007).

Forests' ability to keep other pollutants out of streams depends on the characteristic of the chemical. An extreme simplification of this issue would be to note that pollutants that are in a dissolved form may be degraded in forest soils, and pollutants that attach to sediments may be trapped in forest litter as discussed above. For an in-depth discussion of forests' impact on pesticides, metals, and coliform bacteria, see de la Cretaz (2007) p. 59-64 and p. 199-120.

B. The impact of forest conversion to agriculture and development

Another way to consider the link between forests and water quality is to study the relationship between different types of land use (forest, agriculture, and urban) and water quality. Unfortunately, there are many potential confounders in establishing this link. Atmospheric deposition, for example, is a factor external to land use that could degrade water quality regardless of the functions forests provide in nutrient cycling and sediment retention. Nevertheless, there is a body of literature examining correlations between land use and downstream water quality.

In a USGS study of nutrients in undeveloped watersheds (mostly forested), Clark et al. (2000) found that forests "produced the best water quality in the country" (Wear and John G. Greis 2002, Ch. 21). In a large-scale watershed study analyzing 16 river mixed-use basins in the Northeast, Boyer et al. (2002) found that nitrogen loading reduced as the percentage of forested land increased (de la Cretaz and Barten, 2007). In a study of Ontario watersheds, Sliva and Williams (2001) found that forested lands were important in mitigating water quality degradation (Gabor, North et al. 2004). Houlahan and Findlay (2004) found a negative correlation between stream nutrient levels and forest cover over 2000 meters upland from the stream.

Agricultural and urban lands have both been correlated to degraded water quality (Sliva and Williams 2001; Boyer, Goodale et al. 2002). As compared to forest land, land in agricultural uses can have nutrient concentrations nine times higher, and sediment discharges five times higher than forested watersheds (Omernik 1977; Gianessi, Peskin et al. 1986; from Brown and Binkley 1994). Although agricultural land use has been linked to degraded water quality, four studies referenced in Gabor et al. (2004, p.11) found reduced surface and/or groundwater nutrients when agricultural Best Management Practices had been implemented (Honisch, Hellmeier et al. 2002; Meals and Hopkins 2002; Schilling 2002; Udawatta, Krstansky et al. 2002).

Stein et al. (2005) found that 10.3 million acres of forests were converted into developed areas between 1982 and 1997 nationwide. Using Stein et al's work, Barnes et al. (2007) projected that 12.3 million acres of forest land in a 20-state Northeast-Midwest region would be lost to development between now and 2030, an area close to the size of Vermont and New Hampshire (Little 2006). Development has both short and long-term impacts during construction and post-construction.

As forest lands are developed into urban and suburban neighborhoods, there is a short-term but significant increase in sedimentation during construction. An early paired watershed study found that sediment concentration downstream of construction sites without proper sediment control were up to 70 times the concentration of sediments downstream of forested and agricultural lands (Wolman and Schick 1967; de la Cretaz and Barten 2007). Weiss (1995) cites sediment loads 1,000-2,000 times higher in uncontrolled construction areas as opposed to forests (Dissmeyer 2000).

After construction, impacted soil has a reduced ability to slowly soak up and release water during storms, which increases flooding and scouring. The impervious surfaces that follow development—(e.g., roofs, driveways, and roads)—increase the velocity of precipitation and scouring of the stream channel. Schueler (1994; 2003) found a threshold for changes in hydrologic functions when impervious surfaces covered 5-10% and dramatic hydrologic changes above 25% impervious (Braden and Johnston 2004). Walsh et al. (2005) describe the set of negative impacts from urbanization, such as increased flashiness and peak flows, increased nutrients, etc, as "urban stream syndrome."

Development can also have water quality implications for urban water and storm water infrastructure. In cities that combine their storm and sewer infrastructure, increased peak volumes of storms often surpass the volume that the wastewater treatment plant was designed for, and all surplus combined storm water and raw sewage is discharged directly into streams. This is called Combined Sewer Overflows, or CSOs. Many of the 772 CSO drainage systems in the US are located in the Northeast (U.S. EPA 2004; from de la Cretaz and Barten 2007, Ch. 8). U.S. Environmental Protection Agency (U.S. EPA) notes that thousands of CSO events occur each year nationally (U.S. EPA 2001).

C. The implicit relationship between forests and drinking water treatment

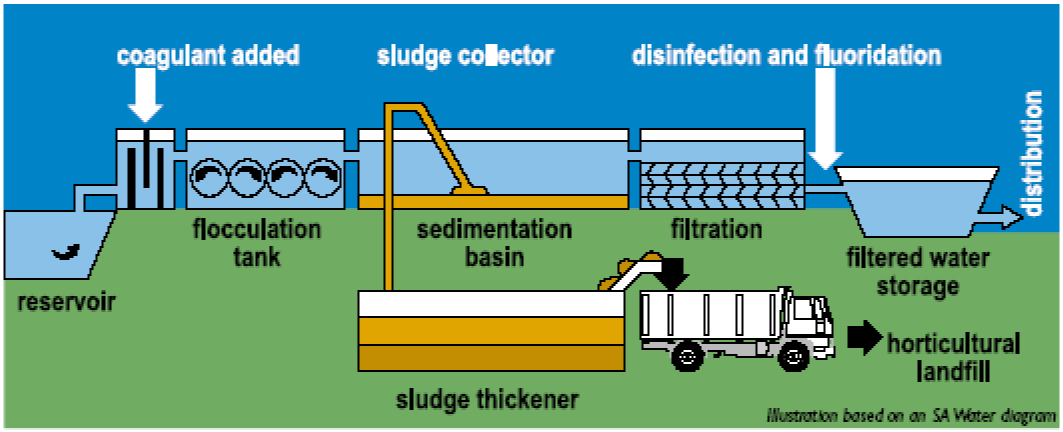
In a study modeling over 40 years of water flow and precipitation in the contiguous United States, Brown, Hobbins and Ramirez (2008) found that 53% of the nation's water supply originates on forests. As those forests are converted to other land uses, the benefits from forests will diminish, and drinking water treatment plants will have to filter more pollutants. However, water treatment plants cannot filter all pollutants (Paul and Meyer 2001; from de la Cretaz and Barten 2007, Ch. 8). In 1996, U.S. EPA amended the Safe Drinking Water Act to reflect a need for a multi-barrier approach, starting with source water protection (U.S. EPA 2007). These discussions relating forests and water quality establish the question whether forests reduce drinking water treatment costs by naturally filtering the raw water that ultimately enters drinking water treatment plants.

D. Drinking water treatment plant processes

The EPA provides a simplified description of drinking water treatment processes on its website as follows:

> "**Coagulation [/Flocculation]** removes dirt and other particles suspended in water. Alum and other chemicals are added to water to form tiny sticky particles called "floc" which attract the dirt particles. The combined weight of the dirt and the alum (floc) become heavy enough to sink to the bottom during sedimentation.
> **Sedimentation:** the heavy particles (floc) settle to the bottom and the clear water

moves to filtration. **Filtration:** the water passes through filters, some made of layers of sand, gravel, and charcoal that help remove even smaller particles. **Disinfection:** a small amount of chlorine is added or some other disinfection method is used to kill any bacteria or microorganisms that may be in the water. **Storage and Transport:** water is placed in a closed tank or reservoir in order for disinfection to take place. The water then flows through pipes to homes and businesses in the community." (U.S. EPA 2007)



(Cooperative Research Centre (AU) 2003)

If the incoming raw water quality is high, treatment plants may be able to bypass flocculation and sedimentation processes (Holmes 1988). In a dataset of 430 U.S. water utilities, Holmes (1988) found that most utilities with raw turbidity levels over 10 NTUs had adopted conventional versus direct filtration process. This indicates that there may be a sediment-related water quality threshold for infrastructure investment. In other cases where water quality is poor, plants may need to augment conventional treatment with additional processes like membrane filtration or activated carbon (Cooperative Research Center (AU) 2003). Seven U.S. cities with excellent water quality have saved from $500,000-$6 billion in avoided water treatment infrastructure costs. (See Table 1 in Postel 2005, p. 29.)

In addition to potential increases in capital costs relating to poor water quality, plants may also face variable costs related to different levels of raw water quality. For example, plants may need to add more chemicals like coagulants, disinfectants, and pH adjusters as water quality degrades (Dearmont, McCarl et al. 1998). In an analysis of over 100 drinking water price models (directly related to cost), Espey et al. (1997) found weather to have an effect on price, presumably through sediment and pollutant loads associated with storm flows. While surveying 24 treatment plants, managers informed Forster (2001) that chemical costs were the variable costs most affected by raw water quality.

E. Review of economic studies suggest a link between turbidity and drinking water treatment plant costs

Four economic studies investigated the effect of turbidity levels in raw water on drinking water treatment costs (Forster et al., 1987; from Holmes 1988; Holmes 1998; Dearmont, McCarl et al. 1998; Forster and Murray 2001). All studies reported a positive relationship between sediment or turbidity levels and drinking water treatment costs. Elasticities reported in the studies indicated that for a 1% increase in sediment or turbidity levels would lead to a 0.07%-0.30% increase in treatment costs. All of the studies assumed that fixed costs such as capital investments would not vary over the short term and thus looked only at variable costs.

While studies differed in some of the variables used in the cost equations, all studies used either turbidity or sediment loading rates as an indicator of raw water quality. Forster et al. (1987) modeled costs on turbidity, volume treated, storage capacity, and watershed soil erosion rates. Holmes (1988) considered regional sediment loading rates, raw water storage capacity, and streamflow. Dearmont et al. (1998) modeled treatment cost on turbidity, pH, volume of water treated, a contamination dummy variable (contamination present or absent), and rainfall. Forster et al. (2001) modeled the same variables as their 1987 study, but also examined agricultural practices, pesticide application, and area of the watershed.

Another economic study determined treatment costs by using water demand and supply models (Piper 1998). During the process, the following variables were considered in treatment cost calculations: water hardness, volume treated, region (to capture differences in regulations or environmental differences), population density (to capture cost of delivery), debt/asset ratio (to see if affects cost), and a groundwater dummy variable indicating presence or absence of groundwater in the water supply. Water quality, the volume of water treated, the population density of the service area, and the source of water supplies all significantly affected the cost per unit of water delivered.

F. Common examples of avoided filtration costs

Some oft-quoted cases of avoided filtration costs are the New York City watershed, which avoided $6 billion in filtration plants and operating and maintenance expenses (Postel 2005) and three watersheds in the Boston area that received a filtration waiver, avoiding costs of about $200 million (Barten, Kyker-Snowman et al. 1998).

While determining the treatment cost avoidance from protecting forests is a valuable exercise, some researchers warn that this dollar value should not be interpreted as either the value of all ecosystem services or a willingness-to-pay value. Banzhaf and Jawahar (2005) note that "just because a service costs a given amount to provide, does not signify that households would receive that level of benefits if it were provided." Banzhaf and Jawahar later argue that the famed NYC watershed case study does not consider "ecological or amenity benefits of the land," noting that non-market valuation studies have never been conducted on the multiple ecosystem services from protected areas in the watershed-and the avoided costs should not be seen as the value of clean water. Braden and Johnston (2004) note that the cost of providing an ecosystem good or service is not the same as willingness-to-pay, but it may be the only available proxy.

G. Changing water quality standards

While this literature review was not targeted specifically towards policy drivers for drinking water standards, there is evidence of a greater demand for safe drinking water, from stricter standards to citizen willingness-to-pay studies. To meet drinking water quality standards implemented since the late 1980s, researchers expect that treatment plants across the U.S. will have to invest hundreds of billions in infrastructure (Dissmeyer 2000, Ch. 4; Maxwell 2005). In an article reviewing top trends from the water industry's perspective, Maxwell notes that although the stringency of other key environmental regulations have fluctuated with the political climate, water quality standards have steadily tightened (2005). Demand for standards may come from an informed public. In studies of citizen willingness-to-pay for water quality improvements, knowledge of water quality problems was a significant variable (Powell and Allee 1990; Jordan and Elnaheed 1993; from Piper 2003). Given a suite of reasons for protecting undeveloped land, surveys found that individuals consistently prioritize environmental objectives like protecting water quality, wildlife habitat, and natural features (Kline and Wichelns 1996; Rosenberger 1998; Krieger 2004; from Banzhaf and Jawahar 2005). In a joint Nature Conservancy and Trust for Public Land poll, protecting water quality was the number one reason that voters support new funding for land conservation (Public Opinion Strategies and Fairbank 2004).

III. Methodology

In this section, the collection and the preparation of the data are discussed in detail. Specifically, data were collected from drinking water treatment plants, land cover statistics for source areas were generated, and a water quality indicator was developed for each drinking water treatment plant.

A. Collecting data from drinking water treatment plants

The data on drinking water treatment plants were collected from the surveys from 60 unique water treatment plants,[2] of which twenty plants were surveyed in 2004 and 40 plants were surveyed in 2006.

Initially, TPL identified drinking water treatment plants with intakes from surface water sources, excluding those extracting water from extremely large bodies of water, such as Lake Michigan. All plants were pre-screened to meet these criteria: 90% or more of the raw water treated comes from surface water sources, the drinking water source areas are smaller than 500 square miles, and the plant treats no less than 1 million gallon per day

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[2] We surveyed drinking water treatment plants as opposed to drinking water suppliers because we were seeking data specific to individual drinking water treatment plants, such as the quality of raw water as it enters a plant and costs associated with treating that raw water. Working with drinking water treatment plants presented less confusion than if we had surveyed water suppliers generally, who often manage multiple plants and combine data. However, one drawback is that when we surveyed plants run by suppliers who had other plants under their purview, some were unable to present exact cost data because costs were based on the collective enterprise and not isolated for specific plants.

and no more than 100 million gallons per day. In 2004, twenty plants participated in the surveys.

In 2006, the selection of the plants were limited within our study area of interest and the plants at the outset that categorically lacked data were further eliminated. Specifically, the study area of interest includes the plants in the United States Forest Service's (USFS) Northeastern Area, a 20-state area which covers New England, the Mid-Atlantic, and portions of the upper Midwest. Further, the states that did not have critical landcover data available in a Geographic Information System (GIS) format, as of 2001, were excluded from the analysis.[3]

The plants in states that either had not produced hydrologically accurate source area delineations or were unwilling to release them were also excluded. Source area delineations for states were obtained from U.S. EPA through a confidentiality agreement. Fifteen of the 20 states had submitted data accordingly. A couple of other states granted access to their data with separate confidentiality agreements. Unfortunately, even among the states that provided data, many of the source areas were not hydrologically defined, but truncated at artificial boundaries such as political borders or a pre-determined distance from a drinking water intake.

From the states with accurate source area delineations, an additional 40 plants were selected for the survey in 2006. Using U.S. EPA's Safe Drinking Water Information System (SDWIS) and GIS database of source area delineations, the plants were selected according to the same criteria used in 2004 study: source area less than 500 square miles; treating 90% or more surface water; and treating between 1MGD and 100MGD.

B. Generating land cover statistics for source areas

In 2004, even though two-thirds of the treatment plants surveyed provided cost, water quality and treatment process data, accurate source area delineations were not readily available. A couple of water treatment plants provided drainage area data and U.S. EPA provided specific source areas for some additional water treatment plants, which was used to determine land cover quantities by typology in those drainage areas.

If no data was provided by the U.S. EPA or the water treatment plant, a drainage area was created in GIS based on specific source area information from the water treatment plant or supplier. In some cases, the water intake coordinates were provided by the water treatment plant. In cases where the water treatment plant's water intake coordinates were not provided, a drainage area was created in GIS based on the combination of reported drainage size, (acres or square miles) established sources (rivers, lakes, etc.) for the water treatment plants, and other information provided (such as proximity of intake estimated by plants to specific landmarks). For example, if a water treatment facility water intake

[3] 2001 National Land Cover Data produced by the Multi-Resolution Land Characteristics Consortium came on line in January 2007 for the entire country and we could have used that data for the entire study area. However, at the time we began this study we did not know that data would become available so quickly, and so we eliminated a couple of states from consideration on the basis of not having landcover.

is located on a river with a source area of 100 square miles, the water intake was mapped on the river at the approximate distance from the water treatment plant that was provided (using the address of the plant and hydrology and topography maps) and a source area (reaching all headwaters) that is 100 square miles in size was created.

In all instances, the source area delineations were used as landcover boundaries and statistics within those boundaries were generated using the 2001 National Land Cover Dataset (NLCD), which is based primarily on data collected in 2000. NLCD characterizes all the features within the boundaries into one of 21 categories, using the Anderson land use and land cover classification system. Then, the data were reclassified into six categories: forest, non-forest vegetation (all vegetation that is not forested and does not fit into one of the other 5 categories), wetland, urban, agriculture, and landform feature. (As an intermediary step, a category for water was created to capture that data and then factor it out.) Additionally, these five land cover classifications were developed for a 100-foot buffer and a 300-foot buffer around water bodies within each source area. All data were processed using ESRI ArcInfo ArcGIS 9.0 software.

C. Developing a water quality indicator for each drinking water treatment plant

An index for water quality was developed for testing the relationship between water quality and treatment costs and the relationships between land cover and water quality. An alternative index to the U.S. EPA water treatment plant model index, which is used for assessing the cost of regulatory actions, was developed from the raw water quality parameters provided by the individual treatment plants. These water quality parameters are total organic carbon (TOC), turbidity, alkalinity, conductivity, temperature, and pH.

It is generally known in the water treatment field that as TOC increases, water quality tends to deteriorate and water treatments costs increase, all else being equal. High turbidities and alkalinities will further elevate costs and/or reduce finished water quality. Even though pH may also be important, the primary affect is already reflected in the alkalinity. With these considerations, it was determined that the index would be developed from the following parameters: TOC, turbidity, and alkalinity. An excellent distribution of raw data within each of these three parameters was confirmed, and it was determined that no internal correlations existed between them (March 2007 correspondence with Dr. David Reckhow).

In the absence of specific regulated contaminants, and with incomplete dissolved organic carbon (DOC) data, TOC was chosen as the best available indicator of general water quality. To create one single index of water quality, an equation that basically incorporates turbidity and alkalinity into the TOC-based indicator was developed based on the known relationship between TOC and the other water quality parameters. The index, referred to as the "Water Quality Index," was calculated for each plant by taking the mean annual TOC[4] and adding to this number the median annual alkalinity and turbidity multiplied by coefficients. The coefficient for alkalinity (0.003) was derived

[4] The annual mean for TOC and turbidity were created by averaging all monthly median measures. Data for alkalinity were collected as the median measure for the year.

from the "Enhanced Coagulation" portion of the Disinfectant/Disinfection Byproduct Rule. This number was used by the U.S. EPA in developing the minimum TOC removal criteria for waters of different initial TOC and alkalinity values. The turbidity coefficient was selected from experience and the relative effect of turbidity on coagulant doses and sludge production.

The Water Quality Index preserves the order of magnitude in water quality. In other words, the plants with higher water quality index have better raw water quality than plants with lower numbers. The equation for the water quality index is the following:

Water Quality Index = 1/(median TOC + 0.003 *(median Alkalinity) + 0.01*(median turbidity))

Note that Water Quality Index does not have multiplicative inference on water quality. For example, an index of .14 does not have water quality two times lower than a plant with an index of .28. The water quality index ranged from 0.14516 to 0.6978.

IV. Statistical Findings

A. Description of Data

Table 1 contains descriptive statistics for the variables in this analysis. There were a total of 60 observations (plants) with a few missing water quality, land cover, or treatment information.

Turbidity had a range between 0.1355 NTU and 20.85 NTU and TOC had a range between 1.3mg/l and 6.6mg/l. As noted above, the water quality index had a range between 0.14516 and 0.698. There is much variation in the land cover category. The greatest range was in forest land cover, which varied between 0 and 0.9915 (0% and 99.15%). The chemical treatment cost had a range of $14.26 per year per million gallon and $391.39 per year per million gallon.

Table 1 Descriptive Statistics

Variable		Mean	Std. Dev.	Minimum	Maximum
Water Quality	Turbidity (NTU)	3.40296	4.56891	0.13550	20.85000
	TOC (mg/l)	3.32135	1.39768	1.30000	6.60000
	Water Quality Index	0.34347	0.15344	0.14516	0.69784
Land Cover Proportion	Agriculture	0.20491	0.21777	0	0.76920
	Forest	0.60327	0.23774	0.07790	0.99150
	Non-Forest	0.04516	0.06176	0	0.25760
	Urban	0.10241	0.09003	0.00270	0.42600
	Agriculture within 100ft Buffer	0.10970	0.13022	0	0.49982
	Forest within 100ft Buffer	0.61965	0.18299	0.29839	0.99466
	Non-Forest within 100ft Buffer	0.03731	0.05589	0	0.26583
	Urban within 100ft Buffer	0.06732	0.04821	0.00513	0.18755
	Agriculture within 300ft Buffer	0.13428	0.15147	0	0.57413
	Forest within 300ft Buffer	0.62736	0.18282	0.23882	0.99238
	Non-Forest within 300ft Buffer	0.03972	0.05557	0	0.25386
	Urban within 300ft Buffer	0.08066	0.05401	0.00472	0.23131
Chemical Treatment Cost (dollar/mill Gal a year)		94.37211	76.41155	14.25561	391.38943

In Tables 2-5, the correlation analyses showed that water quality was correlated with the land cover characteristics. Turbidity seemed negatively correlated with forest land cover (r=-0.508) and positively correlated with urban land cover (r=0.698). The data seemed to indicate that lower turbidity was related to higher forest land cover and at the same time, higher turbidity was related to higher urban land cover. TOC appeared to be negatively correlated with forest land cover within 100ft buffer (r=-0.40). Similarly, water quality index seemed to be positively correlated with forest land cover within 100ft (r=0.567). Chemical treatment cost appeared to be correlated with TOC at correlation r=0.434 indicating higher TOC levels have higher treatment cost. Chemical treatment cost showed low correlation with land cover.

Table 2 Correlations between Water Quality and Land Cover

Land Cover	Turbidity	TOC	Water Quality Index
Agriculture	0.28335	0.17538	-0.24857
Forest	-0.50789	-0.33599	0.46264
Non-Forest	0.37409	0.18273	-0.32266
Urban	0.69819	0.24920	-0.31109
Agriculture within 100ft Buffer	0.27215	0.00302	-0.05190
Forest within 100ft Buffer	-0.33078	-0.40020	0.56697
Non-Forest within 100ft Buffer	-0.13331	0.25550	-0.36114
Urban within 100ft Buffer	0.38963	0.14836	-0.16615
Agriculture within 300ft Buffer	0.28013	0.01479	-0.09354
Forest within 300ft Buffer	-0.41562	-0.33870	0.50828
Non-Forest within 300ft Buffer	-0.09666	0.19778	-0.32630
Urban within 300ft Buffer	0.39456	0.15520	-0.18721

Table 3 Correlation between Chemical Treatment Cost and Water Quality

	Turbidity	TOC	Water Quality Index
Chemical Treatment Cost	0.11470	0.43399	-0.33513

Table 4 Correlation between Land Cover and 2004 Chemical Treatment Cost

Land Cover	Chemical Treatment Cost
Agriculture	0.05099
Forest	-0.09102
Non-Forest	-0.35073
Urban	0.28154
Agriculture within 100ft Buffer	-0.00506
Forest within 100ft Buffer	-0.13566
Non-Forest within 100ft Buffer	-0.31217
Urban within 100ft Buffer	0.07918
Agriculture within 300ft Buffer	0.02922
Forest within 300ft Buffer	-0.11822
Non-Forest within 300ft Buffer	-0.31753
Urban within 300ft Buffer	0.11288

Table 5 Correlation between Land Cover and 2006 Chemical Treatment Cost

Land Cover	Chemical Treatment Cost
Agriculture	0.25481
Forest	-0.27270
Non-Forest	-0.09804
Urban	0.21298
Agriculture within 100ft Buffer	0.17665
Forest within 100ft Buffer	-0.09213
Non-Forest within 100ft Buffer	-0.07396
Urban within 100ft Buffer	0.10779
Agriculture within 300ft Buffer	0.17612
Forest within 300ft Buffer	-0.10338
Non-Forest within 300ft Buffer	-0.02115
Urban within 300ft Buffer	0.06814

In summary, there appeared to be some relationships between source water quality, and land cover characteristics. Based on these exploratory analyses, we can see how some of these variables could be included in a statistical model in order to explain the changes in the treatment cost and the quality of water and confirm their scientific relevance. Nonetheless, due to severe skewness and high variability within the data, the relationships among these variables needed to be further investigated with regression models.

B. Analysis of Source Water Quality, Land Cover, and Chemical Treatment Cost

The relationships between source water quality, land cover, and chemical treatment cost were examined. Since the data on source water quality measurements including turbidity, TOC, and water quality index were only available for 2006, the number of observations for the analysis was limited to 40 plants. Each of these variables was analyzed using a general linear model with land cover characteristics as predictor variables. A general linear model uses the method of least squares to fit the models. The general linear model can be written as $\vec{Y} = \vec{\beta}\vec{X} + \vec{\varepsilon}$, where $\vec{Y}$ is the vector of observed responses, $\vec{X}$ is the design matrix of predictor variables, $\vec{\beta}$ is the vector of regression parameters, and $\vec{\varepsilon}$ is the vector of random errors. The random errors are assumed to be independent and normally distributed with a common variance. For example, the response variable $\vec{Y}$ was a source water quality and the predictor variables $\vec{X}$ were percent land covers. Since the source water quality measurements were positively skewed, logarithmic transformation was applied.

The tables included in this section show some of the key statistics from the significant general linear models such as R^2 and parameter estimates for $\vec{\beta}$. The value of R^2 represents the variation in the data explained by the model with the predictor variables. For example, the model with agriculture, forest, and urban land cover explained 65.67% of variation in Turbidity across the drinking water plants. The parameter estimate $\hat{\vec{\beta}}$ is the estimated parameter value for $\vec{\beta}$ based on the data using least square method. $SE(\hat{\vec{\beta}})$ is the standard error for the parameter estimate $\hat{\vec{\beta}}$. The t-value is the location of $\hat{\vec{\beta}}$ in the *Student's t*-distribution. Finally, the p-value indicates whether $\hat{\vec{\beta}}$ is significantly different from 0. When the p-value is less than 0.05, then the slope of the model regression, $\hat{\vec{\beta}}$ in this case, is significantly different from 0 (a constant relationship between the dependent variable and predictor variables.)

Figure 1. Scatter Plots of Log(Turbidity) vs. Land Cover

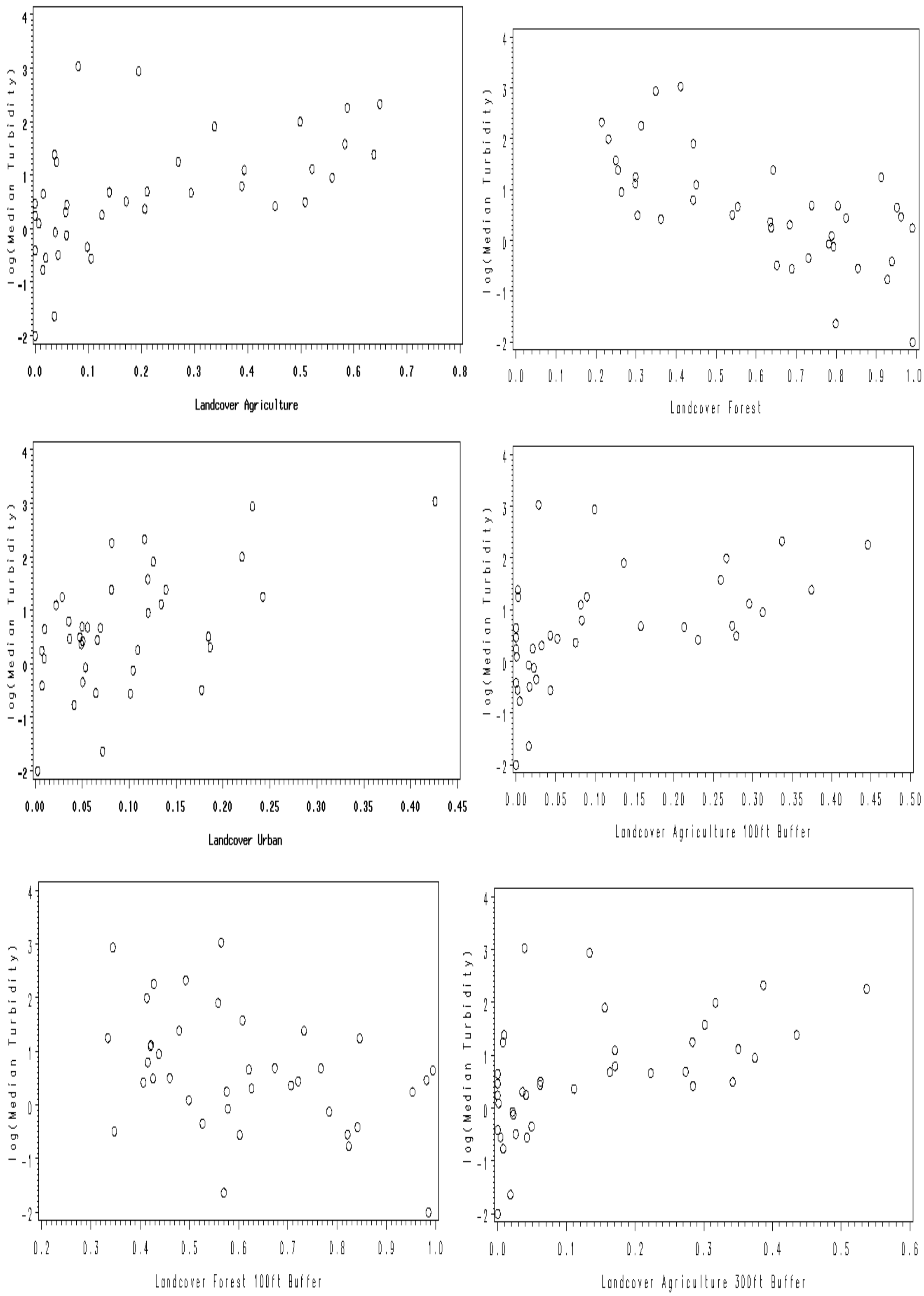


Table 6 Independent Parameter Estimates for $\vec{\beta}$

Dependent Variable: Turbidity

R^2	Parameter $\vec{\beta}$	Estimate $\hat{\vec{\beta}}$	Standard Error $SE(\hat{\vec{\beta}})$	t-value	P-value
0.4815	Agriculture	2.853	0.4803	5.94	<0.0001
0.4622	Intercept	2.4119	0.3413	7.07	<00001
	Forest	-2.9240	0.5185	-5.64	<0.0001
0.4844	Urban	6.8755	1.1508	5.97	<0.0001
0.6567	Agriculture	1.9146	0.5042	3.90	0.0005
	Forest	-0.5325	0.2278	-2.34	0.0251
	Urban	5.6990	1.3397	4.25	<0.0001
0.4400	Agriculture within 100ft Buffer	4.9023	0.8972	5.46	<0.0001
0.1713	Intercept	2.0640	0.5420	3.81	0.0005
	Forest within 100ft Buffer	-2.3443	0.8477	-2.77	0.0088
0.4676	Agriculture within 300ft Buffer	4.1754	0.7226	5.78	<0.0001
0.2648	Intercept	2.4512	0.5207	4.71	<0.0001
	Forest within 300ft Buffer	-2.9203	0.8000	-3.62	0.0008

Table 6 displays various models with significant land cover predictors on Turbidity. The model with agriculture, forest, and urban land cover explained the most of variability within Turbidity data. High agriculture and urban land covers were related to high level of turbidity while low forest land cover was related to high level of turbidity. Among the land cover within 100-ft buffer zone, agriculture had a significant positive relationship with Turbidity. Forest land cover within 100-ft buffer zone had a significantly negative relationship with turbidity, but explained the variation within the data less than agriculture. The model with forest within 300-ft buffer had a higher R^2 than forest within 100-ft buffer zone. This was also the case for agriculture within 300-ft buffer zone. Overall, high agriculture and urban land cover were related to high turbidity and high forest land cover was related to low turbidity. Scatter plots in Figure 1 show visual relationships between the dependent variable and the predictor variables.

Figure 2. Scatter Plots of Log(TOC) vs. Land Cover

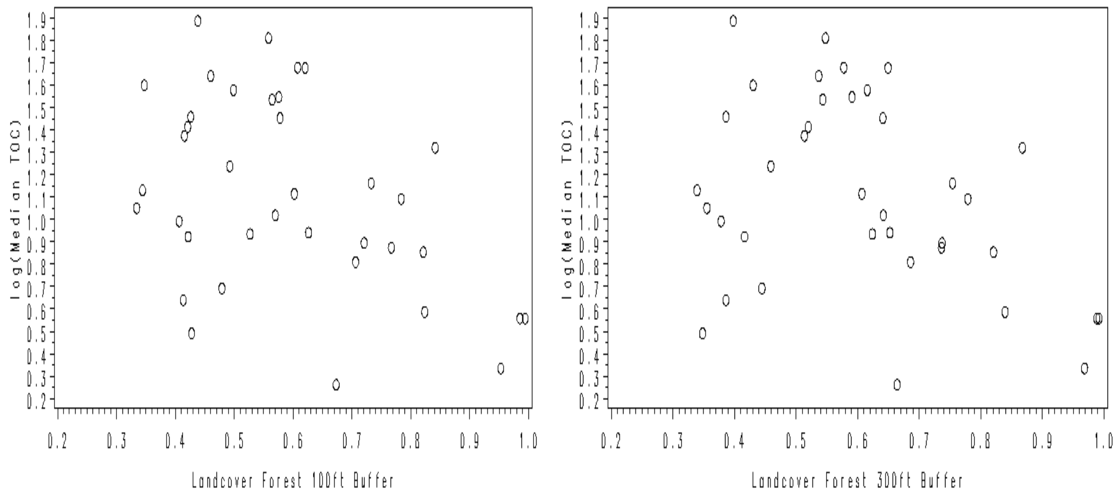
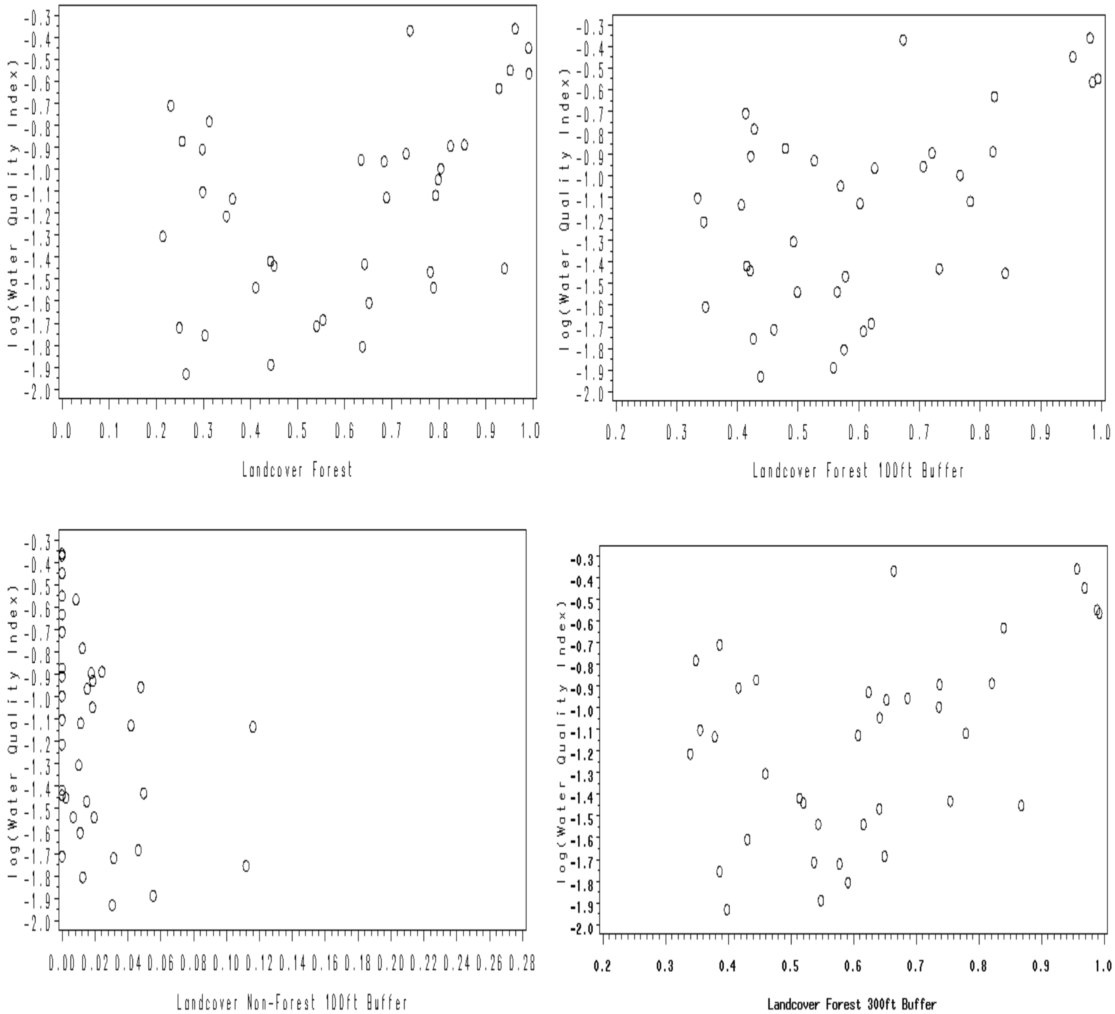


Table 7 Independent Variables Parameter Estimates
Dependent Variable: TOC

R^2	Parameter β	Estimate $\hat{\beta}$	Standard Error $se(\hat{\beta})$	t-value	P-value
0.1171	Intercept	1.4614	0.1754	8.33	<0.0001
	Forest	-0.5909	0.2743	-2.15	0.0382
0.1934	Intercept	1.7235	0.2205	7.81	<0.0001
	Forest within 100ft Buffer	-1.0291	0.3552	-2.90	0.0065
0.1327	Intercept	1.6263	0.2319	7.01	<0.0001
	Forest within 300ft Buffer	-0.8469	0.3659	-2.31	0.0266

Figure 3. Scatter Plots of Log(Water Quality Index) and Land Cover



From Table 7, forest land cover was significantly related to TOC. High forest land cover was related to low TOC. However, the regression coefficients R^2 for TOC models were low indicating high variability in TOC and other unaccounted predictor parameters. The scatter plots in Figure 2 show the relationships and high variability within the data.

Similarly, forest land cover had a significantly positive relationship with water quality index, especially forest cover within 100-ft buffer zone. Additionally, non-forest vegetation land cover within 100-ft buffer zone had a significantly negative relationship with water quality. The regression coefficients R^2 for these models were low, possibly due to high variability within water quality index. See Table 8 and Figure 3.

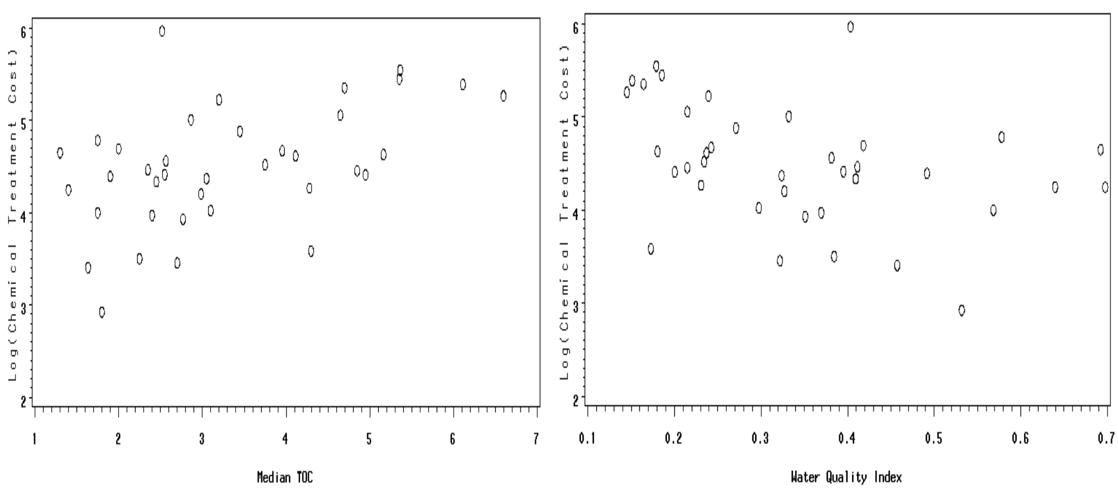
Table 8 Independent Variables Parameter Estimates

Dependent Variable: Water Quality Index

R^2	Parameter β	Estimate $\hat{\beta}$	Standard Error $se(\hat{\beta})$	t-value	P-value
0.1910	Intercept	-1.6240	0.1709	-9.50	<0.0001
	Forest	0.7267	0.2629	2.92	0.0061
0.2628	Intercept	-1.8797	0.2094	-8.98	<0.0001
	Forest within 100ft Buffer	1.1851	0.3308	-3.58	<0.0010
0.1340	Intercept	-1.0508	0.0831	-12.64	<0.0001
	Non-forest within 100ft Buffer	-5.9379	2.4732	-2.36	0.0238
0.2122	Intercept	-1.8225	0.2212	-8.24	<0.0001
	Forest within 300ft Buffer	1.0693	0.3434	3.11	0.0036

The relationship between the chemical treatment cost and the source water quality including source water quality index, turbidity and TOC was examined. Since water quality index was calculated using both turbidity and TOC, water quality index was used as the only covariate in the model. Logarithmic transformation was applied to chemical treatment cost for the positive skewness in the distribution.

Figure 4. Scatter Plots of Chemical Treatment Cost vs. Water Quality



From Table 9, TOC had a significant positive relationship with the cost. Also, water quality index had a significantly negative relationship with treatment cost. Turbidity was not found to be significantly related to the cost. The model coefficient R^2 was low indicating high variability in the cost and other possible unaccounted predictor variables. This was also evident from Figure 4.

Figure 5. Scatter Plots of Chemical Treatment Cost vs. Land Cover

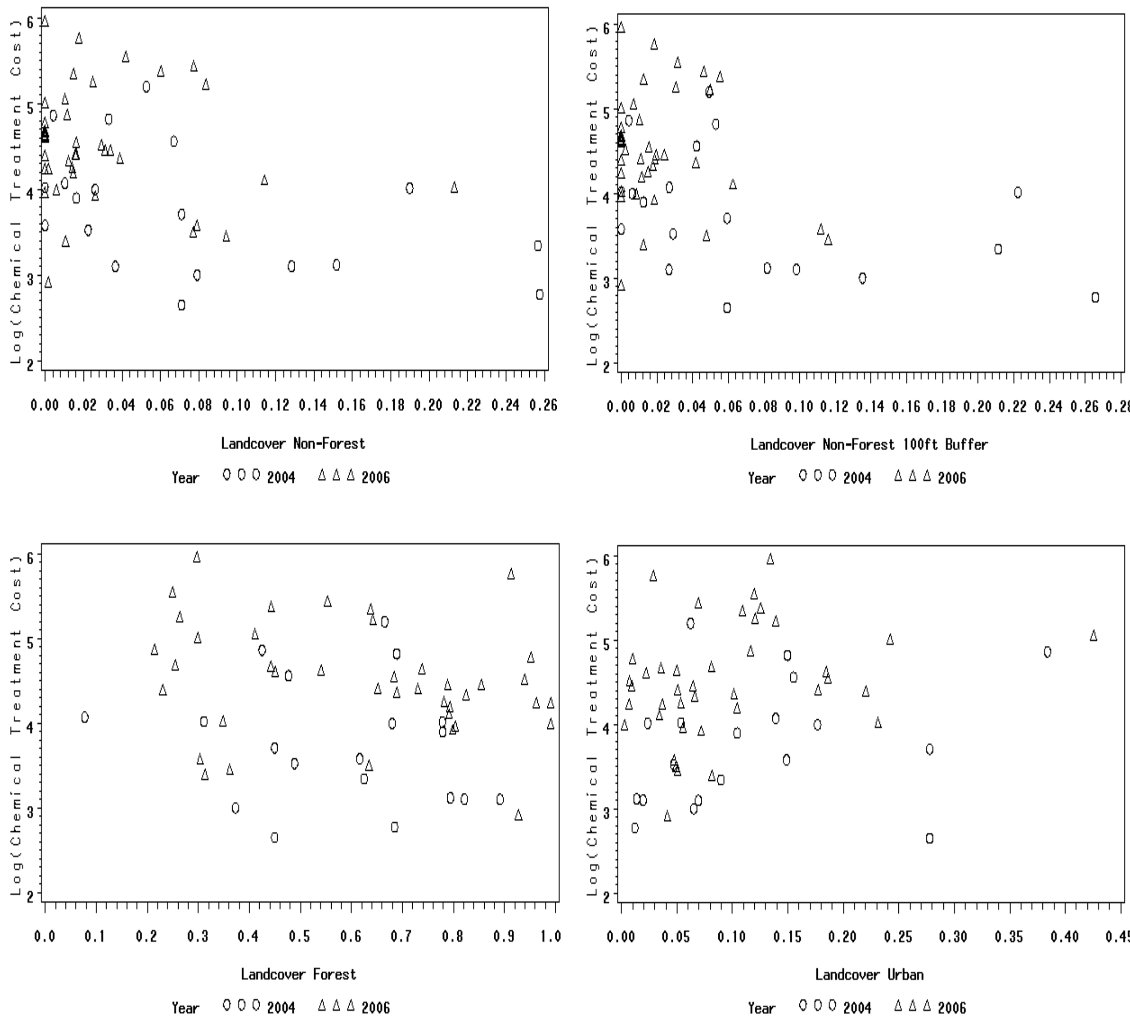


Table 9 Independent Variables Parameter Estimates
Dependent Variable: Chemical Treatment Cost

R^2	Parameter β	Estimate $\hat{\beta}$	Standard Error $se(\hat{\beta})$	t-value	P-value
0.2402	Intercept	3.7384	0.2500	14.95	<0.0001
	TOC	0.2313	0.0695	3.33	0.0021
0.1321	Intercept	5.0303	0.2476	20.31	<0.0001
	Water Quality Index	-1.5445	0.6597	-2.34	0.0249

The relationship between land cover and chemical treatment cost was also examined. From Table 10, non-forest vegetation land cover had a significantly negative relationship with the treatment cost. In other words, non-forest vegetation land cover was related to low chemical treatment cost. Similarly, within 100-ft buffer zone, high non-forest vegetation land cover was significantly related to low treatment cost. On the other hand, high urban land cover was significantly related to high treatment cost. The model coefficient R^2 was low indicating high variability in the cost, which can be also seen from the scatter plots in Figure 5.

Table 10 Independent Variables Parameter Estimates
Dependent Variable: Chemical Treatment Cost

R^2	Parameter β	Estimate $\hat{\beta}$	Standard Error $se(\hat{\beta})$	t-value	P-value
0.2532	Intercept	-777.1049	190.0426	-4.09	0.0001
	Year	0.3898	0.0928	4.11	0.0001
	Forest	-0.6292	0.3757	-1.67	0.0996
0.2793	Intercept	-596.1939	200.2559	-2.98	0.0043
	Year	0.2995	0.0998	3.00	0.0040
	Non-forest	-3.384	1.5238	-2.22	0.0304
0.2792	Intercept	-814.5501	188.0712	-4.33	<0.0001
	Year	0.4082	0.0938	4.35	<0.0001
	Urban	2.1798	0.9818	2.22	0.0305
0.2765	Intercept	-599.3400	208.2021	-2.69	0.0095
	Year	0.2811	0.1038	2.71	0.0090
	Non-forest within 100ft Buffer	-3.7946	1.7507	-2.17	0.0345

Using the parameter estimates $\hat{\beta}$, the multiplicative change in cost given the percentage increase or decrease in the land cover can be estimated. The following equation

$$\left(\exp\left((\hat{\beta} \pm t_{0.975,df}\, se(\hat{\beta}))\Delta x\right) - 1\right) \times 100$$

calculates the 95% confidence interval for the expected change in cost given Δx , change in land cover percentage. Note that $t_{0.975,df}$ is the 97.5th quartile of *Student's t*-distribution given *df*, degrees of freedom. For example, 10% increase in non-forest vegetation land cover resulted in

$\left(\exp\left((-3.384 \pm 2.00324 \times 1.5238)0.1\right) - 1\right) \times 100 =$ (-47.4678%, -3.2690%).

In other words, 10% increase in non-forest vegetation land cover resulted in from 3.27% to 47.47% decrease in treatment cost. If considering just the buffer, there was little difference: a 10% increase in non-forest vegetation land cover within 100-ft buffer zone resulted from 2.83% to 51.82% decrease in treatment cost. Similarly, 10% increase in urban land cover resulted from 2.15% to 51.39% increase in treatment cost.

C. Findings

Overall, there were significant relationships among source water quality, percent land cover and drinking water treatment costs. However, the relationships were rather weak due to high variability within data despite the significance. Further, they do not offer much in the way of a predictive model because a wide range of possible treatment costs may result from a 10 percentage point change in a particular land cover type.

This rudimentary chart illustrates the types of variables considered by category, and significant relationships between each of them will be discussed in turn.

Land Cover:	↔	Water Quality:	↔	Chemical Treatment Costs
- Agriculture		- Turbidity		
- Urban		- TOC		
- Forest		- WQ Index		
- Non-forest				

Land cover characteristics had a significant association with the source water quality. Increased percent agriculture and urban land cover were significantly related to increased turbidity. On the contrary, increased forest land cover was significantly related to decreased turbidity. In fact, agriculture, urban and forest land cover together explain about 66% of the variation in turbidity across the drinking water treatment plants.

Similarly, increased TOC was significantly related to decreased percent forest land cover. As predicted, the Water Quality Index also had positive relationships with forest. This result is in agreement with research cited in Section II, indicating that high percent forest cover ought to correlate with increased water quality.

Chemical treatment cost was significantly related to TOC and the Water Quality Index. Higher TOC was related to higher treatment cost. Further, lower water quality index was related to higher treatment cost, indicating that it costs more to treat lower quality water. Also, the treatment cost was significantly related to urban land cover. Higher percent land cover by urban area is related to higher treatment cost.

Surprisingly, non-forest landcover had a negative relationship with the Water Quality Index, i.e., increased non-forest land cover was associated with decreased water quality. This is illogical given that non-forest land cover has a negative relationship with chemical treatment cost and the Water Quality Index has a negative relationship with the chemical treatment cost. It warrants further examination of the development of the data to identify the cause for this inconsistent result.

In summary, land cover within a drinking water source area can be an indicator of water quality at a drinking water intake. Specifically, high agriculture and urban land cover are related to high turbidity. Conversely, high forest cover is related to low turbidity, low TOC, and high Water Quality Index. Further, poor water quality at a drinking water intake can be an indicator of high treatment costs. In this study, turbidity alone was not found to significantly relate to chemical treatment cost. However, after factoring in TOC and alkalinity to develop a Water Quality Index for each plant, there was a significant relationship between low water quality and high treatment costs.

V. Concluding Remarks

Even with the help of many generous drinking water treatment plant supervisors, lab technicians, and other plant operators, it was not easy to gather enough data for this study to account for the real world variability needed to offer insights as to the nature of drinking water treatment in the United States. There are numerous possible reasons for the high variability shown in the data, which may provide further consideration and guidance to those who wish to endeavor further study in this field.

First, reporting and accounting procedures varied between water plants. For example, the same plant fix may be perceived in one facility as a capital cost because it is an improvement to infrastructure, and in another plant, the labor and part replacement is logged into the operating budget. This made it difficult to isolate annual operating costs from capital costs. As a result, only chemical treatment costs were analyzed.

Second, there was rich diversity in the sequences of treatment and types of chemicals used by the plants in this study. For example, while the majority of plants included a chlorine/chloramines step and a coagulation step, there were several different types and a range of dosages applied for each. It is likely that the combinations and permutations had a confounding effect on this analysis.

Third, raw water sampling methods differed. Some plants used systematic or fixed frequency samples, but others used event-based or random samples. Even though both are valid, comparing results from different sampling strategies likely increased variability and decreased correlations.

Fourth, the quality of water at the intakes also likely varied depending on whether the plant was drawing from a river or stream, or from a reservoir or system of reservoirs. Residence time, storage capacity, and operational flexibility added more variability to the relationship between land cover type and water treatment costs.

Fifth, the plants were located in many different eco-regions, and this analysis did not account for regional differences in climate, soil, and geology. For example, this study included a plant from Maine where the freeze-free period is about 160 days, there are sandy to loamy soils that are excessively to poorly drained, and the geology is characterized by till-mantled, rolling to hilly uplands underlain primarily by granite, gneiss, and schist bedrock. Contrast that to the North Carolina piedmont region, where for one of the plants surveyed the freeze-free period is 230 days, there are generally well-drained loamy to clayey soils, and the geology is characterized by underlying Precambrian and Paleozoic metamorphic and igneous rocks. Water quality and treatment costs are likely affected by these differences.

Sixth, the land cover statistics do not capture the effects of location of specific land cover types and relative loading rates in each watershed, which may greatly affect the water quality. For example, the statistic may be that 60% of the watershed is forested, 30% is agriculture, and 10% is urban. In one watershed, the headwaters are forested, there are fields and pastures in the middle, and there is a city in the lower reaches of the watershed near the drinking water intake. However, the exact same set of statistics could be associated with a different signature in another watershed such that all the riparian buffers are forested, and the agricultural land and urban land is dispersed in clusters. Although two watersheds may have the same percentage of land cover types, the latter has significantly better water quality. The statistical method in this study did not account for the spatial pattern of land cover that impacts the water quality.

Finally, water treatment plants often applied excessive treatment to their raw water. For example, some operators were seemingly not altering chemical treatment on the basis of raw water quality fluctuations, and some were systematically treating beyond required standards as a precaution.

The costs of chemicals varied widely for drinking water treatment. As previously mentioned, the chemical treatment cost ranged from $14.26 per year per million gallon and $391.39 per year per million gallon. Some of this variability can be explained by differences in chemicals used, economies of scale, bulk pricing, and regional pricing. Such inherent variability among the drinking treatment plants must be considered by including as many plants as possible in the future studies in this field.

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