

Water Quality Trading in Integrated Hydrologic Framework

WATER QUALITY TRADING IN AN INTEGRATED HYDROLOGIC MODELING FRAMEWORK

Arthur J. Caplan, Bethany T. Neilson, and Matthew Baker*

ABSTRACT: This paper accomplishes three objectives. First, a novel hydrologic modeling approach is used to estimate (i) nonpoint source (NPS) loadings at the field level (rather than at the watershed or sub-watershed levels), and (ii) delivery ratios at the sub-watershed level (rather than being arbitrarily chosen). Second, our study area includes two receptor points (rather than the typical case of a single receptor point), therefore enabling us to demonstrate how multiple receptor points can be incorporated into a water quality trading (WQT) framework. Third, we develop a basin profile that can be used by regulators to identify specific trades, whether point-to-point, point-to-nonpoint, or nonpoint-to-nonpoint. The profile is operational, i.e., it is easily updatable with time-sensitive environmental and economic data, and can be generalized to any watershed. We then demonstrate how the profile can be used to assess potential trading opportunities. As a result, the paper provides an example of adaptive management of water quality in a large, predominantly agricultural river basin.

KEY TERMS: water quality trading; delivered loads; abatement costs

INTRODUCTION

Over the past 30+ years, pollution-trading research has focused primarily on theoretical complications (and attendant policy formulations) associated with the textbook trading model, and the estimated cost savings associated with trading vis-à-vis command-and-control regulation. With respect to water quality trading (henceforth WQT) in specific, theoretical contributions in two general areas stand out: (i) Malik, et al. (1993) and Shortle's (1987) identification of the key factors determining an optimal trading ratio between point and nonpoint sources (in particular, the uncertainty associated with nonpoint pollution loadings and relative point and nonpoint source enforcement costs), and (ii) Hanley, et al. (1997), Shortle and Horan (2001), and Shortle and Abler's (1997) alternatives to the trading of mean loadings (e.g., trading inputs such as fertilizer applications, which are correlated with loadings). These papers identify key factors affecting the efficiency of WQT markets (in terms of controlling nonpoint source loadings), and which alternatives to consider as part of the design process itself. They are significant contributions in terms of delineating the key issues faced by policy makers in dealing with the inherent uncertainties and (spatial) non-uniformity of nonpoint (NPS) loadings. Nevertheless, a gap persists in the literature between the design of markets as theoretical and numerically simulated constructs, on the one hand, and their actual implementation, on the other, in an adaptive management framework. This paper explores a threefold approach to bridging this gap.

First, we use a novel environmental modeling approach to estimate both NPS loadings at the field level (rather than at the watershed or sub-watershed levels) and delivery ratios at the sub-watershed level (rather than being arbitrarily chosen). The approach consists of a tightly integrated hydrologic model (which determines spatially distributed, seasonal loadings) and an in-stream transport model (which determines associated seasonal delivery ratios). Second, our study area – the Bear River Basin in northern Utah and southern Idaho – includes multiple receptor points (for which receptor-specific delivery ratios are derived). Multiple receptor points are commonly included in the environmental analyses of large agricultural watersheds with multiple water-quality impaired reaches (e.g., in Total Maximum Daily Load (TMDL) studies). However, WQT models are typically developed for markets with single receptor points. Our analysis therefore, demonstrates how to incorporate multiple receptor points into a WQT framework. Third, as a result of the source-specificity of our environmental analysis, we develop a basin profile that operationalizes WQT. By “operationalizes” we mean that the profile (i) can be used by regulators to identify specific trades, whether point-to-point, point-to-nonpoint, or nonpoint-to-nonpoint, (ii) is easily updatable with time-sensitive environmental and economic data on loadings, delivery ratios, best management practice (BMP) effectiveness, abatement costs, etc., and (iii) can be generalized to accommodate any watershed. As a result, we provide an example of adaptive management of water quality in a large, predominantly agricultural river basin.

The U.S. Environmental Protection Agency (EPA) has been pressing for this type of approach since the promulgation of its Water Quality Trading Policy in 2003, the intent of which is “to encourage voluntary trading programs that facilitate implementation of Total Maximum Daily Loads (TMDLs), reduce the costs of compliance with Clean Water Act regulations, establish incentives for voluntary reductions, and promote watershed-based initiatives (U.S. EPA, 2008).” To our knowledge,

* Caplan is Associate Professor of Economics, Department of Applied Economics, Utah State University, 3530 Old Main Hill, Logan, Utah 84322-3530. Phone: 435-797-0775. Fax: 435-797-2701. Email: arthur.caplan@usu.edu. Neilson is Assistant Professor of Engineering, Department of Civil and Environmental Engineering, Utah State University, 8200 Old Main Hill, Logan, Utah 84322-8200, bethany.neilson@usu.edu. Baker is Assistant Professor of Geography, Department of Geography and Environmental Systems, 211 Sondheim Hall, University of Maryland, 1000 Hilltop Circle, Baltimore, MD 21250, mbaker@umbc.edu

Water Quality Trading in Integrated Hydrologic Framework

only a handful of previous studies have utilized watershed or in-stream water quality models in support of WQT. Each of the studies has aggregated their results to the watershed level, meaning that they are not “operational” in the sense of providing regulators with the tools necessary to actually pair potential buyers and sellers of pollution credits (whether the pairings entail point-to-nonpoint or nonpoint-to-nonpoint trading).

STUDY AREA

The Bear River Basin comprises 19,000 square kilometers of mountain and valley lands located in northeastern Utah (44% of watershed), southeastern Idaho (36%), and southwestern Wyoming (20%). It ranges in elevation from 1,283 meters to over 3,962 meters and is entirely enclosed by mountains. Agricultural lands throughout the basin, as well as urban areas, are located in valleys along the main stem of the Bear River and its tributaries. Currently, several water bodies in the basin are on the Clean Water Act’s 303(d) list of impaired waters in each of the three states. Two of these 303(d)-listed water bodies – the Cub River and Cutler Reservoir – form the focus area for this study. They are included on the 303(d) list because of dissolved oxygen depletion during summer months due primarily to excessive total phosphorus (TP) loadings from both point and nonpoint sources. TMDLs are being updated or developed for the Cub River and Cutler Reservoir, and WQT has been identified as one potential solution to the TP problem. To assist in testing the feasibility of a potential WQT program, a novel water quality modeling framework (described below) is applied to the portion of the Bear River Basin encompassing the Cub River and Cutler Reservoir.

HYDROLOGIC MODEL

Key information regarding both loadings (point and nonpoint) and the amount of each loading reaching a location of interest (via a delivery ratio) is necessary to establish a successful WQT program. However, delivery ratios, which are primarily dependent on in-stream processes and withdrawals, can be particularly difficult to estimate. To assist in quantifying loadings and delivery ratios associated with individual owners’ fields, a modeling framework consisting of a combination of models, modeling approaches, and analysis techniques has been developed for this study. The framework utilizes (i) the TOPNET hydrology model (Bandaragoda et al., 2004), (ii) variable source area (VSA) calculations to resolve spatial areas contributing surface runoff (Lyon et al. 2004), (iii) a sub-basin loading model component based on the VSA calculations, event mean concentrations (EMCs), and spatially distributed land-use information, and (iv) a water body response component that incorporates the QUAL2E model to determine delivery ratios (Brown and Barnwell 1987). This combination of models provides for a representation of the physical hydrology at the watershed scale and the associated in-stream response at a daily time step. The approach also results in a representation of the spatial variability of daily loadings at the field scale and daily delivery ratios to receptor points of interest.

In the Bear River application of the modeling framework, TOPNET is populated using (i) SSURGO soils data (Soil Survey Staff, 2007), (ii) the 30-meter National Elevation Dataset digital elevation model (USGS, 2009), (iii) land cover data from the National Land Cover Dataset (NLCD, 2001), (iv) Utah Water Related Land-use data (UDNR, 2009), and (v) local weather data, diversion data, and reservoir discharges for a simulation time period spanning 10/1/1989 – 9/30/2004. TOPNET is calibrated using stream flow measurements at multiple locations throughout the six year time period of 1989-1995. Model validation occurred from 1995-2004.

Uncertainty associated with each of the modeling components is a concern that must be addressed when incorporating modeling results into a WQT program. In this study, the daily values resulting from variable conditions within a season are accommodated by averaging daily loads and delivery ratios over each season (winter, spring, summer, and fall). These seasonal values, which differ over the range of annual hydrologic conditions, are then averaged again over the simulation time period (10/1/1989 – 9/30/2004), providing an average seasonal field load and an average seasonal delivery ratio for each sub-basin.

WATER QUALITY TRADING MODEL AND BASIN PROFILE

The regulator’s primary objective in a WQT market is to mitigate the effects of uncertainty by (i) determining and then fully informing polluting sources about their required abatement levels and their respective delivery ratios, and (ii) establishing a monitoring/enforcement process that verifies reduced loadings, particularly for NPSs. In this paper, we assume the regulator adopts the water quality modeling framework described above to determine a delivery-ratio matrix. Since our goal here is to provide a theoretical motivation for WQT, we abstract from how the regulator determines required abatement levels for NPSs (while acknowledging that, in a watershed such as the Bear River Basin, these levels must be set if WQT is the sole regulatory instrument available for meeting a TMDL). We also abstract from the monitoring/enforcement process that must

Water Quality Trading in Integrated Hydrologic Framework

simultaneously be instituted in support of WQT. Thus, the focus of the paper is on how polluting sources (or firms) behave in a WQT market, rather than how the regulator should set its policies per se.

As we ultimately show, for a given receptor $j = 1, \dots, J$,

$$\frac{C_{ik}(a_{ik})}{t_{ij}a_{ik}} \geq \frac{C_{-ik}(a_{-ik})}{t_{-ij}a_{-ik}} \Rightarrow \begin{cases} \text{firm } i \text{ is potential purchaser from firm } -i. \\ \text{firm } i \text{ is potential seller to firm } -i. \end{cases} \quad (1)$$

where firm $-i$ is any firm other than firm i . Further, $C_{ik}(a_{ik})$ is firm i 's ($i = 1, \dots, I$) total private cost of abatement, a_{ik} , for technology step k , and t_{ij} is firm i 's delivery ratio estimated from the hydrologic model described above. In other words, if firm i 's adjusted average abatement cost is larger than firm $-i$'s, firm i is a potential purchaser of receptor j credits from firm $-i$. To the contrary, if firm i 's adjusted average abatement cost is smaller than firm $-i$'s, firm i is a potential seller of load reductions to firm $-i$. Equation (1) therefore provides a criterion for determining the direction of trading between two firms.

We next develop a basin profile, which compiles the necessary environmental and economic information to assess the potential for individual trading opportunities. The profile combines the environmental information, in particular the estimation of seasonal NPS loadings at the farm-field level and corresponding delivery ratios at the sub-watershed level for our two receptor points with estimates of phosphorus control costs (for both point sources and NPSs) and the percent effectiveness of best management practices (BMPs) (for NPSs) to create the basin profile. Our estimates of phosphorus control costs and BMP effectiveness are taken from the literature. However, as alluded to previously, they are "operational" in the sense that the measures can be updated over time as new information becomes available (e.g., as a result of revisions to existing TMDLs and updated or extended modeling simulations), and therefore can be used by regulators to more accurately assess changes in the potential for WQT over time.

For the purposes of this study, we assume that NPSs are required to reduce their current loadings on each field by 20% in order to be in compliance with the basin's TMDL. With respect to the basin's point sources (which consist of five small- to medium-sized waste water treatment plants (WWTPs)), we use control-cost estimates derived from Lee and Jones (1998), U.S. EPA (2003), and Keplinger, et al. (2004). Based on the basin profile, we then demonstrate an example trade between an NPS and a WWTP.

WATER QUALITY TRADING EXAMPLE

Table 1 lists the environmental and economic information contained in the profile for each point and NPS located in the basin. This information can be used to assess the potential for WQT between any possible pair of firms.

Table 1. Information Contained in the Bear River Basin Profile.

Sub-basin ID No.
Field ID No. ^a
Field Size (acres) ^a
Farm ID No. ^a
Current Load (grams of TP/season and grams of TP/year)
Delivery Ratio (%/season and average %/year) ^b
Delivered Load (Current Load x Delivery Ratio) ^b
BMP Type (e.g., conservation tillage, nutrient management, etc.) ^{a,c}
BMP Total Cost (\$/acre x Field Size) ^{a,d}
BMP Effectiveness (%) ^{a,e}
Delivered Load with BMP in Place (Delivered Load x (1 - BMP Effectiveness)) ^{a,b,f}
% Required Reduction (Determined by Regulator)
Target Delivered Load (Delivered Load - (% Required Reduction x Delivered Load)) ^b
Necessary Load Reduction (Delivered Load - Target Delivered Load) ^b
Abatement Credits (Target Delivered Load - Delivered Load with BMP in Place) ^{b,g}
Adjust. Ave. Cost of Abate. Credits (\$/gram TP = BMP Total Cost/(BMP Effectiveness x Delivered Load)) ^{b,h}

^a Specific to NPSs. ^b Calculated for both the Cub and Cutler Receptor Points. ^c For point sources this is Technology Tier (i.e., Tier 2 or 3). ^d For point sources this is Technology Tier Total Cost. ^e For point sources this is Technology Tier Effectiveness. ^f For point sources this is Delivered Load with Technology Tier in Place (Delivered Load x (1 - Technology Tier Effectiveness)). ^g For point sources this is Abatement Credits (Target Delivered Load - Delivered Load with Technology Tier in Place). ^h For point sources this is Adjusted Average Cost of Abatement Credits (Technology Tier Total Cost/(Technology Tier Effectiveness x Delivered Load)).

Water Quality Trading in Integrated Hydrologic Framework

By way of example, assume the potential seller of abatement credits is an NPS (henceforth Farmer A) that loads to both the Cub and Cutler Receptor Points from its six fields (Farmer A therefore participates in two separate WQT markets). The potential purchaser – the city of Preston’s WWTP – is a point source that also loads to both receptor points. Table 2 presents Farmer A’s annual abatement credit and adjusted average abatement cost information (taken from the Bear River Basin profile). As indicated, she has 16,420 and 10,251 total potential credits (in grams) available for sale for the Cub and Cutler Receptor Points, respectively, from her six fields. Adjusted average abatement costs range from \$0.01/gram to \$0.14/gram.

Table 2. Farmer A’s Annual Abatement Credits and Average Cost Information.

Field	Cub Receptor Point		Cutler Receptor Point	
	Abatement Credits (grams)	Adj. Ave. Abate. Cost (\$/gram)	Abatement Credits (grams)	Adj. Ave. Abate. Cost (\$/gram)
1	57.66	0.08	32.47	0.14
2	5,751.46	0.01	3,927.10	0.01
3	3,132.51	0.01	2,115.97	0.01
4	6,985.81	0.05	3,900.02	0.09
5	462.72	0.05	259.03	0.09
6	29.56	0.05	16.50	0.09
Total	16,419.72		10,251.10	

Based on comparable information, the Preston WWTP has required reductions (to meet its TMDL commitments) of 1,283,971 and 560,931 grams per year for the Cub and Cutler Receptor Points, respectively. Its adjusted average abatement costs to produce abatement credits are \$0.39 per gram for the Cub and \$0.90 per gram for the Cutler Receptor Points, respectively, after implementing tier 3 technology. Hence, applying equation (1) indicates that a potential trade exists between Farmer A (as seller) and the WWTP (as purchaser).

To calculate the *effective* number of Cub and Cutler abatement credits Farmer A has available for sale to the WWTP, we divide Farmer A's credits, respectively, by the WWTP's average seasonal delivery ratios for the Cub and Cutler receptors, which are 0.95 and 0.53. This results in Farmer A's effective credits being increased up to 17,284 (= 16,420/0.95) and 19,342 (= 10,251/0.53) grams for the Cub and Cutler Receptor Points, respectively. In terms of the expected, effective prices of Cub and Cutler credits from Farmer A, first consider the credits from Fields 2 and 3 (the lowest-cost fields at \$0.01/gram/field). If the WWTP purchases all of the Cub and Cutler credits from these fields (5,751 + 3,133 = 8,884 Cub credits and 3,927 + 2,116 = 6,043 Cutler Credits, respectively) for totals of \$89 (= \$0.01 x 8,884) and \$60 (= \$0.01 x 6,043), respectively (i.e., through a bargaining process the WWTP is able to pay Farmer A her WTA), the WWTP receives the equivalent of 9,352 (= 8,884/0.95) Cub credits and 11,402 (= 6,043/0.53) Cutler Credits. This translates into expected, effective per-credit prices for the WWTP of \$0.01 per gram (= \$89/9,352) for its Cub credits and \$0.005 per gram (= \$60/11,402) for its Cutler credits. The WWTP's expected, effective credit prices corresponding to each of Farmer A's fields is presented in Table 3.

Table 3. WWTP's Expected, Effective Credit Prices For Each of Farmer A's Fields.

Field	Cub Receptor Point		Cutler Receptor Point	
	Effective Credits (grams)	Effective Credit Price (\$/gram)	Effective Credits (grams)	Effective Credit Price (\$/gram)
1	60.70	0.073	61.27	0.072
2	6,054.17	0.005	7,409.62	0.004
3	3,297.37	0.008	3,992.40	0.007
4	7,353.48	0.049	7,358.54	0.049
5	487.08	0.048	488.74	0.048
6	29.56	0.047	31.14	0.047
Total	17,283.92		19,341.70	

WQT is therefore “operationalized,” in the sense that the regulator is able to identify any combination of possible pairwise trades in the basin using the same approach as demonstrated here.

Water Quality Trading in Integrated Hydrologic Framework

SUMMARY AND CONCLUSIONS

This paper has accomplished three objectives. First, we have used a novel hydrologic modeling approach to estimate (i) NPS loadings at the field level (rather than at the watershed or sub-watershed levels), and (ii) delivery ratios at the sub-watershed level (rather than being arbitrarily chosen). The approach consists of a tightly integrated hydrologic model (which determines spatially distributed, seasonal loadings) and an in-stream transport model (which determines associated seasonal delivery ratios).

Second, our study area – the Bear River Basin in northern Utah and southern Idaho – includes two receptor points (rather than the typical case of a single receptor point), and therefore demonstrates how to incorporate multiple receptor points into the WQT framework. Third, we have developed a basin profile that can be used by regulators to identify specific trades, whether point-to-point, point-to-nonpoint, or nonpoint-to-nonpoint. The profile is easily updatable with new information on loads, delivery ratios, BMP effectiveness, control costs, etc., and can be generalized to any watershed.

This latter contribution is most useful in terms of operationalizing WQT. As demonstrated above, regulators can use the profile to identify any possible trade in the basin and to update any of the environmental or economic information contained therein. In a sense, therefore, the profile provides a useful accounting framework within which to identify the full extent of trading opportunities.

Of course, several crucial aspects of WQT have not been addressed in this paper, e.g., how to promote and legalize WQT through communication, monitoring, and enforcement programs that involve the wider community of stakeholders. As stressed in U.S. EPA (2004), these types of programs are necessary for the success of WQT in any given basin, as is developing a profile to facilitate the identification of potential trading opportunities. However, it is our belief that existing work in these areas (see for instance Ross and Associates Consulting, 2000) is as generalizable as the basin profile developed in this study for the Bear River Basin. In other words, in concert with previous studies which address the issues of communication, monitoring, and enforcement, the basin profile developed here completes the proverbial puzzle on how to operationalize WQT.

ACKNOWLEDGMENTS

The authors acknowledge generous financial support provided by the U.S. Environmental Protection Agency's Targeted Watershed Program.

REFERENCES

- Bandaragoda, C., D.G. Tarboton, and R. Woods, 2004. Application of TOPNET in the Distributed Model Intercomparison Project. *Journal of Hydrology* 298, 178-201.
- Brown, L.C., and T.O. Barnwell, 1987. The Enhanced Stream Water Quality Model QUAL2E and QUAL2E-UNCAS: Documentation and User Manual. United States Environmental Protection Agency, Athens, GA.
- Hanley, N., J.F. Shogren, and B. White, 1997. *Environmental Economics in Theory and Practice*. Oxford University Press, New York, New York.
- Keplinger, K., J. Houser, A. Tanter, L. Hauck, and L. Beran, 2004. Cost and Affordability of Phosphorus Removal at Small Wastewater Treatment Plants. *Small Flows Quarterly* 5(4), 36-49.
- Lee, G.F., and R.A. Jones, 1998. The North American Experience in Eutrophication Control Through Phosphorus Management. In *Proceedings of the International Conference, Phosphate, Water and Quality of Life*, Paris, France. Available online at <http://www.gfredlee.com/pexfert2.htm>.
- Lyon, S. W., M.T. Walter, P. Gerard-Marchant, and T. Steenhuis, 2004. Using a Topographic Index to Distribute Variable Source Area Runoff Predicted with the SCS Curve Number Equation. *Hydrological Processes* 18, 2757-2771.
- Malik, A.S., D. Letson, and S.R. Crutchfield, 1993. Point/Nonpoint Source Trading of Pollution Abatement: Choosing the Right Trading Ratio. *American Journal of Agricultural Economics* 75, 959-967.
- NLCD, 2001. National Land Cover Data. U.S. Environmental Protection Agency.
- Ross & Associates Environmental Consulting, Ltd., 2000. Lower Boise River Effluent Trading Demonstration Project: Summary of Participant Recommendations for a Trading Framework. Prepared for the Idaho Division of Environmental Quality. Assessed: March 29, 2006. www.deq.idaho.gov/water/data_reports/surface_water/tmdls/boise_river_lower/boise_river_lower_effluent_report.pdf. Retrieved on April 16.
- Shortle, J.S., 1987. Allocative Implications of Comparisons Between the Marginal Costs of Point and Nonpoint Source Pollution Abatement. *Northeast Journal of Agricultural and Resource Economics* 16, 17-23.
- Shortle, J.S. and D.G. Abler, 1997. Nonpoint Pollution. In *The International Yearbook of Environmental and Resource Economics*, H. Folmer and T. Tietenberg (eds.). Edward Elgar, Cheltenham, United Kingdom.
- Shortle, J.S. and R.D. Horan, 2001. The Economics of Nonpoint Pollution Control. *Journal of Economic Surveys* 15(3), 255-

Water Quality Trading in Integrated Hydrologic Framework

289.

Soil Survey Staff, 2007. Soil Survey Geographic (SSURGO) Database for Survey Area Natural Resources Conservation Service. United States Department of Agriculture.

U.S. Environmental Protection Agency (EPA), 2003. Economic Analysis of Nutrient and Sediment Reduction Actions to Restore Chesapeake Bay Water Quality. Region III Report from the Chesapeake Bay Program Office. Annapolis, Maryland: Author.

U.S. Environmental Protection Agency (EPA), 2008. <http://www.epa.gov/owow/watershed/trading/finalpolicy2003.html>, Retrieved on December 16.

U.S. Environmental Protection Agency (EPA), 2004. Water Quality Trading Assessment Handbook: Can Water Quality Trading Advance your Watershed's Goals? EPA 841-B-04-001, Washington, D.C. Available online at http://www.epa.gov/owow/watershed/trading/handbook/docs/NationalWQTHandbook_FINAL.pdf.

U.S. Geological Service (USGS), 2009. Available online at <http://ned.usgs.gov/>.

Utah Department of Natural Resources (UDNR), Water Resources Division, 2009. Available online at www.water.utah.gov/planning/landuse/.