An Integrated Assessment Model for Valuing Water Quality Changes in the United States

Joel Corona *Economist, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.; corona.joel@epa.gov*
Todd Doley *Economist, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.; doley.todd@epa.gov*
Charles Griffiths *Economist, U.S. Environmental Protection Agency, National Center for Environmental Economics, Washington, D.C.; griffiths.charles@epa.gov*
Matthew Massey *Economist, U.S. Environmental Protection Agency, National Center for Environmental Economics, Washington, D.C.; massey.matt@epa.gov*
Chris Moore *Economist, U.S. Environmental Protection Agency, National Center for Environmental Economics, Washington, D.C.; moore.chris@epa.gov*
Stephen Muela *ORISE Participant Oak Ridge Institute for Science and Education (ORISE) with U.S. Environmental Protection Agency, Office of Water, Washington, D.C.; muela.stephen@epa.gov*
Brenda Rashleigh *Biologist, U.S. Environmental Protection Agency, Office of Research and Development, Narragansett, Rhode Island; rashleigh.brenda@epa.gov*
William Wheeler *Economist, U.S. Environmental Protection Agency, National Center for Environmental Economics, Washington, D.C.; wheeler.william@epa.gov*
Stephen D. Whitlock *Environmental engineer, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.; whitlock.steve@epa.gov*
Julie Hewitt *Associate director for economics, U.S. Environmental Protection Agency, Office of Water, Washington, D.C.; hewitt.julie@epa.gov*

ABSTRACT *The U.S. Environmental Protection Agency (EPA) often requires expertise from environmental assessors, hydrologists, economists, and others to analyze the benefits of regional and national policy decisions related to changes in water quality. This led the EPA to develop two models to form an integrated assessment model: HAWQS is a web-based water quantity and quality modeling system, and BenSPLASH is a modeling platform for quantifying the economic benefits of changes in water quality. This paper discusses the development of the component models and applies HAWQS and BenSPLASH to a case study in the Republican River basin.* (JEL Q51, Q53)

1. Introduction

Integrated assessment models (IAMs) combine natural processes and economic systems in a single modeling framework, and research on IAMs related to water quality requires collaborative input from both natural and social scientists (Keiser and Muller 2017). The U.S. Environmental Protection Agency (EPA) often requires expertise from environmental assessors, hydrologists, economists, and others to analyze the benefits of regional and national policy decisions related to changes in water quality. However, full integration of hydrologic models and economic valuation has developed slowly in water regulation (Griffiths et al. 2012). This led the EPA to develop two integral components in a water quality IAM: (1) the Hydrologic and Water Quality System (HAWQS), and (2) the Benefits Spatial Platform for Aggregating Socioeconomics and H_2O Quality (BenSPLASH). These two products bring together national data layers and modeling capability that will allow the EPA, academia, states, and others to perform large, integrated analyses related to water quality impacts and provide a streamlined workflow for anyone interested in this sort of analysis. While the models are designed to work in series, they do not rely exclusively on each

Land Economics • November 2020 • 96 (4): 478–492
ISSN 0023-7639; E-ISSN 1543-8325

Appendix materials are freely available at http://le.uwpress.org and via the links in the electronic version of this article.

other, allowing analysts to use either model independently. This paper describes the water quality and valuation capabilities of the linked HAWQS-BenSPLASH system and provides an applied example at the regional level.

HAWQS is a web-based interactive water quantity and quality modeling system that employs as its core modeling engine the Soil and Water Assessment Tool (SWAT). HAWQS contains preloaded input data and simulates the effects of management practices based on an extensive array of crops, soils, natural vegetation types, land uses, and other scenarios for hydrology and the following water quality parameters: sediment, pathogens, nutrients, biochemical oxygen demand, dissolved oxygen, pesticides, and water temperature. Simulations can be executed and stored on the web servers, thus minimizing personal computing requirements. The models can also be downloaded to local computers if desired. While the goal is to precalibrate all of the watersheds in the United States, currently two calibration projects have been completed, with about 30% of eight-digit hydrologic unit code (HUC-8) watersheds in the United States calibrated and about 25% of four-digit HUCs calibrated (U.S. EPA 2017a; 2017b). HAWQS is configured with all required input data and default model parameters to make setting up and running the model as simple as possible. Outside of the calibrated watersheds, data may need to be adjusted to accurately represent local conditions, and experienced modelers may have data and wish to calibrate watersheds at a higher resolution within the HAWQS calibrated watersheds.[1]

BenSPLASH modeling platform is designed to quantify the economic benefits of water quality improvements to the nation's freshwater rivers and streams. The primary analytical approach uses water quality input data to spatially assign a relationship to a population located in proximity to the waterbodies of interest. BenSPLASH converts multiple water quality parameters into a single-valued water quality index (WQI) and then calculates household willingness to pay (WTP) through a previously estimated valuation function. The current version of the model relies on a metaregression valuation function using demographic data originating at the census block group level, but BenSPLASH is structured so that additional valuation functions can be integrated as they become available.

Newbold, Simpson, et al. (2018a, 469) noted the need for "a general purpose integrated framework that combines a comprehensive set of bio-physical models and observations of ambient environmental quality with data on consumer expenditures and preferences that could produce estimates of benefits on a timely basis for new regulations as they are taking shape." Model linkages are often the weak point in an analysis. Ideally, an integrated model would trace the links from water quality impacts to ecosystem services to valuation of those services, whereas our models go directly from water quality to valuations of improvements in water quality. The complicated interactions depicted by Keeler et al. (2012) continue to be difficult to model in an integrated manner, let alone at a national scale. We view the current HAWQS/BenSPLASH effort as a stepping stone and part of the EPA's continued efforts to improve its ability to value water quality benefit-cost analysis (see Griffiths et al. 2012).[2]

This paper applies HAWQS and BenSPLASH to a case study in the Republican River basin. In addition to demonstrating the ability to use the two models together, the case study highlights the ability to test sensitivity of the results to a variety of assumptions, including extent of the market and scale of the stream network. Advantages of HAWQS include faster, more efficient, less costly modeling (e.g., reduces repeated studies), open-source architecture to promote transparency, and unbiased transboundary water information. The BenSPLASH modeling platform in-

[1] See the Appendix for current HAWQS watersheds calibrated as of March 2020. The developers are continuing to calibrate additional watersheds. In addition, a future HAWQS enhancement will allow modelers to upload SWAT watershed models (originally created in HAWQS) back into HAWQS once they have added more refined data.

[2] As models of changes in ecosystem services as a function of water quality and valuation models based on changes in those ecosystem services become available, it will be possible to include them directly into future versions of BenSPLASH.

corporates rasterization for fast and efficient estimation, provides the analyst with a variety of modeling options, and will be able to collect different complementary or competing benefits approaches in one place. An advantage of starting with the current approach is that it is based on established datasets (National Land Cover Database, U.S. Census, NHDv2) and widely used tools (e.g., WQI, metaregression). Taken together, the integrated use of HAWQS and BenSPLASH can support benefits assessment at national, regional, state, and local scales down to HUC-12. HAWQS is a publicly available model (U.S. EPA 2017a), while BenSPLASH is not publicly available yet. We used a prototype of BenSPLASH for this analysis and continue to work on important modifications before making the model publicly available.

2. Model Overview and Structure

Model Overview

The EPA often estimates the benefits of surface water quality improvements pursuant to Executive Orders 12866 and 13563,[3] guided by the Office of Management and Budget's Circular A-4 on Regulatory analysis and EPA's Guidelines for Preparing Economics Analyses (U.S. EPA 2010), which require methods to be transparent and reproducible. Building BenSPLASH began with a recognition of the need for a faster, more efficient, and replicable valuation capability for the EPA to analyze the monetary benefits of water quality improvements. In order to prioritize aspects of BenSPLASH's development, the project team gathered "user stories" (use cases) from over a dozen economists and water quality experts.[4] Based on the user stories, the project team decided to focus initial efforts on analyses that are potentially national in scope, using data sources that are nationally consistent.

When using an existing water quality model, often the main effort is devoted to preparing policy- and location-specific model inputs rather than running the model. To generate modeling efficiencies in the short run, we put emphasis on gathering and including information that has traditionally been required to estimate benefits. Long-run development focuses on modularity and flexibility so that future capabilities can be added without a complete overhaul of the modeling framework. The EPA plans to make BenSPLASH available to the public via an open source framework so that others may suggest improvements or assess their own policy or counterfactual scenarios.

HAWQS enables use of SWAT and is used to simulate the effects of management practices based on an extensive array of crops, soils, natural vegetation types, land uses, and climate change scenarios for hydrology and the following water quality parameters: sediment, pathogens, nutrients, biological oxygen demand, dissolved oxygen, pesticides, and water temperature. BenSPLASH is a model for calculating the benefits of surface water quality improvements in the conterminous United States.[5] The main user-supplied inputs to BenSPLASH are pre- and postscenario measures of water quality for each waterbody expected to improve due to a regulation or policy, either in the form of water quality parameter concentrations or WQI values. To complement the user-supplied inputs, other information is included in the model, such as waterbody-specific information and U.S. Census data at the census block group level. All input data are rasterized by BenSPLASH into a national data grid to improve the computational efficiency of the model.[6] Each grid cell

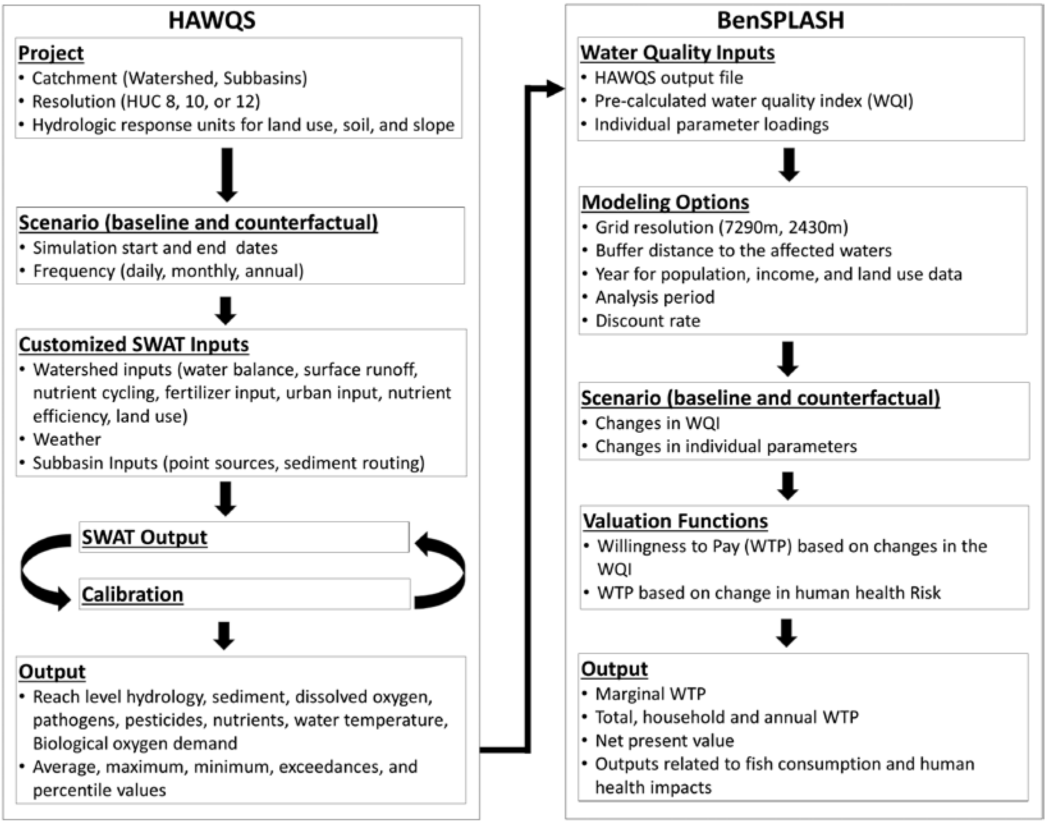
[3] Regulatory Planning and Review, and Improving Regulation and Regulatory Review, respectively.

[4] A user story is in the following format: "As a [blank], I want to be able to [blank]." An example user story is "As a water quality modeler, I want water quality model output sufficiently detailed so that whether particular designated uses are met can be estimated."

[5] Hereafter, we use the term "national" as shorthand for the conterminous United States.

[6] Because the location of any grid cell can be expressed by a Cartesian (x,y) address, spatial calculations (distances, overlaps) in a grid system are very efficient. With vector data, spatial calculations are done using topological operations (e.g., unions, intersections), and processing time can be prohibitive, especially when accounting for double-counting. In some cases, computer memory issues may make calculations impossible. Vector data are more accurate for shapes with irregular boundaries or single points, but because spatial calculations in geographic information systems are so slow, analytics using vector data often use shortcuts,

Figure 1
Flowchart of Integrated Modeling Structure



is then treated as a representative household when applying the valuation functions for water quality improvements within a specified radius of the grid cell centroid. The main outputs of BenSPLASH are marginal WTP per household by grid cell, total WTP by grid cell, and total U.S. WTP. Figure 1 provides a general schematic of the linked HAWQS-BenSPLASH system.

The HAWQS and BenSPLASH models work in series to estimate economic benefits from management practices affecting water quality. Here we describe the components of the models and the intermediate outputs that are generated, serving as inputs to the subsequent steps in the simulation.

Water Quality Modeling

HAWQS is a web-based interactive hydrology and water quality modeling system that runs SWAT as the core model code. HAWQS includes a user interface to allow selection of watersheds and then automatically builds a modeling project with all input data required for SWAT at HUC-8, HUC-10, and HUC-12 scales. Users have the choice to execute HAWQS simulations on the remote server or to download configured SWAT models to run on a local machine. HAWQS provides an output interface that includes tables, charts, graphs, maps, and raw data. HAWQS is a complete modeling system in that it includes a user guide, online model development, exe-

such as representing an irregular shape by its approximate centroid. The accuracy of a raster rendering depends on the size of the grid cells. We explore the benefits of this trade-off by carrying the size of the grid cells and find that smaller grid cells do not measurably improve precision in this application.

cution, output processing, and storage of each user's modeling projects. Because HAWQS is run entirely on a server, personal computing requirements are minimal (U.S. EPA 2017a). Yuan et al. (2018) provide an example of the use of HAWQS within a multimodel system.

HAWQS inputs come from a number of well-known national-level datasets for hydrology, land use, soils, crops, and weather data. Within the model, weather data including precipitation and air temperature are from the Parameter Elevation Regression on Independent Slopes Model (PRISM) from 1981 to 2015. The HAWQS model uses the PET-Hargrave function built into SWAT 670 to model potential evapotranspiration. National land cover data and soil characteristics are taken from the 2006 National Land Cover Database Land Use and Land Cover and State Soil Geographic databases, respectively. Crop data come from the USDA's Cropland Data Layer, supplemented with additional fertilizer and management data from the National Agricultural Statistics Survey according to the methodology laid out by White et al. (2016). All of these datasets as well as the elevation and hydrology data have been preprocessed to increase the efficiency of HAWQS model setup. Experienced modelers who wish to modify the input data with their own localized data may do so by downloading HAWQS watershed models to SWAT, thereby benefiting from their particular SWAT code while still saving substantial time setting up SWAT watersheds.[7]

HAWQS simulates both the land phase and the routing phase of the hydrologic cycle. Based on the input precipitation data, HAWQS simulates the amount of water entering surface runoff, infiltration into the soil, percolation to the underlying shallow and deep aquifer, and evapotranspiration. HAWQS also simulates flow detention and sediment and nutrient settling due to the ponds and wetlands located in the watershed. The water quality associated with these flow components is simulated based on the modified universal soil loss equation, input fertilizer application rates, crop and plant types, input point source flows and loads, and active management practices. This includes the movement and transformation of nitrogen and phosphorus in the watershed due to plant growth and soil properties. HAWQS determines the flow and water quality loads entering the main channel of each subbasin and routes these through the channel to the next downstream channel. For this application of HAWQS, flow is routed using SWAT's variable storage coefficient method, and sediment is routed according to SWAT's simplified Bagnold equation. HAWQS does not currently have the ability to simulate the effects of reservoirs, and so these effects are not included in this project. However, the underlying SWAT model does include options for modeling flow and simplified water quality in reservoirs (Neitsch et al. 2011).

Water Quality Index

The current version of BenSPLASH uses a WQI to value the changes in water quality parameters provided by HAWQS.[8] Use of a WQI requires translating observed or simulated water quality parameter values into subindex values ranging from 0 to 100 and then aggregating those subindex values into a single value, also bounded by 0 and 100 (Walsh and Wheeler 2013). The WQI values serve as the link between the HAWQS model and the valuation exercise performed in BenSPLASH, maintaining the spatial representation by generating a single value for each geo-tagged hydrological unit. The WQI module in BenSPLASH allows for a six-parameter weighted WQI used in past EPA regulations (e.g., U.S. EPA 2009).[9]

WQI subindex curves were originally applied in an economic context by Vaughan (1986), who calculated WQI scores for the

[7] Anecdotally, experienced SWAT users go from setting up a watershed in two weeks to setting one up in a few hours. Plans for HAWQS 2.0 also include the ability to upload modified SWAT watersheds back into HAWQS, allowing modelers to share and run models remotely. A full description of the input data can be found at https://hawqs.tamu.edu/content/docs/HAWQS-Input-Database-Citation.pdf.

[8] Future versions of BenSPLASH are planned to incorporate additional valuation methodologies that rely directly on observed or simulated water quality parameters.

[9] The six-parameter WQI used in this study consists of DO, TN, TP, FC, TSS, and BOD. BenSPLASH also includes an equally weighted seven-parameter version used in the EPA's 2015 Steam Electric Effluent Limitation Guideline (U.S. EPA 2015), which adds an additional subindex for metals.

parameter values necessary to achieve designated uses of water (e.g., fishable and swimmable). The resulting WQI values were then used to construct the water quality ladder that has been widely used in valuation. The WQI employed in BenSPLASH uses subindex curves developed more recently. National subindexes for dissolved oxygen (DO), fecal coliform (FC), and biochemical oxygen demand (BOD) were developed by Dunnette (1979) and Cude (2001). The subindexes for total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) are based on an ecoregion-specific approach developed by Cude (2001). These subindexes are combined as a weighted geometric mean to generate the single-valued WQI.[10]

BenSPLASH uses the U.S. Geological Survey's National Hydrography Dataset (NHD) stream reaches as the primary hydrologic unit of analysis. Each NHD stream reach has a unique identifier referred to as a COMID, and each COMID must have an associated WQI measure for BenSPLASH to generate results. BenSPLASH can use hydrologic data with existing WQI scores. If the scores are calculated at a different scale than the COMID, such as the HUC-12 scale, BenSPLASH will translate the scores to the corresponding COMIDs. BenSPLASH can also be used to convert output from HAWQS that reports individual parameters into individual parameter subindex values and combine these individual parameter subindices into a single WQI value for each COMID.

Valuation and Aggregation

The primary meta-analysis valuation functions used in BenSPLASH capture geospatial factors rarely applied to benefits transfer and are derived in a utility theoretic framework to ensure consistency with the adding-up condition. Diamond (1996) suggests a type of validity test based on an internal consistency condition that any WTP function should satisfy. The WTP for a change from state 0 to 1 conditional on baseline income plus the WTP for a change from state 1 to state 2 conditional on the income remaining after paying for the change from state 0 to state 1 must equal the WTP for a change from state 0 to 2 conditional on baseline income. This type of path-independence is a basic requirement for internal consistency and may be viewed as a necessary condition for a valid benefit transfer function. The default household WTP function used by BenSPLASH is derived in a utility theoretic framework that satisfies Diamond's adding-up criterion.[11]

We can ensure that the WTP metafunction will comply with the adding-up condition by following a three-step procedure (Newbold, Walsh, et al. 2018). First, specify a Marshallian inverse demand curve for environmental quality that includes income and the baseline quality level as arguments; second, derive a compatible indirect utility function; and third, derive from the indirect utility function the associated expenditure function. The difference in the expenditure function evaluated at the initial and final quality levels gives a total WTP function, which can then be used as the metaregression estimating equation. This procedure will guarantee that the WTP function will satisfy the adding-up condition along the quality dimension and account for the income effect. To implement this approach, begin with the following form for the Marshallian inverse demand function for water quality:

$$wtp_{\mathrm{i}} = \exp(\beta_H \mathbf{H}_i + \beta_Y \ln Y_{\mathrm{i}} + \beta_Q Q_{\mathrm{i}}), \quad [1]$$

where i indexes unique WTP estimates, wtp_i is marginal WTP, $\mathbf{H}_i$ is a vector of demand shifters including resource characteristics and design features of the primary study, Y_i is the average

[10] The platform can flexibly accept weights.

[11] WTP and other related stated preference issues continue to elicit lively debate, as evidenced in the *Journal of Economic Perspectives'* Symposium on Contingent Valuation (Kling, Phaneuf, and Zhao 2012; Carson 2012; Hausman 2012) and subsequent responses. At its essence, the debate boils down to whether to put more weight on neoclassical economic theory, which people are sometimes observed to violate, or on enhancements to neoclassical theory that resolve observed behavior but lack a strict theoretical link to the underpinnings of benefit-cost analysis (see also Johnston et al. [2017] for recommendations related to the development and use of stated preference studies). While the case study in this paper uses a meta-analysis based on WTP results from stated preference approaches, BenSPLASH developers are incorporating other valuation methods as well, such as hedonic pricing, recreation demand, cost of illness, and other human health approaches.

income of the survey respondents, Q_i is the WQI level for observation *i,* and β_H, β_Y, and β_Q are parameters estimated via metaregression. See Newbold, Walsh, et al. (2018), equations 9 through 13, for the complete derivation leading to the estimating equation for total WTP,

$$WTP(Q_0,Q_1,Y) = Y - \left[(1-\beta_Y)\left(\frac{1}{\beta_Q}e^{\beta_H\mathbf{H}+\beta_Q Q_0} - \frac{1}{\beta_Q}e^{\beta_H\mathbf{H}+\beta_Q Q_1} + \frac{1}{1-\beta_Y}Y_0{}^{1-\beta_Y}\right)\right]^{\frac{1}{1-\beta_Y}}, \quad [2]$$

where, Q_0 and Q_1 refer to baseline and post-policy water quality expressed in terms of WQI, and *WTP* is household WTP for that change. See Newbold, Walsh, et al. (2018) or the supplemental materials to this article for metaregression results.

The metadata are drawn from primary stated preference valuation studies that estimate per household (use and nonuse) WTP for water quality changes in U.S. water bodies that affect ecosystem services including aquatic life support, recreational uses (such as fishing, boating, and swimming), and nonuse values.[12] Necessary data includes information identifying affected water bodies, the extent of water quality change, and sampled market areas, along with core methodological attributes. Studies are limited to those for which per household WTP estimates could be readily linked to water quality changes measured on the standard 100-point WQI. The resulting metadata include 140 observations from 51 stated preference studies conducted between 1981 and 2011. Independent variables in the metadata characterize (1) study methodology and year, (2) region and surveyed populations, (3) sampled market areas and study site, (4) affected water bodies, and (5) water quality baseline and change.[13]

Demographic data are collected for census block groups, the smallest geographical unit for which sample data are published. The U.S. Census Bureau provides the geometry for each block in the Topologically Integrated Geographic Encoding and Referencing geographic database that we use to rasterize demographic data into the national grid. The baseline water quality level Q_0 and expected water quality under the policy option Q_1 are based on water quality at waterbodies within a 160 km buffer of the centroid of each grid cell. A buffer of 160 km is consistent with Viscusi, Huber, and Bell (2008) and with the assumption that the majority of recreational day trips will occur within a two-hour drive from home. As a sensitivity analysis we also evaluate a 100 km buffer.[14] By focusing on a buffer around the grid cell as a unit of analysis, rather than buffers around affected waterbodies, each household is included in the assessment exactly once, eliminating the potential for double-counting of households. Total WTP is calculated for a representative household in each grid cell and then multiplied by the number of households in the cell. Total national WTP is calculated by summing across all grid cells that have at least one affected waterbody within 160 km of the centroid.

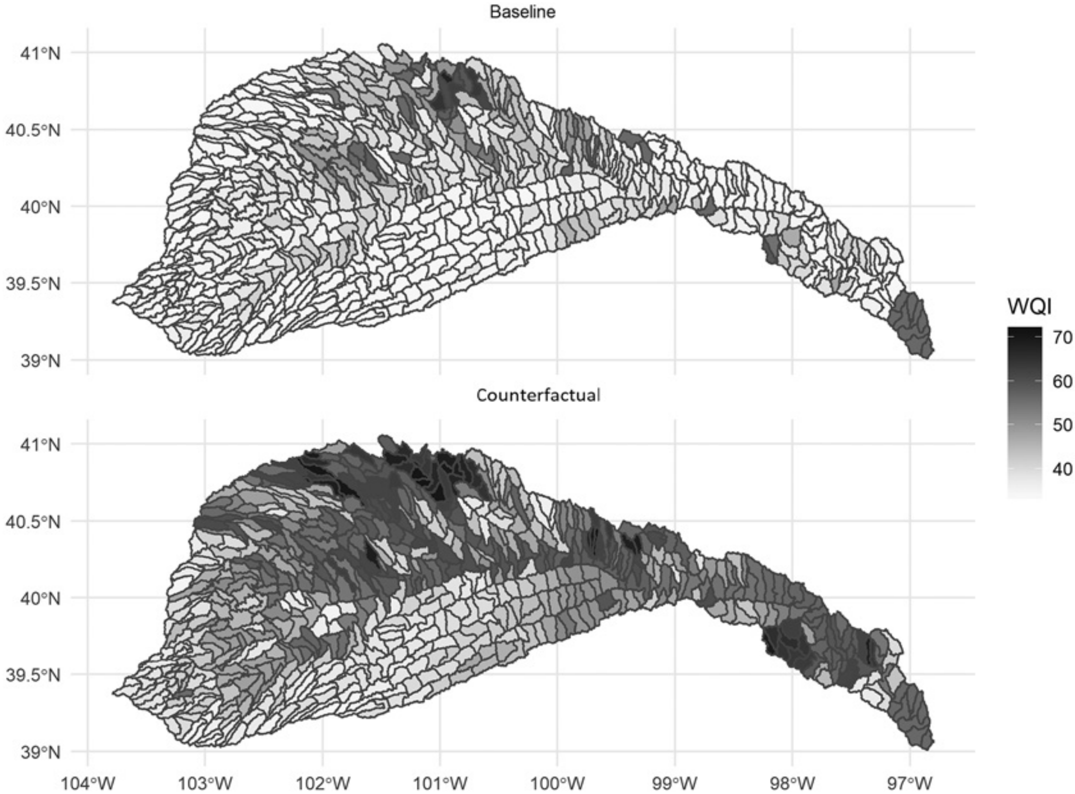
With rare exceptions, theory suggests that transferred welfare estimates should be sensitive to core economic factors including geospatial scale (the geographical size of affected environmental resources or areas), market extent (the size of the market area over which WTP is estimated), and substitute availability (the availability of proximate, unaffected substitutes) (Johnston, Besedin, and Stapler 2017). The valuation metadata combine information reported by primary studies with extensive geospatial data derived from external, spatially explicit databases. Results illustrate

[12] While we have chosen to value ecosystem services collectively through a WQI, other studies (e.g., Lupi et al. 2019) approach environmental modeling and valuation separately for individual ecosystem services.

[13] See U.S. EPA (2015, table H-1) for a list of the primary studies used to populate the metadata.

[14] There is no consensus in the literature regarding the extent of distance decay of WTP. One of the few papers addressing incorporating distance decay in meta-analyses, by Johnston, Besedin, and Holland (2019) finds that environmental improvements farther from respondents are associated with lower WTP values. See also Choi, Ready, and Shortle (2020) for an example of a distance-weighted WQI. For the purposes of this demonstration of the BenSPLASH model we specify a 160 km limit on WTP for water quality changes as our main model and test a 100 km limit as a sensitivity analysis.

Figure 2
Map of Republican River Subbasins Showing Baseline and Counterfactual Scenario Water Quality



theoretically anticipated scale and substitution effects.

3. Case Study: The Republican River Basin

This section illustrates the application of HAWQS and BenSPLASH under hypothetical scenarios of water quality impacts for estimating the economic benefits from water quality improvements to river reaches in a relatively small geographic area. The geographic area selected for the case study is the Republican River basin. The hypothetical scenario is meant to reflect the implementation of pollution control measures within this basin to address water quality impairments.

The Republican River basin, shown in Figure 2, is a 4-digit HUC (1025) comprising 599 12-digit HUCs. The Republican River basin encompasses approximately 25,000 square miles along the border of Nebraska and Kansas, stretching into Colorado on the west and connecting with the Kansas River on the east. The watershed lies mainly within the High Plains and Central Great Plains ecoregions. The predominant water features in the basin are intermittent streams that flow into the larger perennial creeks and rivers. There are over 20 reservoirs along the length of the Republican River and its tributaries, which supply water primarily for agriculture and municipal purposes. Based on geospatial analysis using the high-resolution NHD, there are over 40,000 mapped miles of waters in this watershed.[15]

[15] The Appendix contains additional information about the Republican River basin.

Table 1
Number of Assessed Water Impairments within the Republican River Basin, by State

Cause of Impairment	Colorado	Kansas	Nebraska	Totals
Algal growth			4	4
Cause unknown; impaired biota		3	1	4
Fish consumption advisory			5	5
Metals (other than mercury)		43	2	45
Nutrients		36	8	44
Organic enrichment/oxygen depletion		3	8	11
Pathogens	2		25	27
Pesticides			1	1
pH/acidity/caustic conditions			1	1
Temperature			3	3
Turbidity		12		12
Totals	2	97	58	157

Source: U.S. Environmental Protection Agency, Office of Water 303(d) listing, accessed May 2015.
Note: Waters with multiple causes for impairment are counted more than once.

The land within the Republican River basin is used primarily for cropland; other uses include land for grazing, as well as oil and gas production. Most of the land within the basin is classified as rural, although there are urban clusters scattered throughout.[16] The majority of the urban land is in the eastern portion of the basin, with the largest urban cluster, Junction City, located at the confluence of the Republican and Kansas Rivers.

A significant portion of the assessed waters within the basin have been placed on the EPA's CWA 303(d) List of Impaired Waters. Table 1 provides state tallies of basin waters impaired by different pollutants. Nutrients are the second most frequent cause for impairment. Due to the rural nature of the basin, there are relatively few point sources located within the basin. A review of NPDES permits for point-source discharges found 375 total permits (113 individual and 262 general permits), with 42 of these being for sewage treatment plants. The predominance of agriculture within the watershed suggests it may be a key source of nutrient pollution, as well as pathogens and turbidity.

We devised a "counterfactual" scenario with the intent of demonstrating HAWQS's capabilities and not to demonstrate the effects of a program under current consideration. The scenario simulates the water quality effects due to applying best management practices (BMPs) to reduce stormwater and nutrients from agriculture. These BMPs include applying 25 meter-wide, vegetated filter strips on all agriculture lands and reducing impervious surface on urban lands by 25%. These BMPs are generally considered effective at reducing nutrients and may also help control other pollution sources such as sediment.

Applying the vegetated filter strips to all agricultural land would result in approximately 795 km^2, or 3% of total agricultural land, being taken out of production and devoted to filter strips. This scenario does not account for the instances in which the use of filter strips would not be feasible, nor does it account for any existing vegetated filter strips already in use. Applying impervious surface reduction to 25% of impervious areas results in 6.2 km^2 of impervious surface being removed from urbanized areas within the basin. The extent of these two BMPs for the counterfactual scenario is ambitious and may not be realistic. For example, the EPA does not directly regulate the introduction of vegetated filter strips. These BMPs would likely be enacted by state or local authorities who might benefit from an IAM for water quality changes. However, for demonstrating how the HAWQS and BenSPLASH models could be used together to produce economic benefit estimates, the counterfactual scenario was inten-

[16] The 2010 U.S. Census classifies urban areas as population centers with populations more than 2,500 inhabitants. Urban clusters (UCs) have at least 2,500 and fewer than 50,000 people, while urbanized areas (UAs) consist of 50,000 or more people.

tionally designed to produce sizable changes in water quality.

HAWQS was set up for the 12-digit HUC subbasins in the Republican River basin (HUC-1025) in the Missouri River region and run for a baseline scenario for existing conditions from 2006 to 2010. The HAWQS model had previously been calibrated for flow, sediment, TN, and TP at the pourpoint of the Republican River basin (U.S. EPA 2017a, 2017b). HAWQS was used to calculate daily flows and loads for each subbasin, for both the baseline and counterfactual scenarios, and daily values were averaged over a five-year simulation period.

This example used the default six-parameter WQI in BenSPLASH with default weighting: FC, CFU/100 ml, weight 0.22; TSS, mg/L, weight 0.11; DO, mg/L, weight 0.24; BOD, mg/L, weight 0.15; TN, mg/L, weight 0.14; and TP, mg/L, weight 0.14. HAWQS output was used for TSS, TN, and TP, and water quality monitoring data were used for the three parameters FC, DO, and BOD, which were not part of the calibration for HAWQS; we obtained the monitoring data from the EPA Water Quality Portal.[17] For the purposes of this analysis, the parameters FC, DO, and BOD remain constant between the baseline and counterfactual scenarios. It is important to include FC, DO, and BOD in the analysis because baseline WQI enters the valuation function estimated in the metaregression. Griffin et al. (2019) explores how omitted parameters impact model results.

The baseline and counterfactual scenario subbasin WQI scores were used as inputs for BenSPLASH. BenSPLASH automatically assigns these subbasin-scale results to the more refined, NHD stream COMIDs. BenSPLASH is prepopulated with national census block group data, which contain the relevant household demographic information for estimating household WTP. Running BenSPLASH requires selecting the grid size the model uses for rasterizing the water quality and demographic data. A trade-off exists between the coarseness chosen for a grid size (speed of model run) and the precision of the produced estimates. A coarser grid scale requires fewer calculations but has less precision in the results for at least two reasons. First, the spatial units for the water quality and demographic data are irregular shapes, so approximating them with smaller grid cells will reduce errors on their borders. Second, the analyst must select a distance from the centroid of each cell beyond which WTP for water quality improvements is zero (i.e., extent of market). Using smaller cells will produce a more accurate representation of distance for the households within each cell. For the Republican River case study, BenSPLASH was run using a 7,290 m grid cell length and a 160 km buffer for calculating market area. To test the sensitivity of model results to the grid size and buffer distance, two additional scenarios were considered: a smaller (2,430 m) grid cell size and a smaller (100 km) buffer distance.

[17] See https://www.waterqualitydata.us/.

Table 2
Summary of HAWQS Model Output for Republican River Subbasins

	TSS (mg/L)	TN (mg/L)	TP (mg/L)
Baseline scenario			
Mean[a]	9.38	29.42	3.42
Median	7.19	19.31	3.07
Minimum	0.60	0.77	0.21
Maximum	33.58	372.72	15.59
Counterfactual scenario			
Mean[a]	7.27	8.91	1.91
Median	4.58	8.19	1.85
Minimum	0.47	0.42	0.14
Maximum	32.66	52.28	5.69

Note: TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids.
[a] Mean values are based on an equal weighting of the HAWQS model results for the 599 HUC-12 subbasins.

4. Case Study Results

Table 2 provides an estimate of the HAWQS model results, as mean, median, minimum, and maximum TN, TP, and sediment concentrations for the baseline and counterfactual scenarios. Focusing on the median measure, the predicted changes in concentrations for TSS, TN, and TP resulted in an improvement across the subbasins of 36%, 58%, and 40%, respectively.

Table 3
Summary of BenSPLASH Model Output for the Republican River Basin

Buffer	Grid Size	Cells	WQI Baseline Scenario	WQI Counterfactual Scenario	WQI Delta	Annual MWTP per WQI Point (dollars)	Annual WTP (mean dollars per cell)	Total Annual WTP (millions of 2016 dollars)
160 km	7,290m	6,709	47.34	58.86	11.51	3.148	34.467	63.8
160 km	2,430m	56,730	47.39	59.06	11.68	3.153	35.089	62.0
100 km	7,290m	4,305	47.42	58.87	11.45	3.118	33.382	15.7

Note: WQI, water quality index; WTP, willingness to pay.

Figure 3
Map of Republican River Subbasins Showing Extent of the 100 km and 100 mi (160 km) Buffers

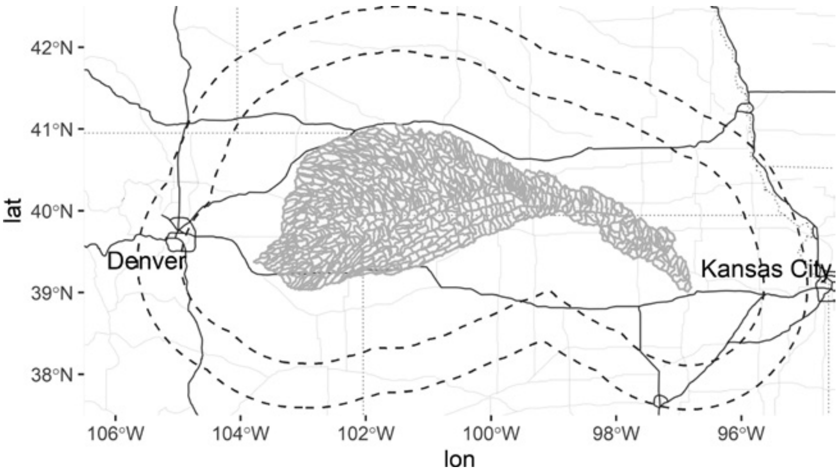


Figure 2 shows a graphical representation of the baseline and counterfactual WQI scores by subbasin. Table 3 provides a summary of the BenSPLASH annual WTP results for the three model runs, varying the grid cell size and the distance buffer radius. To perform comparisons across those two dimensions, we consider annual household, marginal, and total WTP. Household and marginal WTP estimates are stable across all three scenarios, showing that increasing the resolution of the model and constricting the extent of market do not impact WTP on the intensive margin. The radius of the buffer does have a substantial impact on the total WTP, however, with the 160 km buffer producing an estimate about four times as large as the 100 km buffer. Given household WTP does not vary to that degree between buffer size, we can conclude this a result of more households being included in the aggregation, rather than households willing to pay more for additional waters being improved. The difference in grid cell size does not appear to have a meaningful effect on total household WTP, but smaller grid cells take much longer to run, suggesting, at least in this application, the precision gain does not justify the additional cost of computing time.

Figure 3 shows the extent of the 100 km and 160 km buffers around the Republican River basin. The 100 km buffer includes 422,000 households in several urbanized areas such as Topeka and Manhattan, Kansas, to the east and the eastern suburbs of Denver to the west. However, the 160 km buffer includes significantly more urbanized area, with 2.3 million households. To the west it captures much of the Denver metropolitan area within the buffer and several smaller urbanized centers such as Colorado Springs, Boulder, and Fort Collins, Colorado. To the east the buffer extends to the western suburbs of Kansas City and includes urbanized areas like Wichita and Lawrence, Kansas. These comparisons show that the extent of market has a much greater impact on total WTP than increasing the resolution of the model (see also Table 3).

5. Next Steps

The case study presented here uses a proof-of-concept version of the BenSPLASH water quality benefits model. The EPA is currently developing an open source version of BenSPLASH, which will be housed in a public repository. The model will be composed of a front-end user interface and a separate back end built around accessible code (such as R and possibly Python) to perform analysis. This approach will allow us to more easily customize and explore different approaches to valuation in programming languages familiar to economists. The open source nature of the model, along with clear logs detailing assumptions and model options chosen for each model run, will facilitate transparent, reproducible, and testable analyses.

In addition to the programming changes to BenSPLASH, we will also be exploring improvements to the WQI used in the case study. Future versions of BenSPLASH will allow for more flexibility in the parameters included in the WQI and in the weights given to those parameters. Relying on the WQI opens a rich research agenda, including exploring the number and types of parameters to include in an index, the appropriate weighting scheme, the ability and method to construct geographically based regional subindices, and the pros and cons of using an index in relation to other approaches. We will investigate separating the WQI into two indices, a recreation-based index similar to the current WQI and an aquatic health index informed by species abundance and diversity and other ecological factors that are not directly correlated with suitability for human uses.

Our research and development agenda also includes adding capacity to perform additional valuation calculations. Colleagues at the EPA are developing a national hedonic model for water quality that will be incorporated as a module in BenSPLASH when appropriate (Guignet et al. 2019). The current version of BenSPLASH includes a human health valuation module based on reducing exposure to arsenic via fish consumption. We plan to initially expand this module to incorporate other carcinogens associated with fish consumption and human exposure health endpoints. We are exploring how to incorporate a module that will allow using specific valuation data, to be aggregated over different populations and time horizons within BenSPLASH. This will serve as both a prototype for valuing improvements in other iconic water bodies, as well as create a module that will allow outside researchers to use BenSPLASH for their own work. Additional development includes specific valuation of wetlands, estuary/coastal areas, and lakes. For coastal systems, HAWQS can provide loadings from large watersheds, but additional modeling may be needed to estimate nearshore loadings and to account for hydrodynamics and water quality dynamics in the water. Coastal water quality variables could be summarized into an existing index, and a regression similar to the existing BenSPLASH approach (Johnston and Bauer 2019) could be used to assess changes in coastal water quality. Ideally, more coastal studies would be incorporated to reduce uncertainty in the coastal estimates.

We are also improving HAWQS (version 1.0 is currently publicly available). Specifically, we are updating the existing national data layers for land use and weather; adding new data layers for soil and wetlands; updating the water temperature methodology; calibrating for various parameters including flow, nitrogen, and phosphorus; adding enhancements to the user interface, including reporting and visualization of output statistics; and updating the system to more efficiently use larger datasets.

The BMPs used in the hypothetical scenario—vegetative filter strips and reduced impervious cover—are useful in evaluating the effects on water quality and flow. Though immediate adoption of these BMPs is not very plausible, the HAWQS SWAT base code allowed for only immediate adoption. Other conservation practices in HAWQS, such as reducing tillage or restoring managed land to natural conditions, can be implemented incrementally with a variable adoption rate both temporally and spatially in HAWQS, which allows for a more realistic HAWQS-BenSPLASH IAM.

6. Conclusion

We introduce a set of models being developed at the EPA to support water quality benefits valuation and demonstrate their ability to function as an IAM through a case study in the Republican River region. In addition, we outline an active research and development agenda that will result in additional capabilities to perform a variety of water quality valuation analyses across the national landscape. The open source, collaborative approach we have taken to model development is designed to allow us to incorporate new data, approaches, and techniques developed by other researchers in this area.

Acknowledgments

The authors of this paper acknowledge the work of many others that has been integral to the development and implementation of these models, as well as thoughtful suggestions by Matthew Heberling and Michael Trombley. Earlier contributions by Steve Newbold, Patrick Walsh, Dennis Guignet, Robert Johnston, Brad Firlie, Isabelle Morin, Elena Besedin, Alyssa Le, Dave Wells, Arndt Gossel, and Raghavan Srinivasan have made this work possible. We also appreciate the comments of participants at the Social Cost of Water Pollution Workshop, Ithaca, New York, April 3–5, 2019, and the USDA Workshop Applications and Potential of Ecosystem Services Valuation within USDA: Advancing the Science, Washington, D.C., April 23–24, 2019. Disclaimer: The research described in this abstract has been funded in part by the U.S. Environmental Protection Agency through contract EP-C-13-039 to Abt Associates and contract EP-G15H-01113 with ATTAIN, LLC. The views expressed in this document are those of the authors and do not necessarily reflect the views or policies of the U.S. Environmental Protection Agency.

References

Carson, Richard T. 2012. "Contingent Valuation: A Practical Alternative When Prices Aren't Available." *Journal of Economic Perspectives* 26 (4): 27–42.

Choi, Dong Soon, Richard C. Ready, and James S. Shortle. 2020. "Valuing Water Quality Benefits from Adopting Best Management Practices: A Spatial Approach." *Journal of Environmental Quality,* forthcoming.

Cude, Curtis G. 2001. "Oregon Water Quality Index: A Tool for Evaluating Water Quality Management Effectiveness." *Journal of the American Water Resources Association* 37 (1): 125–37. https://doi:10.1111/j.1752-1688.2001.tb05480.x.

Diamond, Peter. 1996. "Testing the Internal Consistency of Contingent Valuation Surveys." *Journal of Environmental Economics and Management* 30 (3): 337–47.

Dunnette, D. A. 1979. "A Geographically Variable Water Quality Index Used in Oregon." *Water Pollution Control Federation* 51 (1): 53–61.

Griffin, Robert, Stefanie Covino, Eivy Monroy, Heidi Ricci, Richard Sharp, Courtney Schmidt, Emi Uchida, Adrian Vogl, and Stacie Wolny. 2019. "Decision Support Modeling for Multi-attribute Water Quality in the Narragansett Bay Watershed." Presented at the 2019 Social Cost of Water Pollution Workshop, Ithaca, NY. Available at https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/1/8608/files/2019/03/Griffin-et-al-1072nq0.pdf.

Griffiths, Charles, Heather Klemick, Matt Massey, Chris Moore, Steve Newbold, David Simpson, Patrick Walsh, and William Wheeler. 2012. "U.S. Environmental Protection Agency Valuation of Surface Water Quality Improvements." *Review of Environmental Economics and Policy* 6 (1): 130–46.

Guignet, Dennis, Matthew T. Heberling, Michael Papenfus, Olivia Griot, and Ben Holland. 2019. "Property Values and Water Quality: A Nationwide Meta-analysis and the Implications of Benefit Transfer." Research in Environmental Economics, NCEE Working Paper Series. 2019-05. Washington, DC: U.S. Environmental Protection Agency, National Center for Environmental Economics.

Hausman, Jerry. 2012. "Contingent Valuation: From Dubious to Hopeless." *Journal of Economic Perspectives* 26 (4): 43–56.

Johnston, Robert J., and Dana Marie Bauer. 2019. "Using Meta-analysis for Large-Scale Ecosystem Service Valuation: Progress, Prospects, and Challenges." *Agricultural and Resource Economics Review* 2019: 1–41.

Johnston, Robert J., Elena Y. Besedin, and Benedict M. Holland. 2019. "Modeling Distance Decay within Valuation Meta-analysis." *Environmental and Resource Economics* 72 (3): 657–90. https://doi.org/10.1007/s10640-018-0218-z.

Johnston, Robert J., Elena Y. Besedin, and Ryan Stapler. 2017. "Enhanced Geospatial Validity for Meta-analysis and Environmental Benefit Transfer: An Application to Water Quality Improvements." *Environmental and Resource Economics* 68 (2): 343–75.

Johnston, Robert J., Kevin J. Boyle, Wictor (Vic) Adamowicz, Jeff Bennett, Roy Brouwer, Trudy Ann Cameron, W. Michael Hanemann, Nick Hanley, Mandy Ryan, Riccardo Scarpa, et al. 2017. "Contemporary Guidance for Stated Preference Studies." *Journal of the Association of Environmental and Resource Economists* 4 (2): 319–405.

Keeler, Bonnie L., Stephen Polasky, Kate A. Brauman, Kris A. Johnson, Jacques C. Finlay, Ann O'Neill, Kent Kovacs, and Brent Dalzell. 2012. "Linking Water Quality and Well-being for Improved Assessment and Valuation of Ecosystem Services." *Proceedings of the National Academy of Sciences U S A* 109 (45): 18619–24.

Keiser, David A., and Nicholas Z. Muller. 2017. "Air and Water: Integrated Assessment Models for Multiple Media." *Annual Review of Resource Economics* 9: 165–84.

Kling, Catherine L., Daniel J. Phaneuf, and Jinhua Zhao. 2012. "From Exxon to BP: Has Some Number Become Better Than No Number?" *Journal of Economic Perspectives* 26 (4): 3–26.

Lupi, Frank, Bruno Basso, Cloe Garnache, Joseph A. Herriges, David Hyndman, and R. Jan Stevenson. 2019. "Linking Agricultural Nutrient Pollution to the Value of Freshwater Ecosystem Services." Presented at the 2019 Social Cost of Water Pollution Workshop, Ithaca, NY. Available at https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/1/8608/files/2019/03/Lupi-et-al-1pze3yb.pdf.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2011. *Soil and Water Assessment Tool Theoretical Documentation Version 2009.* Texas Water Resources Institute Technical Report No. 406. College Station, TX: Texas A&M University System.

Newbold, Stephen, R. David Simpson, D. Matthew Massey, Matthew T. Heberling, William Wheeler, Joel Corona, and Julie Hewitt. 2018. "Benefit Transfer Challenges: Perspectives from U.S. Practitioners." *Environmental and Resource Economics* 69 (3): 467–81.

Newbold, Stephen C., Patrick J. Walsh, D. Matthew Massey, and Julie Hewitt. 2018. "Using Structural Restrictions to Achieve Theoretical Consistence in Benefit Transfer." *Environmental and Resource Economics* 69 (3): 529–53.

U.S. EPA (U.S. Environmental Protection Agency). 2009. *Environmental Impact and Benefits Assessment for Final Effluent Guidelines and Standards for the Construction and Development Category.* November 2009. Washington, DC: U.S. Environmental Protection Agency. Available at https://www.epa.gov/sites/production/files/2015-06/documents/cd_envir-benefits-assessment_2009.pdf (accessed May 9, 2019).

———. 2010. *Guidelines for Preparing Economic Analyses*. Washington, DC: U.S. Environmental Protection Agency. Available at https://www.epa.gov/environmental-economics/guidelines-preparing-economic-analyses.

———. 2015. *Benefit and Cost Analysis for the Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category.* EPA-821-8-11-001. Washington, DC: U.S. Environmental Protection Agency.

———. 2017a. *HAWQS 1.0 (Hydrologic and Water Quality System) Modeling Framework.* Washington, DC: U.S. Environmental Protection Agency, Office of Water. Available at https://www.epa.gov/hawqs (accessed February 28, 2019).

———. 2017b. *HAWQS v1.0 Calibration Process.* Washington, DC: U.S. Environmental Protection Agency, Office of Water. Available at https://hawqs.tamu.edu/content/docs/calibration/HAWQS-Calibration-Methodology.pdf.

Vaughan, William J. 1986. "The RFF Water Quality Ladder." In *The Use of Contingent Valuation Data for Benefit/Cost Analysis in Water Pollution Control, Final Report,* ed. R. C. Mitchell and R. T. Carson, Appendix B. Washington, DC: Resources for the Future.

Viscusi, W. Kip, Joel Huber, and Jason Bell. 2008. "The Economic Value of Water Quality." *Environmental and Resource Economics* 41: 169–87.

Walsh, Patrick J., and William J. Wheeler 2013. "Water Quality Index Aggregation and Cost Benefit Analysis." *Journal of Benefit-Cost Analysis* 4 (1): 1–24.

White, Michael, Marilyn Gambone, Haw Yen, Prasad Daggupati, Katrin Bieger, Debjani Deb, and Jeff Arnold. 2016. "Development of a Cropland Management Dataset to Support U.S. Swat Assessments." *Journal of the American Water Resources Association* 52 (1): 269–74. https://doi.org/10.1111/1752-1688.12384.

Yuan, Yongping, Ruoyu Wang, Ellen Cooter, Limei Ran, Prasad Daggupati, Dongmei Yang, Raghavan Srinivasan, and Anna Jalowska. 2018. "Integrating Multimedia Models to Assess Nitrogen Losses from the Mississippi River Basin to the Gulf of Mexico." *Biogeosciences* 15: 7059–76.