EPA Public Access

Author manuscript

Land Econ. Author manuscript; available in PMC 2021 November 01.

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Published in final edited form as:

Land Econ. 2020 November 1; 96(4): 478–492. doi:10.3368/wple.96.4.478.

An Integrated Assessment Model for Valuing Water Quality Changes in the U.S.

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Abstract

The US 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 EPA to develop two models to form an Integrated Assessment Model (IAM): HAWQS is a web-based water quantity and quality modeling systems 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.

Keywords

Water Quality; Integrated Assessment Model; Economic Valuation

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¹See the Supplementary Materials for currently 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've added more refined data.

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 US 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, fully integrating hydrologic models and economic valuation has developed slowly in water regulation (Griffiths et al. 2012). This led 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 H₂O Quality (BenSPLASH). These two products bring together national data layers and modeling capability that will allow 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 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 pre-loaded 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 onto local computers if desired. While the goal is to pre-calibrate all of the watersheds in the US, currently two calibration projects have been completed, with about 30% of 8-digit Hydrologic Unit Code (HUC-8) watersheds in the U.S. calibrated and about 25% of 4-digit HUCs calibrated (U.S. EPA, 2017a, U.S. EPA, 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

The 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 between a population located in proximity to the waterbodies of interest. BenSPLASH converts

Publisher's Disclaimer: 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 author(s) and do not necessarily reflect the views or policies of the EPA.

multiple water quality parameters into a single-valued water quality index, and then calculates household willingness to pay (WTP) through a previously estimated valuation function. The current version of the model relies on a meta-regression 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 et al. (2018a; p. 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 in 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 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 modelling platform incorporates 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 data sets (National Land Cover Database, Census, NHDv2) and widely-used tools (e.g., water quality index, meta-regression). 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 (US EPA 2017a), while BenSPLASH is not 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

2.a. Model Overview

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 (EPA 2010) which require methods to be transparent and reproducible. Building

²As models of changes in ecosystem services as 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.

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

BenSPLASH began with a recognition of the need for a faster, more efficient, and replicable valuation capability at EPA for analyzing 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 to calculate the benefits of surface water quality improvements in the conterminous United States.⁵ The main user-supplied inputs to BenSPLASH are pre- and post-scenario 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 Water Quality Index values. To complement the user-supplied inputs, other information is included in the model, such as waterbody specific information and Census data at the Census block group level. All input data is rasterized by BenSPLASH into a national data grid to improve the computational efficiency of the model.⁶ Each grid cell 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 willingness to pay per household by grid cell, total willingness to pay by grid cell, and total U.S. willingness to pay. 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

⁴A 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."

⁵Hereafter, we use the term "national" as shorthand for the conterminous US.

⁶Because 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 (GIS) are so slow, analytics using vector data often use shortcuts, 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 tradeoff by carrying the size of the grid cells and find that smaller grid cells do not measurably improve precision in this application.

models and the intermediate outputs that are generated, serving as inputs to the subsequent steps in the simulation.

2.b. 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, 10, and 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, execution, output processing, and storage of each user's modeling projects. Because HAWQS is run entirely on a server, personal computing requirements are minimal (US EPA, 2017a). Yuan et al. (2018) provide an example of the use of HAWQS within a multi-model 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 were from the Parameter Elevation Regression on Independent Slopes Model (PRISM) from 1981 – 2015. The HAWQS model used the PET-Hargrave function built into SWAT 670 to model potential evapotranspiration. National land cover data and soil characteristics were taken from the 2006 National Land Cover Database (NLCD) Land Use and Land Cover (LULC) and State Soil Geographic (STATSGO) databases respectively. Crop data comes from the USDA's Cropland Data Layer (CDL), supplemented with additional fertilizer and management data from the National Agricultural Statistics Survey (NASS) according to the methodology laid out in White et al. (2016). All of these datasets as well as the elevation and hydrology data have been pre-processed 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

⁷Anecdotally, 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>

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 were 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).

2.c. Water Quality Index

The current version of BenSPLASH uses a water quality index (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 sub-index values ranging from 0–100 and then aggregating those sub-index 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 sub-index curves were originally applied in an economic context by Vaughan (1986), who calculated WQI scores for the 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 which has been widely used in valuation. The WQI employed in BenSPLASH uses sub-index curves developed more recently. National sub-indexes for dissolved oxygen (DO), fecal coliform (FC), and biochemical oxygen demand (BOD) were developed by Dunnette (1979) and Cude (2001). The sub-indexes for suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) are based on an ecoregion-specific approach developed by Cude (2001). These sub-indexes are combined as a weighted geometric mean to generate the single-valued WQI.¹⁰

BenSPLASH uses USGS 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 score to the corresponding COMIDs. BenSPLASH can also be used to convert output from HAWQS that report individual parameters into individual parameter sub-index values and combine these individual parameter sub-indices into a single WQI value for each COMID.

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

⁹The six-parameter WQI used in this study consists of dissolved oxygen, total nitrogen, total phosphorus, fecal coliform, total suspended solids, and biochemical oxygen demand. BenSPLASH also includes an equally weighted seven-parameter version used in EPA's 2015 Steam Electric Effluent Limitation Guideline (U.S. EPA 2015), which adds an additional subindex for metals.

¹⁰The platform can flexibly accept weights.

2.d. Valuation and Aggregation

The primary meta-analysis valuation functions used in BenSPLASH captures geospatial factors rarely applied to benefits transfer and is derived in a utility theoretic framework to ensure consistency with the adding up condition. Diamond (1996) suggested a type of validity test based on an internal consistency condition that any willingness-to-pay function should satisfy. The willingness to pay for a change from state 0 to 1 conditional on baseline income plus the willingness to pay 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 willingness to pay 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 meta-function will comply with the adding-up condition by following a three-step procedure (Newbold 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 meta-regression 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,

$$wtp_i = \exp(\beta_H H_i + \beta_Y \ln Y_i + \beta_Q Q_i), \quad (1)$$

where i indexes unique WTP estimates, wtp_i is marginal willingness-to-pay, H_i is a vector of demand shifters including resource characteristics and design features of the primary study, Y_i is the average income of the survey respondents, Q_i is the water quality index level for observation i , and β_H , β_Y and β_Q are parameters estimated via meta-regression. See Newbold et al. (2018), equations 9 through 13 for the complete derivation leading to the estimating equation for total willingness to pay,

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

¹¹WTP 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), and 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. (2017a) 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.

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

The metadata are drawn from primary stated preference valuation studies that estimate per household (use and nonuse) WTP for water quality changes in US water bodies that affect ecosystem services including aquatic life support, recreational uses (such as fishing, boating, and swimming), and nonuse values.¹² Necessary data included information identifying affected water bodies, the extent of water quality change, and sampled market areas, along with core methodological attributes. Studies were 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 is collected for census block groups, the smallest geographical unit for which sample data are published. The Census Bureau provides the geometry for each block in the Topologically Integrated Geographic Encoding and Referencing (TIGER) 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 were 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 et al. (2008) and with the assumption that the majority of recreational day trips will occur within a 2-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 et al. 2017b). The metadata combine information reported by primary studies with extensive geospatial data derived from external, spatially explicit databases. Results illustrate theoretically anticipated scale and substitution effects.

¹²While we have chosen to value ecosystem services collectively through a water quality index, other studies such as Lupi et al. (2019) approach environmental modeling and valuation separately for individual ecosystem services.

¹³See U.S. EPA 2015, Table H-1 for a list of the primary studies used to populate the metadata.

¹⁴There 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, Johnston et al. (2019), find that environmental improvements farther from respondents are associated with lower WTP values. See also Choi et al. (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.

3. Case Study: The Republican River Basin

This section illustrates the application of HAWQS and BenSPLASH under hypothetical scenarios of water quality improvements 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 below, is a 4-digit HUC (1025) comprised of 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 feature in the basin are intermittent streams that flow into the larger perennial creeks and rivers. There are over twenty 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

The land within the Republican River Basin is primarily used 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 water within the basin have been placed on the USEPA'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 included applying 25 meter-wide, vegetated filter strips on all agriculture lands and reducing impervious surface on urban lands by 25 percent. These best management practices are generally considered effective at reducing nutrients and may also help control other sources such as sediment.

¹⁵The appendix contains additional information about the Republican River Basin.

¹⁶The 2010 U.S. Census classifies urban areas as population centers with populations greater than 2,500 inhabitants. Urban Clusters (UCs) have at least 2,500 and less than 50,000 people, while Urbanized Areas (UAs) consist of 50,000 or more people.

Applying the vegetated filter strips to all agricultural land would result in approximately 795 square kilometers or 3% of total agricultural land being taken out of production and devoted to filter strips. This scenario does not account for the instances where 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 square kilometers of impervious surface being removed from urbanized areas within the basin. The extent of these two best management practices for the counterfactual scenario would be 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 integrated assessment model 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 intentionally 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, total nitrogen, and total phosphorus at the pourpoint of the Republican River Basin (U.S. EPA, 2017a, U.S. EPA, 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: Fecal Coliform (FC, CFU/100 ml, weight 0.22), Total Suspended Solids (TSS, mg/L, weight 0.11), Dissolved Oxygen (DO, mg/L, weight 0.24), Biochemical Oxygen Demand (BOD, mg/L, weight 0.15), Total Nitrogen (TN, mg/L, weight 0.14), and Total Phosphorus (TP, mg/L, weight 0.14). HAWQS output was used for TSS, TN, and TP, and water quality monitoring data was 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 (<https://www.waterqualitydata.us/>). 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 meta-regression. 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 contains 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 tradeoff 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 7,290m 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 (2,430m) grid cell size, and a smaller (100-kilometer) buffer distance.

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, TP resulted in an improvement across the subbasins of 36%, 58%, and 40%, respectively.

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 160km buffer producing an estimate about four times as large as the 100km 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 willingness to pay, 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 buffer around the Republican River Basin. The 100-kilometer buffer includes 422 thousand 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.

5. Next Steps

The case study presented here uses a proof of concept version of the BenSPLASH water quality benefits model. 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 sub-indices, 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 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, 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 only allowed for 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 EPA to support water quality benefits valuation and demonstrate their ability to function as an integrated assessment model through a case study in the Republican River Region. In addition, we outline an active research and development agenda which 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.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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 also at the Social Cost of Water Pollution Workshop, Ithaca, NY, April 3-5, 2019, and the USDA Workshop Applications and Potential of Ecosystem Services Valuation within USDA - Advancing the Science, Washington, DC, April 23-24, 2019. The views expressed in this article are those of the authors and do not necessarily represent the views or the policies of the U.S. Environmental Protection Agency.

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Figure 1.
Flowchart of integrated modeling structure

Figure 2:
Map of Republican River Subbasins showing Baseline and Counterfactual Scenario WQI Scores

Figure 3:
Map of Republican River Subbasins showing extent of the 100 kilometer and 100 mile (160 km) buffers.

Table 1:

Number of Assessed Water Impairments within the Republican River Basin, by State (Waters with multiple causes for impairment are counted more than once.)

Causes for 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. EPA Office of Water 303(d) Listing, Accessed May 2015.

Table 2:

Summary of HAWQS Model Output for Republican River Subbasins

	TSS (mg/L)	TN (mg/L)	TP (mg/L)
Baseline Scenario			
Mean ^I	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 ^I	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

^I Mean values are based on an equal weighting of the HAWQS model results for the 599 HUC-12 subbasins.

Table 3:

Summary of BenSPLASH Model Output for Republican River Basin

Buffer	Grid size	Cells	WQI Baseline Scenario	WQI Counter-factual Scenario	WQI delta	Annual MWTP per WQI point	Annual WTP (mean, per cell)	Total Annual WTP (Millions, 2016\$)
160km	7,290m	6,709	47.34	58.86	11.51	\$3.148	\$34.467	\$63,807,644
160km	2,430m	56,730	47.39	59.06	11.68	\$3.153	\$35.089	\$62,007,278
100km	7,290m	4,305	47.42	58.87	11.45	\$3.118	\$33.382	\$15,676,763