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 integral components in a water quality Integrated Assessment Model (IAM): (1) the Hydrologic and Water Quality System (HAWQS), and (2) the Benefits Spatial Platform for Aggregating Socioeconomics and H^2O Quality (BenSPLASH). HAWQS is a web-based interactive water quantity and quality modeling system that simulates the effects of an extensive array management practices and terrestrial landscapes on several key water quality parameters. The BenSPLASH modeling platform is designed to quantify the economic benefits of changes in those key water quality parameters. This paper discusses the development of the models and applies HAWQS and BenSPLASH to a case study in the Republican River Basin.

1. Introduction

Research on Integrated Assessment Models (IAMs) related to water quality requires collaborative input from both natural and social scientists. 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 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 EPA, academia, states and others to perform large scale analyses related to water quality impacts. 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

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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, and Elena Besedin have made this work possible.

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, biological oxygen demand, dissolved oxygen, pesticides, and water temperature. Simulations can be centrally stored and downloaded, and many watersheds in the U.S. are calibrated.

The BenSPLASH modeling platform is designed to quantify the economic benefits of aquatic environmental changes nationwide. 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 multiple water quality parameters into a single-valued water quality index, and then calculates household willingness to pay (WTP) through a meta-regression function. Household WTP values are aggregated over the population of interest through a National Data Grid developed from population, demographic, elevation, hydrography, and land cover data.

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 collects ad hoc benefits approaches in one place. An advantage is that the approach is based on established data sets (National Land Cover Database, Census, NHDv2) and widely-used tools (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.

2. Model Overview

HAWQS enables use of SWAT 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.[1] Our efforts have been focused on analyses that are national in scope, using data sources that are nationally consistent. 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. 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. To complement the user-supplied inputs, other information is included in the model, such as waterbody specific information, Census data at the Census block group level, and functions estimating household level willingness to pay for water quality improvements (see Figure 1).

EPA often estimates the benefits of surface water quality improvements pursuant to Executive Orders 12866 and 13563[2] which require methods to be transparent and reproducible. Building BenSPLASH began with a recognition of the need for a faster and more efficient valuation capability at EPA for analyzing the monetary

[1] Hereafter, we use the term ”national” as shorthand for the conterminous US.

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

benefits of water quality improvements. 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 necessitating 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 scenarios.

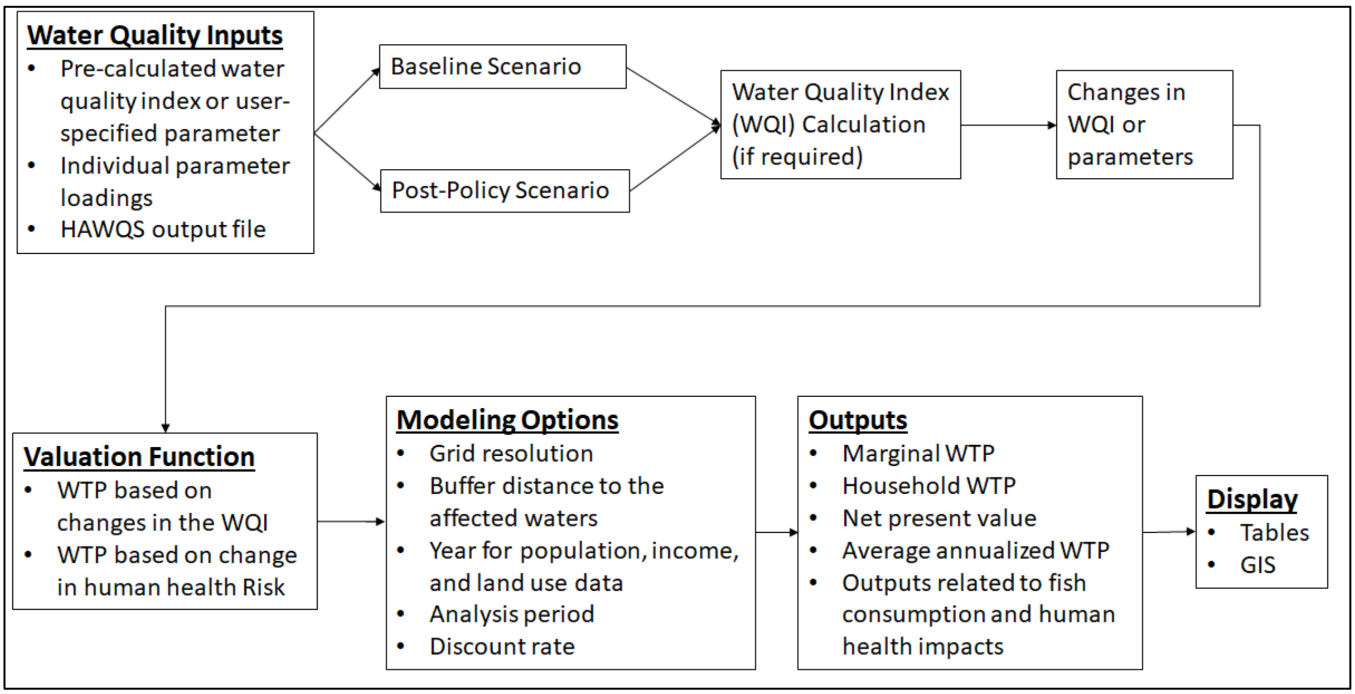

Figure 1. Flowchart of HAWQs-BenSPLASH integrated modeling structure

3. Model Structure

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 along the way, serving as inputs to the subsequent steps in the simulation.

3.a. Water Quality Modeling

The Hydrologic and Water Quality System (HAWQS) is a web-based interactive hydrology and water quality modeling system that runs the Soil and Water Assessment Tool (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 hydrologic unit code (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 unique 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, 2017). Yuan et al. (2018) provide an example of the use of HAWQS within a multimodel system.

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 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).

3.b. Water Quality Index

BenSPLASH uses a water quality index (WQI) to value the changes in water quality parameters provided by HAWQS. 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), as well as an equally weighted seven parameter version used in EPA's 2015 Steam Electric Effluent Limitation Guideline (U.S. EPA 2015).

WQI sub-index curves were originally applied in an economics 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. For dissolved oxygen (DO), fecal coliform (FC), and biological oxygen demand (BOD) these sub-indexes are national and were developed by Dunnette (1979) and Cude (2001). For total suspended solids (TSS), total nitrogen (TN), and total phosphorus (TP) these sub-indices are based on nutrient ecoregions based on Cude (2001).

BenSPLASH uses the 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 HUC12 scale, BenSPLASH will translate the score to the corresponding COMIDs. BenSPLASH can also be used to convert output from water quality models such as HAWQS that report individual parameters into individual parameter sub-index values, and then to combine these individual parameter sub-indices into a single

WQI value for each COMID. These subindices are combined as a geometric mean with each parameter weighted.[3]

3.c. Valuation and Aggregation

The primary valuation function used in BenSPLASH captures geospatial factors rarely applied to benefits transfer and is derived in a utility theoretic framework to ensure compliance 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.[4]

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.

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. 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 Water Quality Index (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.

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

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[3] The platform can flexibly accept weights.

[4] 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), 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.

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,

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

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,

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

where, Q_0 and Q_1 refer to baseline and post-policy water quality expressed in terms of WQI. See Newbold et al (2018) for meta-regression results.

The benefit transfer approach uses census block groups (CBGs) as the geographic unit of analysis. 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 CBG. A buffer of 160 km is consistent with Viscusi et al. (2008) and with the assumption that the majority of recreational trips will occur within a 2-hour drive from home. By focusing on a buffer around the CBG 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 CBG and then multiplied by the number of households in the CBG. Total national WTP is calculated as the sum of estimated CBG-level WTP across all block groups that have at least one affected waterbody within 160 km.

4. 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 identified water quality impairments, including the WTP of household located outside the basin, but in proximity to the waters being improved.

The Republican River Basin, shown in Figure 2 below, was selected to demonstrate the combined use of the HAWQS and BenSPLASH models. This basin 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. Table 1 summarizes hydrographic information for the river basin in terms of the number of stream miles in each flow category and acres of wetlands based on high resolution National Hydrography Data (NHD) and the National Wetlands Inventory (NWI).

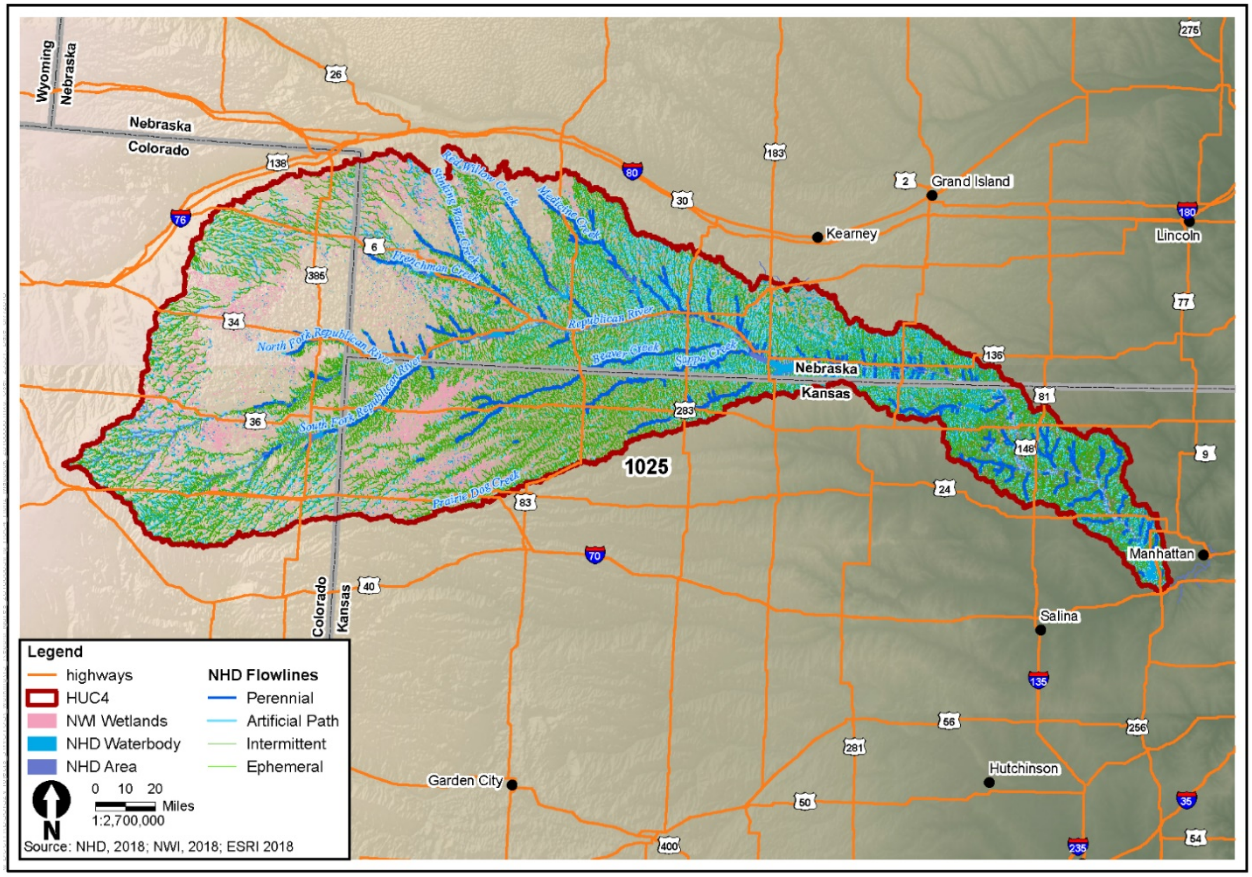

Figure 2: Map of Republican River Basin (USGS HUC 1025) showing high-resolution NHD water features and NWI wetlands in relation to state boundaries, cities, and major roads.

Table 1: Hydrographic profile of the Republican River Basin

Feature type	Feature attributes	Miles or Acres	Percent of total
Streams (miles)	**Total**	40,561	100%
	Perennial	2,339	6%
	Intermittent or Ephemeral	35,032	86%
	Artificial path[1]	2,407	6%
	Other[2]	784	2%

[1] Artificial paths represent the center line through lakes and reservoirs that are part of the Basin's river network.

[2] Includes canal, ditches, aqueducts, and other features without attributes.

Values are based on geospatial analysis of NHD and NWI data.

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.[5] 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. Table 2 provides a breakout of the different types of land use and land cover found within the basin.

Table 2: Land Use / Land Cover for the Republican River Basin

Land Use / Land Cover Categories[1]	Square Kilometers	Percent of total
Cropland	31,794	50.6
Rangeland	28,668	45.7
Urban land	316	0.5
Water	385	0.6
Wetland	1,463	2.3
Forest	177	0.3
Total	62,803	100%

[1] Categories based on USGS 2006 National Land Cover Dataset.

[5] The 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.

A significant portion of the assessed water features within the basin have been adversely impacted by human activities and been placed on the USEPA's CWA 303(d) List of Impaired Waters. Table 3 provides state tallies of basin waters impaired by different pollutants. Nutrients are the second most frequent cause for impairment. However, 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 is a key source of nutrient pollution, as well as pathogens and turbidity. Metals are also a significant source of impairments within the basin, much of it likely attributable to oil and gas production as well as urban sources.

Table 3: 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.

The 303(d) listings show that nutrients are a significant source of impairment for basin waters. We devised a "policy" 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 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.

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 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 policy scenario would be ambitious and may not be realistic. However, for demonstrating how the HAWQS and BenSPLASH models could be used together to produce economic benefit estimates, the policy scenario was intentionally designed to produce sizable changes in water quality.

HAWQS was set up for each 12-digit HUC subbasin 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. HAWQS was used to calculate daily flows and loads for each subbasin, for both the baseline and policy scenarios, and 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), Biological 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, that were not part of the calibration for HAWQS; we obtained the monitoring data from the EPA Water Quality Portal (https://www.waterqualitydata.us/).

These baseline and policy scenario subbasin WQI scores were used as inputs for BenSPLASH. BenSPLASH automatically assigns these subbasin scale results to the more refined, national hydrography data (NHD) stream COMIDs. BenSPLASH is prepopulated with national CBG data, which contains the relevant household demographic information for estimating household WTP. Running BenSPLASH requires selecting the grid size that BenSPLASH would use for performing calculations. 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. The analyst must also select the relevant market area of households to calculate WTP values. 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.

5. Case Study Results

Table 4 provides an estimate of the HAWQS model results, as mean, median, minimum, and maximum TN, TP, and sediment concentrations for the baseline and policy 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.

Table 4: Summary of HAWQS Model Output for Republican River Subbasins			
	TSS (mg/L)	**TN (mg/L)**	**TP (mg/L)**
Baseline Scenario			
Mean[1]	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
Policy Scenario			
Mean[1]	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
1. Mean values are based on an equal weighting of the HAWQS model results for the 599 HUC12 subbasins.			

Figure 3 shows a graphical representation of the baseline and policy WQI scores by subbasin.

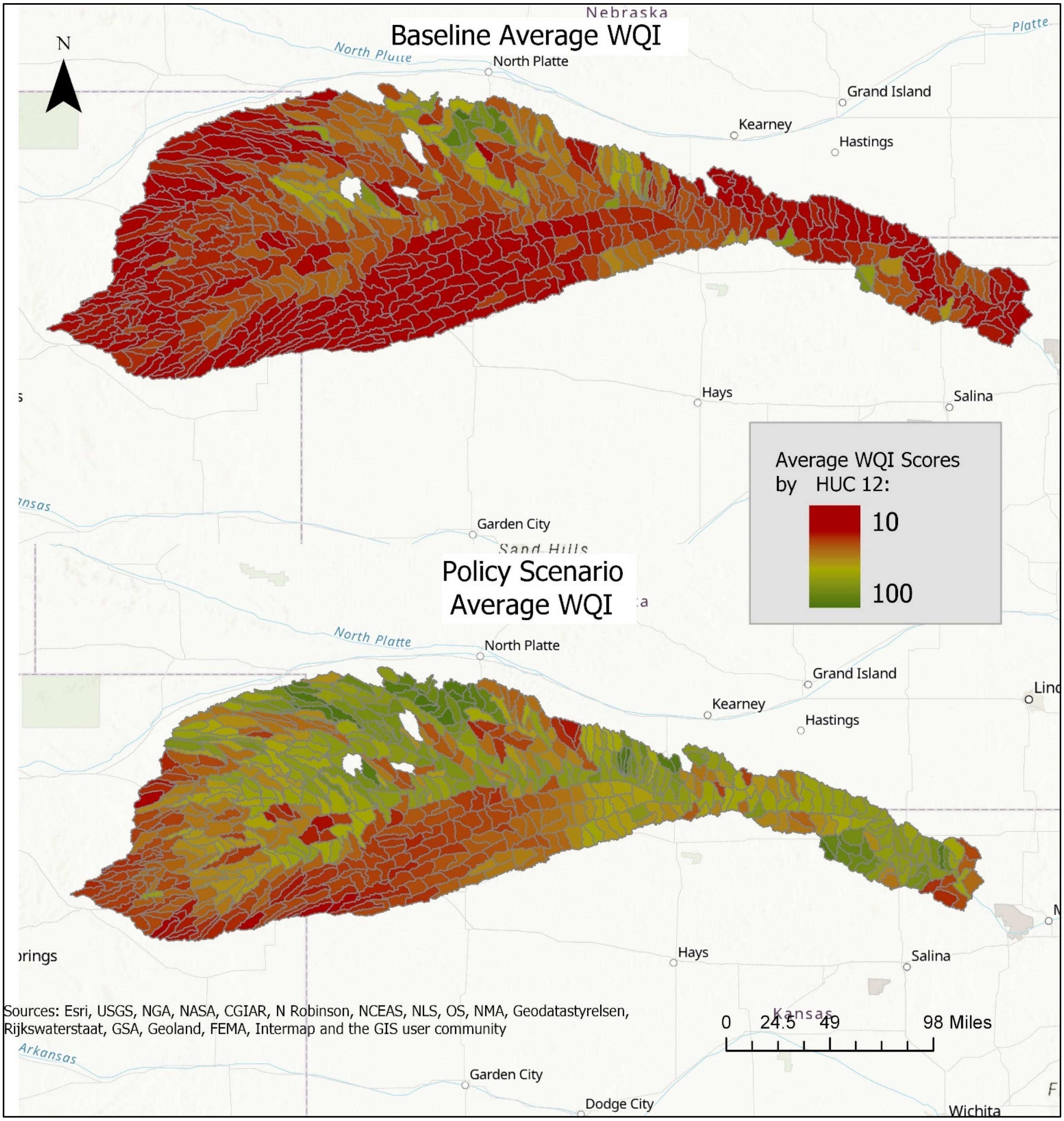

Figure 3: Map of Republican River Subbasins showing Baseline and Policy Scenario WQI Scores

Table 5 provides a summary of the BenSPLASH results for the three model runs, varying the grid cell resolution and the distance buffer. Household marginal WTP and total WTP appear relatively stable between the three runs. The total WTP reflects the summation of household WTP across all grid cells within each of the model runs. The second run total household WTP of $27.6 million is only 26% of the first run total of $105 million. This difference in total household WTP reflects the significant difference in the total number of households included in the analysis between the first run with the 100-mile buffer (or 160km buffer; 2.3 million households) and the second run with the 100-kilometer buffer (422 thousand households). The difference in grid cell size between the first and third run does not appear to have a significant effect on total household WTP.

Table 5: Summary of BenSPLASH Model Output for Republican River Basin

Buffer	Grid size	Cells	WQI Baseline Scenario	WQI Policy Scenario	WQI delta	Households (mean, per cell)	MWTP per WQI point	WTP (mean, per cell)	Total WTP (Millions, 2016$)
160km	7,290m	6,709	47.34	58.86	11.51	345.77	$4.82	$60.70	$105.0
100km	7,290m	4,305	47.42	58.87	11.45	98.47	$4.94	$61.13	$27.6
160km	2,430m	56,730	47.39	59.06	11.68	40.15	$5.02	$64.32	$107.9

Figure 4 shows the extent of the 100-km and 160-km buffer around the Republican River Basin. The 100-kilometer buffer includes 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. 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. The inclusion of these urbanized areas is likely the primary reason for the difference in average number of households per cell between the first and second runs.

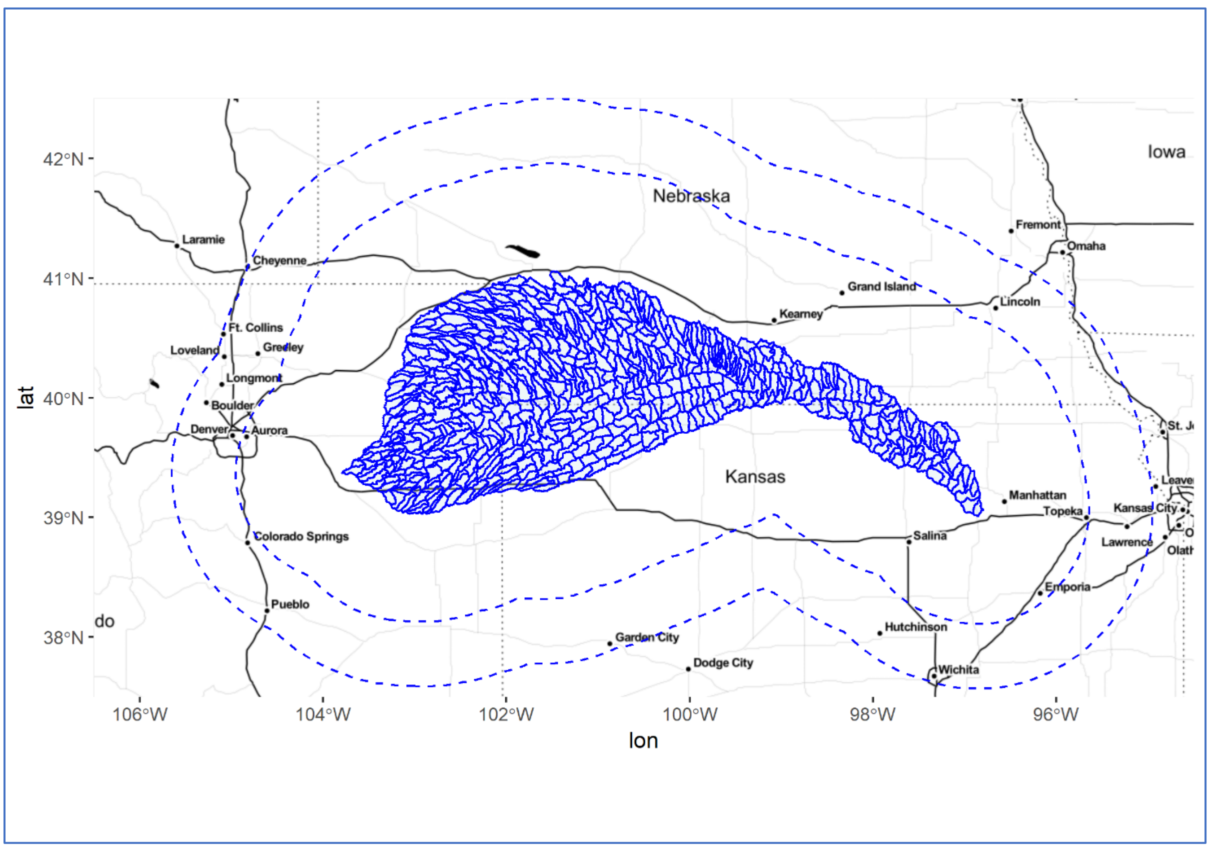

Figure 4: Map of Republican River Subbasins showing extent of the 100 kilometer and 100 mile (160 km) buffers.

6. Next Steps

The case study presented here uses a proof of concept version of the BenSPLASH water quality benefits model developed for EPA by Abt Associates. 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 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, and the ability and method to construct geographically based regional sub-indices. 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 include adding capacity to perform additional valuation calculations. Colleagues at EPA are developing a national hedonic model for water quality which 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.

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.

7. Conclusion

We introduce a set of models being developed at EPA to support water quality benefits valuation, demonstrate their ability to function as an integrated assessment model through a case study in the Republican River Region, and 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.

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