

**A Load Modeling Approach for Evaluating Selenium Stream Standards
Compliance**

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A Load Modeling Approach for Evaluating Selenium Stream Standards Compliance

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Abstract

Elevated selenium concentrations have been observed in several rivers in the western United States and are a concern for healthy aquatic systems. Water quality modeling is a valuable tool for quantifying the importance of sources and assessing management alternatives for stream standards compliance in basins with impaired water quality. This modeling study uses a relatively simple approach to describe the water distribution system and processes that drive loading of dissolved selenium and salts from the naturally occurring Cretaceous shale soils in the extensively irrigated Uncompahgre and Gunnison River Basins in western Colorado. Calibrated model output characterizes processes that load an average total of 4,130 kg (9,100 lbs) of selenium and 2.9×10^8 kg (316,000 tons) of salts per year from agricultural sub-basins to the Uncompahgre River. Simulations of Best Management Practices to minimize seepage and constituent loading predict that extensive implementation would be required to reduce selenium concentrations to comply with current water quality standards.

CE Database subject headings: Selenium, Salinity, Hydrologic models, Water quality, Seepage, Return flow, Agricultural watersheds, Water resource management, Colorado

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Introduction

This research demonstrates the value of a relatively simple model to describe complex geochemical processes driving a water quality problem in portions of the Uncompahgre and Gunnison Rivers in Western Colorado. Elevated levels of dissolved selenium (Se) have been observed; and are related to large-scale irrigation of seleniferous soils in the area. Segments of the Uncompahgre and Gunnison Rivers currently exceed the concentration stream standard for dissolved selenium set by the Environmental Protection Agency (EPA) and The State of Colorado. A segment of the Uncompahgre River from Montrose to Delta, CO and a segment of the Gunnison River from Delta to Grand Junction, CO have been listed on the State of Colorado 303(d) list for exceeding the aquatic life table value standard for dissolved selenium of 4.6 $\mu\text{g/l}$. Temporary standards of 20 $\mu\text{g/l}$ and 6 $\mu\text{g/l}$ respectively are currently in place for these segments while sources are identified and solutions to the impairment are studied. These concentration standards are in place to protect aquatic life based on previous studies showing elevated levels of dissolved selenium in habitat waters are linked to problems with reproduction, mortality and deformities primarily in fish and waterfowl.

Computer models can be valuable tools for the study of remediation options for river basins with water quality problems. Analysis of observed data during the development of even basic models can shed light on many of the processes that contribute to a region's water quality problems. Changes in these processes can be performed synthetically, and the effectiveness of strategies to alter water quality can be predicted and quantified. Model development and analysis plays a strong role in Total

Maximum Daily Load (TMDL) studies required to be performed by states as a part of the EPA's Clean Water Act for river segments with impaired water quality.

Water Quality Problem

The potentially broad impact of irrigated agriculture on water quality is well known. The use of irrigated agriculture often results in return flow to rivers containing elevated levels of problem water quality constituents. The link between naturally occurring elements in soils and rocks and water quality problems through dissolution and weathering by irrigation water has recently been made. In the 1980's, studies of the Kesterson National Wildlife Refuge in the San Joaquin Valley in California yielded a link between the geochemistry of rock in the Coastal Range, dissolution through irrigated agriculture and elevated levels of dissolved selenium in the aquatic environment causing wildlife deaths and deformities. This link, now commonly referred to as "The Kesterson Effect," is well documented (e.g., Presser and Ohlendorf 1987, Presser 1994). In this case, the application of water to soil at a higher than natural rate resulted in elevated levels of dissolved salts and selenium in drain water and downstream receiving waters serving a wildlife refuge.

The lessons learned at Kesterson prompted new geochemical studies of selenium throughout the western U.S., (e.g., Nolan and Clark 1997). Selenium impairment exists throughout the State of Colorado, often combined with high salinity. Based on the 2004 State of Colorado 303(d) impaired river list, 41 of the 117 listed segments (35%) are impaired by elevated selenium concentrations including segments in the Arkansas River Basin, the Lower Gunnison River Basin, the Upper Colorado River Basin and the South Platte River Basin.

The Uncompahgre and Gunnison Basins in western Colorado (Figure 1) have been studied for many years because of elevated levels of salts and selenium possibly influenced by soils derived from the Cretaceous, seleniferous Mancos black shale outcropping throughout the region. Given the extensive irrigated agriculture throughout the basin, seepage and groundwater movement through Mancos Shale have been linked to leaching of selenium to the river systems. Elevated salinity levels also result from this mechanism; and cause reduced crop yields through the application of high salinity irrigation water. The existence of endangered fish species: Colorado Pike minnow, Humpback Chub and the Razorback Sucker in the area and downstream in the Colorado River reinforce the need for healthy aquatic habitats, free from harmful levels of toxins like selenium.

Water quality throughout the Upper Colorado region, including the Uncompahgre Basin and Grand Valley has been well characterized through sampling by the US Geological Survey (USGS), (see Butler et al. 1994, Butler et al. 1996, Butler and Osmundson 1999). These studies have suggested that extensive diversions for irrigation, transport of water through earthen canals, leakage from earthen storage ponds and furrow irrigation practices have increased seepage, leaching natural minerals from the soil, resulting in agricultural return flows that have elevated salt and selenium concentrations in rivers throughout the region.

Changes in agricultural practices to reduce return flows could have a great impact on water quality in the region. The water quality of groundwater seeps and tributaries high in agricultural return waters have been found to have elevated concentrations of total dissolved solids (TDS) and selenium, especially down gradient from soils containing

Mancos Shale. A basic assumption of this and other studies (e.g., Butler 2001), is that by reducing groundwater seepage and irrigation return flow loading, levels of dissolved solids and selenium in the Uncompahgre and Gunnison Rivers could possibly be reduced to safe levels that comply with the current water quality standards.

This paper describes the development of a modeling method used to quantify the agricultural hydrologic components in this basin and the processes that drive selenium and salinity loading to the Uncompahgre River. The model is then used to simulate implementation of Best Management Practices (BMP's) throughout the basin, aimed primarily at reducing seepage and return flows. The predicted influence of water management changes on water quality and standards compliance are analyzed and quantified.

Conceptual Model Design

An approach for hydrologic modeling using increasing refinement of temporal and spatial scales, named the "downward approach" or the "top-down method," has been presented in the literature (e.g., Klemes 1983, and Farmer et al. 2003). This approach focuses on the problem as a whole and starts with a 'big picture' estimate based on measured data for a process, then breaks down elements until a satisfactory level of detail for the solution is obtained, often resulting in a model of minimum complexity for the problem. The downward approach is followed here for model development; where data at a high level and large scale are used first and finer temporal and spatial-scale analysis follows to encompass more details of the problem.

Analysis of the flow and water quality sampling data collected by the USGS (e.g., Butler and Leib 2002) throughout the Lower Gunnison Basin shows that an estimated

56% of the selenium load in the Gunnison River at Grand Junction can be attributed to the Uncompahgre River and its irrigation influence area. Thus the Uncompahgre Basin is a logical study region for development of a selenium management model. This study did not consider the precision of load estimates from monitoring data, but a study by Gossenauer (2004) determined precision of statistical results for load estimation, minimum detectable change and standards compliance based on sample size. Inflow waters above the extensive irrigated agriculture near Montrose, CO have very low concentrations of selenium, while outflows to the Gunnison River at Delta, CO show marked increase in concentration. Irrigation in the Uncompahgre basin is served by comparatively natural flows in the Uncompahgre River above Colona, CO and the Gunnison Tunnel trans-basin diversion. The Tunnel, which opened in 1908 bringing water from the Gunnison River into the Uncompahgre Basin for agriculture, almost triples the annual volume of water available for irrigation. A water mass balance in the Uncompahgre Basin shows an annual loss of $3.5 \times 10^8 \text{ m}^3/\text{yr}$ (280,000 acre feet (AF)) of water through diversion and consumptive use, and a gain of 7.7 kg/day (17 lb/day) of selenium in the Colona to Delta reach.

The selenium loading within the Uncompahgre Basin is strongly related to local geology. Mancos Shale outcrops over roughly 25% of the Uncompahgre Basin and much of the soil in the area is derived from Mancos Shale. The Uncompahgre Valley Water Users Association manages over 925 km (575 miles) of earthen canals and laterals serving over 29,500 ha (73,000 acres) planted in hay, alfalfa, corn and pasture. The primary irrigation technology is furrow irrigation; however some sprinkler and drip tape systems are in place within the basin.

As shown in Figure 2, there are eight major canals in the basin. From upstream to downstream on the east side, South Canal (receives the Gunnison Tunnel water and flows into the Uncompahgre), Loutsenhizer Canal, Selig Canal, East Canal, Garnet Canal; and on the west side of the river are the West Canal, Montrose and Delta Canal and Ironstone Canal. Five major tributaries enter the Uncompahgre in the lower section of the basin. The Dry Cedar Creek, Cedar Creek, Loutsenhizer Arroyo enter from the east and are considered to contribute the highest constituent loading. The Spring Creek and Dry Creek enter from the west.

Based on analysis of the major sources of the selenium loading in the area, the boundaries for modeling were set, focusing on agricultural processes within the Uncompahgre Basin. The model boundary fluxes, canals, tributaries and irrigated parcels are shown in Figure 2.

Water balance

Spatial and hydrologic data provided by the USGS (unpublished) and the State of Colorado Hydrobase (CWCB and DWR 2004) showed that the majority of irrigated parcels reside in agricultural sub-basins where return water flows to major tributaries of the Uncompahgre (Figure 2). In the five major sub-basins, a total of 17,700 ha (43,700 acres) are irrigated and served by a total of 424 km (263.4 miles) of major canals and laterals. Annually, an average $6.8 \times 10^8 \text{ m}^3/\text{yr}$ (550,000 AF/yr) of water, more than 100% of the total basin inflow, is diverted to the major canals.

Assuming that all water applied to land inside sub-basin boundaries in excess of evapotranspiration enters the sub-basin tributary and eventually leaves at the sub-basin outlet; a water balance can be performed for each sub-basin. Data or estimates of sub-

basin totals of: precipitation, evaporation, field application, pond seepage, canal and lateral seepage, crop consumptive and deep percolation can be used to describe all the components of the water balance. Based on these fluxes, surface and sub-surface return fluxes can be calculated. Note that “deep percolation” is used here to describe water applied to fields that infiltrates below the root zone to contribute to sub-surface return flow.

Return flows are divided into two components: quick-returning surface flows and slower-returning sub-surface flows. Based in unit hydrograph theory (e.g., Chow, Maidment and Mays 1988), and used previously for groundwater return flows (e.g., Illangasekare and Morel-Seytoux 1986), the discrete convolution method (kernel function) is used to lag these returns over time.

A schematic of this water balance approach to quantify surface and sub-surface return flow components is portrayed in Figure 3 (top). The data required by each of the five sub-basin water balance models are: total irrigated parcels, canal and lateral lengths and widths, pond area, seepage rates, consumptive use and evaporation rates. Model parameters are used to partition canal flows into sub-basins, partitioning coefficients are also used to separate surface and sub-surface flows, and convolution parameters are used to describe two surface and six sub-surface lags. These parameters are fit during calibration.

Constituent Transfer

Analysis of water quality grab sample data collected by the USGS at the mouths of the major tributaries of the Uncompahgre show spatial and temporal variability in concentrations of dissolved selenium and TDS. Groundwater concentrations of dissolved

selenium and TDS have been observed to be much higher than surface water concentrations. This observation has been used previously by Butler et al. (1996) and Butler (2001) to quantify surface and sub-surface contributions of selenium loads from sampling data. Analysis of time series of flow and concentration data showed wide seasonal changes in both flow and concentration, where summertime high flows were of low concentration and wintertime low flows were of high concentration. This time series pattern can be attributed to mixing and dilution processes driving water quality at the downstream points.

As shown in Figure 4, high concentrations correspond to low flow volumes and high flow volumes result in lower concentrations. Sub-basin outlet water quality data and discharge can be used to identify a representative average concentration and volume of groundwater sources contributing mass to the outlet point. During winter, this groundwater source provides a low flow at a high concentration. In summer, this groundwater source occurs also, but surface drain water of lower constituent concentration also contributes to outlet flow, thereby increasing the flow volume and reducing the concentration of the outlet flow via dilution. To portray the shape seen in Figure 4, the mixing of only two water sources is required. Therefore, the outlet water quality sampling data describing both flow and concentration can be used to build a model that describes the overall water quality signature of a drainage area.

The complexities of the water movement through surface drains and subsurface flow pathways, complex soil chemistry, soil variability and non-point sources are distilled into average representative signatures of conditions seen in the different sub-basins and entering the mainstem river as a point loading source. A schematic describing

the design of the sub-basin constituent transfer model is presented in Figure 3 (bottom). The surface and sub-surface water volumes available from the sub-basin water balance model are assigned concentrations using parameters for groundwater concentration (based on sampling data). An additional model parameter for in-canal constituent uptake is included, based also on sampling data.

Advective Water Quality Model

Most of the predictive capability of the model in this study is housed in the sub-basin models described above. However, to describe the link between river water quality, diversion water quality and receiving water quality downstream of tributary inflows, a longitudinal water quality model is used to calculate constituent concentrations of TDS and Se throughout the Uncompahgre mainstem. An instantaneous advective mixing model of source waters is described by a feed-forward set of continuously-stirred tank reactors (from Chapra 1997). This model is described in Figure 3 (bottom left) where water quality is driven primarily by mixing of tributary inflow loads with in-river water volumes. Diffusive mixing, chemical reactions, adsorption/desorption and decay are not considered. Dissolved Se and total dissolved solids are assumed to be conservative in the river. In-river concentration predictions at canal headgates are used as input data to the sub-basin constituent transfer models.

Total Model Structure

The total model structure emerges from the combination of three sub-models for agricultural water mass balance, constituent transfer and conservative constituent mixing within the river (Figure 3). Using monthly timesteps, this conceptual model describes water movement from the river and through a sub-basin to return to the river carrying

constituent load. For the Uncompahgre Basin, five sub-basins are used, corresponding to the major tributaries. Two tandem models are utilized, one describing dissolved selenium and one describing TDS. The conceptual model has been implemented in Microsoft Excel utilizing spreadsheet functions and macros programmed in Visual Basic for Applications.

Model Input Data Sources

Colorado Hydrobase (CWCB and DWR 2004) was used for all monthly flow data describing historical river flows and historical diversions. Consumptive use predictions from the StateCU model (CWCB and DWR 2004), using the Blaney-Criddle method, were used to estimate historic actual crop evapotranspiration (crop consumptive use). The model used one representative set of crop type distributions, based on a sampling of crops in the Uncompahgre Basin. Historic meteorological data were used to describe historical precipitation and potential evaporation in the basin (from evaporation pans) (CWCB and DWR 2004). These sources were used to develop one representative set of monthly conditions for the model.

Total canal and lateral seepage volume estimates were developed using U.S. Bureau of Reclamation (USBR)-measured estimates of volume of seepage per day per unit wetted area of canal (USBR 1982). Total seepage volume estimates when diversions were occurring were calculated using the unit seepage estimate, total lengths of canals and laterals in individual sub-basins and representative wetted perimeters.

An extensive database of sampling data was obtained from the USGS (unpublished) as part of the National Irrigation Water Quality Program (NIWQP). These data provided point measurement of flow, TDS and dissolved selenium. These flow and

concentration data pairs at tributary outlet points were absolutely essential to the present study since they are the basis of the constituent mixing models for each sub-basin.

Calibration

The model calibration process involved supplying a set of historical data to the model and adjusting model parameters to minimize the discrepancies between model output and a corresponding historical set data. This process develops a model that, given a set of measured conditions, predicts a corresponding set of conditions measured at other points. By comparing model predictions with the measured data, the model predictive error is quantified and provides a measure of the accuracy of the process description in the model.

The calibration period of water years 1991 – 1996 was chosen to portray a range of hydrologic conditions based on available flow and water quality data. Model calibration began by calibrating each pair of sub-basin water balance and constituent transfer models. After this initial tuning, final tuning was performed to best fit basin-wide water quality conditions.

An external method was used to determine the flow and constituent uptake components that fit measured observations for each sub-basin individually. The Excel Solver was used to minimize the error between calendar-month averages of flow volume and concentration simultaneously, by adjusting monthly field application, surface and sub-surface flow partition coefficients, surface and sub-surface convolution parameters and representative groundwater concentrations. Adjusting parameters to increase groundwater flow increased return flow concentrations. Adjustment of convolution parameters changed the magnitude and timing of return flows during winter months.

Using a weighted-error approach allowed for an overall best fit of the combination of flow and concentration data at specific times of the year.

This external, optimization-based calibration was performed for all five sub-basins. The optimization was constrained to ensure that parameters remained physically realistic. Calibrated model output for the Loutsenhizer Arroyo sub-basin are presented in Figure 5. For the simulation of flow and water quality for the calibration period, output signatures from the sub-basins matched the measured data very well. However, the combination of the five sub-basin outflows did not completely characterize conditions in the Uncompahgre River downstream at Delta. In-river flows were lower than expected at the Basin outflow at Delta, requiring the addition of baseflow throughout the entire river.

Through the calibration and a separate validation process (not described here), analysis of the model errors and goodness of fit metrics were used and some general statements can be made about the model's ability to predict flows, concentrations and loads. For sub-basin outlets, the monthly average flow predictions are within 20% of observed; monthly average selenium concentrations are within 10-20%; and monthly average TDS concentrations within 15% of observed values. For the Uncompahgre at Delta, monthly flow predictions are within about 5%, monthly selenium predictions are within 7% and monthly TDS predictions within 5%. At Delta, these errors translate into monthly average model predictive capability for flow to within 0.4 m³/s (15 cfs), for selenium concentration to within 2 µg/l, and for TDS concentration to within 30 mg/l.

Baseline Generation

All recent hydrologic data were obtained from Hydrobase and used to develop a baseline historical simulation for October 1990 - September 2003, encompassing the

calibration and validation time periods. This simulation time period and the corresponding predictions of water balance components and water quality are used as the baseline for hydrologic analysis and the BMP model simulations.

Historical Hydrologic Conditions

Analysis of the model predictions using baseline historical data as input was performed to quantify various aspects of the water quality problem in the Uncompahgre Basin.

The inflows to the Uncompahgre basin describe the background conditions to the basin. These water sources have had limited direct exposure to the Mancos Shale soil and are considered "clean" sources of water that are used for irrigation downstream. Average annual volumes and average conditions from the baseline model simulation are presented in Table 1. Even though the concentration of selenium in these water sources is at most 1 µg/l (based on USGS sampling data), the high flow volumes result in large annual loads to the Uncompahgre River.

Annual average flow volume and average quality in the eight major canals based on the baseline model simulation were analyzed. A majority of the water diverted to the Loutsenhizer, West, Montrose and Delta and from the South canal is "clean" water from the upper basin sources. However, water diverted to the Selig, East, Garnet and Ironstone canals contains more drainwater with high concentrations of salts and selenium.

Diverting water at the downstream portions of the Uncompahgre (below Montrose and the Cedar Creek inflow) loads a considerable mass of TDS and selenium to irrigated parcels.

The average return flow conditions from the five major tributaries based on the baseline model simulation are tabulated and presented in Table 2. Comparison of the annual averages of concentration and load shows the influences of the various sub-basins. The Dry Cedar creek sub-basin returns high concentration water, but not an excessive load of either constituent. Cedar Creek and Loutsenhizer Arroyo sub-basins are the highest contributors of selenium. Cedar Creek, Loutsenhizer Arroyo as well as Dry Creek are high contributors of saline waters. All tributaries of the Uncompahgre between Montrose and Delta are listed by the State of Colorado as being impaired for selenium, and these model results are consistent with these listings. The irrigation and non-irrigation season selenium concentrations at the outlets of the east side tributaries are all above 4.6 µg/l and usually far above 20 µg/l during the wintertime. Spring Creek and Dry Creek can be considered dilution water sources all year, given the comparatively lower selenium concentrations, even though winter concentrations are above 4.5 µg/l.

Model-predicted characteristics of the outflow from the basin are calculated as follows. The total annual flow volume out of the basin is $2.96 \times 10^8 \text{ m}^3/\text{yr}$ (240,000 AF/yr), with an average TDS concentration of 1,030 mg/l and an average selenium concentration of 12.6 µg/l. This translates into annual average loads of selenium of 3,220 kg/yr (7,100 lbs/yr) and annual average TDS load of $2.85 \times 10^8 \text{ kg/yr}$ (314,000 tons/yr).

The annual conditions show the magnitude of selenium and salt loading that occurs as water moves through the Uncompahgre Basin. Net loading of 2,900 kg (6,300 lbs) of selenium and $1.6 \times 10^8 \text{ kg}$ (177,000 tons) of dissolved solids are predicted to occur annually in the Uncompahgre River as it flows from Colona to Delta.

Historical Compliance to Water Quality Standards

Output from the baseline simulation of water years 1991 - 2003 is analyzed to determine compliance with water quality standards. A longitudinal computation of the 85th percentile using all model output for [Se] (the $X_{0.85}$ of [Se]) for the baseline simulation is shown in Figure 6. This computation is consistent with the State of Colorado method used for water quality compliance; if the 85th percentile of all recently-sampled data within a river segment exceeds the table value standard, the segment is not in compliance. For the reach between Montrose (location 14) and Delta (location 1) Figure 6 shows that the Uncompahgre River is most likely in violation of the 4.6 $\mu\text{g/l}$ standard. Based on where sampling is performed, the river may be considered in violation of the 20 $\mu\text{g/l}$ temporary standard also. For areas of the River above Montrose, selenium concentrations are below the strict 4.6 $\mu\text{g/l}$ standard.

Best Management Practice Simulations

Model simulations were performed to evaluate the impact of BMP implementation scenarios on basin-wide flows, concentrations, constituent loading and the ability to comply with water quality standards. Management practices analyzed in this study fall into four major categories: 1) canal, lateral and pond seepage changes, 2) irrigation efficiency changes, 3) total irrigated land changes and 4) treatment options. Model values have been isolated and switches included in the model to allow users to adjust various aspects of the agricultural hydrology for synthetic simulation. The values adjusted to simulate BMP's involve changes in model data, not changes in calibration parameter values. Output from the BMP simulations is primarily the longitudinal 85th percentile of the predicted monthly mean concentrations of selenium, as these simulations

are designed to test water quality standards compliance. For these simulations, it is assumed that the hydrology and water management in the basin accounts for the majority of the influence behind changes in river water quality. Model predictions for these BMP simulations are shown in Figure 7.

In the first set of BMP simulations, seepage is reduced in various sections of earthen canals and laterals in sub-basins as the canals are lined with concrete or the flows piped. Assuming wetted perimeters for canals and laterals of 4.3 m (14 ft) and 2.1 m (7 ft) respectively, seepage of $7.6 \times 10^{-2} \text{ m}^3/(\text{m}^2 \text{ day})$ ($0.25 \text{ ft}^3/(\text{ft}^2 \text{ day})$) occurs when the irrigation system is operating. By lining all the major canals and laterals in both the Loutsenhizer sub-basin (containing 42 km (26 mi) of canals and 85 km (53 mi) of laterals) and Cedar Creek sub-basins (containing 16 km (10 mi) of canals and 55 km (34 mi) of laterals), 860,000 m^3/mo (700 AF/mo) of seepage on average could be reduced, with a decrease of the 85th percentile of [Se] at Delta by 6.2 $\mu\text{g}/\text{l}$. A reduction in selenium and salt loads are predicted by this simulation. Lining all canals and laterals in Cedar and Loutsenhizer sub-basins reduces the load of selenium and total dissolved solids out of the basin at Delta by an average of 1,100 kg (2,400 lbs) of selenium per year and $3.3 \times 10^7 \text{ kg}$ (36,000 tons) of dissolved solids per year. As a result of reducing in-river concentrations, this BMP also reduces the total constituent load diverted to canals by an average of 84 kg (185 lbs) of selenium per year and $3.3 \times 10^6 \text{ kg}$ (3,600 tons) of salts per year.

In the second set of BMP simulations, increases in irrigation efficiency are simulated by the model, resulting in reduced application water requirements for the current cropping levels. If an increase in irrigation efficiency is not followed by a

corresponding reduction in diversion, minimal benefit to river water quality is predicted. A model simulation is performed to triple the irrigation efficiency to east side sub-basins of Dry Cedar Creek, Cedar Creek and Loutsenhizer Arroyo from the historical levels of 30%, 20% and 26%, respectively and reduce the diversions to 1/3 of their historical levels. Due to the decrease in diversions, flows at Delta are predicted to increase an average of $7.0 \times 10^6 \text{ m}^3/\text{mo}$ (5,700 AF/mo). A predicted reduction in the $X_{0.85}$ of [Se] at Delta would be $6.4 \text{ }\mu\text{g/l}$ (a 30% reduction from the baseline), with a corresponding reduction of load at Delta of 910 kg (2,000 lbs) per year of selenium. Increasing the irrigation efficiency to 60 – 90% would be a difficult enhancement, possibly requiring the installation of well-managed drip irrigation systems; however the change in return flow and loading from sub-basins would be substantial.

In the third set of BMP simulations, the model is run to simulate reductions in acreage under irrigation with corresponding reductions in river diversions. Diversion reductions of 50% of historical levels for the east side of the Basin results in the average flow at Delta to be increased by $6.3 \times 10^6 \text{ m}^3/\text{mo}$ (5,100 AF/mo) with corresponding reductions in $X_{0.85}$ of [Se] at Delta of $4.1 \text{ }\mu\text{g/l}$, a reduction of 19% from the baseline. The predicted average selenium load at Delta for this simulation shows a reduction of 426 kg/yr (939 lbs/yr). This management change is predicted to reduce the constituent loads to canals by 508 kg/yr (1,120 lbs/yr) for selenium and $9.3 \times 10^7 \text{ kg/yr}$ (102,000 tons/yr) for salts.

Finally, more aggressive BMP simulations are presented for comparison in Figure 8. These are shown to quantify the magnitude of management change that might be required to comply with the $4.6 \text{ }\mu\text{g/l}$ selenium standard. A water treatment option is

simulated, which involves no water management changes, but offers a reduction in selenium concentration to obtain "clean" return water with 0.5 µg/l selenium concentration. Such a process is possible but expensive and would likely involve batch treatment of water similar to that performed to reduce concentrations of toxics in mining leachate. "Clean" return waters from both the Cedar Creek and Loutsenhizer Arroyo sub-basin are predicted to be required to reduce in-river concentrations to below 4.6 µg/l.

The most drastic management change involves the removal of all irrigation to land on the east side of the Uncompahgre Basin, 7,500 ha (18,500 acres) in Mancos Shale. This measure is predicted to reduce the selenium concentrations in the river to below the 4.6 µg/l standard with a corresponding benefit of reducing the total salt load from the basin by 1.8×10^7 kg/yr (20,300 tons/yr).

To put the magnitude of these BMP's in perspective, current level of BMP's proposed in the Uncompahgre Basin is lining of 45 km (28 mi) of laterals in the Cedar Creek sub-basin (Baker, 2005). This relatively small-scale BMP is very likely to reduce selenium and salt loading as well as reduce in-river selenium concentrations. However, these reductions are small compared to the magnitude of reductions required to meet water quality objectives.

Discussion

Objectives for this study were to quantify the influence of best management practices to reduce selenium concentrations in the Gunnison Basin. An analysis was performed to first identify and quantify the high selenium sources that elevate concentrations in segments of the Uncompahgre and Gunnison Rivers to their impaired status. A mathematical model was then built to describe the spatial and temporal patterns

of return flows from irrigated agriculture and to predict the selenium and salt concentrations in those return waters. The model was then calibrated to match measured data. A set of historical conditions was predicted and analyzed in order to describe the current agricultural influence on in-river concentrations. A variety of management changes were performed by using the historical hydrologic data as input to the model with adjusted values to simulate a change in water management. The benefits of various management changes were quantified as changes in outflow load from the basin and the ability to meet water quality concentration criteria.

The agricultural components of hydrology were studied and the results were surprising. For many of the sub-basins, the total return flows, when normalized on a unit irrigated acreage basis, were actually larger than the annual application water right of $1.45 \text{ m}^3/(\text{m}^2 \text{ yr})$ ($4.76 \text{ ft}^3/(\text{ft}^2 \text{ yr})$) for Mesa soils (non-Mancos, primarily west side) and $1.21 \text{ m}^3/\text{m}^2\text{yr}$ ($3.97 \text{ ft}^3/\text{ft}^2 \text{ yr}$) for Adobe soils (Mancos Shale, primarily east side). Total pond, canal and lateral seepage accounted for a fairly small fraction of the return flow. Deep percolation from fields was also surprising low. The distribution of return flows into surface and sub-surface components (combined canal seepage and deep percolation) showed a much larger surface component volume than expected. The groundwater component volumes are low, but carry a large constituent mass loading.

The flow conditions throughout the river reach in the Uncompahgre Basin were also investigated. The area of the river below all the diversions but above the most downstream return flows has very low flows during the irrigation season, reducing the dilution capacity of the river to absorb return flows with high concentrations of selenium. In the section of the river below the most downstream diversion (Ironstone Canal) and

above the return flow from the Loutsenhizer Arroyo, the Uncompahgre River is often dewatered during the irrigation season. Therefore, the flow from the high contributing Loutsenhizer Arroyo and the Dry Creek comprise the bulk of the river water leaving the Basin at Delta during the summer months.

From the analysis of model predictions for current conditions, valuable information about agricultural impacts on downstream water quality was identified. Specifically, total input Selenium loads of and estimated 365 kg/yr (805 lbs/yr) and dissolved solids of 1.3×10^8 kg/yr (138,000 tons/yr) flow into the Uncompahgre via the Gunnison Tunnel and the upper Uncompahgre above Colona. Through reuse of irrigation return flows, 128% of the total inflow volume to the Uncompahgre is diverted on average each year by the eight major diversion structures for irrigated agriculture. This results in volumes of return flows in five major tributaries that comprise 74% of the outflow of the basin at Delta. Return flows load 4,130 kg/yr (9,100 lbs/yr) of selenium and 2.9×10^8 kg/yr (316,000 tons/yr) of dissolved solids to the river on average. Water reuse actually diverts high concentration water for irrigation and results in the loading of 1,200 kg/yr (2,600 lbs/yr) of selenium and 3.3×10^8 kg/yr (360,000 tons/yr) of salts to irrigated parcels in the basin. An estimated 3,200 kg/yr (7,100 lbs/yr) of selenium and 2.85×10^8 kg/yr (314,000 tons/yr) of dissolved solids leave the basin at Delta. Additional loads of selenium and dissolved solids are predicted to leave the Uncompahgre Basin to return directly to the Gunnison River.

Model-predicted concentrations throughout the Montrose-to-Delta reach of the Uncompahgre River exceed the table value standard of 4.6 $\mu\text{g/l}$ for dissolved selenium (requiring that 85% of sampled concentrations are below the standard for compliance).

Concentrations are very near the temporary standard of 20 µg/l with the 85th percentile of the highest concentrations nearing 30 µg/l just downstream of the Loutsenhizer arroyo inflow.

The BMP simulation results demonstrate the magnitude of a management change that might be required to reduce selenium concentrations to the strict water quality standard. An estimated selenium load reduction of 2,300 kg/yr (5,000 lbs/yr) would have to occur for the concentration of the Uncompahgre River at Delta to be within the water quality standard of 4.6 µg/l. Widespread pond, canal and lateral lining is predicted to reduce in-river concentrations but to a limited degree. The greatest benefit of canal lining is predicted to be within the Loutsenhizer Arroyo sub-basin area, given the highest overall groundwater selenium concentrations seen there. Even a tripling of the current irrigation efficiency to over 60% throughout east side of the valley is predicted to have limited benefit. Management changes on the order of full retirement of land on the east side or drastic reductions in the return flow (or loads through treatment) from the Cedar Creek and Loutsenhizer Arroyo sub-basins are predicted to be required in order to meet the 4.6 µg/l concentration standard.

Conclusions

This study presents a new modeling method for water quality compliance evaluation. The top-down approach combined the analysis of available hydrologic and water quality sampling data in a systematic way to develop a model describing the influence of irrigated agriculture on the mobilization of selenium and salts to a river. The development of a water quality model specifically for the evaluation of in-river standards compliance fills in a common gap in studies in the literature. Additional benefit is

derived from the model when simulation of selenium and total dissolved solids occurs in tandem; thus the multiple benefits of selenium concentration reduction and salinity reduction from a given BMP can be evaluated. Although the model presented here is specific to the Uncompahgre River Basin, the general approach should be acceptable throughout the irrigated West where selenium and salinity problems are common. The cost of developing such models, though not trivial, is perhaps orders of magnitude less than the cost of implementing BMP's such as canal lining. This cost would be recovered many times over through guiding the selection and implementation of the most cost-effective BMP's.

Within the Uncompahgre (and Gunnison) Basins the model suggests that changes to water management required to meet water quality goals may be great and expensive. However, the benefits may be far reaching: providing healthier habitat for all aquatic life in the Uncompahgre River and downstream and reducing salinity in the Gunnison River and eventually the Colorado River that serves a huge population of downstream users. These model results, along with further application of the model, should provide a foundation for maximizing the effectiveness of large investments required to meet water quality objectives within the basin and downstream. The magnitude of the problem is identified; the range and magnitude of possible solutions are at least partially quantified through this study, hopefully paving the way for implementation.

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Table 1. Annual average conditions for input water sources based on the baseline model simulation

Quantity	Uncompahgre at Colona	Gunnison Tunnel inflow to South Canal
Average annual total flow volume	$2.2 \times 10^8 \text{ m}^3/\text{yr}$ (181,000 acre feet/year)	$2.9 \times 10^8 \text{ m}^3/\text{yr}$ (232,000 acre feet/year)
Average [Se] ($\mu\text{g/l}$)	1	1
Average [TDS] (mg/l)	478	354
Se load	223 kg/yr (491 lbs/yr)	142 kg/yr (314 lbs/yr)
TDS load	$9.1 \times 10^7 \text{ kg/yr}$ (100,100 tons/yr)	$3.4 \times 10^7 \text{ kg/yr}$ (37,400 tons/yr)

Table 2. Annual average conditions for sub-basin return flows based on the baseline model simulation

Quantity	Sub-basin Name				
	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Annual total return flow volume	9.6 x 10 ⁶ m ³ /yr (7,800 acre ft/yr)	8.3 x 10 ⁷ m ³ /yr (66,900 acre ft/yr)	5.4 x 10 ⁷ m ³ /yr (44,000 acre ft/yr)	4.0 x 10 ⁷ m ³ /yr (32,600 acre ft/yr)	1.0 x 10 ⁸ m ³ /yr (82,700 acre ft/yr)
Average return flow [Se] (µg/l)	29	20	80	1.6	5.5
Average return flow [TDS] (mg/l)	2,100	1,200	2,500	810	930
Average return flow Se load	180 kg/yr (400 lbs/yr)	950 kg/yr (2,100 lbs/yr)	2,500 kg/yr (5,400 lbs/yr)	64 kg/yr (140 lbs/yr)	500 kg/yr (1,100 lbs/yr)
Average return flow TDS load	1.4 x 10 ⁷ kg/yr (15,300 tons/yr)	6.0 x 10 ⁷ kg/yr (65,700 tons/yr)	9.1 x 10 ⁷ kg/yr (100,500 tons/yr)	3.1 x 10 ⁷ kg/yr (34,500 tons/yr)	9.1 x 10 ⁷ kg/yr (100,000 tons/yr)

Figure 1. The Uncompahgre Basin and Mancos Shale outcropping in western Colorado

Figure 2. Uncompahgre Basin input and output fluxes, sub-basins, tributaries and canals included in the model

Figure 3. Schematic of the water balance model (top) and constituent loading model (bottom) and the connection to the longitudinal water quality model (bottom left) for the river

Figure 4. Example of the relationship between selenium concentration and flow observed at sub-basin outlets

Figure 5. Example of calibration plots comparing model prediction to measured data for Loutsenhizer Arroyo sub-basin outflow and [Se]

Figure 6. The longitudinal 85th percentile of selenium concentration for the baseline simulation

Figure 7. Predicted longitudinal 85th percentile of selenium concentration for BMP simulations

Figure 8. Predicted longitudinal 85th percentile of selenium concentration for selected extreme BMP's















