DISSERTATION

A LOAD MODELING APPROACH FOR EVALUATING SELENIUM STREAM STANDARDS COMPLIANCE

Submitted by

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY R. BLAIR HANNA ENTITLED A LOAD MODELING APPROACH FOR EVALUATING SELENIUM STREAM STANDARDS COMPLIANCE BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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ABSTRACT OF DISSERTATION

A LOAD MODELING APPROACH FOR EVALUATING SELENIUM STREAM STANDARDS COMPLIANCE

This research involves the demonstration of water quality modeling methods for assessing management alternatives for in-river standards compliance in a basin with impaired water quality. The modeling case study involves using available flow and water quality data to explain the water distribution and processes that change concentrations of salinity and dissolved selenium in the extensively irrigated Uncompahgre and Gunnison River Basins in western Colorado. A relatively simple top-down modeling method is proposed, in which observed data and physical principles of mass balance are used as the basis to describe large-scale processes driving constituent loading. The model development process reveals the historic agricultural water use, adherence to current and proposed water quality standards and major contributing factors influencing water quality throughout the basin. The model is then used to simulate a range of Best Management Practices for irrigated agriculture and basin development scenarios to predict changes in water quality throughout the Uncompahgre River and its region of influence. The goals of this research are twofold: to illustrate the value of using top-down methods to describe drivers of water quality and to specifically quantify these processes and offer potential solutions for the problem of elevated selenium levels influenced by water use in the Uncompahgre Basin in western Colorado.

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LIST OF SYMBOLS

AF	acre feet
AF/mo	acre feet per month
AF/yr	acre feet per year
cfs	cubic feet per second
EPA	United State Environmental Protection Agency
GIS	geographic information system
lbs/day	pounds per day
lbs/yr	pounds per year
mg/l	milligrams per liter
mo	month
μg/l	micrograms per liter
μS/cm	micro Siemens per centimeter (electrical conductivity unit)
ppb	parts per billion (same as μg/l in water)
ppm	parts per million (same as mg/l in water)
Se	selenium
[Se]	selenium concentration
TDS	total dissolved solids
[TDS]	total dissolved solids concentration
USBR	United Stated Bureau of Reclamation
USGS	United Stated Geological Survey
$X_{0.85}$ of [Se]	the 85^{th} percentile of selenium concentration
yr	year

Chapter 1

INTRODUCTION

When correctly applied, computer models can be valuable tools for the study of remediation options for river basins with impaired water quality. Analysis of observed data in 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 Environmental Protection Agency's (EPA) Clean Water Act for river segments with impaired water quality. Often water quality problems are complex, involving interplay between natural and anthropogenic water movement and chemical reactions at every step.

Many complex modeling methods have been proposed to describe every detail of water movement, use and chemical reaction. While these methods have been used with success, the data requirements are often vast to completely describe mass fluxes and accurately account for all model parameters. If these data requirements are unable to be met, estimates are used in place of measurements, reducing the accuracy of the complex model description applied to a water quality problem. Even when measurements are available, many sources of natural variability seen in natural systems are not fully quantified. A method that describes the majority of influential processes, uses basic physical principles, acknowledges variability and errors associated with sampling the real world may provide a useful solution to many complex problems.

This research endeavors to demonstrate the value of a relatively simple model to describe complex geochemical processes driving a water quality problem: the impairment of segments of the Uncompahgre and Gunnison Rivers in Western Colorado with elevated levels of dissolved selenium possibly linked to large-scale irrigation of seleniferous soils in the area. 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 μg/l. Temporary standards of 20 μg/l and 6 μg/l respectively are currently in place 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.

The chapters following describe the development of this method and application. Chapter 2 provides a literature review of the water quality problem and modeling methods used previously for this type of problem. The study objectives and proposed methods are presented in Chapter 3. Details of model development, calibration and validation are presented in Chapter 4. An analysis of the model output is presented in Chapter 5. Simulation of changes in water management practices and predicted influence on water quality are outlined in Chapter 6. The implications of this research and a summary of the conclusions are discussed in Chapter 7.

Chapter 2

LITERATURE REVIEW

A review of literature follows. The historical aspects of selenium as a water quality problem are discussed. Toxicity, geochemistry and previous studies of the water quality problem in the Uncompahgre are presented. Hydrologic and water quality modeling methods used previously for this type of problem are investigated. Additional methods found in the literature used as a basis for this approach are also discussed.

2.1 Water Quality Problem Description

2.1.1 Historical Perspective

The potentially broad impact of irrigated agriculture on water quality is well known. Common examples include: flow reductions in natural waterways from irrigation withdrawals, transport of leached minerals, pesticides, fertilizers and animal wastes to water bodies and concentrating effects as a result of evaporation. 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 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, 1994b). 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. Lemly (2004) presents a survey of several aquatic selenium pollution problems from a wide variety of sources in a global perspective emphasizing the strong influence of bioaccumulation.

2.1.2 Selenium Toxicity

Selenium is known to be a trace mineral required for healthy growth of plants and animals, however illness can occur from deficiency or high concentrations. Many vitamin supplements contain small amounts of selenium required for human health. The recommended daily allowance for selenium for adults is 55 μg/day (FNB and IOM, 2003). Keshan's Disease was first discovered in the Keshan province in China as a potentially fatal disease of the heart muscle associated with selenium deficiency in the body. Kashin-Beck disease is a bone and joint disease associated with child development under selenium deficiency (Medterms.com, 2004). Short-term moderately high levels of selenium in the human diet result in hair and nail brittleness and loss, damages to the peripheral nervous system, irritability and fatigue (FNB and IOM, 2003 and USEPA, 2004a). The Environmental Protection Agency (EPA) has drinking water standards for selenium of a maximum of 0.05 ppm (50 μg/l) (USEPA, 2004a).

Observation of selenium toxicity in animals due to excessive selenium dates back to an expedition through China by Marco Polo in 1275 (e.g., Marsden and Wright, 1926), where horses grazing on plants growing in high selenium soils became ill, lost hair and hooves. In the habitat at the Kesterson site, 64% of embryos and hatchlings of aquatic birds were either dead or severely deformed as a result of elevated levels of selenium in water and sediment (Presser, 1994a). Selenium was found to bioaccumulate through the food chain producing high concentrations in bird diet, resulting in high concentrations in eggs and in bird livers indicating toxicity. Bioaccumulation also occurs through the fish food chain. Hamilton et al. (2002), showed that toxicity in endangered razorback sucker fish larvae was more influenced by selenium in zooplankton food sources (>5μg/g) over selenium in their aquatic environment. The bioaccumulating nature of selenium through the food chain has prompted further study before finalizing numeric aquatic life water quality standards (USEPA, 2004b) that may result in a very low water concentration standard (2 μg/l as suggested by the US Fish and Wildlife Service) or future adoption of an animal tissue concentration standard over a water concentration standard. On 12/17/2004, the USEPA issued a draft aquatic life criterion document and requested comments from scientists (USEPA, 2005). This document recommends a nationwide freshwater whole-body fish tissue concentration not to exceed 7.91 μg/g (same as mg/kg) dry weight (a whole-body fish concentration standard of 4 μg/g is suggested by the US Fish and Wildlife Service) and if tissue concentrations exceed 5.85 μg/g in summer or fall, then winter sampling would be required to ensure that the 7.91 μg/g standard is not exceeded as selenium in fish tissue concentrates as fish lose weight under winter stress conditions. Field investigations in certain locations have shown elevated selenium concentrations in waters and no observed negative aquatic life effects and conversely low water concentrations in areas associated with organism effects attributable to selenium toxicity and high tissue concentrations. These data have prompted efforts to develop site-specific standards that would apply to specific ecosystems, e.g., Toll et al. (2005) and Brix et al. (2005). Even in light of these recent studies, as of this writing the State of Colorado provides selenium toxicity protection for aquatic life through a water column concentration standard for dissolved selenium in waterways of 18.4 μg/l (acute) and 4.6 μg/l (chronic) (USEPA, 2004c).

2.1.3 Selenium in the Uncompahgre and Gunnison Basins

The lessons learned at Kesterson prompted new geochemical studies of selenium, e.g., Elrashide et al. (1989). Screening studies of other geologic areas for selenium problems similar to Kesterson have been published, e.g., McNeal and Balistreri (1989), Presser et al. (1994a) and Nolan and Clark (1997). Presser et al. (1994a) indicates many 'reasons for concern,' for selenium toxicity problems in the Gunnison River Basin and Grand Valley. The Upper Colorado River Basin, specifically the Uncompahgre and Gunnison Basins in western Colorado (Figure 2.1) has been studied for many years because of elevated levels of salts and selenium possibly influenced by soils derived from the seleniferous, Cretaceous Mancos black shale outcropping throughout the region (Figure 2.2). Mancos shale outcrops over 182,000 acres or roughly 25% of the 716,000 acres of the Uncompahgre Basin. Given the extensive irrigation throughout the basin, seepage and groundwater movement through Mancos shale have been linked to leaching of selenium to the river systems (e.g., Butler et al, 1994) (Figure 2.3). 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. At least one case of selenium toxicity in a human is known to have occurred in the area (Marc Catlin, Personal Communication, 2004). At least one case per year of selenium toxicity in horses is seen in the Uncompahgre Basin (Karla Brown, Personal Communication, 2002). The combination of high selenium levels from a locally-grown diet, untreated water and living environment on the Mancos soil is blamed. Even in light of these cases, it should be noted that the elevated selenium concentration problems in the Uncompahgre and Gunnison Basins do not pose a serious human health risk, just a risk to aquatic animal health.

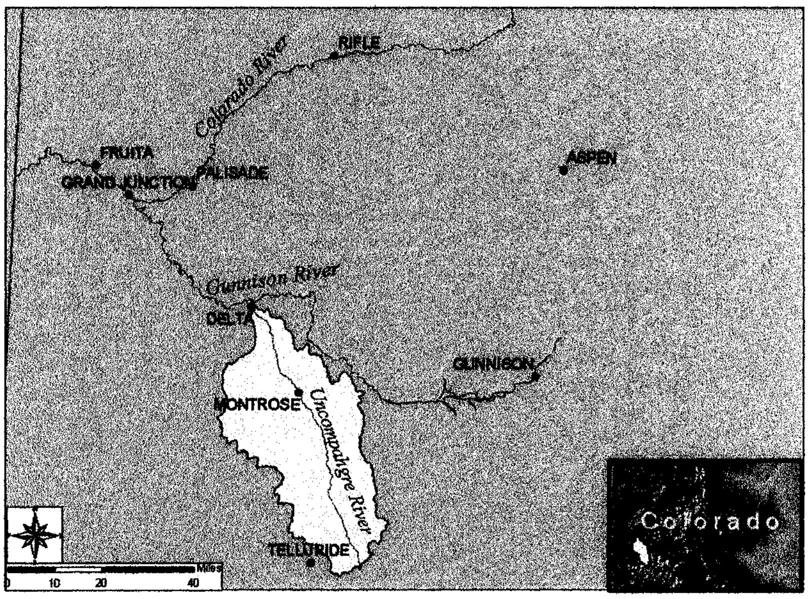


Figure 2.1. The Uncompahgre Basin in western Colorado

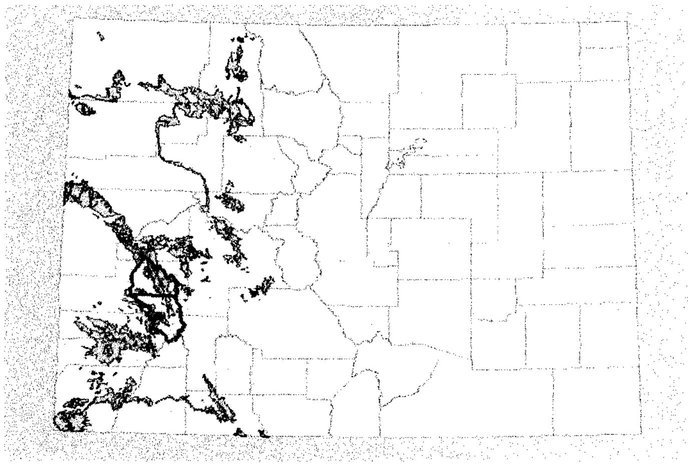


Figure 2.2. Mancos Shale surface contact throughout western Colorado

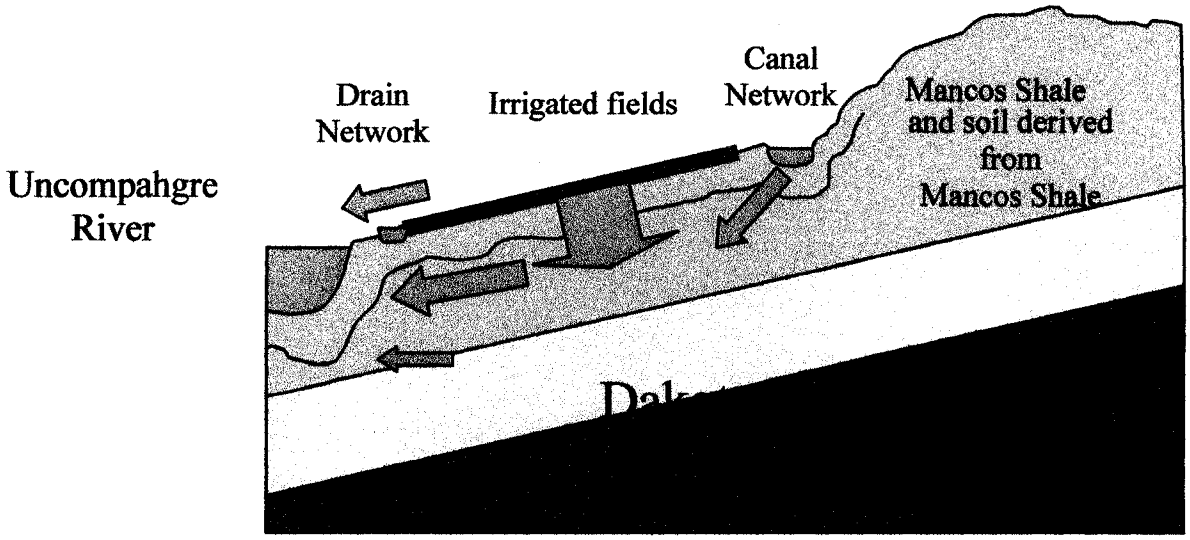


Figure 2.3. Schematic of assumed return flows and geologic structure in the Uncompahgre Basin, looking to the north

Other rivers in Colorado have been observed to have elevated selenium concentrations. Specifically, many river segments and tributaries within the Arkansas River Basin and river segments and tributaries within the South Platte Basin, in eastern Colorado have high selenium concentrations based on field sampling. No elevated selenium concentrations have been found to date in the San Juan or the Rio Grande Basins (Beley, 2004).

2.1.4 Geochemistry in the Uncompahgre and Gunnison Basins

There are many geochemical similarities between the Uncompahgre and Gunnison Basins and the San Joaquin area of Kesterson. The Mancos black shale that outcrops throughout western Colorado (Figure 2.2) has its origin as the Cretaceous Seaway sea bottom sediment deposited during the volcanic Cretaceous period 144 - 65 million years ago. The Pierre Shale that outcrops in areas of eastern Colorado (Arkansas

River Basin), South Dakota and Nebraska is very similar to the Mancos. In this marine shale, as with the Moreno formation and the Kreyenhagen Shale in California, metallic iron sulfide pyrite (FeS_2) occurs where much of the sulfur (S) is postulated to have its origin as volcanic detritus such as ash, dust, sediments and gases driven by rainfall into seas (Presser, 1994b). Substitution of trace amounts of Se for S in pyrites is known to occur. There are several reduction-oxidation (redox) conditions that produce different selenium species. Selenium substituted into pyrite exists in the Se^{-II} selenide form. Through weathering and oxidation elemental selenium Se^0 and $Se^{IV}O_3^{2-}$ selenite species form. The selenite form exists under reducing conditions in soils has been shown to adsorb highly to aquifer materials and be considered a non-mobile form. The adsorption is specific adsorption by Fe, Al and Mn oxide minerals and clay mineral edges. Further oxidation results in the $Se^{VI}O_4^{2-}$ selenate form. This form does not tend to adsorb to soils and is considered to be the mobile form of selenium in groundwater (Lindsay, 1979 and Sposito, 1994). Donnelly and Gates (2004) present initial results in their study of statistical relationships between selenium species, iron species, electrical conductivity and sulfate concentrations in groundwater in the Arkansas River Basin. The influence of nitrate fertilizers to mobilize selenium from the Mancos Shale by creating oxidizing conditions has been studied by Wright (1999) and shows promise as a chemically-based BMP that could be implemented to reduce selenium load in the basin. The present study assumes that BMP's implemented to change flow patterns do not drastically alter the geochemical processes currently observed to mobilize dissolved selenium.

2.1.5 Salinity in the Uncompahgre and Lower Gunnison Basins

Elevated salinity and the impact of the Mancos Shale on salt levels throughout the Upper Colorado region has been studied for over 25 years (e.g., Laronne, 1977). Many more complete studies have been performed by federal agencies, e.g., Butler et al. (1994), Butler and Osmundson (1999) and USBR (1999). A study aimed towards estimating the reduction in salinity that could be achieved by reductions in seepage by lining irrigation canals was extensively studied by USBR (1982). This study involved complete estimates of the water balance and economic evaluation of the proposed canal lining of all major canals on the eastern side of the basin. While the idea of this study and many of the methods are solid and trustworthy, the discussion of the modeling methods used for salinity prediction is weak, did not include variability and average hydrologic conditions only were used in the water balance.

The Uncompahgre River is not considered impaired by saline water, however high concentrations do exist; salinity concentrations of 1000 mg/l TDS at Delta are common. The Uncompahgre is considered just one of the many sources of salinity that influences the Colorado River.

2.1.6 Correlation Between Selenium and Other Water Quality Constituents

Elevated selenium concentrations have been observed in concert with other elevated constituent concentrations and may be driven by similar processes. Correlations between selenium, salinity, electrical conductivity (EC) and sulfate (SO_4) in surface and sub-surface waters have been found in the literature. Linear and non-linear relationships have been developed between selenium and salinity, conductivity and SO_4 associated with the Kesterson problem (White et al., 1991, Fujii and Deverel, 1989). The combined impact of salinity and selenium observed in the Uncompahgre Basin is also found in other basins in Colorado, specifically the Arkansas River Basin, where extensive irrigation there may also be elevating in-river concentrations of both constituents (Donnelly and Gates, 2004 and Gates et al., 2002). Donnelly and Gates (2004) have also identified statistical correlation between selenium, EC and SO_4 in Arkansas Valley groundwater samples. Observations of electrical conductivity are commonly used as an explanatory variable for a measure of total dissolved solids describing salinity. Expanding this relationship to include selenium concentration allows for a reliable link between conductivity measurement and selenium concentration. The benefits of this connection in the context of monitoring, specifically double sampling strategies for the Uncompahgre Basin have been studied by Gossenauer (2004). In regards to selenium toxicity in aquatic systems, there are data that indicate that the presence of sulfate reduces the bioavailability of selenate to aquatic biota. This connection may benefit aquatic life in areas with elevated selenium and sulfate and may be included in site-specific criteria for selenium concentrations to protect habitat (Gensemer at al., 2005).

2.1.7 Water Quality Compliance

Segments of the Lower Uncompahgre River (town of Montrose to the confluence with the Gunnison River at Delta) and Lower Gunnison River (Delta to Grand Junction) are included on the state of Colorado Clean Water Act section 303(d) list of impaired rivers for exceeding the EPA dissolved selenium concentration standard in water of 4.6 μg/l, set to maintain healthy aquatic ecosystems. The State of Colorado 303(d) list for 2002 (CDPHE, 2002), lists the river segments in the Uncompahgre and Gunnison with boundaries and current standards in place. Further refinement and additions to these segments were made for the 2004 303(d) list based on efforts to identify sources of selenium impairing downstream reaches. The most current 303(d) list (CDPHE, 2004) segments in the Gunnison Basin and Lower Colorado Basin are as shown in Table 2.1. Note that not all of these segments are directly influenced by activities in the Uncompahgre Basin, but all segments impaired in this part of the State of Colorado are listed for completeness.

Table 2.1 State of Colorado 2004 303(d) segment listings for impairment of Selenium in the Gunnison Basin and Lower Colorado Basin

Water Body ID	Segment Description	Portion	Priority	Standard
COGUNF05	Tributaries to N. Fork Gunnison River, USFS boundary to N. Fork	Leroux Creek, Jay Creek, Big Creek, Short Draw	High	std = 4.6 μg/l, Se tmod = 20 μg/l
COGUNF05	Tributaries to N. Fork Gunnison River not on USFS property	Cottonwood Creek	Low	std = 4.6 μg/l, Se tmod = 20 μg/l
GOGUUN04b	Uncompahgre River, LaSalle Road* to Confluence Park	All	High	std = 4.6 μg/l, Se tmod = 20 μg/l
COGUUN04c	Uncompahgre River, Confluence Park to Gunnison River	All	High	std = 4.6 μg/l, Se tmod = 20 μg/l
COGUUN12	Tributaries to Uncompahgre River, South Canal to Gunnison River	All	High	std = 4.6 μg/l, Se tmod = ambient conditions
COGUUN14	Sweitzer Lake	All	High	std = 4.6 μg/l, Se tmod = 20 μg/l
COGULG02	Gunnison River, Uncompahgre River to Colorado River	All	High	std = 4.6 μg/l, Se tmod = 6 μg/l
COGULG04a	Tributaries to Gunnison River, Crystal Reservoir to Colorado	All	High	std = 4.6 μg/l, Se tmod = ambient conditions
COGULG04b	Tributaries to Gunnison River, Kannah Creek	Below USGS station 09152000	High	std = 4.6 μg/l, Se tmod = ambient conditions
COLCLC03	Colorado River, Gunnison River to State Line	All	Medium	std = 4.6 μg/l

Water Body ID	Segment Description	Portion	Priority	Standard
COLCLC04a	Tributaries to Colorado River, Roaring Fork to Parachute Creek except for specific segments	All	Medium	std = 4.6 μg/l, Se tmod = ambient conditions
COLCLC13b	Tributaries to Colorado River from Government Highline Canal Diversion to Salt Creek	Tributaries on north side of river	Medium	std = 4.6 μg/l, Se tmod = ambient conditions
COLCLC13c	Walker Wildlife Area Ponds	All	Medium	Unknown
COLCLC14b	Roan Creek and tribs, Clear Creek to the Colorado River	Dry Fork	Low	std = 4.6 μg/l, Se tmod = ambient conditions
COLCWH09b	White River tribs, North and South Forks to Piceance Creek	Flag Creek	Low	std = 4.6 μg/l, Se tmod = ambient conditions

*LaSalle Road is just upstream of the Cedar Creek inflow to the Uncompahgre, 2 miles south of the intersection of highways 50 and 550 in the center of Montrose, CO.

The State of Colorado determines water quality standards compliance in the following manner: the 85th percentile of all available water quality sampling data, especially from the last five years is calculated and compared to the standard. If the computed 85th percentile is less than the standard, then the river segment is in compliance. The 85th percentile of sampling data at each sampling location is computed but not pooled over space, nor is compliance determined at a point. All points within segments are to be in compliance with the standard, so any point exceeding the standard results in the listing of the segment. However, if a tributary is found to be the cause of the high concentration, the tributary is then listed and a note is added to the impairment of the receiving segment. The idea behind this is to not just add to the list of impaired segments, but to find the source of impairment, (Dan Beley, State of Colorado, personal communication, 2003, 2004). Based on the current set of water quality sampling data, the Uncompahgre and Gunnison River segments are out of compliance with the dissolved selenium concentration standard of 4.6 μg/l. Temporary modification to the standard is in place due to uncertainty, while the problem is studied. These temporary standards are listed also in Table 2.1 and are 20 μg/l in the Uncompahgre and 6 μg/l in the Gunnison. From the dataset currently available to the State, the segments are in compliance with the temporary Se concentration standards. However, one year of monthly grab samples throughout the Uncompahgre River collected as part of this research demonstrates that the 85th percentile calculated at several locations exceed the 20 mg/l temporary standard. These data will be presented in Chapter 3.

As previously noted, selenium impairment exists throughout Colorado. Based on the 2004 303(d) list for Colorado, 41 of the 117 listed segments (35%) are impaired by elevated selenium concentrations. These listings have resulted in 41 corresponding temporary modifications to allow for elevated selenium concentrations while solutions are studied. This includes 17 segments in the Arkansas Basin, 9 segments in the Lower Gunnison Basin, 6 segments in the Lower Colorado Basin, 7 segments in the South Platte Basin and 2 in the Upper Colorado Basin. Seven of the 147 segments on the Colorado Monitoring and Evaluation list (5% of listed segments) have been placed on the list based on selenium concentrations (Beley, 2004).

2.2 History of Water Use in the Uncompahgre Basin

The Uncompahgre Valley was initially described as a "desert unfit for cultivation and inhabitation only by savages," by Captain J. W. Gunnison in 1853 (Dudley, 2004). However, compared to the nearby mountains, the rolling adobe hills could in fact be farmed with irrigation. 30,000 acres of crops were served by the Montrose, Uncompahgre and Delta Ditch Companies by the 1890's. Given the short supply of water for the developing farms, federal engineers planned and built the six-mile long Gunnison-Uncompahgre Tunnel, bringing water from the Gunnison River above what is now the Black Canyon of the Gunnison National Park and downstream of the Cuercanti National Recreation Area. The Tunnel officially opened on September 23, 1909.

The Uncompahgre Valley Water Users' Association (UVWUA) is a public mutual company and sole holder of the historical water right for the irrigation delivery system. They charge farmers only for annual operation and maintenance costs of canals and laterals for water served. The amount of water provided to a parcel depends on the soil type. Mesa soils (west side) receive 0.02 cfs/share for 120 days (4.76 acre ft/acre annually, or 4.76 ft per unit area) for $25.75/share. Adobe soils (east side, primarily composed of Mancos Shale) receive 0.0167 cfs/share for 120 days (3.97 acre ft/acre annually, or 3.97 ft per unit area) at a cost of $20.60/share. Parcel owners receive roughly one share per acre, however a re-evaluation of land in the mid-1900's allowed for the addition of acreage at 0.6 shares per acre (UVWUA, 2003). Hand-drawn maps of parcel plots are still the primary information source for the assignment of water shares to parcels, therefore a complete description of the spatial division of these application water rights is not in a usable form for this study. Annually a decision is made to provide full or partial water rights based on snowpack estimates. Currently the UVWUA manages over 250 miles of canals and laterals serving over 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 throughout the basin. There are eight major canals in the Uncompahgre Basin, 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, the Montrose and Delta Canal, West Canal and Ironstone Canal. Given the nature of the system and the large quantity of water delivered, agricultural drainwater is captured and served to other farmers. The water users, "sell water four or five times over," (Catlin, 2004).

Detailed information and historic data for the Uncompahgre Basin irrigation system is available from the Colorado Water Conservation Board and Colorado Division of Water Resources. Colorado Water Conservation Board and Boyle Engineering Corp., 1999, describe the details of the STATEMOD water allocation model for the Gunnison Basin. This report and data from the Hydrobase database, part of the Colorado Decision Support System are very valuable sources for data describing water movement throughout the Uncompahgre and Gunnison Basins (CDSS 2004a, 2004b, 2004c, 2004d). These data are used by the State Engineer's office for the monitoring and evaluation of water management for water rights throughout the whole of the Gunnison Basin, which the Uncompahgre is just a small part.

2.3 Previous Studies Linking Agriculture and Selenium in the Uncompahgre Basin

The combined influence of salts and selenium in the Upper Colorado region has been well documented with frequent addition of new data, see, Butler et al. (1994, 1996, 1999). A complete discussion of many of the complex geologic, geochemical and biological aspects of the selenium problem in the Uncompahgre Basin and Grand Valley are presented in Butler et al. (1996). This work describes also the water distribution systems in the area and presents data from a synoptic water quality study performed in the Uncompahgre Basin in 1992. The term synoptic sampling describes samples gathered at several locations at one instant in time to quantify a snapshot of the state of a system. Butler et al. (1994) and Butler et al. (1999) are primarily data reports but also very complete and detailed. These studies, while mainly scientific in nature, have concluded that extensive diversions for irrigation, transport of water through earthen canals and furrow irrigation practices have altered the natural hydrology in the Uncompahgre Basin. Through increased seepage, water application to soils at a higher than natural rate and leaching of natural minerals, agriculture return flows may have elevated salt and selenium concentrations throughout the lower Uncompahgre River and portions of the Gunnison River. The complexities of water movement through the basin are difficult to describe. The resulting chemical processes that mobilize dissolved constituents as water contacts soil compounds the complexities of the water quality problem.

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 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 flows (Figure 2.3), levels of dissolved solids and selenium in the Uncompahgre and Gunnison Rivers could possibly be reduced to safe, background levels that comply with the current water quality standards.

There have been several reports describing focused selenium studies on Uncompahgre Basin. Butler (2001) presented the details of the Montrose Arroyo lateral piping demonstration project in which 8.5 miles of previously earthen irrigation laterals were replaced with 7.5 miles of pipe. Water quality sampling was performed before and after the project and average reductions in flow, salinity and selenium were measured possibly as a result of a reduction in seepage. A 28% decrease in annual selenium load (194 lbs/year) and a 16% decrease in annual salt load (2,900 tons/year) were associated with the reduction in lateral seepage in the area. These reduction fractions are average load reductions for the localized area below the lateral piping (site MA2, Montrose Arroyo at East Niagara Street), not measured anywhere in the Uncompahgre River. A calculation of the volume of seepage reduced is not presented in the report but from the output presented one can calculate that 6.6 AF/month/mile of lateral was reduced through piping (reported groundwater load reduced through piping = 178 lbs/yr, assumed groundwater concentration = 98μg/l, 178 (lbs/yr)/98 (μg/l) $*(10^6/0.0022/1000/0.3048^3/43560/12/8.5) = 6.6$ AF/month/mile of lateral). This demonstration study reports a successful method to reduce selenium and salt load. However, no discussion of the impact of this small-scale improvement (albeit quite expensive at $1.3 million) on overall river basin water quality improvement is presented.

Butler and Leib (2002) summarize the basin wide water quality sampling data performed by the USGS. Sampling was performed over many years in order to quantify the magnitude and distribution of selenium sources in forks of the Gunnison and Uncompahgre Rivers along with the identification of high-contribution tributaries and reaches. Analysis of the report data shows that 78% of the selenium load in the Gunnison at Grand Junction is identified by sampled point loads. 38% of this load is provided by the Uncompahgre at the confluence with the Gunnison at Delta, CO. An additional 18% of load is accounted for as the return flow draining from parcels outside the Uncompahgre Basin boundary but irrigated by diversions from the Uncompahgre River, therefore an additional Uncompahgre Basin influence. This report is very valuable; however, best estimates of loading fractions based on the data with statistical analysis were not performed.

Based on soil survey results in the Uncompahgre basin, total selenium in soils ranges from 1 – 20 mg/kg soil; where the highest concentrations are found to be in Mancos Shale alluvium and residual soils. Studies of drain seeps and through soil column experiments, 2% - 25% of this total selenium is soluble. Levels of solubility of selenium from these soils change with irrigation history, with the highest available selenium seen in never before irrigated soils and lower levels seen in soils that have been irrigated for many years (Dearstyne, Brummer and Fahy, 2003 and Fahy personal communication). This draft report falls short of clearly presenting representative averages for selenium content of soils in the area and estimates of dissolution rates seen. Some hearsay data with weak analysis regarding water balances and the influence of housing development on previously un-irrigated lands is also presented. The soil analysis indicates that a high "first-flush" could have occurred in the basin when irrigation began back in the early 1900's and if new areas of soil are irrigated or developed, extreme levels of selenium could be released. This process may have been seen in the sampling data. Extreme concentrations of Se (> 10,000 μg/l) were measured in seeps below the Devil's Thumb Golf Course, north of Delta, CO in 2001, following the first year of operation and irrigation (Based on USGS sampling data).

Using many of these data sources, simplified analysis reports for graduate engineering classes have also been prepared by the author; see Hanna and Schaefer (2000) and Hanna and Carney (2002).

2.4 Water Quality Modeling Methods

Water quality modeling studies vary greatly in the constituent of interest (i.e., temperature, dissolved solids, dissolved oxygen, nutrient-food-chain interactions, pH, metals and toxics), the water body type (i.e., lakes, reservoirs, rivers, estuaries, bays) and anthropogenic influence (i.e., pristine, managed reservoir, managed irrigation system, urban). The methods used given the problem at hand also vary greatly.

Details of water quality modeling methods continue to be well documented in texts and throughout the literature. Chapra (1997) presents a complete discussion of mathematical methods used in deterministic surface water quality models. Use of site-specific data for calibration and validation exercises and limitations of model solutions are well discussed.

Novotny (2003) describes many cause and effect relationships between water use and the prediction of resulting water quality. However, often during the presentation of specific deterministic modeling methods in these texts, the difficulty in obtaining all the required data to facilitate such modeling is ignored or not given adequate consideration. Specific discussion of the impact of model structure and parameter uncertainty on water quality model prediction is represented in the literature. Beck (1987) presents a comprehensive discussion of the topic of uncertainty analysis for water quality models, while Sexton et al. (2003) provides a general overview. An easy-to-follow water quality application of uncertainty quantification with increasing model complexity is discussed by Van Der Perk (1997).

2.5 Coupling of Water Quantity and Quality Models

The coupling of water quality models with other models describing water management, operations and distribution are fairly common. The author has been involved in several studies, see, Hanna et al. (1999), Campbell et al. (2001), Saito et al. (2001) and Bartholow et al. (2001). Water quality models are often coupled to water allocation models in order to determine an optimal water management strategy given water quality constraints, e.g., Jolma et al. (1997), de Azevedo et al. (2000), Dai and Labadie (2001). While knowledge of an optimal strategy that solves a problem is valuable, the feasibility of implementing this solution in the real world is not always presented.

Water quality studies that have included and quantified natural hydrologic variability are fairly rare but have been performed (e.g., Melching and Bauwens, 2001, Chiang and Gates, 2004). Chiang and Gates (2004) used classic stochastic methods in the creation of realizations of river conditions and for parameter estimation for a QUAL2E water quality model application of the South Platte River in northeastern Colorado. Simulations of several management strategies were performed and the uncertainties of predicted constituent concentrations were presented along with the probability of violation of water quality standards.

2.6 Water Quality Sampling Methodologies

The application of specific sampling strategies is vital for determining precise estimates of water quality based on values measures throughout a basin or throughout time. These methods are well documented by Gilbert (1987) and somewhat in Berthouex and Brown (1994). Often these methods are overlooked when analyzing water quality data for use in modeling studies and all available raw data used instead. Predictions of changes in water quality based on model output should also be correctly analyzed given variability. Specific monitoring strategies designed to detect expected changes given natural variability have been presented (e.g., Loftis et al., 1991). Methods describing the use of sampling data from naturally-varying water quality conditions for use in standards compliance have also been presented by Loftis and Ward (1981) and similarly by Gibbons (2003).

In addition to real variability of water quality, laboratory analysis of the water quality sample itself can introduce variability into the data set. This variability is usually considered as a portion of the "error" between the real world water quality and the resulting sampled dataset describing the real world as sampled and analyzed at a point in time. Many of the data used in this study were collected by the USGS as part of the USBR National Irrigation Water Quality Program (NIWQP, USBR 2004). As part of this program, a large suite of water quality constituents are analyzed from each water quality sample. Data collection and analysis follows a rigorous quality assurance/quality control process to allow for good comparison between samples. Data collected specifically for this study followed many of these procedures and utilized the same laboratory analysis technique for dissolved selenium as performed by the USGS to enable comparisons.

In the context of natural variability, a change in water quality as a result of a BMP may be difficult to detect in the real world. The idea of a Minimum Detectable Change is important to keep in mind, where a sample of size n is taken of conditions before a BMP is implemented, and another sample of size n is taken after. Based on the sample size and variability, there is a minimum change that can be detected by that sampling and considered significant above the natural variability. Modeling may provide information about potential changes that could occur, but being able to detect these changes in the field may require extensive sampling. In a companion study to this research, Gossenauer (2004) studied the sample size and water quality sampling plans that would be required to detect various levels of change in selenium load. From his study, in the Uncompahgre at Delta, six samples taken throughout a year using simple random sampling could only detect a change in mean load of 47 percent, although the use of double sampling with discharge, a sample size of six could detect a 3% change in mean load.

2.7 Water Quality Modeling for Standards Compliance and TMDL Studies

Management solutions for reduction of the Kesterson problem that involve modeling and monitoring have been published (e.g., Quinn and Karkoski, 1998, Lemly, 1999, and Quinn, 1989). Lemly (2002) has outlined some general methods for selenium TMDL studies. Specific applications of water quality models in TMDL studies also appear in the literature. A valuable paper by Borsuk et al. (2002) discusses the increasingly important use of water quality models for TMDL studies and the impact natural variability has on interpretation of the results from models. The authors quantify the inability of deterministic models to capture all variability of natural systems and propose these errors are used to bound model predictions. Statistical methods can be used to develop confidence intervals around model predictions. These methods, combined with a percentile-based water quality standard, can be used to predict the number of probable violations that could occur. Herr et al. (2003) discusses a water quality model with a complex geochemical component for acid-mine drainage and the specific application in a state TMDL study; however the details of the model use for the

TMDL guidelines are weak. Water quality TMDL studies considering nutrients are common in the literature, e.g., Harned et al. (2004), Smith and Wheater (2004), Reckhow and Chapra (1999), Dalzell et al. (2004), Vieux and Moreda (2003). Many of these studies have implemented linear regression, empirical and physically based models that fit point source concentrations as a function of tributary discharge as a portion of a model to analyze river water quality. Some of the published relationships and methods for quantifying source water quality are practical for model simulation especially in the context of small sampling data sets. However, given seasonal and year-to-year variability in flow and quality, the simple linear relationships found in the literature appear to be quite statistically weak and barely adequate for a modeling analysis of standards compliance in a natural system. However, many of the methods of modeling, providing error bounds on model predictions and use of the model for management practice assessment are similar to the present study.

In Colorado, no selenium TMDL studies have been completed to date. Based on the 2004 303(d) list, 41 selenium TMDL's are planned. Three studies are in progress: for the Uncompahgre River mainstem, the Gunnison River mainstem and the tributaries to the North Fork of the Gunnison River (Beley, 2004).

2.8 Hydrologic Modeling of Source Water Components

Many studies addressing agricultural flow allocation, and the impact of return flows from groundwater on river flows have been published, e.g., Snyder and Asmussen (1972), Illangasekare and Morel-Seytoux (1986) and Fredericks et al. (1998). The impact of agricultural practices on water quality has been widely studied (e.g., Fujii and Deverel, 1989, Fio, 1997). Coupled water quantity and quality modeling has been performed for the simulation of groundwater-surface water interactions, e.g., Bicknell et al (1985), Goff et al. (1998), Gates et al. (2002), de Azevedo et al. (2000) and De Marchi et al. (1999).

Large-scale hydrologic problems are often solved through the use of water balance models. Many studies have been purely academic to outline methods and prove annual balances can in fact be calculated, e.g., Eagleson (1978) but others have been applied for specific problems, e.g., Yates and Strezepek (1998). Specific focus on the difficulty of water balance computations for agriculture using irrigation efficiency estimates has been presented, e.g., Clemmens and Burt (1997) and Burt (1999). Given this difficulty in computing overall loss of water given the data commonly available, different approaches for calculating large-scale evapotranspiration have been proposed. The complementary relationship Advection Aridity model proposed by Brutsaert and Stricker (1979) has been enhanced and tested for many basins in the U.S. by Hobbins et al. (2001). This modeling approach can be applied at any time scale using only meteorological data to predict total evapotranspiration in a region. Irrigation efficiency estimates and a model of crop consumptive use (StateCU) are available for the Gunnison Basin, (CDSS, 2004c).

While hydrologic models are often coupled or used for assisting water quality modeling, data analysis and investigations for determining characteristics of source flows for use in distributed and nonpoint source water quality studies are often not well-described in the literature. The link between specific volumes of water flowing into the river and their potential source as irrigation water is important for this study.

2.9 Top Down Method For Model Development

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), Eder et al. (2003), Sivapalan et al. (2003), Farmer et al. (2003) and Jothityangkoon et al. (2001). This approach for hydrologic problem solving starts with measured data for a process and develops a 'big picture' estimate including some of the details that may have lead to the overall result. By continuing to break down components into finer detail by adding more descriptive processes or changing the spatial or temporal scale, a better description of the process and comparison with measured data arises. The downward approach focuses on the problem as a whole and 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 at hand. At each step in this process, new details about the hydrologic process are learned and flaws in the current model description demonstrated. While a survey of uses for the downward approach in Sivapalan et al. (2003), mention applicability to water quality, studies that use the downward approach for water quality modeling, TMDL or water quality standards compliance were not found in the literature.

2.10 Economic Impact and Modeling

Elevated selenium concentrations in irrigation water do not directly impact crop yields; rather elevated salinity in irrigation water reduces crop yields (Schuck, 2002). Salinity and selenium concentrations are positively correlated in the basin and the link between these concentrations may allow for economic drivers within the basin to reduce both constituents when focused primarily on crop yield benefits of BMP's. Remediation strategies involving BMP implementation will most certainly cost money. Funds may or may not be supplied through federal programs. Incentives, either in the form of direct funds or higher crop yield will ultimately determine if a management practice is accepted by farmers.

A field demonstration project showing the advantages of a drip irrigation system was performed in the basin (Cooley, 2004). This study showed that for an additional expense of $500/acre annually for materials, an increased yield of 57% was realized for a high-value onion crop with water application 55% of that used for furrow irrigation. The relative annual cost of the drip tape materials is on the order of 12.5% for the high value crop of onions ($500/$4,000 = 12.5% on a per acre basis, using $3,500/acre net profit value from Cooley, 2004 and Hla, 2005).

Another demonstration of phytoremediation was performed in the basin (Fisher, 2004). In this study, Poplar trees and other crops were planted and demonstrated selenium uptake from the soil into the leaves (1-4 ppm [Se]) and trunk wood (<1 ppm). This study shows a way to possibly extract small amounts selenium from soils (up to 8 g/acre), but also may present alternative crops than can be grown in the basin for profit.

Given the water reuse in the basin, implementation of a BMP to reduce salt and selenium at one point in the basin may enhance the water quality of irrigation water for downstream users. High salinity in source water from evaporation and in soil water from high water tables and field evaporation reduces crop yield; an historical problem in irrigated systems in the western U.S. Conversely, reduced salinity in irrigation water is known to increase crop yield (e.g., Francois, Grieve and Maas, 1994). A demonstrated feedback process between BMP's that reduce salt and selenium concentrations and increased crop yield may prove to be a valuable incentive for BMP implementation.

Economic modeling studies of the influence of water availability, price and irrigation water quality are quite common, e.g., Kan et al. (2002), Lee and Howitt (1996), Weinberg (1997), Green and Hamilton (2000), Wichelns (1999, 2004) and Schuck and Green (2001). Gardner and Young (1988) have performed specific economic studies that include the Upper Colorado Basin and the influence of the Mancos Shale on irrigation-induced salinity. The inclusion of economic and policy-oriented models into water quality modeling studies have also been found in the literature. Bouzaher et al. (1993) describes "metamodeling" as a method to analyze complex relationships using various model output from large sets of simulations. Cai et al. (2003) documents a very complex economic and agricultural hydrologic model and presents a case study. The hydrologic model presented is not physically based and is not driven by historical data; however the ability of the authors to combine a large set of complex relationships between water, agriculture and economic drivers has merit.

2.11 Summary of Literature Review

These references provide a broad background of the water quality problem in the Uncompahgre and Gunnison Basins. The problem is a complex interaction of geochemistry and water management, where water quality standards, federal law and economics also play a role. References for problem solving methods that can be applied in this study have also been shown.

While many individual aspects of the research topic have been investigated, the presentation of a data-driven, large-scale water quality model utilizing a physically-based mass balance approach to describe salinity and selenium for use in assessing the outcome of BMP implementation for water quality standards compliance has not been found to date. A study utilizing the top-down method for a water quality problem has not been found to date. A study that presents a quantitative link between model-predicted BMP simulations that influence water quality for standards compliance will be a valuable contribution.

Chapter 3

OBJECTIVES AND METHODS

This chapter discusses the objectives of the research and the general methods used to analyze the water quality problem in the Uncompahgre basin. The conceptual model developed in this study is also outlined.

3.1 Research Objectives

There are both stakeholder and academic objectives to this research. Stakeholders are interested in information regarding the sources of the water quality problem in the basin and to what extent BMP's can be used to move towards water quality standards compliance. Academic interests involve the presentation of sound methods for problem solving and to develop "new and significant contributions" to the knowledge base on computer applications to aid in water management decision support.

Investigation and quantification of the predicted benefits of BMP's to meet water quality standards for dissolved selenium in the basin is the ultimate goal of this study. Towards this end, a model will be developed and a modeling method will be presented that utilizes available data and general physical principles to predict the basin-wide water balance components, salinity and dissolved selenium concentrations. Analysis of the output from various modeling scenarios will quantify the influence of BMP's to change water quality.

3.1.1 Stakeholder objectives

1) Identify and quantify high selenium and salinity concentration and source areas throughout the Uncompahgre Basin influence area.
2) Develop cause and effect relationships between irrigation system use and measured impact on concentrations and loads of salinity and dissolved selenium.
3) Quantify the expected change in water quality and flow as a result of a range of agricultural BMP's aimed to change return flow patterns and loads of salinity and selenium.

3.1.2 Academic objectives

1) Assess the value of a relatively simple top-down loading model method to quantify the hydrologic and water quality impact of agriculture.
2) Demonstrate the value of a direct link between water quality modeling and standards compliance evaluation.

3.2 Thesis Statement

Based on the goals of the study, a thesis statement for this research would be as follows:

It is the author's belief that even in the context of a complex natural and managed hydrologic system, a model can be developed using basic physical principles that will be valuable to describe the major driving factors behind a water quality problem. This model can be used in an engineering problem-solving approach to offer guidance on management decisions to improve water quality conditions to acceptable standards.

3.3 Original Solution Direction

The original plan for a problem solving direction for this project relied on the use of the State of Colorado STATEMOD water allocation model for the Gunnison River Basin (Division 4) as the source of all hydrologic information in the area (CDSS, 2004a). The water quality component for selenium would have been an extension of this model. After a great deal of analysis of the STATEMOD model application for the Uncompahgre Basin, the author and his advisor decided that, while this model provided a great deal of valuable data, it lacked all the requirements to allow for a water quality enhancement. The STATEMOD model is a node-link water allocation model where nodes describe diversions structures from the mainstem river, consumptive uses are modeled using irrigation efficiency values and return flows are partitioned to one or more downstream nodes. These downstream nodes often did not correspond with natural tributary returns and comparison of predicted return flows at nodes with grab sampling data did not correspond well. Accurate descriptions of return water flowpaths, volumes and timing for correspondence with measured data was paramount. It was also discovered that, while water balances within the Uncompahgre Basin, the portrayal of water flows longitudinally within segments of interest, appeared physically inaccurate. Specifically, the baseflow component of flow in the Uncompahgre segment was added (and subtracted) at one downstream location instead of being distributed spatially. It should be noted that this model application is working as designed for its intended use in predicting water availability in a large scale for a complex water rights priority system with a large number of nodes. Analysis of the modeling methods used in STATEMOD and output for the Uncompahgre Basin yielded abundant information about water movement throughout the basin. The return flow lagging method (standard convolution equation) used by STATEMOD was also used in this study. After discussions with Colorado Water Conservation Board (CWCB) and their consulting engineer (Erin Wilson, Leonard Rice Engineers) the spatial detail of available flow data in the basin became quite evident, providing a starting point for the approach used here, which yields greater spatial resolution and accuracy compared to STATEMOD.

3.4 Downward Approach Method

The lessons learned from analysis of the STATEMOD model and available data reinforced the point that often when important pieces of a puzzle are missing, a systematic approach of continued refinement of the details of the problem may prove to be quite effective. This method outlined by Klemes (1983) and coined the Downward Approach to Hydrologic Analysis, is a general approach of continued refinement where large-scale analyses are used first and details are added in a stepwise fashion in order to create a model with the minimal detail to solve the problem at hand. This method results in a robust model, with the fewest parameters and accurate to the level of detail of the available data. Conversely, a bottom-up method would apply a (usually complex) model to a problem and often continue to adjust model parameters until a satisfactory fit to the data is achieved. Processes in this case are pre-described by a model and parameters adjusted to fit a specific dataset. This is probably the approach that was used to develop the STATEMOD application for a large basin like the Gunnison. While the bottom up approach is often used with great success in other fields (e.g., software development, where the detailed processes are described first, then combined to create a software product), the lack of accurate information required at the lowest-level detail may alter the accuracy of the large scale results. In the case of the Uncompahgre basin, a bottom-up approach for solving part of the problem might apply a complex, fully-mechanistic, geochemical model to portions of the basin in an attempt to describe processes of selenium and salinity uptake from soils. These processes, combined within a groundwater flow and transport model would be required to simulate the influence of agriculture on in-river water quality. While this approach has merit for advancing the knowledge of soil chemistry and water movement in the basin, all required data may not be available and a basin-scale model might be difficult to develop from this focused study. The overall objectives of this study may benefit more from the top-down approach.

The downward approach is followed for model development; where data at a high level and large scale are used first. Then the scope is narrowed in a stepwise fashion to a scale capable to solve the problem at hand with the simplest model possible. The start of the downward approach in practice allows for an identification of areas of water quality concern and potential sources of constituents. Following the top-down idea, analysis would first proceed by developing the model boundary of the control volume and describing the input and output water and constituent fluxes and constituent balance leading to a computation of total constituent uptake. If data were available at finer spatial and temporal scales, further refinement could include dividing the basin spatially into sub-basin control volumes and analyzing seasonal or monthly data. Given seasonal or monthly data analysis, a focus on agricultural processes that distribute water and load constituents to the river in accordance with the data could be created. These large and more detailed analyses are outlined in the following sections.

3.4.1 Large-Scale Analysis

Analysis of data from a synoptic sampling study of selenium sources loading the Lower Gunnison River (Figure 3.1) reinforced the observation that of the 78% of the total sources identified, the largest contributing areas of selenium to the lower Gunnison River were based inside the Uncompahgre Basin. From these data, 39% of the selenium load in the Gunnison River at Whitewater (just upstream from Grand Junction, CO) is attributed to Uncompahgre River. The Uncompahgre Basin's influence area, slightly larger than the natural basin boundaries due to trans-basin diversions by canals and laterals, contributes additional loads (totaling approximately 18%) directly to the Gunnison River. Additional selenium loads throughout the Lower Gunnison Basin, totaling approximately 20% of the load at Whitewater, are attributed to the mainstem and main forks of the Gunnison River itself. Other sources and other tributary inflows from the north not included in Figure 3.1. Therefore, the boundaries for modeling were set with input fluxes being Uncompahgre flows at Colona, Gunnison Tunnel inflows to the South Canal and output fluxes being the Uncompahgre at Delta and out-of-basin fluxes to the Gunnison above and below the confluence with the Uncompahgre. These fluxes are described by arrows in Figure 3.2. The yellow boundary line is the physical watershed boundary for the Uncompahgre Basin. At the scale of this analysis it was assumed that these fluxes provided the vast majority of basin water and other inputs such as net precipitation to the basin and groundwater baseflow from regional sources were small. This assumption seemed justified for net precipitation based on annual average precipitation at Montrose of 10 inches and annual potential evaporation estimated by evaporation pan 55 inches, (based on monthly precipitation data from 1900-2003 and monthly evaporation data for

1948 – 1983, CDSS, 2004b). The Uncompahgre Basin is primarily an alluvial valley and water input to the Uncompahgre River from a regional unconfined aquifer connection is assumed to be small. However, uplands to the east forming the western rim of the Black Canyon of the Gunnison, do receive higher precipitation, especially in winter, compared to Montrose within the Basin. This additional water may provide a groundwater source through the unconfined alluvium above the irrigated area. A study to quantify this water inflow and the selenium loading from the Gunnison Gorge National Recreation Area is underway by the USGS Geologic division, although no results are currently available. To facilitate a mass balance modeling approach, this additional water flux is assumed to be small as compared to the irrigation water sources within the Uncompahgre Basin.

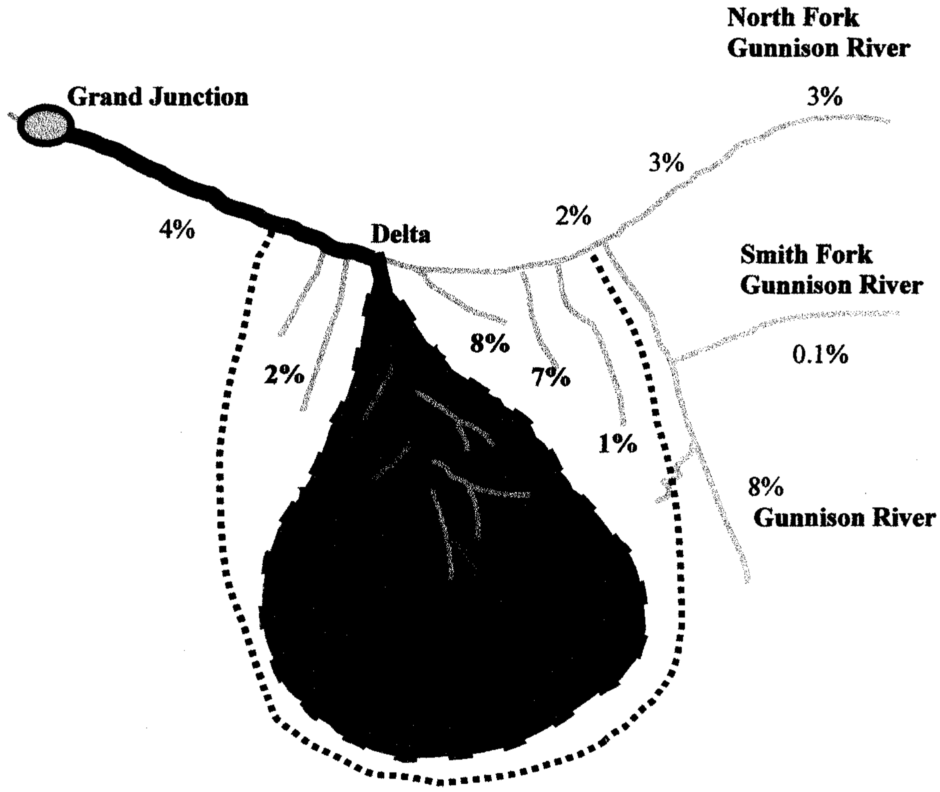


Figure 3.1. Estimates of source distribution of selenium sources contributing to load in the Gunnison River at Whitewater (near Grand Junction) based on data from Butler and Leib (2002)

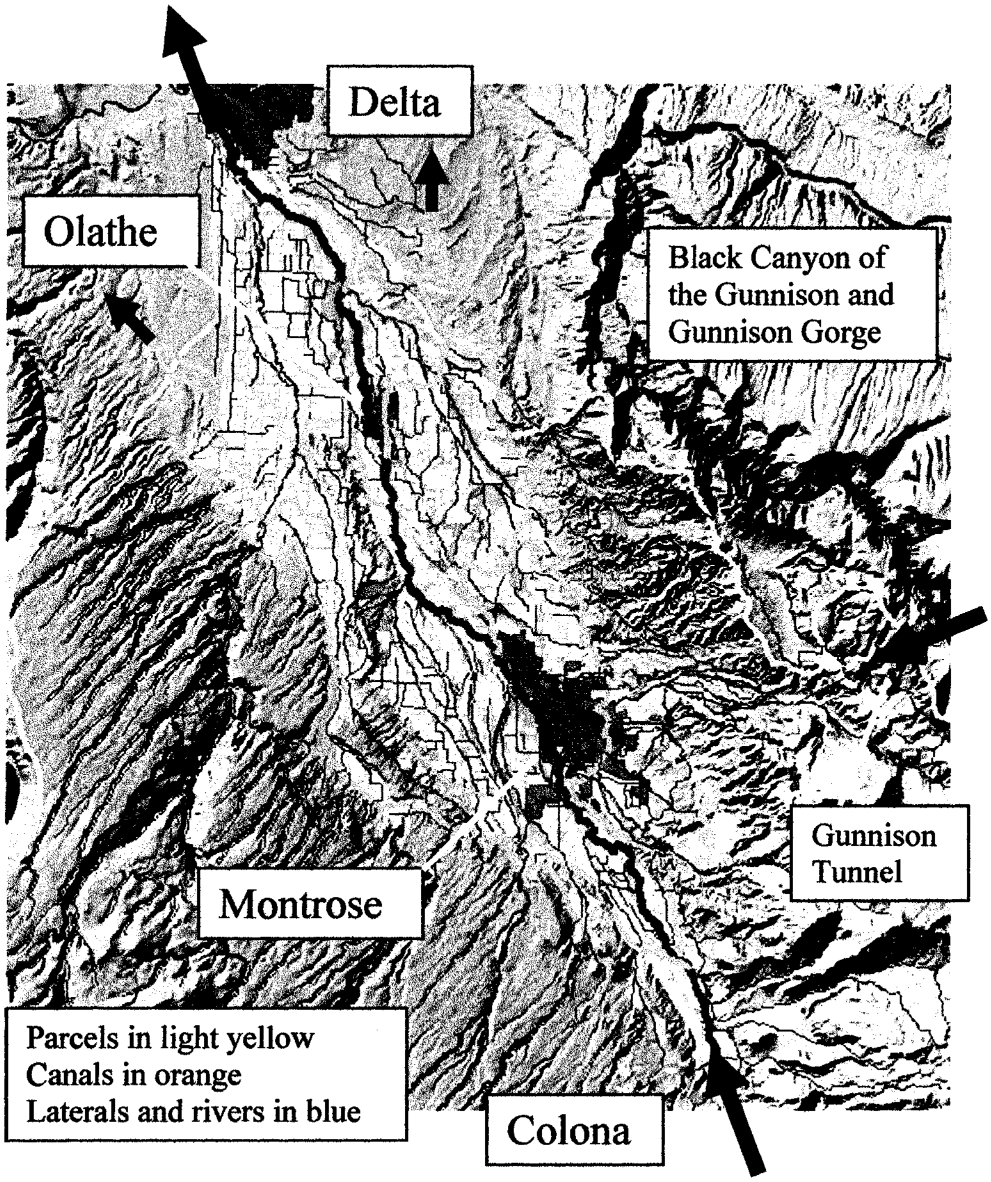


Figure 3.2. Uncompahgre Basin input and output fluxes

Using hydrologic data for 1950 – 1996 (CDSS, 2004a), and representative concentrations based on USGS sampling data, analysis of the boundary fluxes at Colona and the Gunnison Tunnel inflow yielded estimates of the annual input selenium load from "clean" sources of water to the basin, where [Se] < 1 μg/l is considered "clean," compared to the high levels seen in hotspot groundwater seeps. [Se] < μg/l is also near the minimum detection limit for most analytical lab techniques. Values from the large-scale analysis are presented in Table 3.1. Inflow and outflow values were computed from flow data and concentration sample values. A balance yielded a required input selenium load in the basin and an overall basin water loss. Analysis of total diversions of water from the Uncompahgre River to irrigated lands within the basin quantified the magnitude of irrigated agriculture in the basin. An annual balance yielded a calculation of total required returns (from a combination of groundwater and surface water sources) in order to make up balance of water leaving the basin annually. Combining the selenium uptake and required returns calculation, returning water would have a concentration of 8.4 μg/l as a whole to provide that loading.

Table 3.1 Large scale mass balance analysis values

Source Water	Annual Flow (AF/yr)	[Se] (mg/l)	Se load (lbs/day)
Colona inflow	180,000	0.5	1
Gunnison Tunnel inflow	300,000	0.5	2
Total diversions	550,000	Unknown	unknown
Required total returns	270,000*	8.4*	17*
Required basin loss	280,000	Unknown	unknown
Delta outflow	200,000	13.4	20

Values based on flow and sampling data except where indicated by *, these were calculated based on mass balance.

Estimates of total annual basin crop consumptive use (CU) were calculated from monthly output of the STATECU model (CDSS, 2004c). These values (also used by the STATEMOD model) are monthly consumptive use for the total aggregated acreage and crop type estimates on a per diversion basis. Cropping pattern data are based on a survey from the year 2000 and are considered by the State Engineer to be a good representation of crop distribution in the basin. Output from the STATECU model simulation of water years 1950 – 2000 utilizing the representative crop dataset and using meteorological time series data is used to develop an annual average monthly pattern of consumptive use used in this study. Annually, this crop consumptive use is estimated as 113,094 AF. Based on these data, a measure of basin-wide irrigation efficiency would therefore be estimated as 21% (using the ratio of total consumptive use to average total diversions of 550,000 AF). This CU value was used to estimate the total water that would flow out of the basin in canals to serve agricultural lands outside the Uncompahgre Basin boundary. A fraction of this water will return directly to the Gunnison. This total out-of-basin flow volume estimate is 165,445 AF or about 80% of the flow at Delta. Therefore the out-of-basin flow could be a large influence on the Gunnison River in addition to the direct influence by the Uncompahgre River inflow. This total influence is also not the complete picture of potential selenium loads to the Gunnison river, other tributaries and seeps may add to the problem (e.g., the Devil's Thumb Golf Course north of Delta, CO, [Se] > 10,000 μg/l observed). However it was decided that the scope of this study would only include the Uncompahgre Basin's impact.

These mass balance computations describe overall net values based on estimates of annual average conditions and water of homogeneous quality, which is unlikely to occur based on the variability seen in monthly sampling data. However, this information is useful to gain insight to the complexities of the water and selenium mass movement that probably occur inside the basin. Note that the values presented here were used for analysis and model design. Better estimates of these values based on the final model design are presented in Chapter 5, Historical Hydrologic Output. Finer detail data inside the basin were available in the form of grab sampling data of flow and selenium concentration at several tributaries, often monthly for several years.

3.4.2 Finer Scale Analysis

Based on analysis of water quality grab sample data (obtained from USGS Water Resource Division, Grand Junction CO) and previous synoptic sampling (USGS, 1991), several tributary inflows to the Uncompahgre showed a wide range of concentrations of dissolved selenium, indicating spatial variability. 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 (Figure 3.3). This pattern had been studied previously by Butler et al. (1996). Analysis in Butler (2001) to quantify surface and sub-surface contributions of selenium load from sampling data assumed that groundwater quality conditions equaled winter water quality conditions returning to the river via tributaries. A process was assumed in which canal and lateral seepage and deep percolation during irrigation season increased total soil storage and elevated unsaturated aquifer groundwater tables below parcels. Following the irrigation season, groundwater with elevated selenium concentrations would be released from saturated and unsaturated soil storage to return to the river. This return would be slow and occur throughout the entire winter. During the summer irrigation season, unused irrigation water with low selenium concentrations would return via the surface drain network proving a source of dilution water. The process would repeat itself each year, and the magnitude of the flow and concentration patterns would return to nearly the same extremes. In the Uncompahgre Basin with the Gunnison Tunnel trans-basin diversions, water scarcity is not a large problem in most years. Irrigation water volumes are driven mostly by water rights and provide nearly the same volume of flow each year. These observations and assumptions were used to build a conceptual model of this flow and water quality system, where seasonally-changing volumes and concentration signatures of surface and sub-surface waters combine throughout the year to produce the patterns seen in the data.

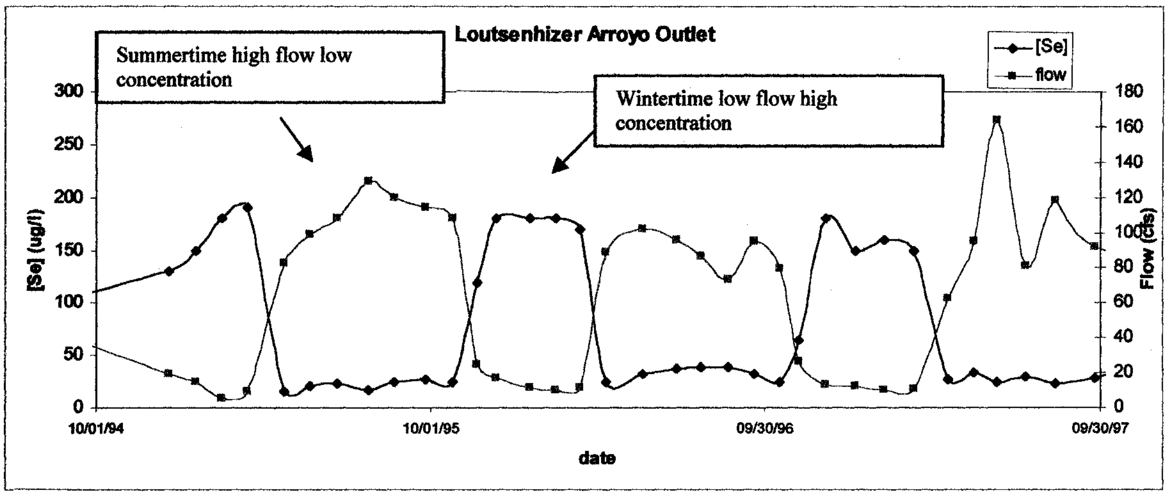


Figure 3.3. Time series of [Se] and discharge for Loutsenhizer Arroyo outlet

3.5 Conceptual Model

The finer-scale analysis is extended through the creation of a model that captures both temporal variability by using a monthly timestep and spatial variability by disaggregating the basin into smaller, homogeneous areas. A modeling method, as opposed to a non-modeling analysis-only method, is justified based on the linkage between the river and agricultural lands, spatial differences throughout the basin and the time-varying nature of the process suggested by the data.

3.5.1 Sub-Basin Water Balance Model

An analysis of hydrography throughout the Uncompahgre Basin (CDSS, 2004d) showed the presence of several major tributaries. Return flows to the Uncompahgre River are assumed to follow a drain network, eventually flowing to these natural tributaries before entering the mainstem. A parallel GIS-based analysis was underway by Ken Leib, USGS WRD that involved agricultural sub-basin delineation and spatial analysis of land characteristics and land use. Digital elevation model data and agricultural sub-basin boundaries were provided from his study for this work. A subset of these sub-basins was used as the basis for the finer scale analysis. For the agricultural portion of the Uncompahgre Basin modeled here, i.e. the 34 mile section of river between Colona and Delta, the five major sub-basins account for 293,382 acres or 41% of the total Uncompahgre Basin area of 716,387 acres.

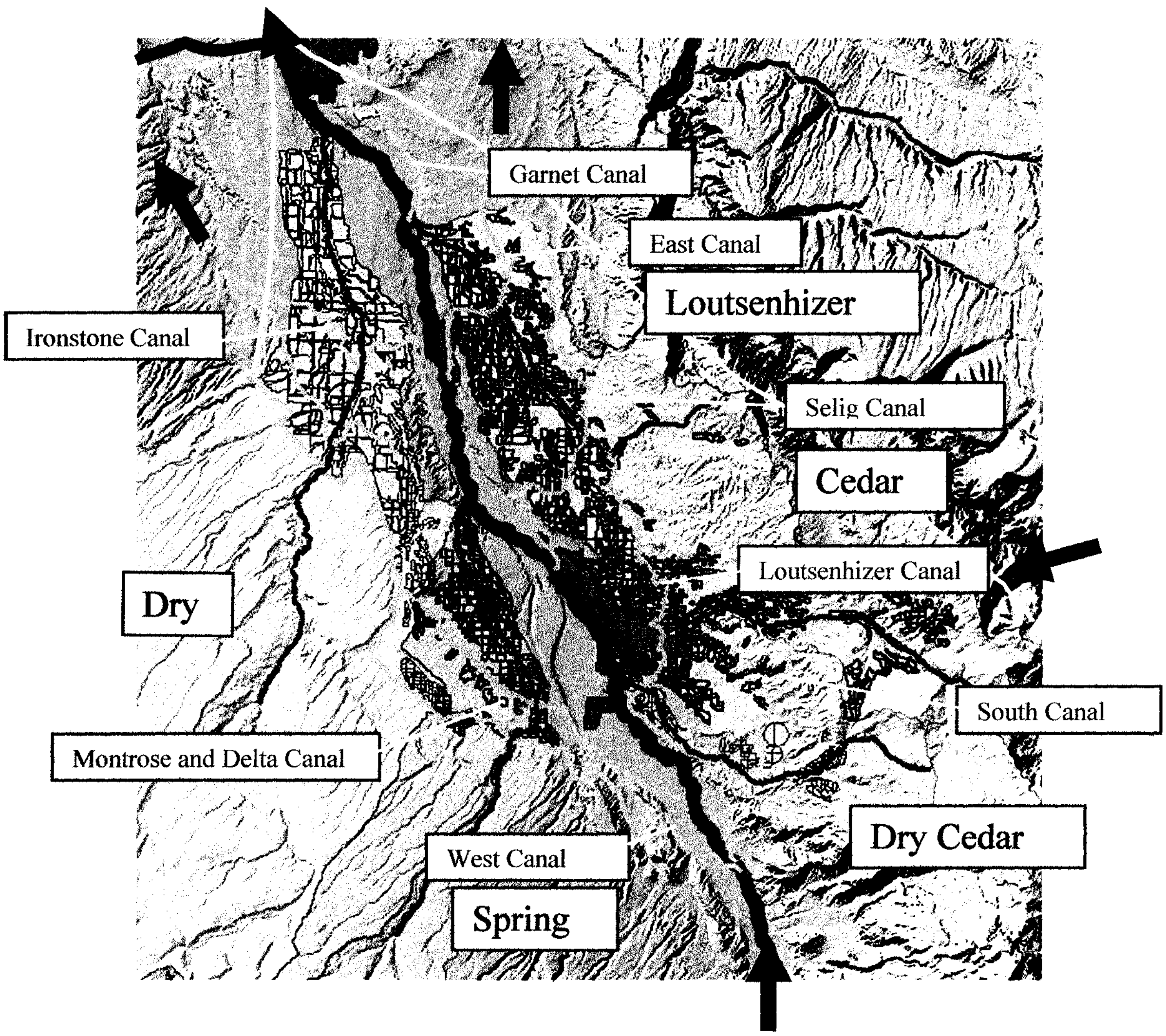


Figure 3.4. Uncompahgre Basin input and output fluxes, sub-basins and tributaries (black text), and canals (orange text) included in the model

A water balance is performed for each sub-basin based on the following assumption. All water that is applied to land inside sub-basin boundaries (less losses to crops, surface evaporation and evaporative upflux from high water tables) enters the sub-basin tributary and eventually leaves at the sub-basin outlet (the tributary confluence with the mainstem Uncompahgre). Data or estimates of sub-basin totals of: precipitation, evaporation, field application, pond, canal and lateral seepage, crop consumptive and deep percolation can be used to describe 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. Deep percolation here does not describe a loss term in this alluvial system. Also in this conceptual model, unsaturated zone thickness and water table depths are not specifically quantified. Therefore no prediction of long-term changes in basin-wide groundwater storage can be made from historical model simulations.

Return flows are divided into quick-returning surface and slower-returning sub-surface components. Based in Unit Hydrograph theory (e.g., Chow, Maidment and Mays, 1988), used previously for groundwater return flows (e.g., Illangasekare and Morel-Seytoux, 1986) and following the lead of the STATEMOD model, the discrete convolution method is used to lag these returns over time. This convolution method or kernel function is described by Equation 3.1, where Q_n is the surface or sub-surface return flow at month n, P_m is the flow input to surface or sub-surface "storage," at a previous month m and U_{n-m+1} is the convolution (lag) coefficient the defines the fraction to store at that step. The sum of all convolution coefficients equals one to ensure water mass balance and the total water volume input eventually will be output later in time.

$$Q_n = \sum_{m=1}^{n} P_m U_{n-m+1} \qquad \text{Equation 3.1}$$

Unfortunately the magnitudes of all components of the agricultural water balance are not known. The total return flows are well-characterized by sampling data. Seepage rates for canals and pond as well as total areas of ponds have been estimated (USBR and NRCS, 2004). Using these data, total lengths of canals and laterals from GIS analysis and using estimated wetted perimeter values, total pond, lateral and canal seepage volumes can be estimated. Precipitation, evaporation and CU data estimates are available. Data describing the irrigation water application to fields in sub-basins is not available. The water right data tied to parcels is not in a usable form for modeling. However, individual parcel sizes and the link between each parcel and the diversion serving it are available in the GIS data (CDSS, 2004d). Diversion water volumes were initially partitioned into sub-basins by assuming all parcels are served with equal water. Given the known difference in water right share volumes between parcels based on soil type and full vs. 0.6 share parcels (described in section 2.2), this partitioning is only a large-scale estimate. Given these constraints, partitioning parameters were included to further spatially divide diversion volumes into sub-basins (in addition to the equal application depth per acre assumption) to characterize the application depth on parcels in sub-basins. This assumes that all parcels within sub-basins are served equally, but variations may occur from sub-basin to sub-basin.

To finalize the water balance, another partition to separate return flows into surface and sub-surface components is available with the partition ratio as parameters. This allows for the division of field returns (gross application minus crop consumptive use) into surface drain returns and deep percolation returns. After fitting the model to data using these partitioning and convolution parameters (described in Chapter 4), a description of agricultural practices at the sub-basin level will be available. A schematic of this conceptual water balance model is shown in Figure 3.5.

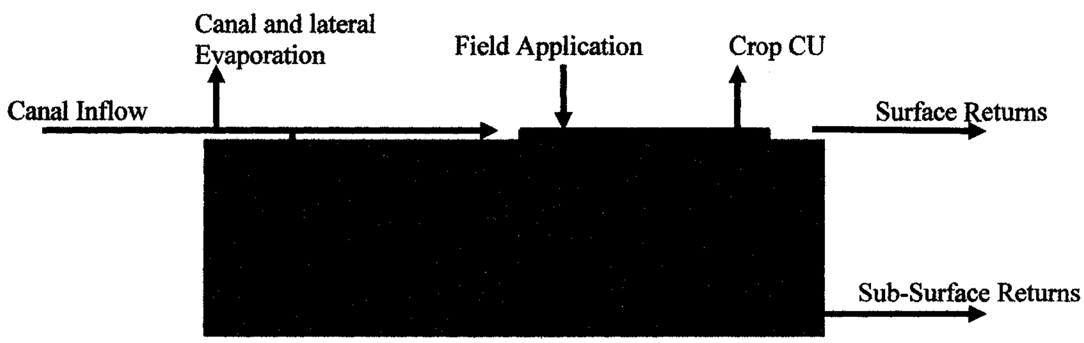


Figure 3.5. Schematic of sub-basin water balance components

The data required by each of the five sub-basin water balance models are: total irrigated parcels, canal and lateral lengths and widths, pond acreage, seepage rates, consumptive use and evaporation rates. Model parameters are the sub-basin diversion partition, surface to sub-surface partitioning coefficient and convolution parameters for the surface (two) and sub-surface lags (six).

3.5.2 Sub-Basin Constituent Transfer Models

A similar balance of constituent mass can also be performed for agricultural return water quality. Return water in groundwater seeps has been shown to be higher concentration of dissolved selenium and total dissolved solids. Sampling data for a tributary portray the uptake signature over a certain region. As shown in Figure 3.6, high concentrations correspond to low flow volumes and high flow volumes result in lower concentrations. This indicates mixing and dilution processes may be occurring and driving water quality at the downstream drain point. 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 average 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 3.6 the mixing of only two water sources is required. For a given volume of flow, a small portion of that volume is one water source at a constant low flow and constant high concentration and the balance of the flow volume at constant lower concentration. The volume and concentration of the low flow source as well as the concentration of the dilution water source drives the shape of the curve.

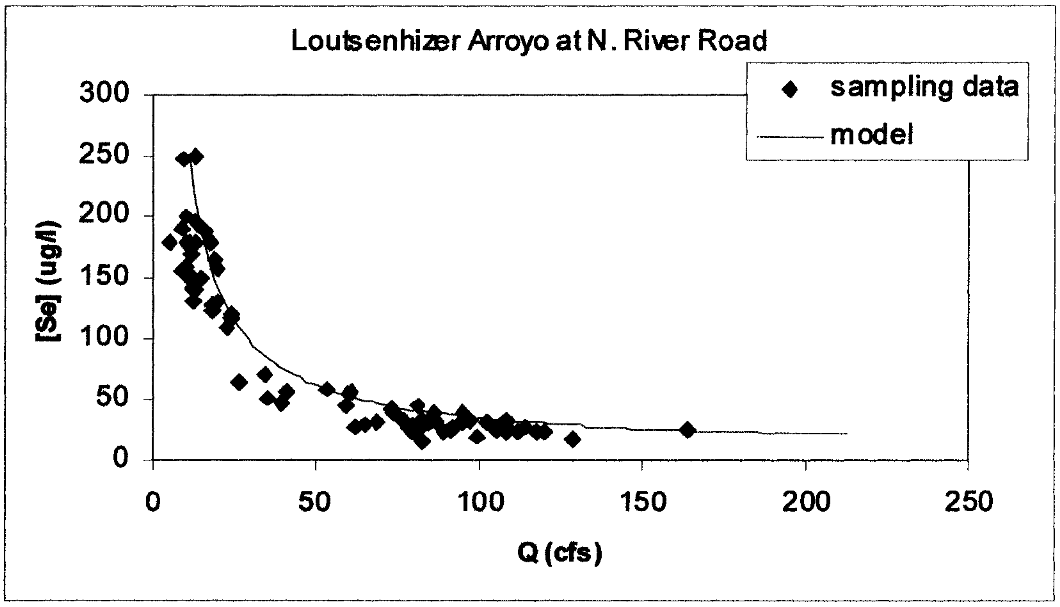


Figure 3.6. Example of the relationship between selenium concentration and flow observed at sub-basin outlets

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. As water moves through the complex pathways of surface drains; little constituent uptake occurs as a result of water interaction with soil in canals. Return water that enters the groundwater system, either by seepage from earthen canals and laterals or through deep percolation can be assumed to enter the sub-basin tributary as point or non-point sources and emerge eventually at the sub-basin outlet with a representative high concentration, as a result of dissolution processes that occur as selenium on the surface of soil grains dissolves into groundwater. These two waters are assumed to mix at or above the sub-basin outlet to produce the flow and concentration pattern seen in the sampling data. The surface and sub-surface water volumes available from the sub-basin water balance model are assigned concentrations based on parameters for groundwater concentration (based on sampling data) and for any change in canal water concentration at the diversion point (based on data). It is assumed that the water quality signature of a sub-basin is persistent from year to year, as has been seen in the sampling data (Figure 3.3, above). This persistence is a general assumption for modeling. In reality, a long history of irrigation shows reduced selenium concentrations in downstream drainwater, indicating that selenium in soil grains available for dissolution within groundwater does change over long time periods. Following this persistence assumption, the geochemistry, availability of soluble salts and selenium in soil, influence of fertilizers and other constituents in irrigation waters are assumed constant and do not influence this persistent signature based solely on flow volumes. Surface and sub-surface water volumes used by each sub-basin's constituent transfer mixing model can and will change from year to year based on changes in diversions due to hydrologic variability. 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 3.7 below.

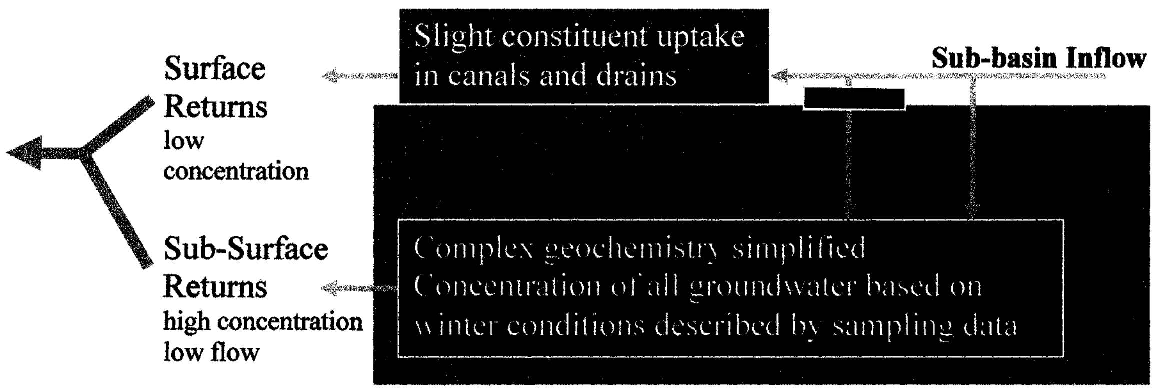


Figure 3.7. Schematic of the sub-basin constituent loading model

The parameters of this model are the representative groundwater concentrations for Se and TDS. These are well-estimated from the sampling data observed during winter conditions. An additional model parameter for in-canal concentration uptake is included also, based on longitudinal canal sampling study by the USGS/CSU (described in detail in section 4.1.3).

3.5.3 Longitudinal 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. A basic water quality model method is utilized to calculate constituent concentrations of total dissolved solids and dissolved selenium throughout the Uncompahgre mainstem and in the Gunnison River. An instantaneous advective mixing model of source waters is used, described by a feed-forward set of continuously-stirred tank reactors (from Chapra, 1997). This model is described in Figure 3.8 below, where Q1 and Q2 are inflow sources with constituent concentrations C1 and C2, respectively. The river upstream quality is defined by the flow and concentration of Q1, C1. After the inflow of flow Q2, C2, the river flow becomes Q3, where Q3 = Q1 + Q2 and concentration, based on conservative mixing, becomes C3, where C3 = (Q1*C1+Q2*C2)/(Q1+Q2), a weighted average. As water moves downstream, only other inflow sources change the quality. Withdrawals for irrigation will reduce downstream flow volume, (i.e., Q4 = Q3-Q5). Irrigation water will be the quality of the river where with water was withdrawn (e.g., Q5, with concentration C3).

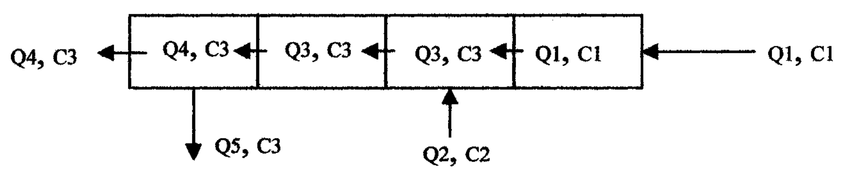


Figure 3.8. Schematic of computational elements in the advective instantaneous mixing water quality model

This modeling method is sufficient for the task at hand and the level of detail of the data. The model timesteps are large; simulating changes either annually or monthly. Inflow sources (either high concentration or low concentration dilution water) are the drivers of water quality changes throughout the Uncompahgre mainstem. Chemical reactions, adsorption/desorption and decay are not considered, the constituents dissolved Se and total dissolved solids are assumed conservative in the river. Diffusive mixing is not considered.

This modeling method allows for the prediction of water quality longitudinally along the river and allows for the prediction of the water quality of diverted irrigation water, at points along the river. Concentrations of selenium and TDS and their corresponding loads are calculated for each in-river computational unit as well as all inflow and outflow points.

3.5.4 Summary of Conceptual Model Design

The total model structure emerges from the combination of three sub-models for agricultural water mass balance, constituent uptake and return in sub-basins and conservative constituent mixing in-river. This complete model is described in Figure 3.9 below.

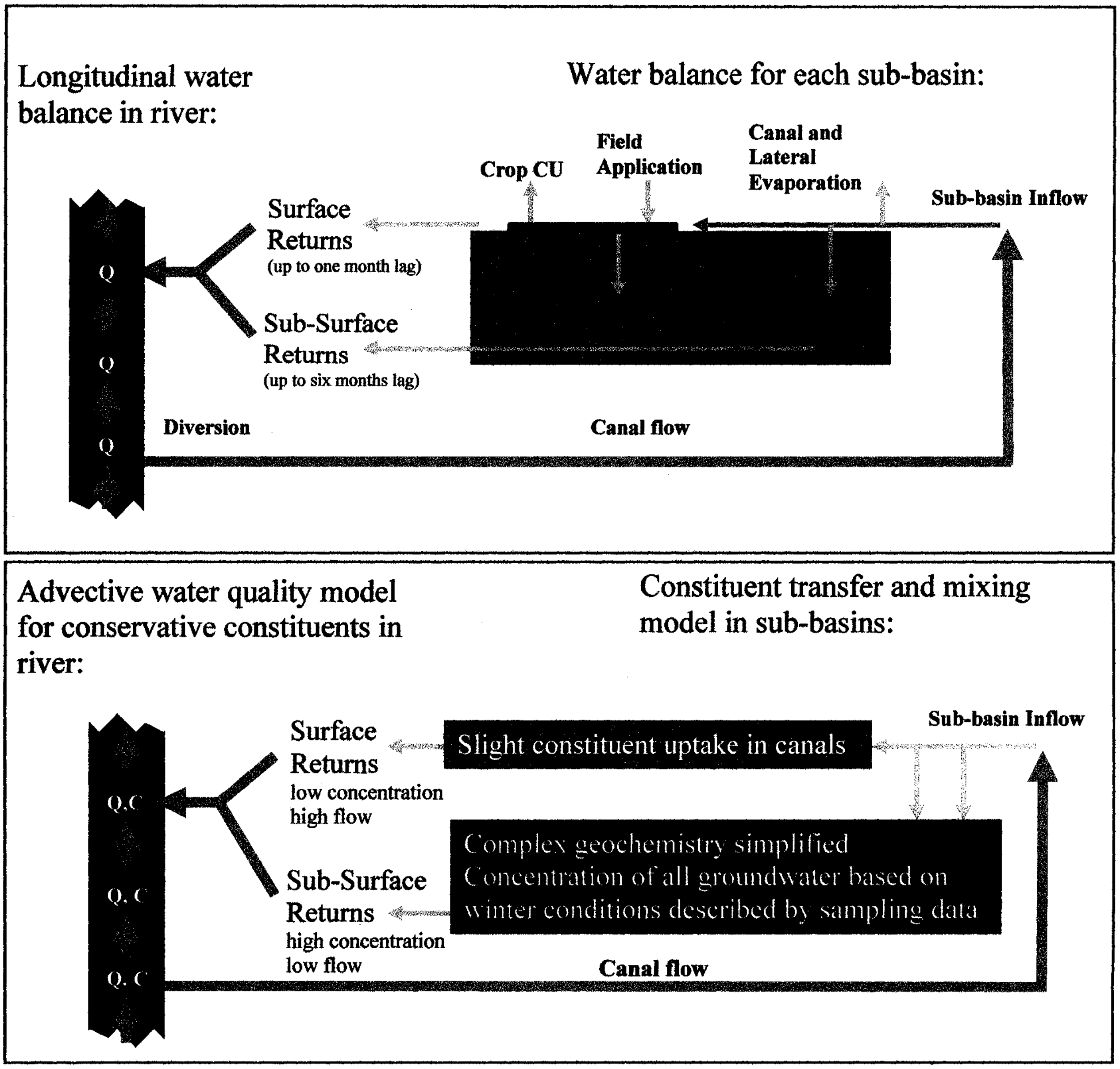


Figure 3.9. Schematic of the water balance model (top) and constituent loading model (bottom) and the connection to the longitudinal water quality model for the river

This conceptual model describes water movement from the river, through one sub-basin to return to the river. For the Uncompahgre Basin, five sub-basins are used for the major tributaries. Two additional models are also added to describe agriculture and water use in the out-of-basin above and out-of-basin below areas that return to the Gunnison River.

The conceptual model has been implemented in Microsoft Excel utilizing spreadsheet functions and Visual Basic for Applications programmed macros. The model spreadsheet has been designed to be a complete package and contains all model input data, source code, calibrated model output and the ability for users to adjust model parameters to simulate additional BMP's and compare output with the calibrated baseline simulation. The Uncompahgre Basin flow model spreadsheet page is shown in Figure 3.10.

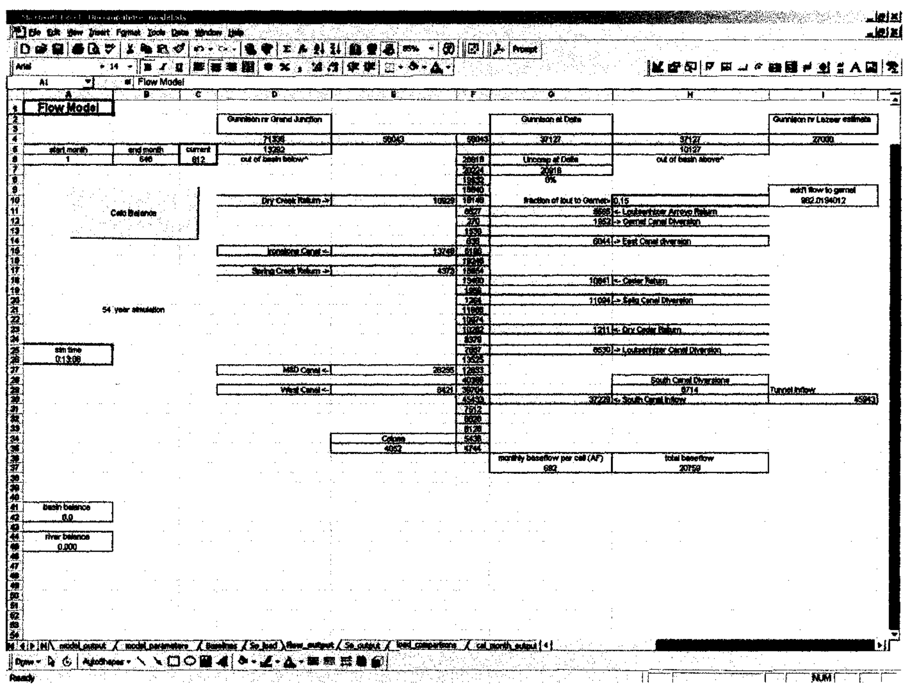


Figure 3.10. The flow model implementation in Microsoft Excel

3.6 Model Parameters

The conceptual model assumes that the movement of water through each of the sub-basins with their individual characteristics is the driver of water quality in the Uncompahgre River. Therefore, for each sub-basin, a set of model parameters is used to control the movement of water and to characterize the uptake of constituents. Many of these parameters are based on data but have been externalized as model parameters for sensitivity analysis and for use in the BMP simulations. The set of parameters for each sub-basin include:

Application water: partition of water from each canals as application water to the sub-basin (based originally on spatial data).

Pond, canal and lateral seepage: total canal and lateral lengths, widths and seepage rates, pond acreage, days in use annually and seepage rate (based on measured data).

Surface vs. subsurface drainage: partition of field return water to surface drains versus deep percolation. Pond and canal seepage is additional sub-surface water.

Constituent uptake: Sub-basin representative groundwater quality concentrations of selenium and TDS (based on sampling data). Additional adjustment concentration for canal waters (based on sampling data).

Water return timing: Convolution parameters for surface and sub-surface return lags, up to two for surface, up to six for sub-surface.

Additional BMP data values and switches: total parcel acreage, fraction of historical diversion volumes to divert, fraction of Loutsenhizer Arroyo returns to divert to the Garnet Canal at the mouth (described in detail in Chapter 4), selenium concentrations of return water following a treatment technology (override of sub-basin constituent uptake models), target sub-basin irrigation efficiencies (override of water balance of historic data). Input data for total crop consumptive use, precipitation and evaporation are also externalized and can be adjusted for specific BMP simulations.

3.7 Initial and Boundary Conditions

Given the nature of the system and corresponding model design, inflow and outflow loads to the Uncompahgre River primarily drive water quality. Therefore initial conditions are not specifically required by the model; instead the boundary conditions for each monthly timestep are required. The boundary conditions are the flow and water quality for all input water sources. The input sources include the Gunnison Tunnel, Uncompahgre at Colona and the Gunnison River upstream of the Uncompahgre influence area (Gunnison near Lazear Colorado, USGS gage). While not specifically located at the model boundary, the outflow volumes for all diversions act like boundary condition drivers. These outflow volumes include monthly diversions from the South Canal and diversions from the Uncompahgre River to the: Loutsenhizer Canal, Selig Canal, East Canal, Garnet Canal, West Canal, Montrose and Delta Canal and the Ironstone Canal.

The convolution models for surface and sub-surface return flow lags involve a slow release of water from storage during each month for surface and for up to six months for sub-surface flows. Therefore the model is required to start at the beginning of a water year (October) and run for one full year as a "spin-up" period in order to correctly quantify the water stored during the irrigation season and the release from storage during the non-irrigation season.

The methods used to apply this model to predict a set of historical conditions is described in the following chapter.

Chapter 4

BASIN-SCALE MODEL DEVELOPMENT, CALIBRATION AND VALIDATION

This chapter discusses the details of creation of the model application for the Uncompahgre Basin influence area from the conceptual model design outlined in the previous chapter. The process utilizes many data sources and methods for calibration. A brief sensitivity analysis and a separate validation exercise are performed. Development of useful model output for hydrologic analysis and standards compliance evaluation are also presented.

4.1 Data Requirements

The data requirements for model application fall into categories of: spatial land-use data, hydrologic data and water quality data. Data are required as input to the model as well as for comparison with model prediction output.

4.1.1 Spatial Data

Geographic Information System (GIS) data were used with the ArcMap software (ESRI, 2004) to provided information about locations, sizes and attributes of spatial data throughout the study area. Data from the Colorado Department of Transportation (CDOT, 2004) provided information on roads, rivers and cities. The State of Colorado Decision Support Systems geographic data products (CDSS, 2004d) provided data on hydrologic structures and stations, detailed hydrography, hydrologic unit boundaries, land use and irrigated parcels. Data obtained from the USGS (Leib, 2001 - 2004) provided location and attribute data for water quality sampling points, geologic contact boundaries for Mancos Shale, elevation data and agricultural sub-basin boundary delineations. Data from Mike Baker (2002) described in detail the canal and lateral system in place in the Uncompahgre Basin, although only the major canals and the most significant laterals appear to be included. Details of structures comprising the drain network were not available. GIS analysis of these data included locating valuable sampling points, locating tributary returns in relation to canal diversions, aggregating irrigated parcel data by diversion and within sub-basin boundaries, summing irrigated parcel acreage and total lengths of canals and laterals in sub-basins, as well as producing figures for presentations and reports.

4.1.2 Hydrologic Data

Colorado decision support systems Hydrobase data (CDSS, 2004b) is used for all monthly flow data describing historical river, historical diversions and historical gauged flows at the Uncompahgre at Delta and in the Gunnison River up and downstream from the confluence with the Uncompahgre.

Consumptive use data from the StateCU model (CDSS, 2004c) applied to the basin was used as the estimate of 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 with the Blaney-Criddle consumptive use procedure to estimate water requirements by crops served by diversions in the basin. The resulting data used in this modeling study are one set of monthly patterns of crop consumptive use (described as depth per unit area) in each sub-basin.

Historic meteorological data were used to describe historical precipitation and potential evaporation in the basin (from evaporation pans) (CDSS, 2004b). These data were used to develop one representative set of monthly precipitation and evaporation as depth of water per unit area. See section 3.4.1 for a more detailed discussion of these data.

Total canal and lateral seepage volume estimates for sub-basins were developed using USBR-measured seepage expressions 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. Pond attributes and seepage rate estimates were also obtain from a draft report describing the study of ponds in the Uncompahgre Basin (USBR and NRCS, 2004).

Data from the Uncompahgre Water Users' Association describing the distribution of water from canals into laterals and to individual farms were not available in a usable form, as described below. These data are collected each year by the ditchriders who are in charge of water deliveries to customers served by the individual ditches. Flow observations at staff gages are taken daily at several points along canals as ditchriders adjust gates to deliver water to laterals and sub-laterals for irrigation rotations throughout the growing season. At the end of the water year, the ditchrider paper logs are collected and stored and a large paper report is generated by the Water Users' staff that describes an accounting of water in each major canal as it is distributed into laterals and sub-laterals (and often many more sub-levels). This accounting appears quite complete and painstaking as a monetary accounting software is used and water is accounted for to the hundredth of acre feet. However, the goal of this procedure each year is for billing and deliveries are accounted for to a customer, not a specific parcel or set of parcels that could be found in the GIS data (although these can be found on paper map plates stored at the Water Users Office). The layout of the accounting worksheet does not allow for aggregation of volumes in order to perform a water balance for a description of water distribution. Lastly, these data are in paper form only with each year being described in hundreds of pages. It was decided that these data were not in a form that could be used for the study and another technique was used to estimate water deliveries to sub-basins.

A spatial analysis technique was used to estimate the distribution of canal water into sub-basins. An initial estimate of total volumes of diversion water serving sub-basins was made by assuming that all parcels are served equally (i.e., the depth per unit area was uniform throughout the basin). GIS data linking individual parcels of known size with diversions was used with basin and sub-basin boundary polygons in a spatial analysis to find fractions of individual diversions that serve parcels in areas. This analysis made the assumption that all parcels were equally served, which is unlikely given the wide variety of crops grown throughout the basin, but a reasonable initial estimate. These distributions are presented in Table 4.1.

Table 4.1. Distribution of canal water into sub-basins based on GIS data

Sub-basin	South Canal	Loutsenhizer Canal	Selig Canal	East Canal	West Canal	Montrose and Delta Canal	Ironstone Canal
Dry Cedar	22%	2%	0%	0%	0%	0%	0%
Cedar	71%	35%	0%	0%	0%	0%	0%
Loutsenhizer	6%	59%	64%	33%	0%	0%	0%
Spring	0%	0%	0%	0%	40%	23%	0%
Dry	0%	0%	0%	0%	18%	45%	38%
Out of Basin Above	1%	4%	36%	67%	0%	0%	0%
Out of Basin Below	0%	0%	0%	0%	43%	32%	62%

The calibration method used is actually a check and adjustment of this distribution set of estimated data.

4.1.3 Water Quality Data

An extensive database of sampling data was obtained from the USGS (Leib 2001 - 2004). These data provided point measurement of flow and a large set of water quality constituents including specific conductance (conductivity), TDS and dissolved selenium. These data were collected throughout the Gunnison Basin for specialized investigations of surface water and some sub-surface conditions and for continued monitoring at several locations. The flow and concentration pairs at tributary outlet points proved to be very valuable data. The scope of this study could not have been performed without this vital and important dataset.

A set of concentration data at multiple points along the Uncompahgre River was also collected specifically for this study. Monthly grab samples were taken at nine locations on the Uncompahgre River between Colona and Delta by Montrose High School staff and students for a full year from March, 2003 through February 2004. Concentrations of conductivity and dissolved selenium were analyzed. Flow measurement was not performed as part of this study. Composite samples at each site were created from three grab samples taken across the width of the river via a bucket from bridges. Conductivity was measured in the field using a Hanna 8733 multi-range conductivity meter recalibrated each month. Dissolved Se analysis is performed by Severn Trent Labs in Arvada, CO. Grab samples were placed on ice and shipped directly to the lab where they were filtered with a 0.45 micron filter and the ICPMS method was performed to compute dissolved selenium concentration. Although the usual reporting limit of this method is 5.0 μg/l, the lab was instructed to provide data values down to the minimum detection limit of the method 0.24 μg/l. Each month, one blind duplicate was analyzed for a quality check. These data are described in Figure 4.1 below.

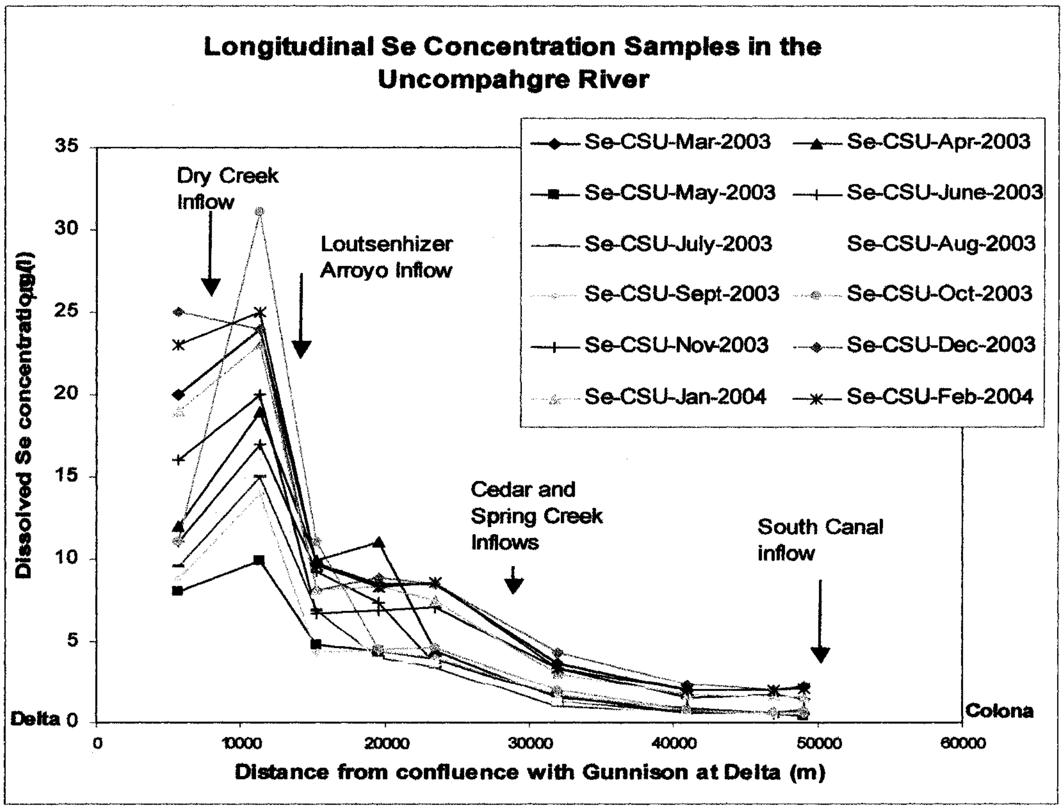


Figure 4.1. Water quality sampling data collected by Montrose High School staff throughout the Uncompahgre River, monthly from March 2003 to February 2004

An additional set of flow and water quality sampling in the Uncompahgre River and in the canal system was collected in a cooperative agreement between this study and the USGS, WRD in Grand Junction. Two synoptic sampling runs were performed in April and July of 2003 with the goal to characterize constituent uptake as water moves along earthen canals as well as to provide estimates of mass flux at basin and sub-basin boundary points. Some of these data are described in Figure 4.2 and Figure 4.3 below. Good agreement exists between the two data sources sampling in-river [Se]. The USGS sampling was performed at the confluence of the Loutsenhizer Arroyo and the Uncompahgre River, (the Montrose High School data were sampled further upstream and downstream) and shows very high localized concentrations in the Uncompahgre at the mixing point and slightly downstream (Figure 4.2).

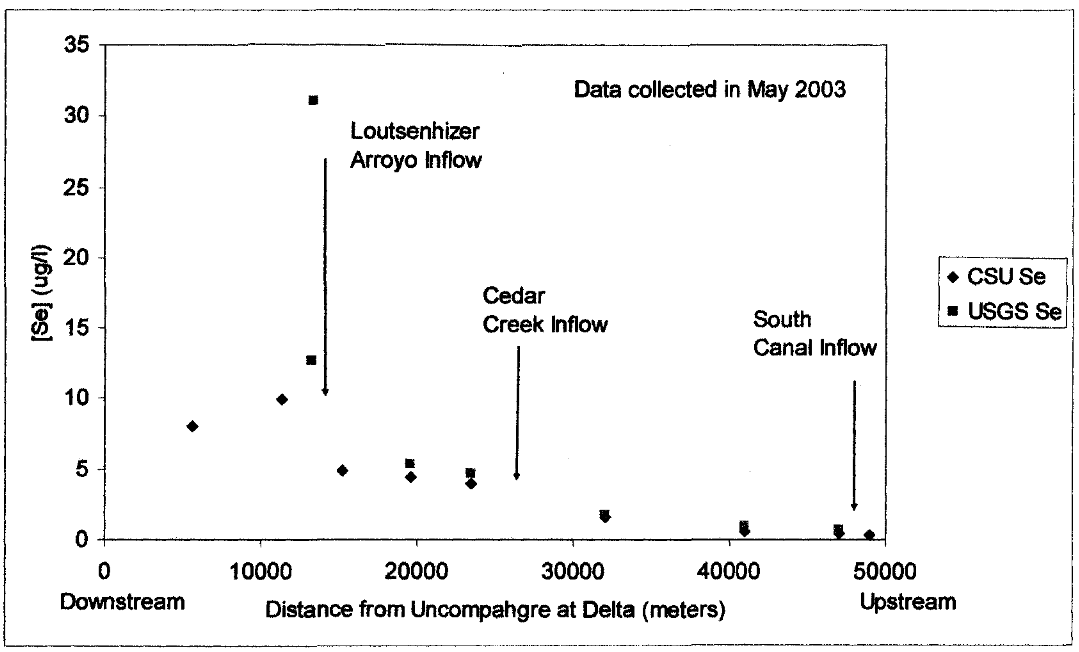
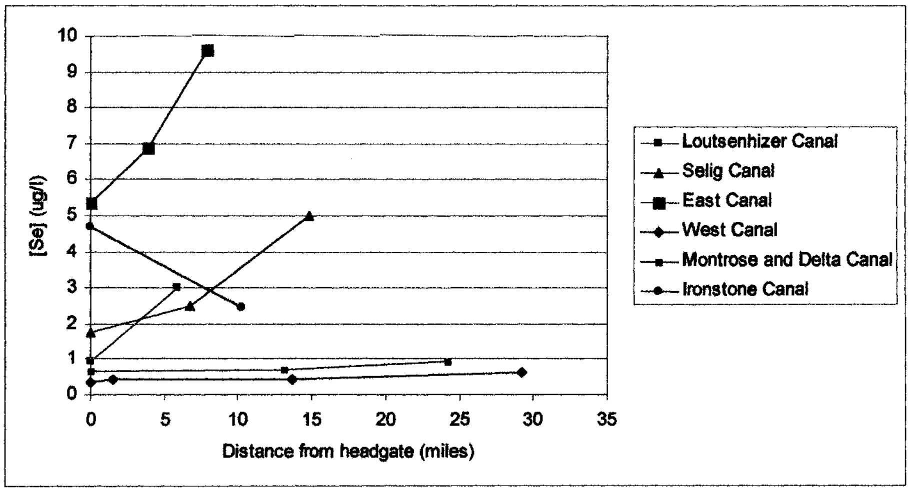


Figure 4.2. Comparison of in-river data collected by Montrose High School and the USGS

Sampling at various points along canals was performed by the USGS twice during 2003 (Figure 4.3). With the exception of the Ironstone Canal, these data show increases in concentration as water moves downstream through the earthen canal system. Calculation of selenium load shows that for the East and Loutsenhizer canals, increases in concentration and mass load are occurring in water as it moves down these earthen canals. An increase in concentration could be a result of evaporative concentration effect as water evaporates from canals leaving constituent mass, however the increase in load shows that additional constituent uptake is occurring as water moves through the distribution system.



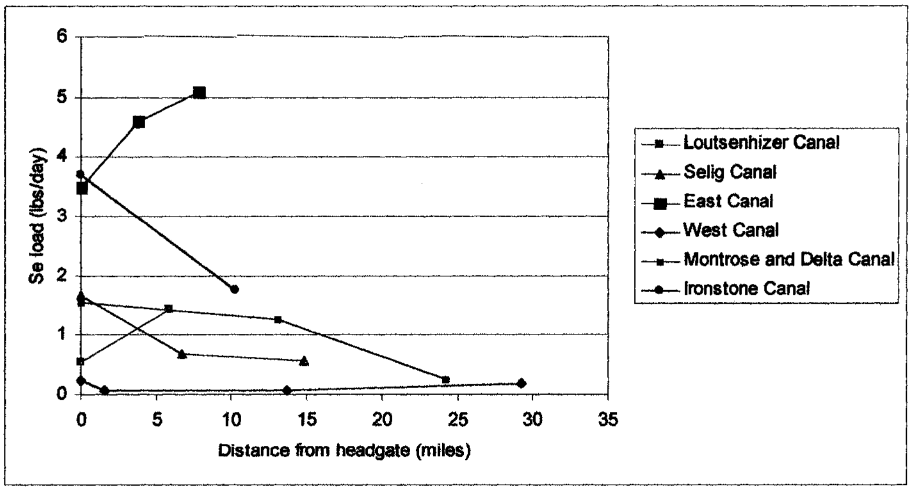


Figure 4.3. In-Canal sampling data showing changes in selenium concentrations and loads measured in May 2003 by the USGS

4.2 Water Quality Relationships

Analysis of water quality sampling data in the Uncompahgre Basin (Uncompahgre River at Colona and Delta, South Canal inflow, Dry Cedar Ck., Cedar Ck., Loutsenhizer Arroyo, Spring Ck. and Dry Creek) from the USGS show a good relationship between sampled conductivity and sampled TDS. This linear relationship, presented in Figure 4.4 is found to be the following:

[TDS] (mg/l) = 0.9098*(Conductivity in μS/cm) - 206.54, with an $R^2 = 0.98$.

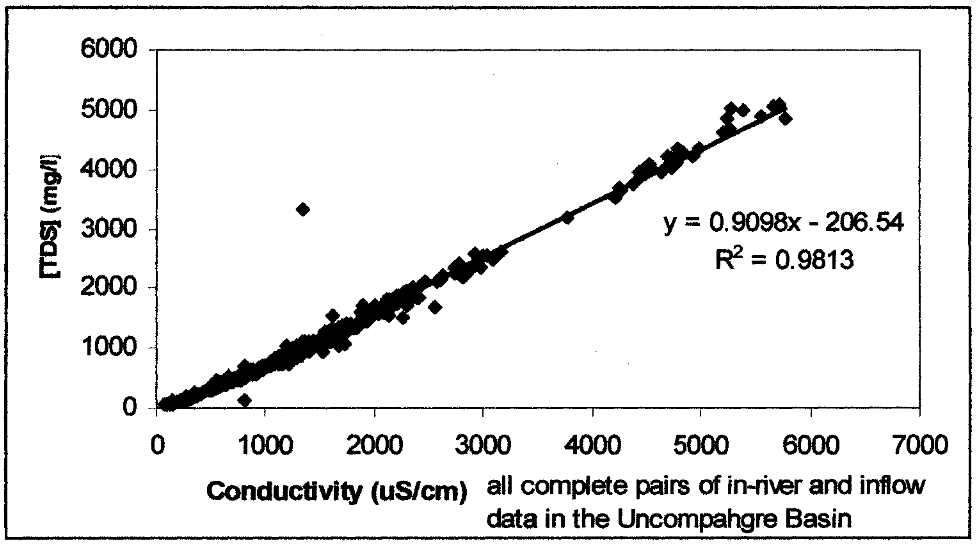


Figure 4.4. Relationship between conductivity and TDS based on USGS sampling data in the Uncompahgre Basin

Further investigation into water quality relationships shows a linear relationship between [Se] and [TDS] (Figure 4.5); although at high concentrations the linear relationship breaks down. The $\log_{10}$ of the [TDS] and [Se] data were plotted and a linear regression used to find a best fit line. The fit of this log-linear relationship is slightly better than the linear fit and results in a power relationship as follows:

[Se] (μg/l) = $(10^{-4.2037})$ * (Conductivity in μS/cm)$^{1.7431}$ with an R^2 of 0.79.

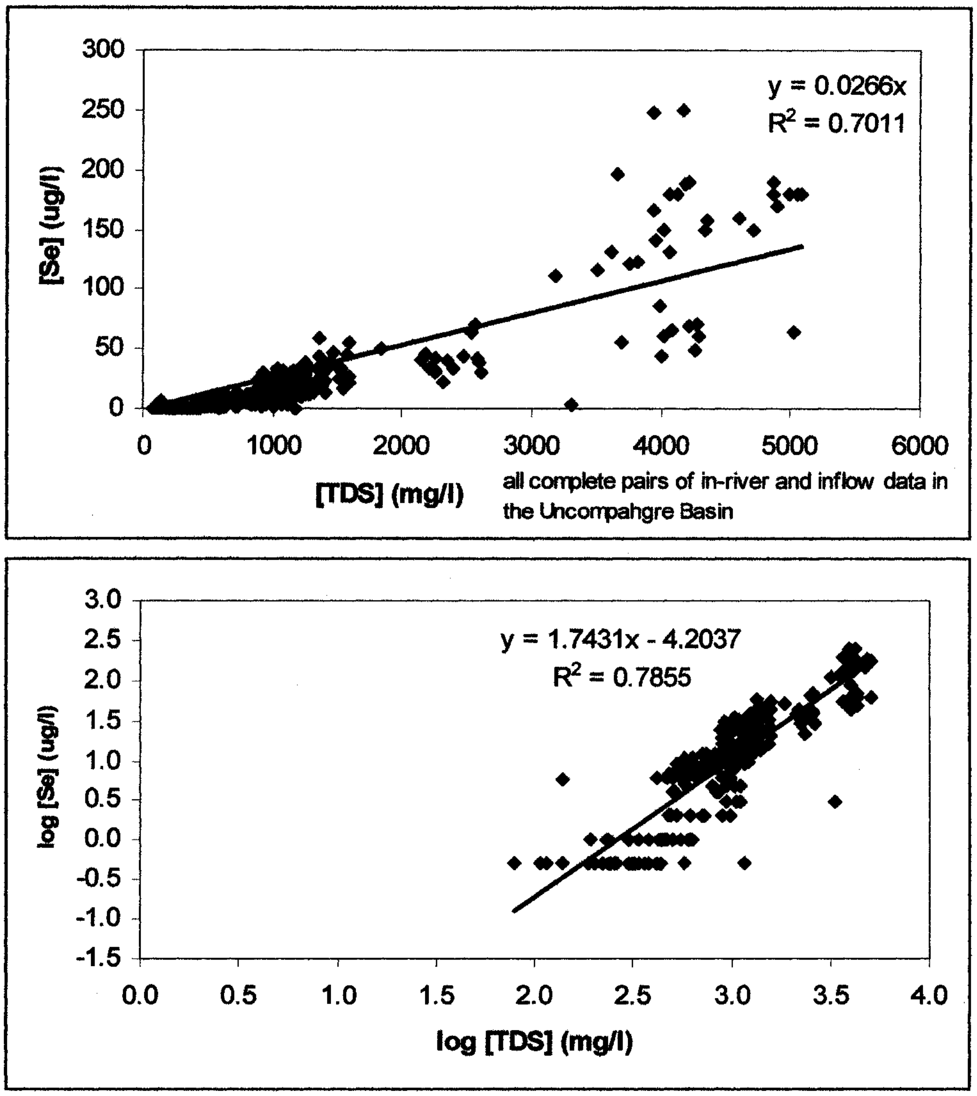
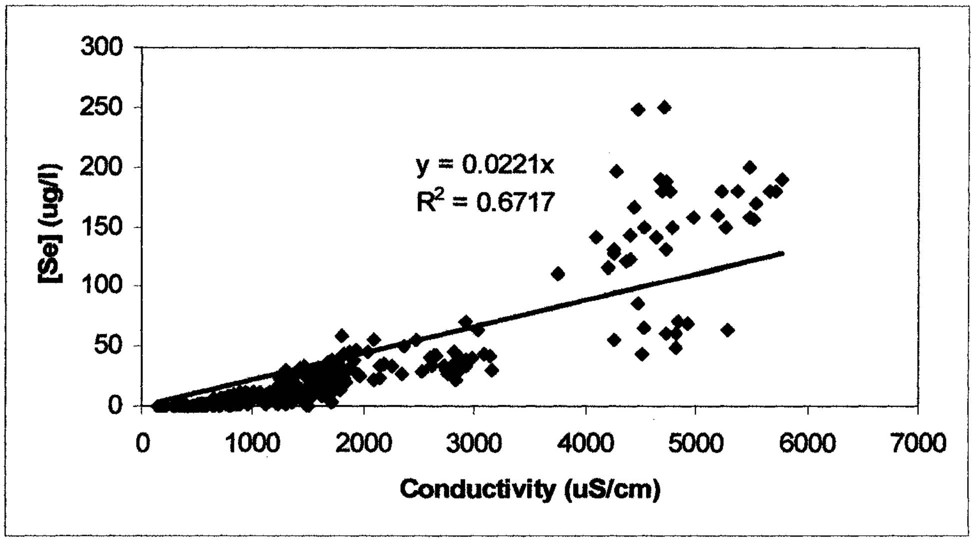


Figure 4.5. Relationships between [TDS] and [Se] from data measured by the USGS in the Uncompahgre Basin

Investigation into the relationship between specific conductance and selenium concentrations yield similar relationships to those seen between [TDS] and [Se]. This is expected given the linear relationship between [TDS] and conductivity. These relationships are presented in Figure 4.6. A linear fit is successful for values of conductivity below about 3000 μS/cm; above that the relationship breaks down. The $\log_{10}$ of the conductivity and [Se] were plotted and a linear regression used to find a best fit line. The fit of this log-linear relationship is slightly better than the linear fit and results in a power relationship as follows:

[Se] (µg/l) = $(10^{-5.313})$ * (Conductivity in µS/cm)$^{2.0246}$ with and R^2 of 0.83.



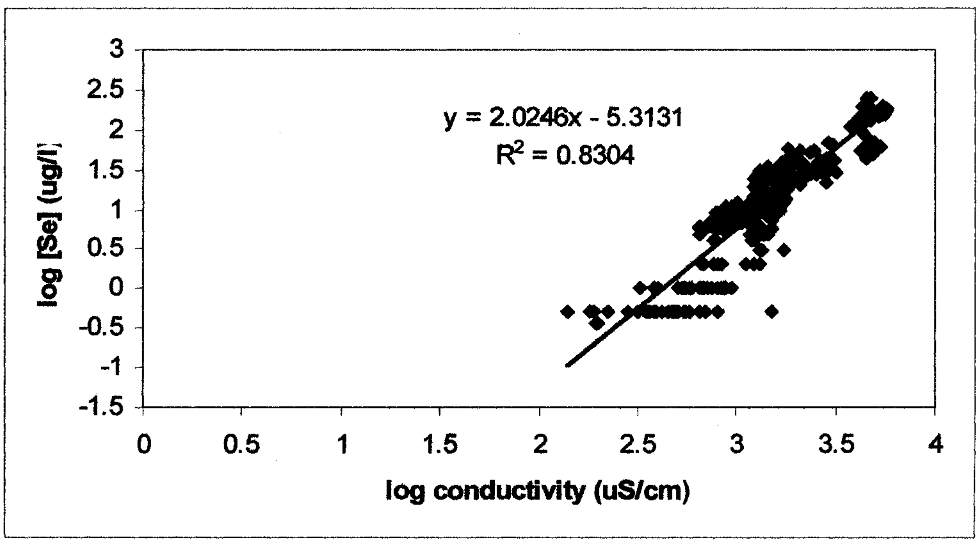


Figure 4.6. Relationships between conductivity and [Se] from data measured by the USGS in the Uncompahgre Basin

Analysis of in-river sampling data of conductivity and [Se] show a valuable relationship. For a quick test for compliance with the [Se] standard of 4.6 µg/l, an inexpensive and easy sampling of conductivity can be made. In the Uncompahgre, if conductivity is > 1000 µS/cm, or in the Gunnison, if conductivity is > 500 µS/cm, then it is very likely that [Se] is greater than the standard. These thresholds are presented in Figure 4.7.

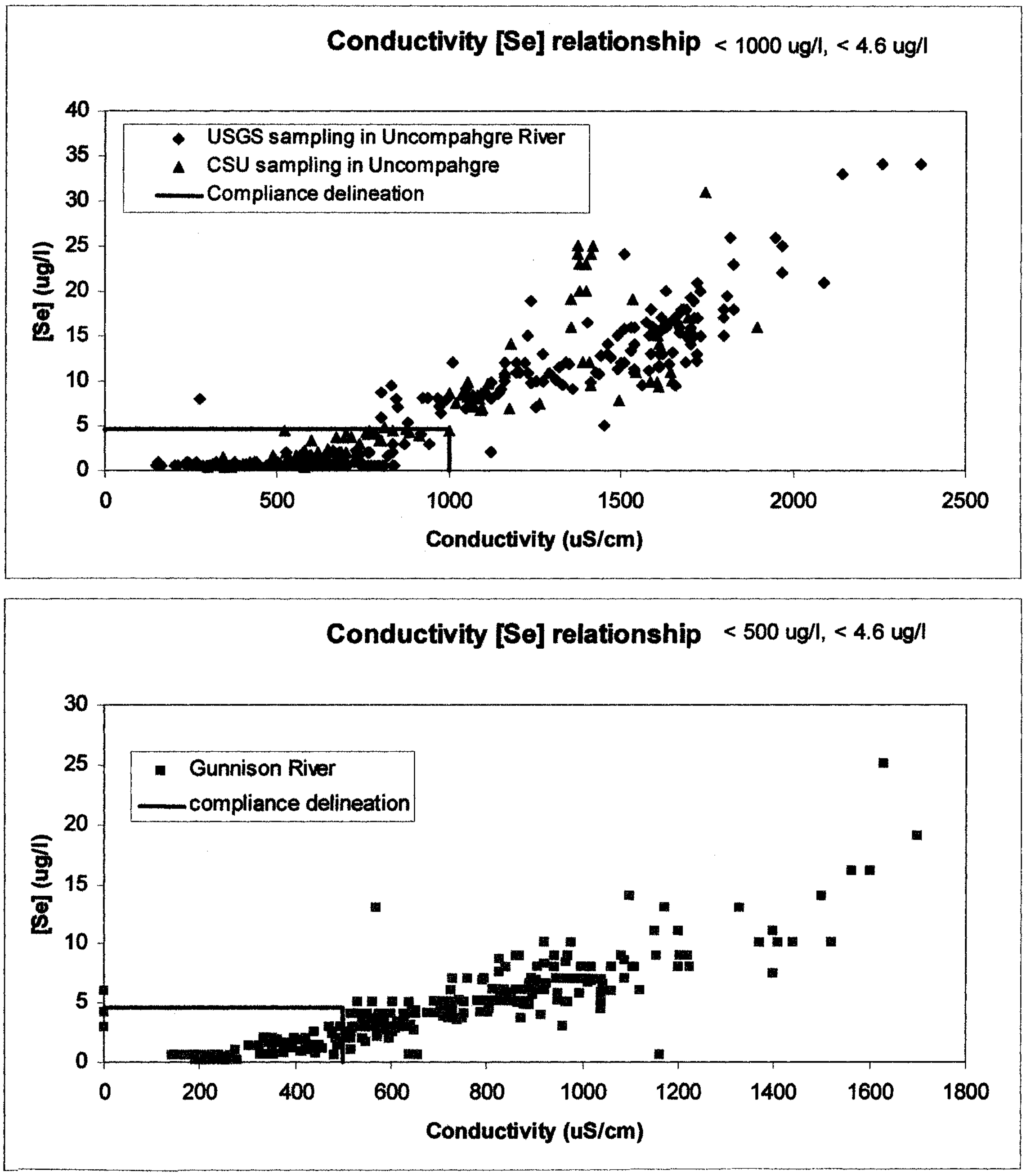


Figure 4.7. In-river relationships between sampled conductivity and [Se]

A groundwater sampling dataset was available for several sites within the Loutsenhizer Arroyo sub-basin. These data were collected by the USBR as part of an irrigation and drainage study on the Meaker Farm and available as part of the USGS-provided GIS data records describing water quality sampling. The groundwater quality data were compared to wintertime surfacewater data (collected by the USGS) as a confirmation of the assumption that winter surfacewater conditions are similar to groundwater conditions. Analysis of these data is presented in Table 4.2. For [TDS] this assumption holds as the means between groundwater concentration and surface water concentration are within 4%. Conductivity in the wintertime surfacewater is higher than groundwater. Selenium concentration in the groundwater is on average higher compared to wintertime surfacewater conditions. These comparisons are rough given variability throughout the sub-basins, but show possible contributions of groundwater versus other surfacewater contributions of various constituents. Surfacewater concentrations of conductivity much higher than groundwater indicate that there are most likely high conductivity surfacewater sources mixing with groundwater to produce higher concentrations than observed directly in the groundwater. Conversely, lower concentrations of selenium in surfacewater as compared to groundwater indicate that for selenium, low-concentration surfacewaters are likely mixing and diluting groundwater contributions.

Table 4.2. Comparison of groundwater to surfacewater sampling data in the Loutsenhizer sub-basin

	Conductivity (μS/cm)	**[TDS] (mg/l)**	**[Se] (μg/l)**
Groundwater samples			
Mean	3559	3172	265
Standard Deviation	1794	1368	334
n	79	5	89
Winter surface water samples			
Mean	4652	3292	155
Standard Deviation	775	1772	43
n	35	35	35

4.3 Model Boundary Conditions

Data for flows for the Gunnison Tunnel and the Uncompahgre at Colona are used as flow boundary conditions, as data for the full period of record for calibration and validation exists. However, there are limited water quality data available. These two sources are considered "clean" of selenium, with sampling data for Colona in the 0 – 2 μg/l range, and the Gunnison Tunnel water between 0.35 and 0.5 μg/l. Values for [TDS] for the Tunnel range between 114 - 140 mg/l, so the representative average value of 119 mg/l is used for each timestep. There exists a dilution-type relationship for [TDS] as a function of flow in the Uncompahgre at Colona, where low flows show high concentrations of TDS (up to 840 mg/l) and high flows show low concentrations (as low as 140 mg/l). A log rhythmic trend line was fit to this relationship using Excel. The function: [TDS] (mg/l) = -94*ln(Q in cfs) + 965, fits visually very well (Figure 4.8) but has an R^2 value of 0.51. This function was used as the boundary condition for [TDS] in the Uncompahgre at Colona as a function of flow.

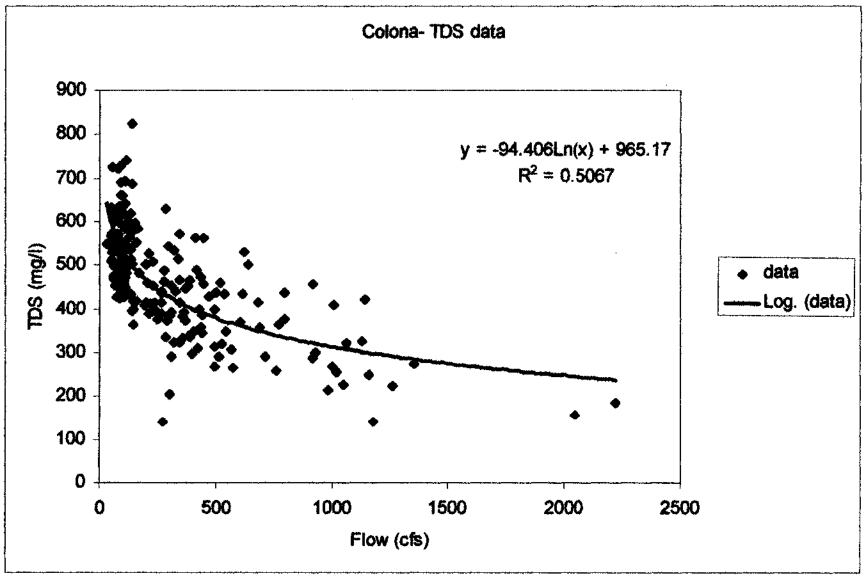


Figure 4.8. TDS boundary condition relationship for Uncompahgre at Colona

4.4 Model Calibration

The model calibration process involves 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. It is hoped that the calibrated model therefore accurately simulates processes that drive water quality changes as seen in observations. By quantifying comparisons of model predictions with the measured data, the model predictive error is quantified and leads to a measure of the accuracy of the process description in the model.

The calibration period of water years 1991 – 1996 was chosen based on available flow and water quality data. More recent water quality data existed for the Basin, but the most recent complete flow dataset available in Hydrobase during the calibration process was water year 1996. The average and standard deviation of monthly flows at Colona and Delta for water years 1991 – 1996 are very close to the long term statistics of the full period of record of complete flows available at the time of model calibration (1975 – 1996). Average of monthly flows at Colona for 1991 – 1996 was 99.6% of the long term average, and the monthly values showed 76% of the variability seen in the long term record. For Delta, the average of monthly flows for 1991 – 1996 was 99.7% of the long term average, and the monthly values showed 64% of the variability seen in the long term record. Based on these criteria the calibration period of record sufficiently described the hydrologic conditions in the basin.

Model calibration began by calibrating the individual sub-basin water balance and constituent transfer models. After this initial tuning, final tuning was performed to best fit basin-wide water quality conditions.

4.4.1 Sub-basin Model Tuning

An external method was used to determine the flow and constituent uptake components that fit measured observations for each sub-basin individually. This set of components fully describes the total pond, canal and lateral seepage volumes and timing, gross field application volumes and timing, surface and sub-surface return volumes, timing and quality. The total gross field application, less crop consumptive use and evaporation yields the net field application. The net field application is the portion predicted to return, which is partitioned into surface and sub-surface components by calibration parameters. The sub-surface component is combined with the total pond, canal and lateral seepage to produce the total sub-surface return flow. Estimates of diversion water concentration were used in this external method with groundwater concentration parameters to calculate the return flow water quality (as the mix of surface and sub-surface flow components).

The objective of this calibration was to minimize the difference between the model predictions and average monthly conditions seen in the data for the calibration time period. These calendar-month average values (i.e., average for the month of June over the calibration time period, average for the month of July, etc.) were appropriate given that calibration parameters in the model applied to the full simulation run. The average monthly conditions also are warranted given that only one representative set of monthly CU and evaporation were used. A model that produces a calendar-month average model prediction that matches well with a calendar-month data computation is likely to produce a time series of monthly output that fits the overall pattern of monthly data well. The Excel Solver was used to minimize the error between calendar-month averages of flow volume and selenium concentration, by adjusting monthly gross field application (originally estimated using fractions presented in Table 4.1), surface and sub-surface flow partition coefficients, surface and sub-surface convolution parameters and representative groundwater concentrations. Adjusting parameters to reduce returns or increase groundwater flow increased return flow concentrations. Adjustment of convolution parameters changed the magnitude and timing of return flows during winter months. Using a system of weights on errors for individual months' flows and concentrations, the overall objective function could be altered to better fit flows or concentrations at specific times of the year. This weighted approach allowed for an overall best fit of the combination of flow and concentration data. This external, optimization-based calibration was performed for all five sub-basins. The optimization was constrained to ensure that parameters remained physically realistic. The convolution parameters summed to one to provide mass balance for the surface and sub-surface components separately. For an example of these comparisons for the Loutsenhizer Arroyo Sub-basin, see Figure 4.9 below.

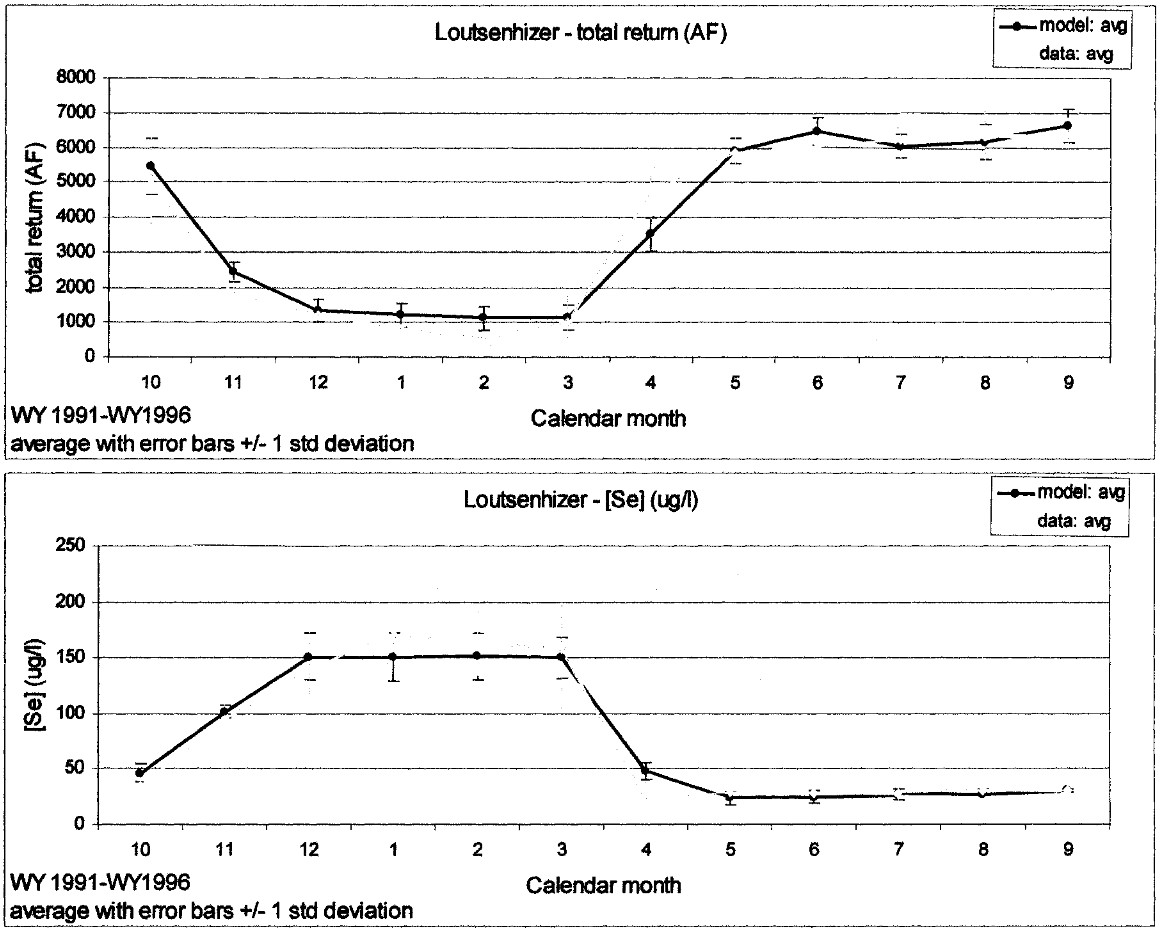


Figure 4.9. Example of calibration plots comparing model prediction to measured data for Loutsenhizer arroyo sub-basin outflow and [Se]

A vital output from the automated calibration was an estimate of total flow volumes that were applied to fields in the sub-basin on a calendar-month basis during the historical period. Data describing the time series of actual applications were not available from any source, nor was a time series of actual (or predicted) consumptive use data. This data gap presented an information disconnect between diversion water volumes and simulated returns. These missing data can therefore be filled in by calculating a representative set of application volumes that, when used with consumptive use estimates, allow a sub-basin model to perform well. The field return volumes are a valuable piece of the agricultural hydrology that has not been estimated beyond hearsay evidence to date. This water mass balance approach provides a way to quantify the total surface and sub-surface flow contributions as a result of irrigated agriculture, even in light of missing or estimated data. A benefit of *not* having parcel application data available is realized, where the results from the mass balance are not biased towards any data set, but rather an independent method is used to describe the total flow and quality of the surface and sub-surface components based on their signatures and contributions to the sub-basin outlet return flows.

Completing the connection between diversion volumes and application volumes was approximated through linear regression. By using a linear regression between the application flow volumes from the sub-basin calibration (the expected volumes based on the model structure and calibration fit) and application volumes from the GIS analysis (a gross estimate), a factor was obtained that better partitions these diversion flows for calibration. Given this empirical technique, a check was performed to ensure that enough diversion was available to serve sub-basins. These linear regressions all resulted in R^2 values greater than 0.8 in all sub-basins with the exception of the Spring Creek. A linear combination could not be created such that a fraction of the calendar month average diversions predicted the application rate (where, adding canal seepage and subtracting CU resulted in the net returns shown in the sampling data). For Spring Creek sub-basin only, the gross application pattern through the year is set and is not driven by the timing and volume of diversion data. This reduces the functionality of the model for BMP predictions in the Spring Creek sub-basin slightly (i.e., adjusting diversions will not directly adjust application), application rates must be adjusted independently of diversions.

Another important piece of information falls out as a byproduct of this analysis- the total volume of flow that is expected to flow out of the Uncompahgre Basin in canals to serve out-of-basin parcels where these returns would flow to the Gunnison River instead of the Uncompahgre. These flows are calculated as diversion flows at the headgate less total application flows in sub-basins in series as canals flow through them. Sampling data in the out-of-basin area above Delta: Peach Valley Arroyo, Sunflower Drain and the Garnet Canal near the confluence with the Gunnison and the out-of-basin area below Delta: Cummins Gulch, Rubideau Creek and Seep Creek all exhibited similar [Se] vs. flow relationships of high concentration with low flow and low concentration with high flow as in tributaries of the Uncompahgre. This suggests that similar constituent uptake processes occur in these areas. However, as compared to within-basin areas, the total return flows from these out-of-basin areas enter multiple tributaries before entering the Gunnison, and a good comparison of model output to measured data is not available.

For simplicity, the return flows predicted by the model are left in a lump form as a bulk influence to the Gunnison. A simplified water balance is performed for the out-of-basin areas in which no canal and lateral seepage is estimated and estimates only of consumptive use and canal evaporation are included. A water balance is performed based on this simplified set of components; sub-surface flow is considered deep percolation, and the surface and sub-surface partition parameters drive this flow separation. Surface water concentrations are weighted based on concentrations of various canals flowing out to these areas after leaving the Uncompahgre Basin. Specific representative groundwater constituent concentrations are included for these two out-of-basin areas.

The full set of model calibration parameter values and sub-basin calibration comparison plots are available in the Appendix.

4.4.2 Basin Model Tuning

Parameter values obtained from the sub-basin tuning were used in the full model combining the in-river quality with the sub-basin models for all five sub-basins. For the simulation of flow and water quality for the calibration period, output signatures from the sub-basins matched the measured data well, as expected. However, the prediction of flows downstream did not appear to be completely characterized.

4.4.2.1 Baseflow Characterization

The combination of the sub-basin return flow contributions, along with diversions at several points along the river did not predict flows at Delta very well. Additionally, in-river flows in the reach between Montrose and Delta were lower than expected and often were predicted as negative. Flows at the downstream point at Delta were also lower than expected. This result was interpreted as the fact that the sub-basin flows, while a vast majority of the return and inflows throughout the river reach under study, the sub-basin flows did not provide the complete picture. Therefore, a monthly balance of water was assumed for the river and the balance of required inflows in order to match the flow at Delta was calculated. This additional inflow, if required for balance, was distributed equally throughout the computational elements of Colona to Delta reach. It was assumed that this inflowing water, even though a combination of groundwater and surface flow from small tributaries or return flows from smaller diversions not specifically modeled, provided no additional constituent load. This assumption may be incorrect, but this assumes that all external Se sources are driven by irrigation returns from sub-basins and are measurable at the sub-basin outlets. Therefore, it is assumed that no distributed load to the river occurs that is not directly connected to irrigated agriculture as modeled by the major diversions and returns.

Based on this need for baseflow, the available data from Hydrobase may not describe accurately all of the sources and sinks of water in the Uncompahgre Basin between Colona and Delta. A monthly water mass balance of inflows, diversions and predicted return flows from tributaries (at the level portrayed by the), predicts dewatering for many historical months in sections of the river. For this reason additional "Baseflow" is added. It is assumed to have zero selenium no concentration and therefore provides a small dilution effect. The addition of baseflow is also found in STATEMOD. In the case of STATEMOD this water was added in bulk at one downstream point and upon further inspection changed from inflow to outflow throughout any given year. Over the long term this baseflow was found also to be slightly negative, or predicting a losing basin. The one addition point, as well as positive and negative baseflows seem unrealistic, but the STATEMOD modelers did recognize the need for this additional water for mass balance with the observed flow data. Note that this volume of baseflow is calculated for the calibrated model and will remain static and unchanged for the BMP simulations.

The time series of baseflow used in this study was calculated such that, when added as an evenly distributed water source over the Colona to Delta reach, the flows predicted at Delta accurately matched the measured monthly data. Even with the distributed inflows, during some summer months in the data period of record, the large volumes of irrigation diversion result in zero or negative calculated flows in portions of the river. Very low flows in downstream sections below diversions and above some return flows were expected based on personal observations in the Basin (see photo in the Appendix), but zero and negative flows (or flow volumes lower than the baseflow per cell volume) cause water quality model calculation errors. Therefore, specific computations are made for these low flow conditions by both the selenium and TDS water quality models. If the flow balance model calculates zero or negative flows in a computational cell, the river water quality models will assume the flow is too low for an accurate calculation of a new cell concentration and the concentration of the water from the adjacent cell upstream will be used. This modeling assumption is conservative and assumes that extremely low flow conditions in river sections below diversions does not drastically alter river water concentrations. It is assumed that even in these low flow conditions, some water of the upstream concentration flows downstream.

4.4.3 Sub-basin Outflow Redirection

The need for additional out-of-basin water movement was indicated from field monitoring. Near the mouth of the Loutsenhizer Arroyo, a direct connection exists between the Arroyo return flow and the Garnet canal (which has its headgate on the Uncompahgre upstream of the Arroyo return flow). See the photo of this connection in the appendix. Through basin calibration, an estimated 15% of the return flow of the Loutsenhizer is diverted directly into the Garnet canal and never reaches the Uncompahgre River. This redirection is possibly in place because of low flows observed the Uncompahgre in this area (observed in the field and in model predictions) are unable to satisfy the Garnet Canal diversion volume requirement or hydraulic requirements to maintain flow in the canal. This type of reuse, redirecting drainwater directly into canals is not uncommon in the Basin (Leib, personal communication, 2003), especially given the magnitude of water reuse by the overall distribution system (Catlin, 2004). This specific movement of water with a high concentration of selenium is possibly decreasing load to the Uncompahgre at the cost of increasing load to another problem area: water from the Garnet Canal serves Sweitzer Lake, another impaired waterbody.

4.4.4 Quantification of Model Predictive Errors

Measures of error between model prediction and measured data were calculated to guide calibration towards a good fit between the two. Error values are calculations of model prediction (monthly mean) minus sampled data (instantaneous measurements within the month). Valuable goodness of fit metrics include mean error, median error, max error, R^2 and a pooled standard deviation of the error discussed below. The number of data comparisons, n is also calculated. For all locations where sampling data exists, a measure of the model prediction error can be calculated. Specifically, predictive errors are calculated for all sub-basin outlets and in the Uncompahgre at Delta. These metrics for flow, [Se] and [TDS] for the calibration time period are presented in Tables 4.3a, 4.3b and 4.3c.

Table 4.3a. Calibration goodness of fit metrics for flow

Metric	Dry Cedar Ck. Outlet	Cedar Ck. Outlet	Loutsenhizer Arroyo Outlet	Spring Ck. Outlet	Dry Ck. Outlet	Uncompahgre at Delta
Mean Error (cfs)	0.99	8.18	2.05	34.55	18.63	15.78
Median Error (cfs)	1.73	13.52	3.71	16.38	12.54	0.00
Relative Median error[1]	14%	13%	6%	35%	10%	5%
Max Error (cfs)	9.17	111.11	37.08	112.82	80.54	164.05
R^2	0.74	0.78	0.89	0.25	0.64	0.96
Standard Deviation of Error (cfs)	5.61	54.72	16.62	52.12	100.73	37.20
Relative Standard Deviation of errors[2]	47%	54%	25%	113%	82%	11%
n	29	21	38	27	13	72

Table 4.3b. Calibration goodness of fit metrics for selenium concentration

Metric	Dry Cedar Ck. Outlet	Cedar Ck. Outlet	Loutsenhizer Arroyo Outlet	Spring Ck. Outlet	Dry Ck. Outlet	Uncompahgre at Delta
Mean Error (µg/l)	-2.78	-3.07	-0.06	0.26	1.31	-0.48
Median Error (µg/l)	1.7	-0.49	-1.90	0.25	0.49	-0.43
Relative Median error[1]	6%	-3%	-2%	15%	9%	-3%
Max Error (µg/l)	15.36	4.43	40	1.61	6.00	14.62
R^2	0.74	0.70	0.92	0.67	0.02	0.51
Standard Deviation of Error (µg/l)	17.52	12.27	21.57	1.89	12.50	7.70
Relative Standard Deviation of errors[2]	60%	64%	28%	115%	226%	55%
n	29	21	38	13	13	44

Table 4.3c. Calibration goodness of fit metrics for TDS concentration

Metric	Dry Cedar Ck. Outlet	Cedar Ck. Outlet	Loutsenhizer Arroyo Outlet	Spring Ck. Outlet	Dry Ck. Outlet	Uncompahgre at Delta
Mean Error (mg/l)	-150.27	-85.05	116.21	161.72	72.68	-28.50
Median Error (mg/l)	77.94	-16.26	99.67	278.5	115.81	-3.94
Relative Median error[1]	4%	-1%	4%	34%	13%	0%
Max Error (mg/l)	695.62	586.64	1479.09	1030	265.00	396.20
R^2	0.80	0.81	0.92	0.33	0.38	0.55
Standard Deviation of Error (mg/l)	993.97	690.10	550.48	705.6	550.73	270.09
Relative Standard Deviation of errors[2]	47%	59%	23%	86%	60%	26%
n	27	17	36	27	13	43

[1] median error divided by the average predicted quantity
[2] standard deviation of errors divided by the averaged predicted quantity

Following ideas from Borsuk et al. (2002), the variance of the error can be calculated and used in the creation of model confidence bounds. The model predicts monthly mean conditions. Grab sampling data for water quality are good estimates of instantaneous conditions. Errors can be calculated as the difference between the monthly mean prediction and a data value collected during that month (in only a few cases were there multiple water quality samples collected in the same month). Assuming that the error between the model and the data are constant for any month, a pooled measure of the variance can be applied as expressed in Equation 4.1 below.

The model prediction provides the expected value of the water quality conditions (the monthly mean) and assuming the errors are normally distributed with zero mean, the pooled variance can be used with the standard normal deviate (Z value at a given level of significance), to produce a confidence bounds on the model output. These bounds would describe the magnitude of the error between the monthly mean and an analysis of an instantaneous grab sample (as estimated from comparisons between model prediction and available sampling data). This error includes both the difference between the true monthly mean and true instantaneous concentration and error between grab-sample data as analyzed and actual real-world instantaneous conditions in river.

$$\text{monthly mean prediction} \pm Z_{0.85}\sigma_{err}$$

$$\sigma^2_{err} = \frac{\sum\left((\text{model} - \text{data}) - \frac{\sum(\text{model} - \text{data})}{n}\right)^2}{n-12} \qquad \text{Equation 4.1}$$

An example of this confidence bounds is shown in Figure 4.10 below.

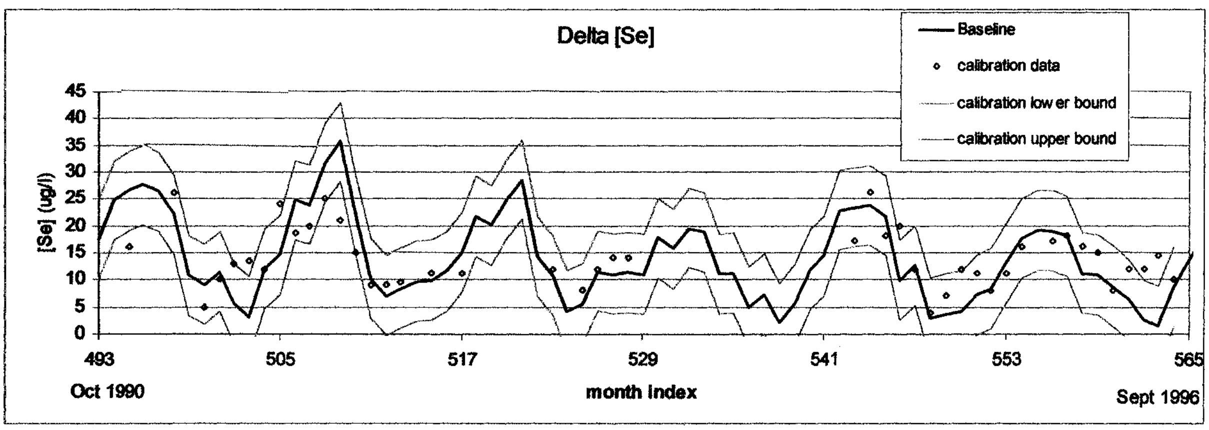


Figure 4.10. Calibrated model output prediction with 85% confidence bounds for [Se] in the Uncompahgre River at Delta

4.5 Sensitivity Analysis

In order to estimate the sensitivity of the model output to the estimates of the model parameters, a general sensitivity analysis was performed. All parameters were systematically adjusted one at a time within a range of +/- 10%. The range of model prediction of [Se] at Delta was investigated. Output from these forty six simulations is shown in Figure 4.11.

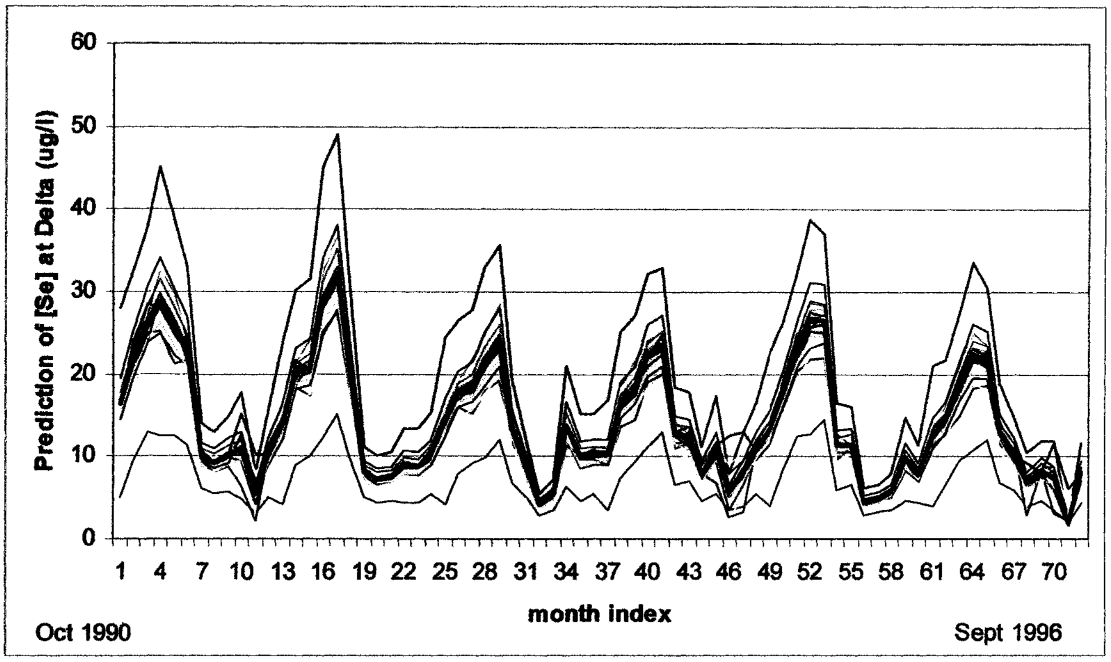


Figure 4.11. Variations in [Se] at Delta model predictions by varying each parameter +/- 10%. The baseline is shown in black

This analysis shows that parameters driving groundwater volumes and concentration in the Loutsenhizer Arroyo Sub-basin were the most influential, while adjustment of the rest of the parameters resulted in small changes in selenium concentration at Delta. Simulations where the sub-surface flow partition parameter for Loutsenhizer Arroyo sub-basin was adjusted above and below the calibration value are the two simulation traces that depart most from the cluster of results shown in Figure 4.11. This general sensitivity analysis describes a change in the model prediction of [Se] at Delta as a function of variability in model parameters. With the exception of the two parameters discussed above, a change in a parameter value of +/-10% results in a change in model prediction of less than 25%. Another sensitivity analysis was performed by adjusting parameter values by +/- 50% (or to 0 and 1, the extremes of the range for fractional parameters). This analysis showed higher departures from the clustering seen in Figure 4.11, but the same parameters for the Loutsenhizer sub-basins were the most sensitive. Based on this analysis, the need to precisely quantify the parameters describing surface/sub-surface partition and the representative groundwater concentration in Loutsenhizer sub-basin are of the highest importance since small variations in these values influence model predictions. This analysis investigated only independent variation in parameters. Sensitivity of correlation between parameters was considered beyond the scope of this research.

4.6 Model Validation

An additional set of data was used for an independent model validation. This model validation exercise was performed to test whether the calibrated model can perform equally well on a separate set of conditions. This set of data for water years 1997 – 2000 was obtained from the Hydrobase database and used as input data. Model predictive error metrics were calculated for the resulting simulation. A model predictive bound for this time frame is also calculated using the pooled variance of Equation 4.1 above. The goodness of fit metrics are shown in Tables 4.4a, 4.4b and 4.4c.

Table 4.4a. Validation goodness of fit metrics for flow

Metric	Dry Cedar Ck. Outlet	Cedar Ck. Outlet	Loutsenhizer Arroyo Outlet	Spring Ck. Outlet	Dry Ck. Outlet	Uncompahgre at Delta
Mean Error (cfs)	-5.77	9.14	-2.17	NA	-53.62	14.94
Median Error (cfs)	-5.77	3.08	1.99	NA	-53.62	0.00
Relative Median error[1]	-55%	3%	3%	NA	27%	4%
Max Error (cfs)	1.25	99.40	29.17	NA	-53.62	164.05
R^2	1	0.74	0.84	NA	NA	0.95
Standard Deviation of Error (cfs)	NA	58.06	27.84	NA	NA	38.22
Relative Standard Deviation of errors[2]	NA	64%	47%	NA	NA	11%
n	2	19	20	0	1	66

Table 4.4b. Validation goodness of fit metrics for selenium concentration

Metric	Dry Cedar Ck. Outlet	Cedar Ck. Outlet	Loutsenhizer Arroyo Outlet	Spring Ck. Outlet	Dry Ck. Outlet	Uncompahgre at Delta
Mean Error (µg/l)	-1.76	0.04	12.43	NA	1.47	-1.46
Median Error (µg/l)	-1.76	-0.89	13.00	NA	1.47	-0.81
Relative Median error[1]	-6%	-5%	16%	NA	27%	-8%
Max Error (µg/l)	-0.26	9.44	66.29	NA	1.47	4.57
R^2	1.00	0.84	0.90	NA	NA	0.57
Standard Deviation of Error (µg/l)	NA	9.34	34.72	NA	NA	5.42
Relative Standard Deviation of errors[2]	NA	47%	42%	NA	NA	50%
n	2	19	19	0	1	28

Table 4.4c. Validation goodness of fit metrics for TDS concentration

Metric	Dry Cedar Ck. Outlet	Cedar Ck. Outlet	Loutsenhizer Arroyo Outlet	Spring Ck. Outlet	Dry Ck. Outlet	Uncompahgre at Delta
Mean Error (mg/l)	NA	-23.77	168.11	NA	374.87	14.24
Median Error (mg/l)	NA	-31.41	123.82	NA	374.87	42.81
Relative Median error[1]	NA	-3%	5%	NA	40%	4%
Max Error (mg/l)	NA	2244.58	1081.90	NA	374.87	370.54
R^2	NA	0.50	0.94	NA	NA	0.38
Standard Deviation of Error (mg/l)	NA	1195.77	705.41	NA	NA	680.67
Relative Standard Deviation of errors[2]	NA	98%	28%	NA	NA	29%
n	0	19	17	0	1	28

[1] median error divided by the average predicted quantity
[2] standard deviation of errors divided by the averaged predicted quantity

4.7 Analysis of the Model Predictive Ability

Through the calibration and validation process and analysis of the model errors and goodness of fit metrics, some general statements can be made about the model's ability to predict flows, concentrations and loads.

For flow calibration, relative median error at Delta is 5% and all sub-basins except Spring Creek relative median errors are less than 20%. For selenium calibration for all sub-basins, errors are less than 20% (all less than 10% excluding the Spring Creek). R^2 values for the Dry Cedar, Cedar and Loutsenhizer sub-basins are 0.74, 0.70 and 0.92, respectively. Selenium concentration error at Delta is 3% with an R^2 of 0.51. For TDS calibration, relative median errors at all sub-basin outlets are less than 40%, or all less than 15% excluding the Spring Creek.

Less data was available for validation. No flow data were available for Dry, Dry Cedar and Spring Creeks, but for the Cedar and Loutsenhizer, relative errors were less than 5%. The predictions for validation were similar to those seen in validation with relative errors for the Dry, Dry Cedar and Loutsenhizer less than 20% and R^2 values greater than 0.84. The relative error in selenium prediction at Delta was 7% with an R^2 of 0.57, similar to calibration. For TDS, relative errors for Cedar and Loutsenhizer were less than or equal to 5%.

Generally, for sub-basin outlets the monthly flow predictions are within 20% of observed, monthly selenium concentrations within 10-20% and monthly TDS concentrations within 15%. For the Uncompahgre at Delta, monthly flow predictions are within about 5%, monthly selenium predictions within 7% with about 50% of the variability captured by the model and for monthly TDS predictions within 5% with about 40% of the variability captured. At Delta, these errors translate into monthly average model predictive capability for flow within 15 cfs, for selenium concentration within 2 μg/l and for TDS concentration within 30 mg/l.

4.8 Baseline Generation

An additional set of flow data was obtained from Hydrobase for Oct 2000 - Sept 2003. These data were not available during the validation process due to incremental updates to this database. These flows were added to the period of record of the data and input to the model. Return flows, [Se] and [TDS] predictions were calculated and add to the information regarding the magnitude and variability of flows and concentrations for various hydrologic conditions. The full simulation run from October 1990 - September 2003, encompassing the calibration and validation time periods is shown in Figure 4.12a-c, the calibration and validation error bounds for selenium are shown for October 1990 - September 2000 only. This simulation time period is considered to be the baseline for model hydrologic analysis and the BMP model simulations.

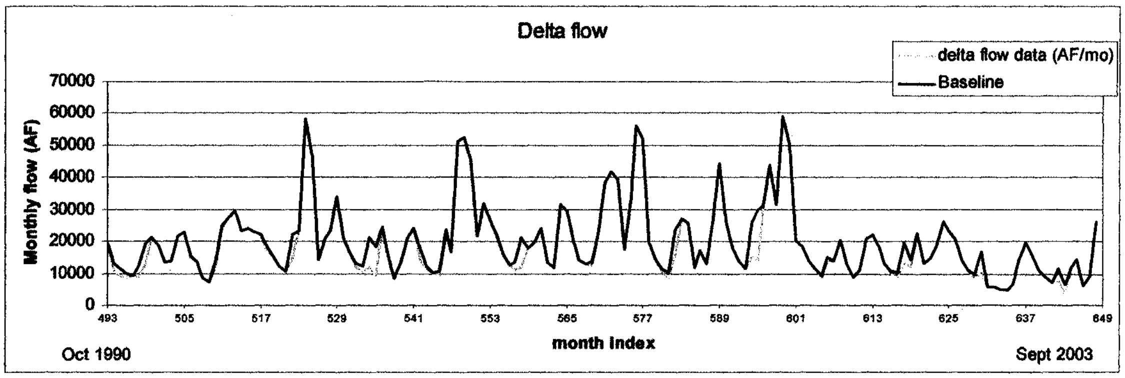


Figure 4.12a. Baseline calibrated flow model output for the October 1990 - September 2003 simulation

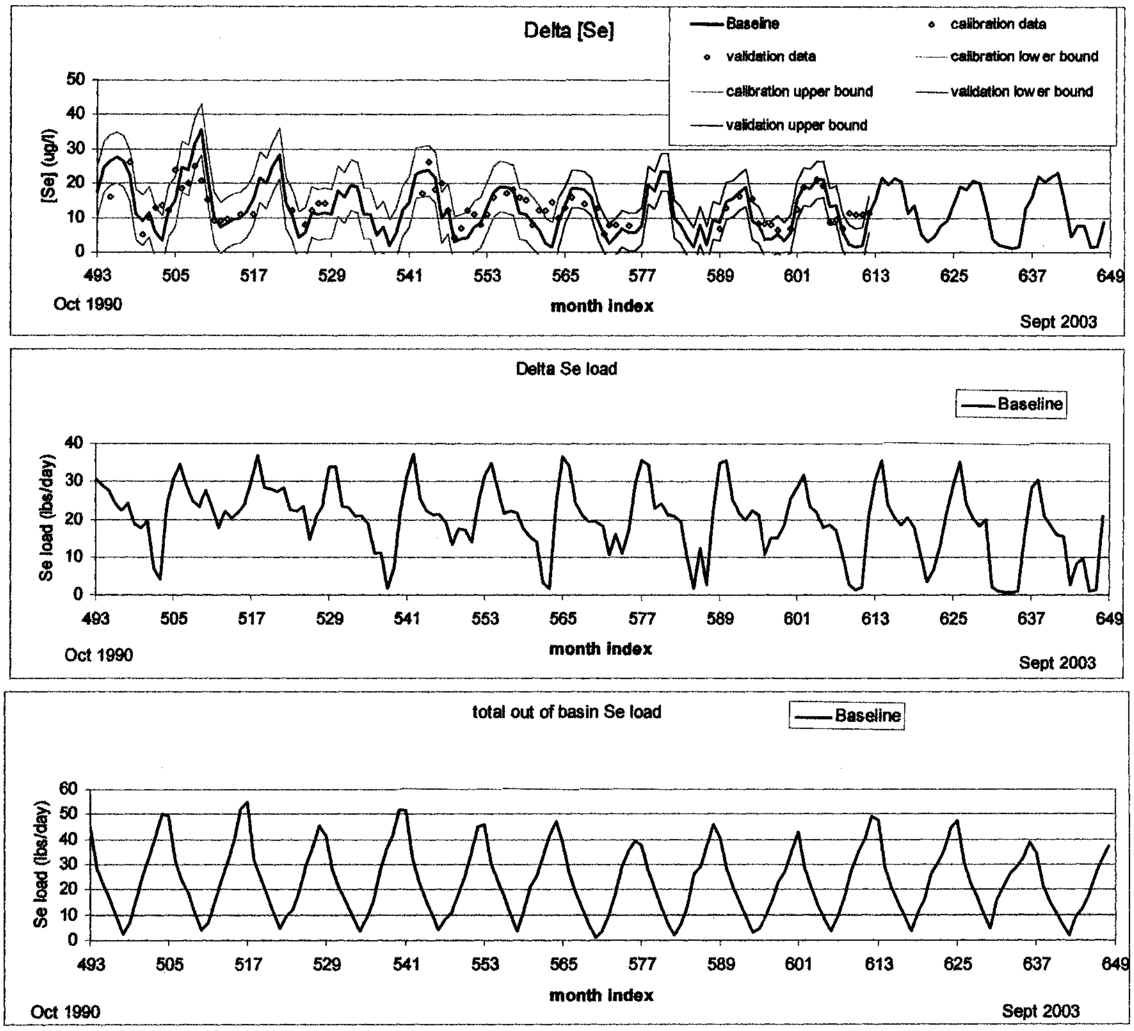


Figure 4.12b. Baseline calibrated selenium model output for the October 1990 - September 2003 simulation

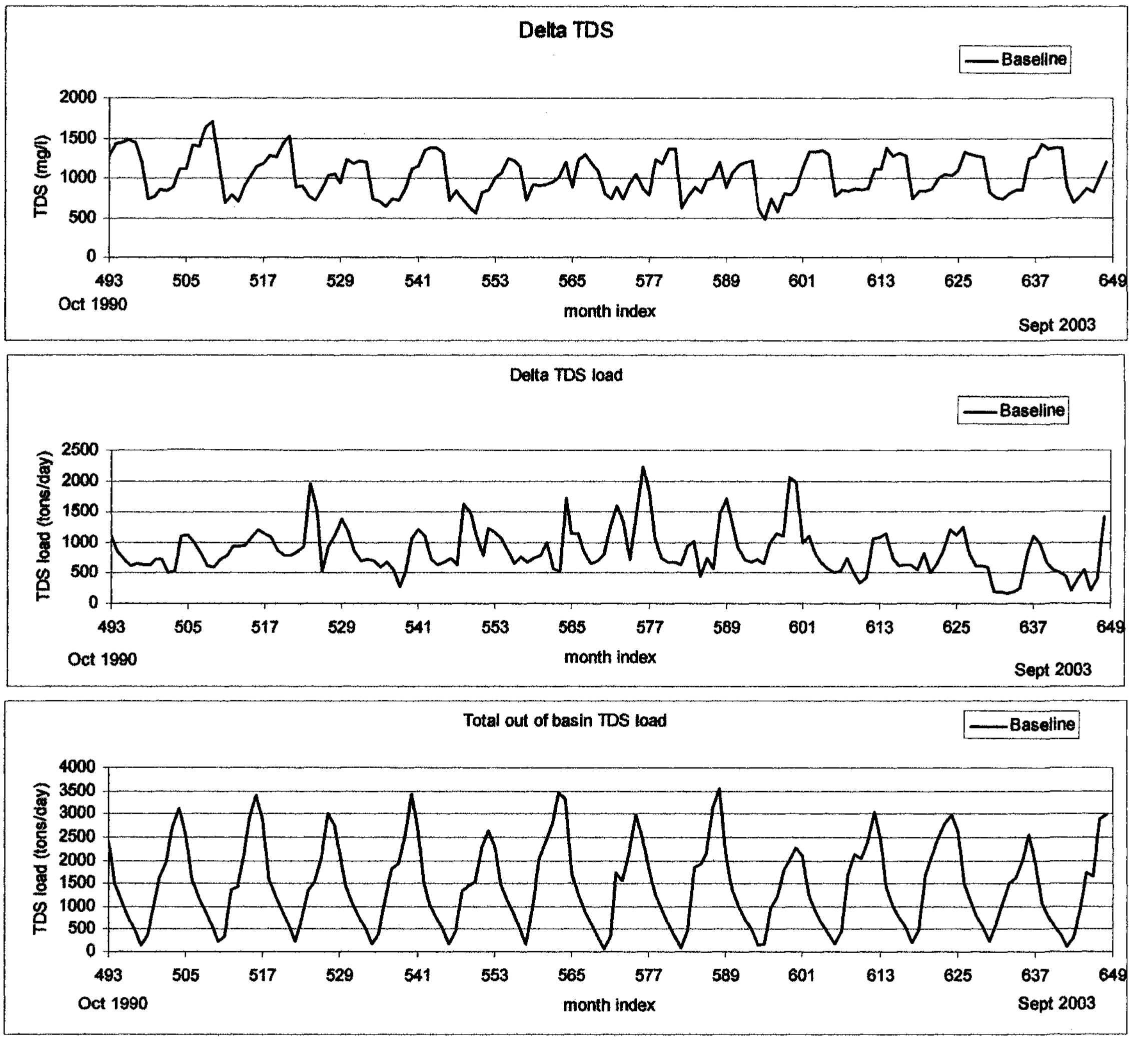


Figure 4.12c. Baseline calibrated TDS model output for the October 1990 - September 2003 simulation

4.9 Special Model Output for Analysis of Water Quality Standards Compliance

Water quality predictions of monthly mean conditions in computational elements in the impaired reach of the Uncompahgre were used to calculate a metric for a working definition of predicted standards compliance. This working definition as described by the State of Colorado (Beley, 2003, 2004), is that a river reach is considered impaired if the 85^{th} percentile of recent concentration samples taken at any point within the reach exceeds the table standard. To translate this standard compliance from *observed samples* to *model predictions*, some assumptions must be made. The monthly mean concentrations predicted by the calibrated model are assumed to be good measures of the true monthly mean of concentrations from observations. For a location, monthly means for the period of record of the simulation are predicted by the model. The 85th percentile of these values at each point in space is calculated and is used for testing with the water quality standard. This method includes seasonal variability and year-to-year variability in the calculation of the 85th percentile. The spatial variation of these percentiles is portrayed and named the longitudinal 85th percentile of [Se] as shown in Figure 4.13.

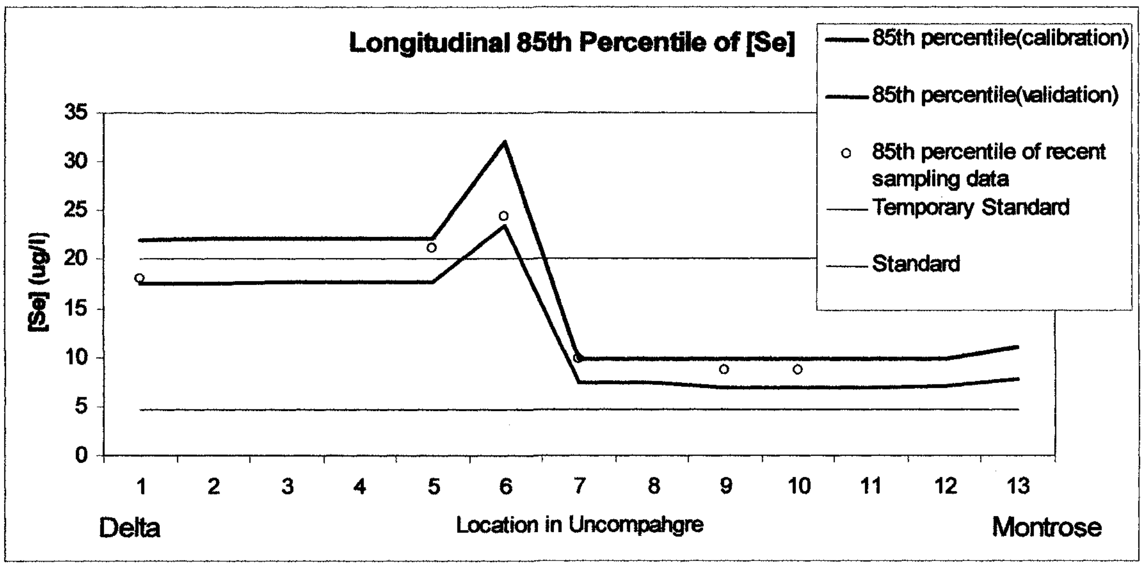


Figure 4.13. The longitudinal 85th percentile of selenium concentration for the calibration and validation time periods

Two longitudinal profiles are shown in Figure 4.11, one for the calibration time period (WY 1991-1996), one for the validation time period (WY 1997-2000). These are also compared with the 85th percentile of recently sampled data (collected by CSU/Montrose High School monthly for March 2003 - February 2003). The two longitudinal profiles from the model predictions indicate that the metric for standards compliance is predicted to vary depending on the period of record simulated. The 85th percentile of observed data falls within this range of variability. All these three sources indicate that the selenium concentrations throughout the Uncompahgre River between Montrose and Delta exceed the 4.6 μg/l standard as defined by the working definition assumed here and portions of the river reach exceed the 20 μg/l standard. It should be noted that variance calculated from instantaneous grab samples of concentration includes within-month variability, seasonal variability, possibly year-to-year variability if a long period of record as well as variability from collection technique and lab analysis. Only the seasonal variability and year to year variability are portrayed by the model output, so a calculation of the 85th percentile from observations is most likely higher given these additional sources of variability.

Chapter 5

HISTORICAL HYDROLOGIC OUTPUT

This chapter discusses what has been learned about the basin conditions from the calibrated model. The model baseline simulation of water years 1991 - 2003 was used to estimate general characteristics of the agricultural hydrology, historical agricultural practices and their influence on return flow quantity and quality. This analysis yields many cause and effect relationships between agricultural practice and resulting water quality at several scales. These characteristics have been analyzed on an average total annual basis and seasonal basis for irrigation vs. non-irrigation season.

5.1 Input "Background" Conditions

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 5.1. Even though the concentration of selenium in these water sources is at most 1 μg/l (based on USGS sampling data), the high flow volume (from Hydrobase flow data) results in quite a large annual load to the Uncompahgre River. These flow volumes have also been normalized to a depth of water for total area of irrigated parcels in the basin in order to demonstrate how far these water resources can extend for irrigation.

Table 5.1. Annual average conditions for input water sources based on the baseline model simulation

	Uncompahgre at Colona	Gunnison Tunnel inflow to South Canal
Average annual total flow volume (AF/yr)	181,359	231,786
Depth per acre[1] (ft)	2.5	3.2
Average [Se] (μg/l)	1	1
Average [TDS] (mg/l)	478	354
Se load (lbs/yr)	491	314
TDS load (tons/yr)	100,141	37,405

[1]calculated based on serving 73,481 acres, the total parcel acreage served by the eight major diversions.

Another inflow source that provides water in the Uncompahgre River is precipitation. Precipitation and pan evaporation data are input to the model as one set annual pattern describing representative conditions. These data show that the average precipitation in the basin is 10 inches annually with potential evaporation of 55 inches annually. In the model, precipitation that influences the river is assumed to be input to the irrigated parcels only. It is assumed that precipitation falling on other areas throughout the basin provides little net inflow after evaporation and infiltration. The total annual net precipitation rate on parcels accounts for 0.5 ft on average, or 22,094 acre feet.

As described in Chapter 3, a monthly baseflow component is calculated through a water balance. This baseflow is assumed to be a combination of ungaged sources of groundwater or surfacewater and can be partly explained by flow measurement errors at diversion structures and gage sites. This water is distributed uniformly through the Uncompahgre River, Colona to Delta reach. This water volume fluctuates but it is in the range of 85,000 to 200,000 acre feet annually. This water volume is considerable when calculated as a basin total, but only small volumes of water inflow to each of the computational elements in the model. The model mass balance suggests that the baseflow provides no significant inflow mass of selenium. Therefore the baseflow water selenium concentration is set to zero. However additional total dissolved solid sources were found to be required during calibration, therefore the baseflow TDS concentration is set to 900 mg/l, similar to that of the Uncompahgre River downstream of Montrose.

5.2 Diversion Flows

Annual average flow volume and average quality in the eight major canals based on the baseline model simulation are tabulated and presented in Table 5.2. The average annual volume of diverted water to each canal is shown as well as the distribution of these volumes basinwide. Data from Hydrobase (CDSS, 1994b and 1994d) directly links diversion structures to parcels with accompanying data on parcel sizes. Analysis of these data shows a calculation of the gross annual depth of water that is diverted for these parcels. This gross volume is not the water actually applied to fields, but these high values reinforce the magnitude of the water diverted from the Uncompahgre River for irrigation. The total annual diversion for these eight structures is 598,614 acre feet, 1.4 times the total inflow volumes from the Tunnel and the river at Colona, as shown in Table 5.1.

This analysis also demonstrates the extent of water reuse in the basin, where the capturing of drainwater for re-diversion downstream occurs. This re-use is also portrayed in the water quality at the diversion points. 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 East, Garnet and Ironstone canals probably contains significant 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.

Table 5.2. Annual average conditions in diversion water based on the baseline model simulation

	South Canal	Loutsenhizer Canal	Selig Canal	East Canal	Garnet Canal	West Canal	Montrose and Delta Canal	Ironstone Canal
Average Annual total diversion flow volume (AF/yr)	55,657	48,884	75,488	49,766	18,793	52,948	192,816	104,262
Fraction of total diversion	9%	8%	13%	8%	3%	9%	32%	18%
Total acreage served (acres)	5893	4435	10,596	4958	941	4892	21,162	20,604
Gross depth (AF/acre)	9.4	11.0	7.1	10.0	20	10.8	9.1	5.1
Average [Se] (μg/l)	0.75	0.73	2.07	5.72	5.54	0.75	0.74	5.72
Average [TDS] (mg/l)	364	438	610	813	853	372	396	772
Se load (lbs/yr)	115	81	258	530	186	93	334	1080
TDS load (tons/yr)	27,870	26,303	59,154	50,808	20,336	20,681	84,494	93,669

The diversion volumes for the eight major canals listed in Table 5.2 account for roughly 92% of the total water diverted from the Uncompahgre River. The STATEMOD model for the Gunnison Basin (CDSS, 2004a) lists 18 total diversions from the river where four of these are aggregated diversions by smaller structures. One historical note: before water year 1994, water was diverted for livestock watering during the winter months.

After 1994, diversions to the largest canals were discontinued for the months of November - March. Given more diversion water, higher return flows probably occurred.

5.3 Return Flows

The average return flows from the five major tributaries based on the baseline model simulation are tabulated and presented in Table 5.3. The annual return flow volumes from sub-basins have been normalized to a depth of water per acre from parcels inside sub-basin boundaries. This return water includes pond, canal and lateral seepage as well as deep percolation, but these numbers indicate the magnitude of the return flows from the overall practice of irrigation in the sub-basins.

Table 5.3. Annual average conditions for return flows based on the baseline model simulation

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Annual total return flow volume (AF)	7,772	66,891	43,924	32,553	82,726
Total acreage irrigated (acres)	1,383	5,739	11,415	6,751	18,390
Return water as depth per acre (ft)	5.6	11.7	3.8	4.8	4.5
Average [Se] (µg/l)	29	20	80	1.6	5.5
Average [TDS] (mg/l)	2,121	1,197	2,476	812	934
Se load (lbs/yr)	396	2,111	5,398	140	1,053
TDS load (tons/yr)	15,300	65,740	100,516	34,452	100,016

Comparison of the annual averages of concentration and load show 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. The parcel acreage presented in Table 5.3 includes only those parcels served by the major canals (South Canal, Loutsenhizer Canals, Selig Canal, East Canal, Garnet Canal, West Canal, Montrose and Delta Canal and the Ironstone Canal); an additional 5,538 acres are served by smaller diversion structures in the Uncompahgre Basin (based on the STATEMOD model input data).

These annual values are valuable for comparison but are not the complete picture, especially for water quality standards compliance. Flows and concentrations have been measured as fluctuating temporally and the portion of the year dominated by high concentrations is of interest for compliance. Table 5.4 below describes the average seasonal conditions of return flows based on the model baseline simulation.

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 generally consistent with these listings. The irrigation and non-irrigation season selenium concentrations at the outlet of the east-side tributaries: Dry Cedar, Cedar and Loutsenhizer are all above 4.6 μg/l and during the wintertime are far above 20 μg/l. Spring Creek can be considered a dilution water source all year, given the low selenium concentrations. Dry Creek is considered a dilution water source also. Even though winter concentrations are above 4.5 μg/l, the concentrations in Dry Creek both in the summer and winter are lower than those seen in the Uncompahgre just above the Dry Creek inflow.

Table 5.4. Seasonal average conditions for return flows based on the model baseline conditions

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Irrigation season average monthly flow (cfs)	16	142	90	66	145
Non-Irrigation season average monthly flow (cfs)	4	25	21	17	75
Irrigation season average [Se] (µg/l)	13.5	9.3	31	1.5	3.1
Non-Irrigation season average [Se] (µg/l)	50	34	149	1.9	8.9
Irrigation season average [TDS] (mg/l)	1,096	588	1,362	724	817
Non-Irrigation season average [TDS] (mg/l)	3,556	2,049	4,035	936	1,097
Irrigation season average Se load (lbs/day)	1.1	6.9	14.3	0.5	2.4
Non-Irrigation season average Se load (lbs/day)	1.0	4.3	15.5	0.2	3.6
Irrigation season average TDS load (tons/day)	46	217	319	131	312
Non-Irrigation season average TDS load (tons/day)	37	129	214	43	220

Total dissolved solids concentrations fluctuate seasonally as well, with wintertime outlet concentrations much higher than summer concentrations. Comparisons show much smaller differences in the highest concentrations among sub-basins. Loutsenhizer arroyo non-irrigation season concentration is highest for TDS as well as selenium.

Loads fluctuate much less on a seasonal basis. At first this might seem a bit surprising, but the extremely high concentrations of low-flow winter return flows provides nearly the same load of selenium as the higher-flow summertime months.

Similarly, TDS loads are fairly consistent from winter to summer, with slightly more salt load entering the river in summer.

5.4 Agricultural Hydrology in Sub-basins

Model data describing total irrigated acreage, total canal and lateral lengths and estimates of total pond acreage are presented in Table 5.5. The sub-basin areas and total irrigated acreage were obtained through spatial analysis of the GIS data.

Table 5.5. Agricultural data for sub-basins used in the model

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Total sub-basin area (acres)	15,947	46,770	47,025	54,654	128,987
Total sub-basin areas in Mancos soil (acres)	6,710	18,862	34,232	4,330	13,462
Fraction of sub-basin in Mancos soil	42%	40%	73%	8%	11%
Total irrigated acreage (acres)	1,383	5,739	11,415	6,751	18,390
Total length of canals (miles)	3.5	10.1	26.1	12.2	26.3
Total length of laterals (miles)	10.4	33.9	53.0	25.2	62.7
Total area of ponds (acres)	69	69	69	92	92

In the five major Uncompahgre sub-basins a total of 43,678 irrigated acres are simulated and served by a total of 263.4 miles of major canals and laterals. The wetted perimeters of canals and laterals are assumed to be 14 ft and 7 ft, respectively. The seepage rate for canals and laterals is 0.25 $ft^3/(ft^2$ day), where seepage occurs over the entire wetted perimeter only when diversions are operating. Canal and lateral seepage rates used in the model are taken from data and estimates presented in USBR, 1982. Ponds are assumed to be full for 225 days of the year, seep at a rate of 0.1 $ft^3/(ft^2$ day); and only 2/3 of the ponds seepage is assumed to reach the river. The estimated total pond acreage of 206 acres on east side and 183 acres on west side of the valley is distributed equally among sub-basins. The pond data and attributes used in the model are taken from data and estimates in USBR and NRCS (2004).

For the baseline simulation, average values of each agricultural water balance component can be computed. These values, as monthly values averaged over the irrigation seasons of water years 1991 - 2003 are presented in Table 5.6. These are flow *inputs* to the agricultural components during the irrigation season. Return flows are the sum of surface and sub-surface components lagged and summed by convolution. Quantifying the input sources may lend insight regarding the influence of a given agricultural practice, such as a change in irrigation application method.

Table 5.6. Irrigation season average monthly agricultural components based on the model baseline simulation

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Application (AF/mo)	1,035	10,215	7,409	5,056	12,316
Precipitation (AF/mo)	100	414	824	487	1,328
CU (AF/mo)	306	1,933	1,897	1,568	3,017
Evaporation (AF/mo)	6	19	36	17	40
Canal Seepage (AF/mo)	113	350	681	321	746
Pond Seepage (AF/mo)	86	86	86	114	115
Deep Percolation (AF/mo)	82	1,306	850	2,575	3,393
Surface Returns (AF/mo)	739	7,371	5,322	1,406	7,195
Total returns (AF/mo)	943	8,669	5,379	3,947	8,603

Further analysis of the distribution of these components and the mass loads associated with them is presented in Table 5.7. This analysis points out the highest contributors of Se and TDS mass loads to the Uncompahgre River. If the largest load contribution is from a surface source, then surface drains are indicated as the contributor. If largest load is from sub-surface sources, then the largest volume source is identified as the contributor, as it is assumed that all sub-surface sources have the same representative concentration in a sub-basin.

Table 5.7. Sub-basin agricultural components based on the baseline model simulation

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Irrigation efficiency (CU/application)	30%	19%	26%	31%	24%
Irrigation efficiency (CU/diversion)	25%	18%	23%	28%	23%
Fraction of returns from canal and lateral seepage	12%	4%	13%	8%	9%
Fractions of returns from pond seepage	9%	1%	2%	3%	1%
Fractions of returns from deep percolation	9%	15%	16%	65%	39%
Fractions of returns from sub-surface sources	30%	20%	30%	76%	49%
Fractions of returns from surface drains	70%	80%	70%	24%	51%
Fraction of Se load from surface returns	2%	31%	6%	13%	27%
Fraction of Se load from sub-surface returns	98%	69%	94%	87%	73%
Fraction of TDS load from surface returns	11%	33%	33%	12%	54%
Fraction of TDS load from sub-surface returns	89%	67%	67%	88%	46%
Estimated largest contributor of Se	Canal and lateral seepage	Deep percolation	Deep percolation	Deep percolation	Deep percolation
Estimated largest contributor of TDS	Canal and lateral seepage	Deep percolation	Deep percolation	Deep percolation	Surface Drains

Using annual constituent load values from sub-basins (Table 5.3) with total irrigated acreage within each sub-basin (Table 5.5), a normalized value for annual load per irrigated acre is computed. These values are presented in Table 5.8 and allow for the comparison of return flow loading with the magnitude of agriculture performed in each sub-basin. Annual selenium loads contributed by irrigated agriculture on a per acre basis is highest in the Loutsenhizer and Cedar Creek sub-basins. Salinity loads on a per acre basis are highest in the Cedar Creek and Dry Cedar Creek sub-basins.

Table 5.8. Normalized annual average constituent loads from sub-basins based on the model baseline conditions

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Annual average Se load (lbs/year acre)	0.29	0.37	0.47	0.02	0.06
Annual average TDS load (tons/year acre)	11.06	11.45	8.81	5.10	5.44

Unit constituent loads from sub-surface component return flows are calculated on a per sub-basin basis in Table 5.9. These calculations estimate the selenium and TDS loads associated with unit volumes of groundwater seepage that return to the River from the major sub-basins in the Uncompahgre. These values also offer a method for estimating expected load reductions from each sub-basin based on sub-surface return flow component reductions, on a mass per volume of water basis.

Table 5.9. Unit constituent loads from surface and sub-surface flows from sub-basins based on the model baseline conditions

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Unit Se load from sub-surface flow (lbs/AF)	0.16	0.11	0.46	0.01	0.02
Unit TDS load from sub-surface flow (tons/AF)	5.7	3.3	6.1	1.4	1.5

5.5 Outflows from the Uncompahgre Basin

Model-predicted characteristics of the three outflows from the basin are tabulated in Table 5.10. The confidence in the model's predictive ability for the Uncompahgre

River outflow at Delta is high. The out-of-basin predictions are less complete and include only the canal water contribution, estimates of crop consumptive use, a partition of water into surface and sub-surface components and average sub-surface constituent concentrations based on data. No direct comparison of these flows or concentrations can be made with data, as multiple tributaries drain these out-of-basin areas. USGS sampling data in these tributaries were used to characterize sub-surface representative concentrations.

Table 5.10. Annual average conditions for outflows from the Uncompahgre Basin based on the baseline model simulation

	Delta	Out of basin Above	Out of Basin Below
Annual total flow volume (AF/yr)	240,290	88,780	187,383
Total irrigated parcels (acres)	43,679	8,285	21,517
Depth per acre (ft)	5.5	10.7	8.7
Average [Se] (μg/l)	12.6	77	6.2
Average [TDS] (mg/l)	1,027	3,9512	1,264
Se load (lbs/yr)	7,106	5,609	2,712
TDS load (tons/yr)	314,449	247,947	282,177

The annual conditions show the magnitude of selenium and salt uptake that occurs as water moves through the Uncompahgre Basin. By comparing these values with Table 5.1 above, an uptake of 6301 lbs of selenium and 176,903 tons of dissolved solids are predicted to occur annually in the Uncompahgre River as it flows (with the Gunnison Tunnel as a major inflow) from Colona to Delta. The overall Uncompahgre Basin influence on the Gunnison River is predicted to be, on average 15,427 lbs of selenium and 844,574 tons of dissolved solids annually. Of those totals, the movement of water through and irrigation processes in the Uncompahgre Basin are predicted to result in the annual average uptake of 14,621 lbs of selenium and 707,028 tons of dissolved solids.

Using the annual flow values for the Uncompahgre at Delta shown above, to achieve a concentration of selenium of 4.6 μg/l, only a load of 3041 lbs/yr can be added. This general estimate for illustrative purposes shows that a reduction on the order of 4000 lbs of selenium per year would be required to be within the water quality standard at Delta.

Seasonal average conditions, shown in Table 5.11 below show one portion of the water quality compliance problem in the Uncompahgre at Delta. Seasonal average selenium concentrations exceed the standard of 4.6 μg/l. However, based on these output it appears that the water quality at the outlet of the Basin is in compliance with the temporary standard of 20 μg/l.

Table 5.11. Seasonal average conditions for outflows from the Uncompahgre Basin based on the baseline model simulation

	Delta	Out of basin Above	Out of Basin Below
Irrigation season average monthly flow (cfs)	398	205	368
Non-Irrigation season average monthly flow (cfs)	250	12	113
Irrigation season average [Se] (μg/l)	7.6	19.9	4.3
Non-Irrigation season average [Se] (μg/l)	19.6	157	8.9
Irrigation season average [TDS] (mg/l)	895	1,895	893
Non-Irrigation season average [TDS] (mg/l)	1,213	6,828	1,783
Irrigation season average Se load (lbs/day)	16.0	19.4	9.0
Non-Irrigation season average Se load (lbs/day)	24.6	10.1	5.4
Irrigation season average TDS load (tons/day)	923	1,002	937
Non-Irrigation season average TDS load (tons/day)	775	218	540

5.6 Historical Compliance to Water Quality Standards

Output from the baseline simulation of water years 1991 - 2003 is analyzed to determine seasonal averages for flow and water quality as well as compliance with water quality standards. Longitudinal plots are used to show variations in conditions throughout the river reach. Table 5.12 provides information about locations of diversions and inflows.

Table 5.12. Location information for points along the Uncompahgre River

Location number	Landmark
30	Colona
25	South Canal inflow
24	West Canal diversion
22	Montrose and Delta Canal diversion
20	Loutsenhizer Canal diversion
18	Dry Cedar Creek return
15	Selig Canal diversion
13	Cedar Creek return
12	Spring Creek return
10	Ironstone Canal diversion
9	East Canal diversion
7	Garnet Canal diversion
6	Loutsenhizer Arroyo return
5	Dry Creek return
1	Delta

Seasonal averages and estimates of the mean plus and minus one standard deviation for simulated flow, [Se] and [TDS] during the baseline time period are presented in Figure 5.1 below. These plots show the magnitudes and range of flow and concentration predictions for the irrigation and non-irrigation seasons in a longitudinal fashion.

For flow, note the changes in flow longitudinally during irrigation season. The highest river flows are just downstream from the South Canal inflow. Other diversions and returns subtract and add from the river flow throughout the reach. The lowest river flow occurs just above where the Loutsenhizer Arroyo enters the Uncompahgre. During winter the flow is more constant throughout the reach and shows gaining conditions as return flows contribute water.

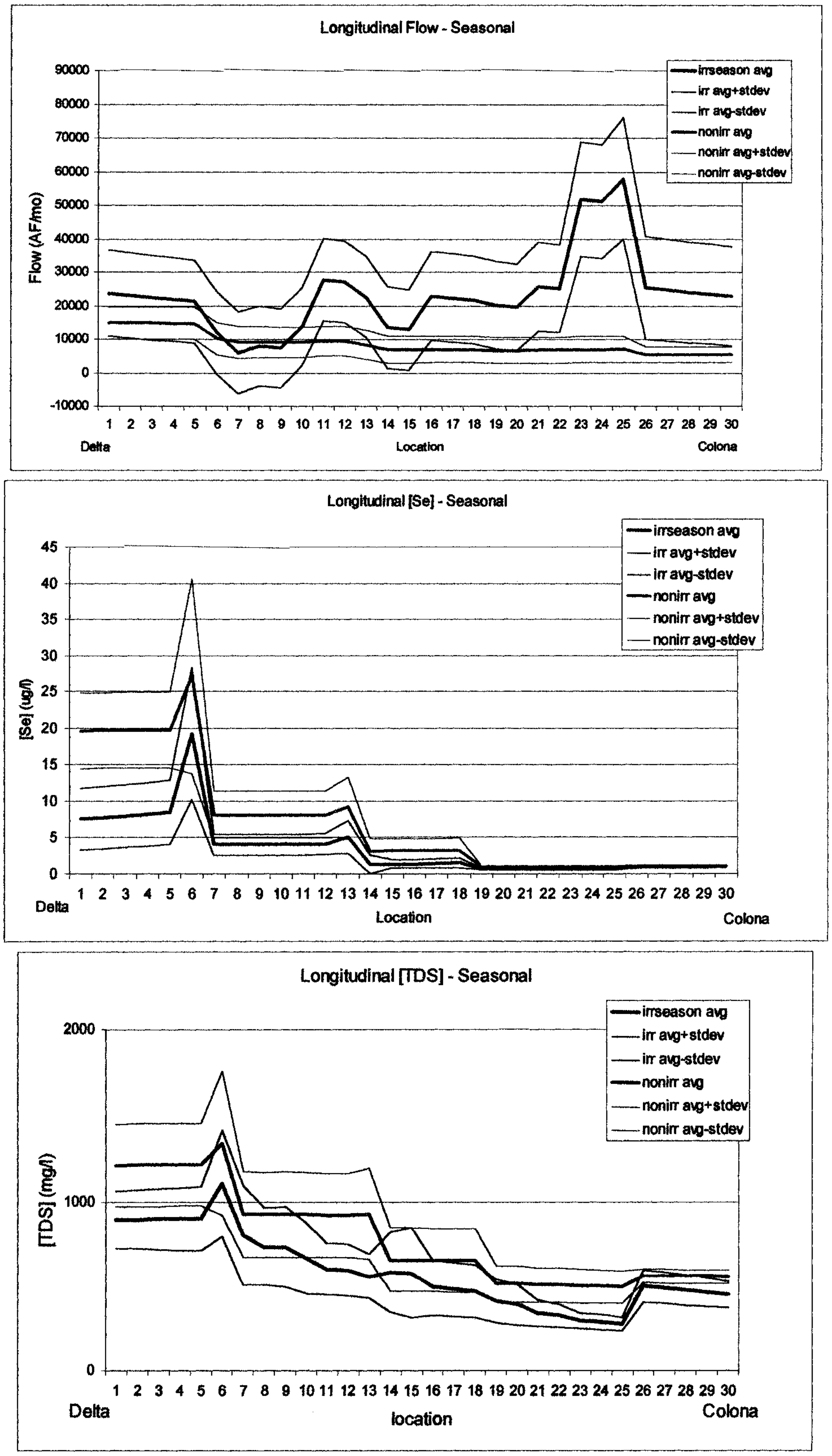


Figure 5.1. Seasonal flow and water quality averages from the baseline simulation

For [Se], the influence of tributary returns is very evident. Selenium loads enter at locations 18, 13 and 6, the Dry Cedar, Cedar and Loutsenhizer sub-basin returns. At locations 12 and 5, dilution water sources of the Spring Creek and Dry Cedar Creek enter. This pattern persists for both the irrigation and non-irrigation seasons, with higher concentrations during winter. By comparing the flow and [Se] patterns, the highest concentration in the river occurs downstream from the largest selenium source, the Loutsenhizer Arroyo, but this water returns to the river at the point of lowest flow from dewatering. This combined effect increases the concentrations in the river drastically because there is no little water to provide dilution just above Loutsenhizer Arroyo inflow.

For [TDS], the pattern is similar to that of selenium, with inflow sources and dilution sources, but changes in concentration occur to a lesser degree. Note also that the South Canal inflow provides a slight dilution effect to the water from Colona during irrigation season. The large range of [TDS] predicted in the river below the Cedar Creek and Loutsenhizer Arroyo is apparent from the large standard deviation range.

Model-predicted selenium concentrations for all months of the baseline simulation can be analyzed and the 85^{th} percentile can be calculated. Based on location and time of year, how this calculation is made changes the outcome. As shown in Figure 5.2, if the 85^{th} percentile is calculated using only output during the irrigation season for all locations in the reach, the result is the lowest and is always below 20 μg/l for the years simulated. In contrast, if only output at the worst-case location for concentration, just below the Loutsenhizer Arroyo inflow, is used for the calculation, the value is much higher and places the river conditions above the temporary standard for nearly all years.

These calculations can be compared to the expected outcomes from a large-scale sampling plan, where sampling occurs at many points in the river, each month for many months. In practice, this sampling would be cost-prohibitive, as lab analysis alone may cost $50 per sample. This plot also demonstrates how a sampling plan could be biased towards a result of either in or out of compliance. If sampling is only performed during irrigation (high flow) season and samples are taken far away from the Loutsenhizer Arroyo inflow, the 85th percentile of concentration will probably be lowest. Conversely, if samples are taken during wintertime and only just below the Loutsenhizer Arroyo inflow, the 85th percentile value will probably always be above the 20 µg/l standard, defining impairment for selenium.

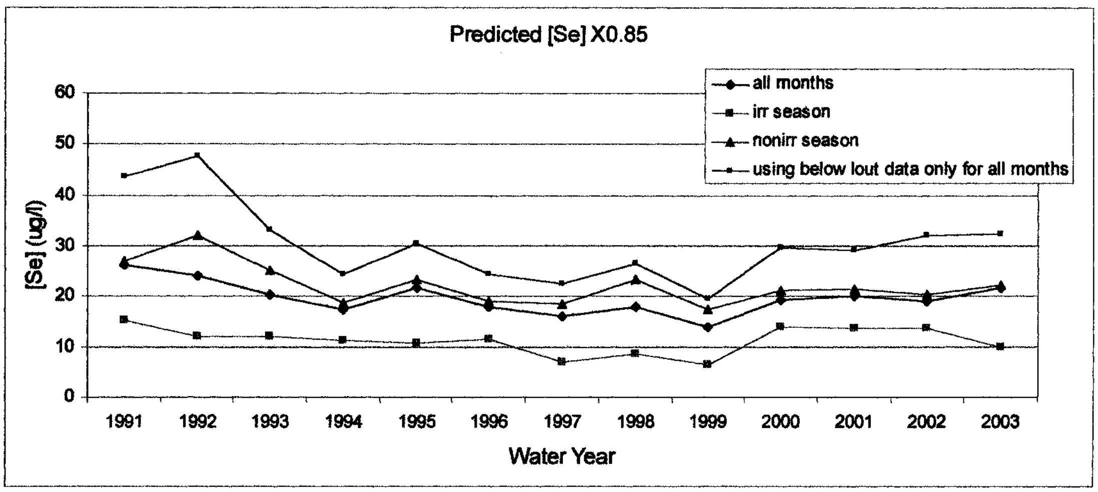


Figure 5.2. Calculation of the 85th percentile several ways based on the baseline model simulation

A longitudinal computation of the 85th percentile using all model output for [Se] during the baseline simulation is shown in Figure 5.3. For the reach between Montrose (location 14) and Delta (location 1) this plot shows that the Uncompahgre River is most surely in violation of the 4.6 µg/l standard. Based on where sampling is performed, the river may be considered in violation of the 20 μg/l temporary standard also. For areas of the River above Montrose, the river water quality is below the strict 4.6 μg/l standard.

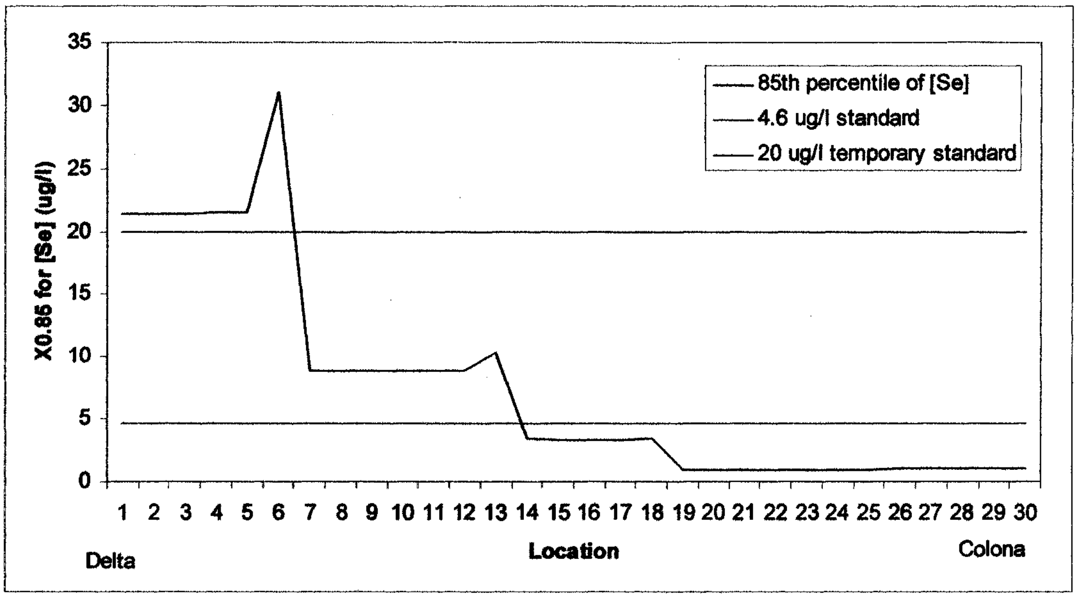


Figure 5.3. Longitudinal computation of the 85th percentile of [Se] for the baseline simulation

5.7 Influence on the Gunnison River

The Uncompahgre basin influences the Gunnison river water quality at three locations: the out-of-basin returns above Delta, the Uncompahgre inflow at the confluence at Delta and the out-of-basin returns below Delta. A complete water quality model for concentrations in the Gunnison has not been performed, but rather the influence of these three sources only is predicted. Boundary conditions for flow and water quality in the Gunnison were set based on data and the out-of-basin contributions and Uncompahgre River contributions mixed as conservative constituents and concentrations were calculated at the three locations of influence. These concentrations predictions are only based on the influence of the Uncompahgre and do not include other selenium and salt sources draining from other areas of Mancos Shale north of Delta, (e.g., Devil's Thumb Golf Course, Jay Creek, Leroux Creek, see Butler and Leib, 2002)

Figure 5.4 shows the predicted selenium concentrations in the Gunnison River as if the Uncompahgre Basin were the only contributor. Above the Uncompahgre influence, [Se] is represented as 3 µg/l. [Se] is predicted to fluctuate from that level to no higher than 10 µg/l from the "out-of-basin above" influence. The highest selenium concentrations during the year downstream of the Uncompahgre inflow range between 7 and 15 µg/l. The "out-of-basin below" contribution seems to provide a slight diluting effect. These predictions demonstrate that based on Uncompahgre influence alone, selenium concentrations in this section of the Gunnison River are above the 4.6 µg/l [Se] standard for most of each year and most likely also above the 6 µg/l temporary standard for a portion of each year.

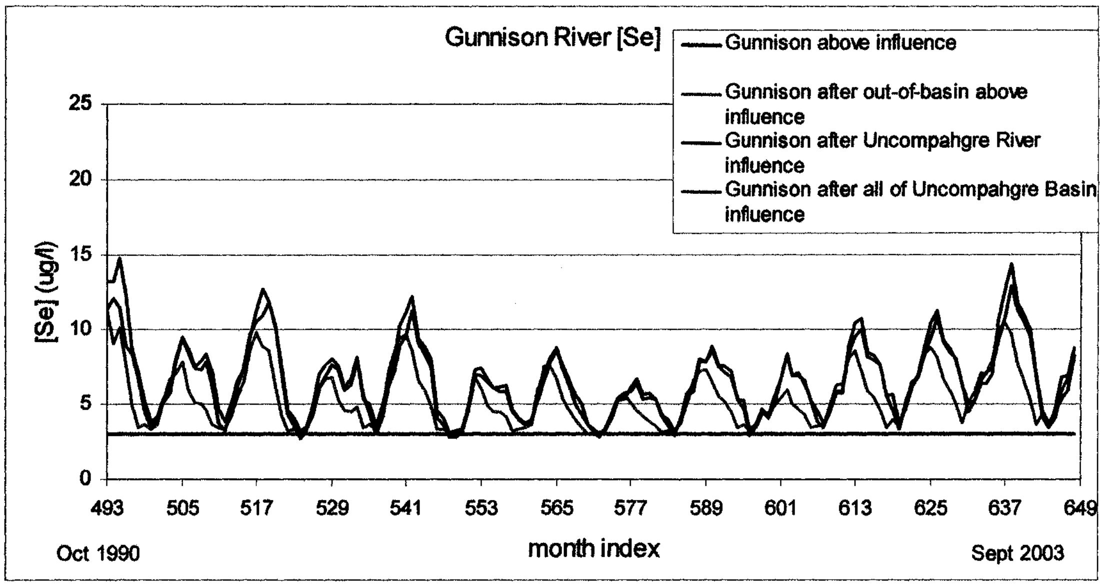


Figure 5.4. Predictions of Gunnison River selenium concentrations for the baseline model simulation as influenced only by the Uncompahgre Basin

5.8 Summary

Analysis of the calibrated and validated model output for the time frame of water years 1991 - 2003 helps to quantify the individual factors that influence the water quality impairment problem. The reach of the Uncompahgre between Montrose and Delta has elevated selenium concentrations far above the 4.6 μg/l standard. It is also likely that the 85th percentile criterion for water quality in this reach is very close to or above the temporary standard of 20 μg/l and the calculation of whether the standard is exceeded is very dependent on the location and time of year the samples are taken. The Cedar Creek and Loutsenhizer Arroyo tributaries are the highest contributors of selenium load to the river. The west-side tributaries contribute dilution water that lowers in-river concentrations of selenium. The decreased flow volume in the river as a result of diversions compounds the impact of the high concentration return water on in-river water quality.

Water for crops is provided almost fully through irrigation deliveries, since net precipitation influence is quite small. Regarding agriculture return flows, most of the volume of water returns quickly through surface drains, while most of the constituent loading is provided by a small fraction of sub-surface flow driven by canal, lateral and pond seepage and field deep percolation. From this modeling analysis, water diversions from the Uncompahgre reduce dilution water availability in some portions of the river and allow a relatively small volume of sub-surface water, returning from agriculture to drive selenium concentrations even higher. The magnitude of total constituent load that enters the river in the Colona to Delta reach is very large, both for selenium and salts. In addition to the load from the Uncompahgre River, additional constituent mass is loaded to the Gunnison directly by irrigation returns that do not drain back to the Uncompahgre River.

Based on the model predictions for the water years 1991 – 2003, the general quantifications of average basin conditions under the current water management and agriculture structure are presented in Table 5.13.

Table 5.13. Average basin conditions based on calibrated model for the baseline model simulation

	Selenium Load (lbs/yr)	Dissolved Solids Load (tons/yr)
Inflow load from Uncompahgre at Colona	491	100,141
Inflow Load from Gunnison Tunnel	314	37,405
Total load diverted from river with irrigation water	2,561	355,446
Total load returning to river from five major tributaries	9,099	316,025
Total outflow load of leaving the Uncompahgre Basin at Delta	7,106	314,449
Additional outflow load of leaving the Uncompahgre Basin via out of basin returns to the Gunnison River	8,320	530,125

A subset of data presented above in Table 5.3 is presented again in Table 5.14. The annual model predictions for each sub-basin demonstrate the magnitude of return flows in sub-basins. The return flows on a per acre basis are greater than the annual gross application water right of at most 4.76 ft/acre for Adobe soils. These high return flow values indicate that water application in sub-basins is possibly exceeding the water right value or that abundant waste or carrier flows (additional water not applied to fields to allow canals to flow properly and serve all laterals) are returning unused to the River carrying constituent load. The Cedar and Loutsenhizer sub-basins are the highest contributors of both selenium and salt loads.

Table 5.14. Average annual conditions for return flows based on the baseline model simulation

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Return water as depth per acre (ft)	5.6	11.7	3.8	4.8	4.5
Se load (lbs/yr)	396	2111	5398	140	1054
TDS load (tons/yr)	15,300	65,740	100,516	34,452	100,016

In the next chapter, the model will be used in a predictive mode in order to test various management changes and quantify expected influences on flows, instream concentrations and overall loads.

Chapter 6

BEST MANAGEMENT PRACTICE SIMULATION AND RESULTS

This chapter discusses model simulations to evaluate the impact of BMP implementation scenarios on basin-wide flows, concentrations, constituent loading and the ability to comply with water quality standards.

6.1 BMP Descriptions, Model Implementation and Results

Management practices analyzed in this study fall into five major categories: 1) canal, lateral and pond seepage changes, 2) irrigation efficiency changes, 3) total irrigated land changes, 4) treatment options and 5) combined changes. 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 tested during the sensitivity analysis. These simulations depart from the calibrated model conditions and use the model in a predictive mode. As with any modeling study, a departure from the calibrated model conditions results in a decreased confidence in the results. Confidence in the model predictions for these simulations is based on the following assumptions. 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 in-river water quality. It is assumed that changes in water management shown here do not significantly alter the hydrologic signature of return flows through sub-basins, (i.e., the surface to sub-surface partition fraction and the return flow convolution coefficients do not change). It is further assumed that changes in hydrology do not alter the geochemical processes currently occurring in the basin to a great degree and that the sub-basin average signatures of groundwater concentrations observed remain the same. Management changes designed to specifically alter geochemistry (i.e., changes in fertilizer composition) are not included in this study. While chemistry does play a large role in the complete picture, the magnitudes of water volumes loading constituent mass to the river are more directly influential and easier to quantify. Some of the scenarios focus management changes only to the east side of the basin, specifically Dry Cedar, Cedar and Loutsenhizer sub-basins. These have been shown to load the highest levels of selenium to the river based on proximity to Mancos Shale outcrops and the predominant soil type being Mancos Shale or derived from Mancos Shale. Most of these management changes are designed to move water quality towards compliance with standards. However, other changes are presented to show the influence of scenarios of future development that may occur in the basin.

Output from the BMP simulations is primarily the longitudinal 85th percentile of the predicted monthly mean concentrations of selenium ($X_{0.85}$ of [Se]), as these simulations are designed to test water quality standards compliance. Comparisons for the magnitude of change in [Se] are made between predictions of the $X_{0.85}$ of [Se] downstream at Delta, as a way of quantifying the full extent of a BMP influence on the Uncompahgre River. Changes in flow, [TDS] and load are also investigated where appropriate. The baseline simulation of water years 1991-2003 is used to test the BMP's.

This time period encompasses the calibration and validation time frames as well as the latest hydrologic data available from Hydrobase and describes a range of water year types.

6.2 Canal, lateral and pond seepage

Implementation of the BMP's in this category involves lining or piping earthen canals and laterals and lining landscape and irrigation ponds to reduce seepage. The goal of lining canals and laterals is to reduce seepage loss to sub-surface returns during conveyance of irrigation water to farms. Lining of ponds also reduces seepage to sub-surface returns while water is stored on farms. A development scenario of increased pond acreage is also presented as a "what if" scenario, to portray the influence of new pond creation on water quality. For model implementation, the lining of specific canals and laterals is not implemented, rather sub-basin wide seepage is reduced through reducing total miles of earthen canals and laterals that seep. Lining or piping a length of canal or lateral is assumed to result in the total removal of seepage water for that length for the representative width of the canal or lateral piped. A range of seepage reductions is performed by simulated lining of a fraction of the total current canals and laterals within specific sub-basins.

Starting with the knowledge that the Loutsenhizer and Cedar sub-basins provide the largest sub-surface loads to the Uncompahgre, canals and laterals in these sub-basins were "lined" first in a stepwise fashion followed by all canals and laterals in all sub-basins and the lining of all ponds. A "development simulation" was performed to predict the change in flow and water quality that might occur if the total acreage of ponds were doubled in the basin. The results from these simulations, as compared to the baseline conditions are presented in Figure 6.1.

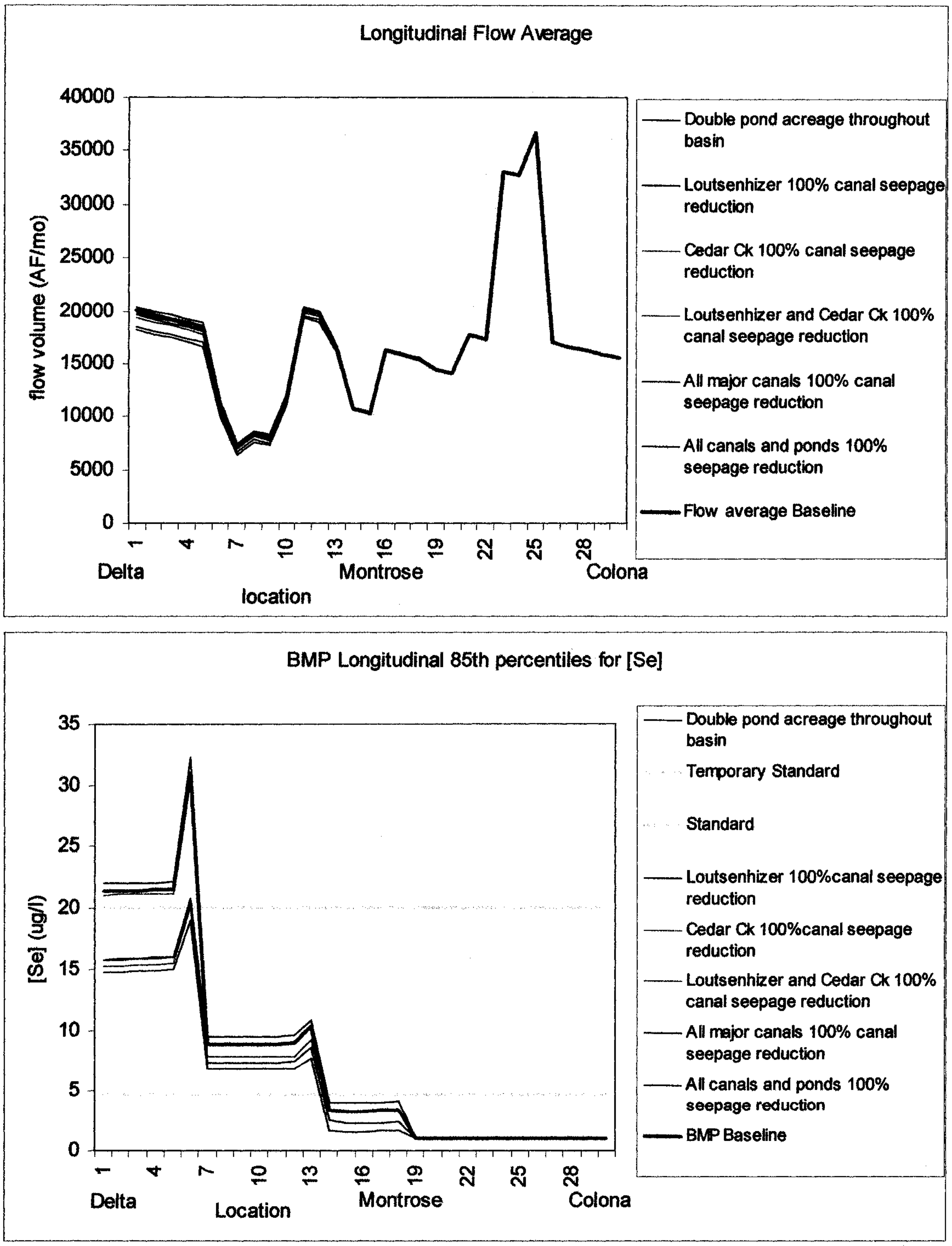


Figure 6.1. Predicted change in flow and water quality from canal, lateral and pond seepage BMP's

The relatively small change in flow was first evident from the levels of lining. The change in average flow at Delta for the lining of all canals in Loutsenhizer sub-basin (26 miles of canals and 53 miles of laterals) is only 434 AF/mo. However, this small change in seepage results in a change in the 85^{th} percentile of [Se] at Delta by 5.7 μg/l, or a reduction of 27% from the baseline. By lining all canals and laterals in the Cedar Creek sub-basin, only 263 AF/mo on average is reduced, with about a 0.4 μg/l reduction in [Se] at Delta. By lining the canals and laterals in both the Loutsenhizer and Cedar Creek sub-basins, 697 AF/mo of seepage on average could be reduced, with a decrease of the 85^{th} percentile of [Se] by 6.2 μg/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 2,402 lbs of selenium per year and 36,387 tons of dissolved solids per year. This BMP also reduces the total constituent load to canals by an average of 185 lbs of selenium per year and 3,583 tons of salts per year.

Complete lining of all canals that would provide seepage water to the Uncompahgre, (served by the seven of the eight major diversions as Garnet canal seepage would return out-of-basin), would require the lining of 78 miles of canals and 185 miles of laterals. The influence of this would decrease the average flow at Delta by 1525 AF/mo on average and reduce the 85^{th} percentile of [Se] by 5.7 μg/l. Some dilution water received from the west-side seepage would be lost through this complete lining and the concentration of selenium is predicted to be slightly higher than if just Cedar Creek and Loutsenhizer Arroyo sub-basins were lined. Pond lining throughout the basin is predicted to reduce seepage by 343 AF/mo when ponds are full and decrease the $X_{0.85}$ of [Se] by 1 μg/l.

A comparison of the benefit of lining laterals in Cedar Creek sub-basin to lining an equivalent length of laterals in the Loutsenhizer sub-basin is presented in Figure 6.2. This simulation reduces seepage from laterals only (with representative wetted perimeters of 7 feet), not the canals serving them. In this case nearly equal volumes of seepage are reduced in each sub-basin (97 AF/mo in Cedar, 82 AF/mo in Loutsenhizer). The slight differences occur because the canals in these sub-basins do not operate the same number of months. Lining 20 miles of laterals in Cedar Creek sub-basin reduces the $X_{0.85}$ for [Se] downstream at Delta by 0.14 μg/l and reduces the average total selenium and salt loads at Delta by 89 lbs/yr and 2,841 tons/yr, respectively. Lining the same length of laterals in the Loutsenhizer sub-basin results in a slightly larger decrease in downstream selenium concentrations of 0.98 μg/l at Delta and reduces the average total selenium and salt loads at Delta by 416 lbs/yr and 5,588 tons/yr, respectively. While this degree of lateral lining is predicted to reduce groundwater seepage, reduce selenium load and reduce Uncompahgre River [Se], the magnitude of the predicted change in the 85^{th} percentile of [Se] downstream at Delta is quite small. The detection of this small change through field sampling would require a rigorous sampling plan.

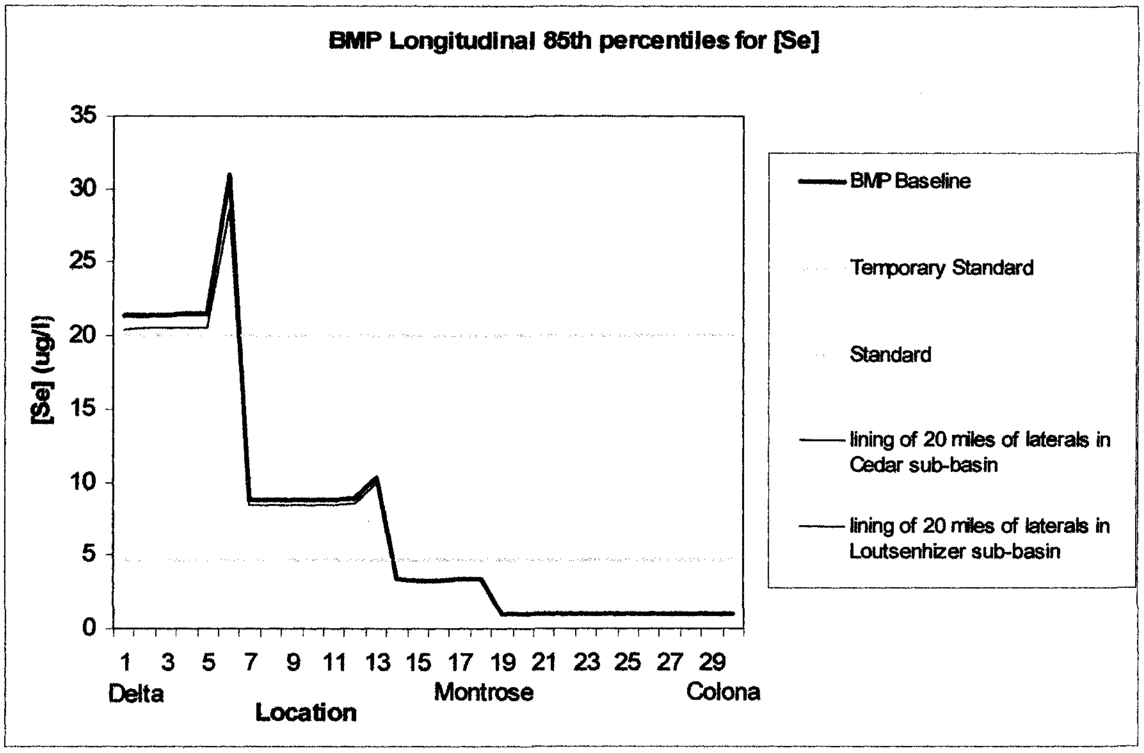


Figure 6.2. Comparison of predicted water quality changes from equivalent canal lining in Cedar and Loutsenhizer sub-basins

The scenario that results in the highest change in [Se] per unit change in seepage would be any lining in the Loutsenhizer Arroyo sub-basin. The representative sub-surface concentration of groundwater in this sub-basin is highest, and the outlet of this sub-basin is downstream of all diversions (with the exception of diversion of a portion of the Loutsenhizer Arroyo to the Garnet Canal), discharging to an area of the Uncompahgre with the lowest dilution capacity, caused by low flows below other diversions.

The results from these simulations rely fully on the spatial data describing canals and laterals within sub-basin boundaries and estimates for total canal and lateral length, wetted perimeters of canals and laterals as well as seepage estimates. An implementation of canal lining or piping in the field may not result in a uniform change in seepage per unit length of earthen canal due to soil variations.

Based on the lateral piping study that has been performed, a total of 8.5 miles of laterals have been piped in the area of the Cedar Creek sub-basin at a cost of $1.3 million or $173,000 per mile of lateral (Catlin, 2004) with plans in place for twenty more miles to be piped. Extrapolating this cost estimate, piping all the canals and laterals in the Cedar Creek sub-basin would cost $7.6 million, and for the Loutsenhizer sub-basin an estimated $13.7 million. An estimated cost analysis for the Loutsenhizer sub-basin piping would result in $13.7 million for a change in $X_{0.85}$ of [Se] of 5.7 μg/l, or $2.4 million per 1 μg/l concentration reduction.

6.2.1 Montrose Arroyo Piping Project Simulation

The USGS demonstration BMP project involving lateral piping in the Montrose Arroyo area (Butler, 2001) was simulated by the model. This demonstration project involved piping 8.5 miles of laterals in the Cedar Creek sub-basin (Montrose Arroyo is a major tributary of Cedar Creek). In the study, flow and water quality sampling were performed before and after piping to estimate changes in groundwater seepage and selenium load as a result of the BMP implementation. For model simulation of this demonstration project, the total length of laterals in the Cedar Creek sub-basin was reduced by 8.5 miles and the model output compared to the historical baseline.

Predicted seepage reduction from the Cedar Creek sub-basin was on average 41 AF/mo (or 4.9 AF/mo/mile of lateral) as compared to 6.6 AF/mo/mile of lateral calculated from the study data (see section 2.3 for more details of this calculation). Selenium load reduction at the Cedar Creek outlet was predicted to be only 54 lbs/year as compared with the 194 lbs/yr at the Montrose Arroyo outlet presented in the report. The reason for this discrepancy lies in the slight differences in seepage changes between the measured and modeled as well as a large difference in the representative concentrations of groundwater estimated (see section 6.8 for more information regarding the groundwater concentration differences). Loads of total dissolved solids (salinity) were also predicted to be reduced through the reduction in sub-surface flow as a result of the canal lining. In the study, a load reduction of 2,900 tons salt/yr below the piping area was reported. In the model simulation, an average annual reduction of 1,613 tons/yr of TDS was predicted at the Cedar Creek sub-basin outlet.

No downstream changes in concentration or load were presented in the USGS report. Compared to the baseline simulations, this small-scale BMP results in an average reduction in selenium load at Delta of 38 lbs/yr (0.534 % reduction from the baseline conditions) and 1,251 tons/yr TDS reduced at Delta (0.398 % reduction from the baseline conditions). Downstream concentrations were reduced only very slightly, the 85th percentile of [Se] at Delta was reduced by 0.06 μg/l.

The model predictions show more conservative flow and load changes as compared to those reported by the USGS. Considering either the study results or the model predictions, the changes in load and concentration downstream at Delta as a result of this BMP implementation are most likely very small.

6.2.2 USBR Hydrosalinity Study Comparison

A salinity reduction BMP modeling study was performed by the USBR (1982). In this study, a simulation of seepage reductions through removal of winter diversions for stock watering and concrete lining of all Uncompahgre Basin east side canals and laterals was performed. The results of this study indicate that a decrease in annual average salt load of in the range of 53,990 - 60,060 tons/yr could be realized through the lining of 58.9 miles of canals and 195.4 miles of laterals.

A comparison simulation was performed using the present model. All major canals and laterals in the Dry Cedar, Cedar and Loutsenhizer sub-basins (total of 39.7 miles of canals and 97.3 miles of laterals) were "lined" and the total TDS load compared with the baseline simulation. The average annual TDS load reduction predicted at Delta was 40,472 tons/yr. The total length of canals and laterals considered in the USBR study is larger than the total length in the sub-basins contributing return flow to the Uncompahgre. The two model predictions are similar, as should be expected based on the use of the same unit canal seepage data. However, the predicted TDS reductions from this study are slightly conservative compared to the salinity reductions predicted by the USBR study.

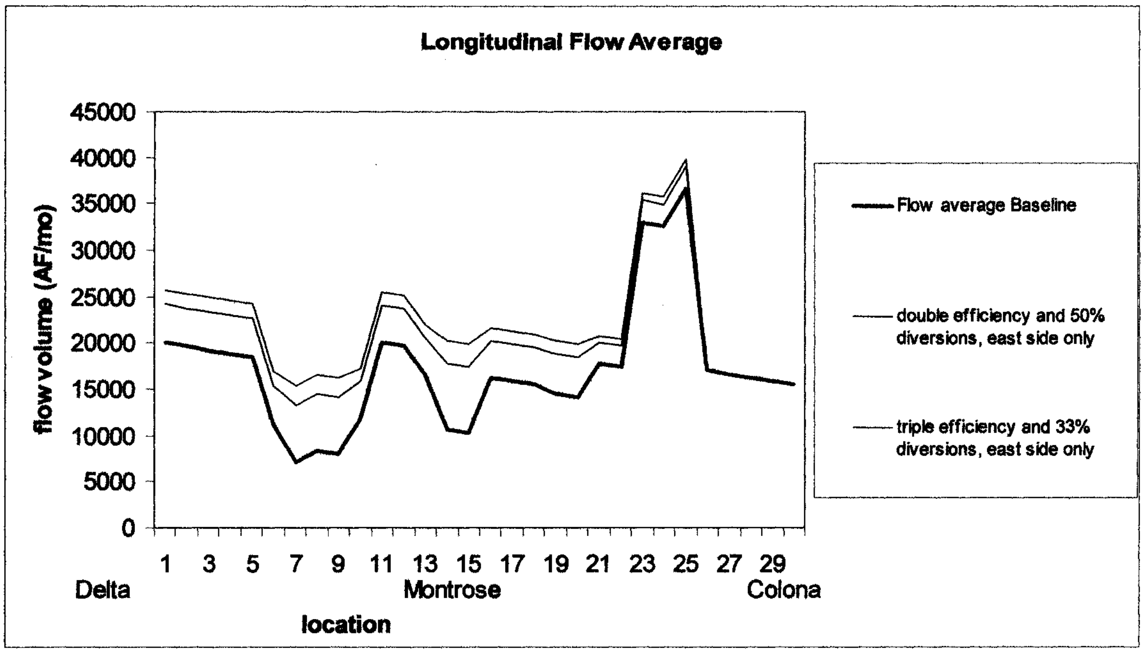
6.3 Irrigation Efficiency Changes

These BMP simulations involve synthetic changes from the current predominant use of furrow irrigation to increased use of sprinkler or drip systems. It is assumed that the total consumptive use to grow crops is satisfied with the new technologies even though water application rates are greatly reduced. Implementation of these management changes in the model involves adjusting the gross application rates to sub-basins such that the ratio of the CU to application is the prescribed irrigation efficiency. The sub-basin water balance components from the model are checked to ensure that the target efficiencies and consumptive uses are met. In these scenarios it is assumed that diversions from the Uncompahgre are changed correspondingly and an increase in irrigation efficiency has an accompanying decrease in river diversion. The assumption of a corresponding diversion reduction is made here to illustrate management changes that would have the greatest influence on downstream water quality. When irrigation efficiencies are increased without corresponding diversion reductions, the change in water quality is greatly reduced (see figure 6.4 below).

These simulations are similar to the simulations of change in irrigated acreage described below. Both effectively reduce the total volume of water applied to sub-basins with a corresponding change in river diversion, but in these simulations it is assumed that the current level of farm production and consumptive use are unchanged. These simulations assume that flexibility exists for changing water distribution to irrigated parcels in areas of the basin. Given the water rights structure and the senior water right held by the Uncompahgre Value Water Users Association, changes in diversions to accompany changes in irrigation efficiency may be difficult to implement legally. The sub-basin irrigation efficiencies for the baseline are presented in Table 6.1, and simulation results are presented in Figure 6.3.

Table 6.1. Irrigation efficiencies in sub-basins based on the calibrated model baseline simulation output

	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry
Baseline irrigation efficiency (CU/application)	30%	19%	26%	31%	24%



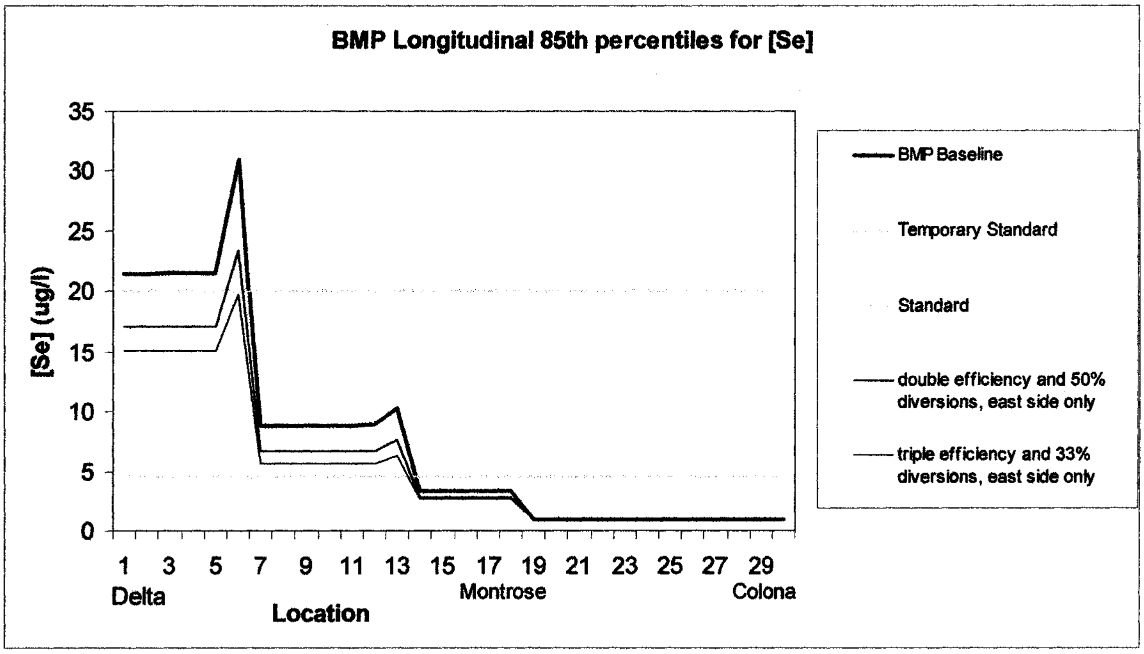


Figure 6.3. Changes in flow and water quality with changes in irrigation efficiency

By increasing irrigation efficiency, return flows and constituent loading are reduced. By reducing diversions more water is left in the river for dilution of return flows carrying load. Doubling the irrigation efficiencies in the Dry Cedar, Cedar and Loutsenhizer sub-basins as well as diverting only 1/2 of the historical volumes in the South, Loutsenhizer, East and Selig Canals, flows in the river are increased by 4,147

AF/mo on average with a decrease in $X_{0.85}$ of [Se] at Delta of 4.4 μg/l. This management change is predicted to reduce selenium load at Delta by 1,402 lbs/yr. The total constituent load to canals is also predicted to change dramatically through improved source water quality and reduced diversions; a reduction in selenium load of 1,168 lbs/yr and salt load of 102,576 tons/yr is to canals predicted. Tripling the irrigation efficiency and reducing the diversions to 1/3 of the historical levels further increases flow and reduces return flow, reducing in-river concentrations. Due to the decrease in diversions, flows at Delta are predicted to increase an average of 5,688 AF/mo. A predicted reduction in the $X_{0.85}$ of [Se] at Delta would be 6.4 μg/l (a 30% reduction from the baseline), with a corresponding reduction of load at Delta of 2,041 lbs/yr of selenium. Tripling the irrigation efficiency would be a difficult enhancement probably involving well-managed drip systems, however the change in return flow and loading from sub-basins would be substantial. For example, the total return flow from the Loutsenhizer Arroyo sub-basin is predicted to be decreased by 30,432 AF/yr (a 69% reduction from the baseline of 43,924 AF/yr). The total selenium loading would be reduced by 2,243 lbs/yr (a 42% reduction from the baseline of 5338 lbs/yr). The total TDS load would be reduced by 53,980 tons/yr (a 54% reduction from the baseline of 99,806 tons/yr).

If an increase in irrigation efficiency is not followed by a corresponding reduction in diversion, a lesser benefit to river water quality is predicted. A simulation was performed to illustrate this point where the east-side irrigation efficiencies were doubled but the diversions were left to their historical values. In this case it was assumed that the diversion water that was not applied in a sub-basin (because of decreased application needs from irrigation efficiency changes), was directed into the drain network to return to the sub-basin outlets via the surface. The results from this simulation in comparison with the doubled efficiency change with reduced diversion are presented in Figure 6.4.

The model predictions for the efficiency change with diversion reduction shows an increase in the water left in the river as well as reduction in concentration due to the combined effect of reduced seepage and dilution water availability. The simulation where the diversions are left at historic levels shows little change in river flows compared to the baseline as water is diverted and simulated to return to sub-basin outlets as occurs in the baseline. However, through irrigation efficiency changes, not as much water is applied to fields as done in the baseline, but just flows through the drain system back to the river with only a small amount of selenium uptake, as it flows through the canal and drain network. The result of the decreased sub-surface flow, compared to the baseline reduces constituent loading and in-river concentrations, but high concentrations are still seen in parts of the reach since the dilution capacity of the river is the same as the baseline. If unused application was to flow out of the basin in canals instead of returning through sub-basin drains, less water would be predicted in the river reach, reducing the dilution capacity, possibly increasing localized concentrations even higher.

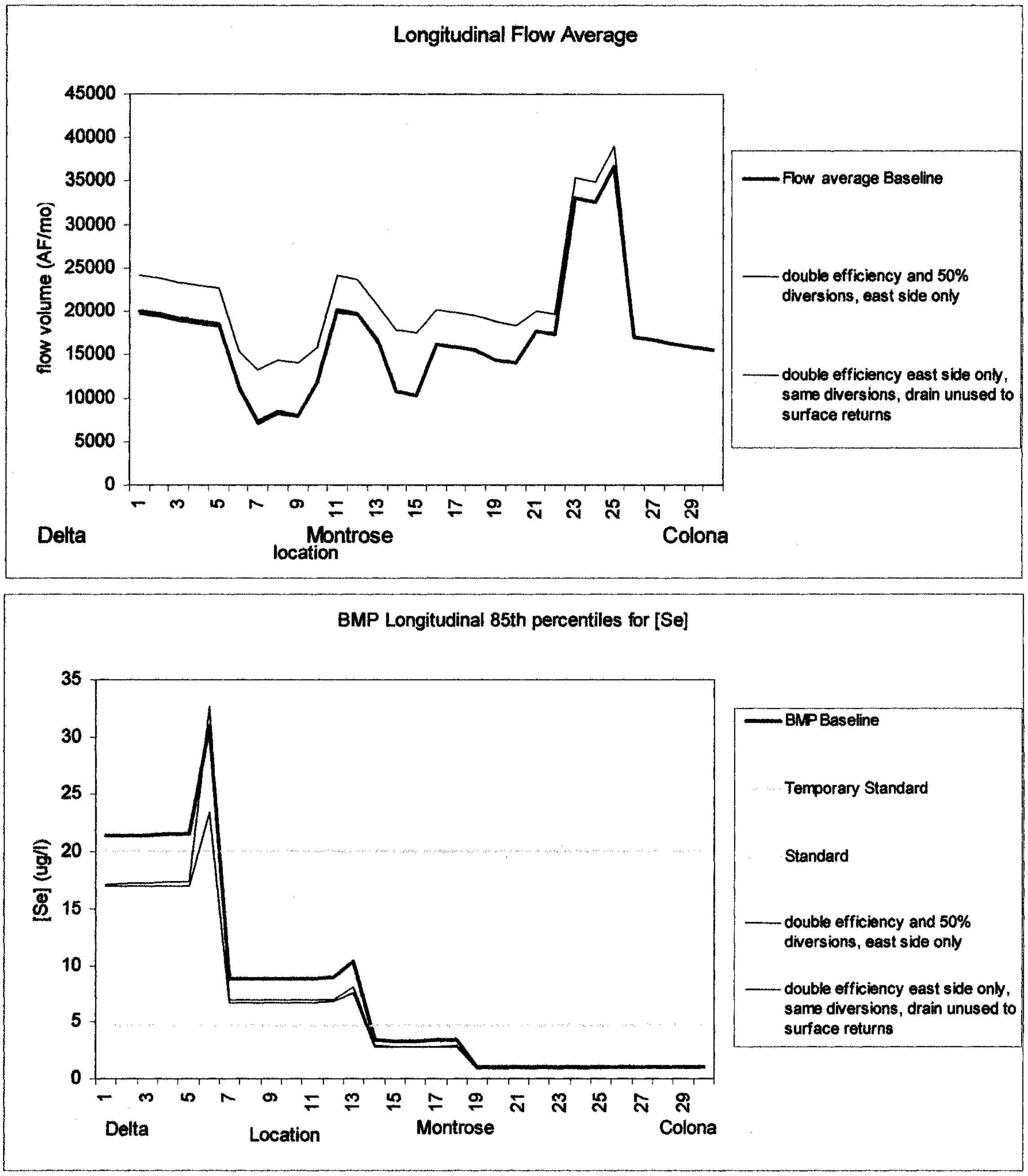
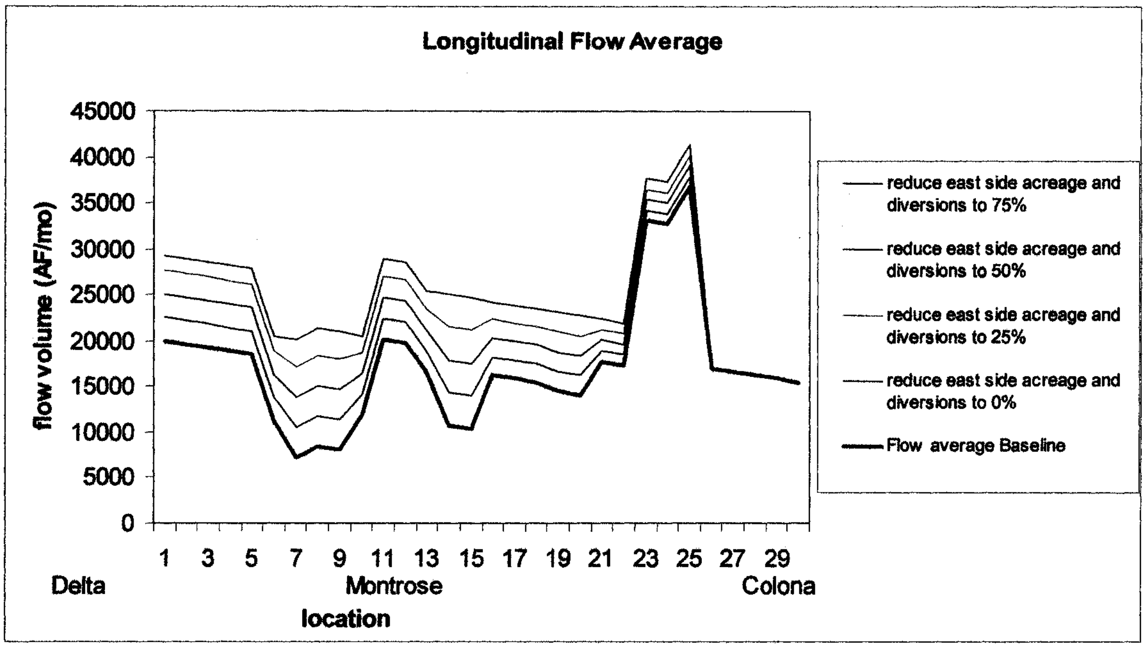


Figure 6.4. Comparison of simulations with efficiency changes with and without diversion changes

6.4 Total Irrigated Land Changes

These model runs simulate changes in total irrigated lands throughout the basin. Reduction of total acreage of irrigated agriculture is demonstrated as lands are retired from cropping or converted to sub-divisions or ranchettes. This management change assumes land is taken out of production and the water rights tied to that land are transferred to an instream beneficial use instead of being diverted for agriculture. This scenario is synthetic, as the transfer of water rights would undoubtedly be a complex water court issue as well as a potential economic loss for farmers in the basin. In these simulations, the total irrigated acreage, total water applied in sub-basins and river diversions are altered. The parameters for total irrigated acreage and historical diversion fraction to use are altered to simulate a fractional change in irrigated land use. When changing acreage, these simulations assume that the application patterns within a sub-basin are the same as the current conditions, i.e., there is no change in irrigation efficiency, just a change in total acreage served. The influence of precipitation, evaporation and consumptive use are tied to total irrigated acres in a sub-basin, so by reducing the total area, the effective precipitation volume, evaporation volume and volume of consumptive use will all be decreased. Simulation results are presented in Figure 6.5.



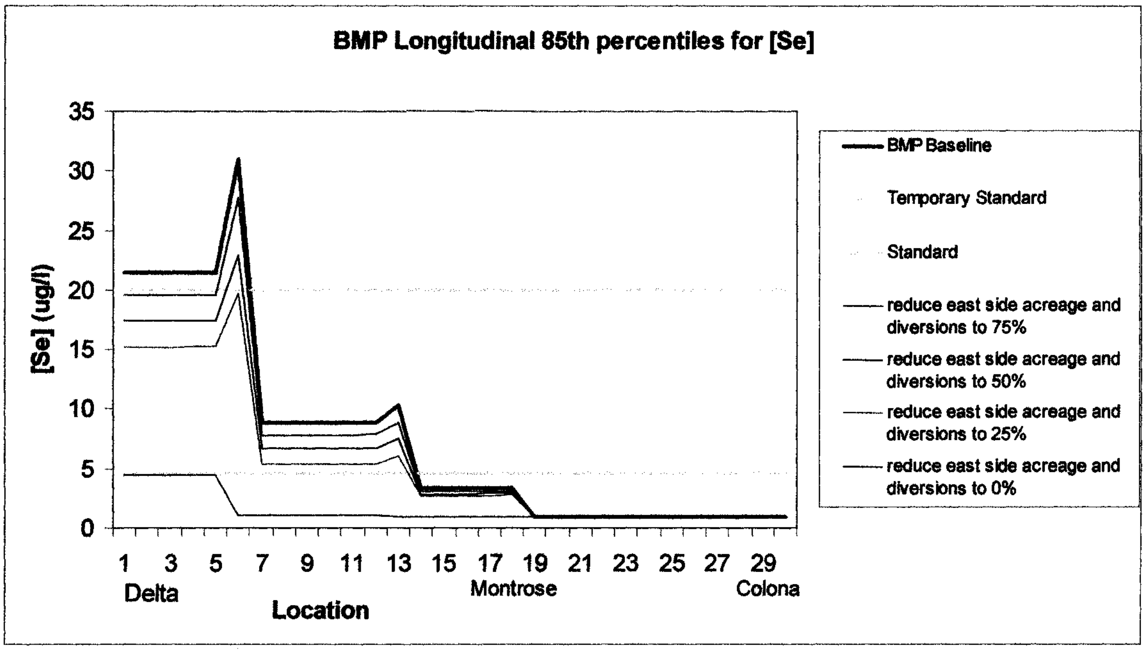


Figure 6.5. Predicted changes in flow and water quality from changes in irrigated lands

The management options simulated are changes in irrigated acreage to 75%, 50%, 25% and 0% of the current levels on the east side of the valley only. The diversions volumes in the South, Loutsenhizer, Selig and East Canals are reduced accordingly to 75%, 50%, 25% and 0% of their historical volumes. Diversion reductions of 75%, 50%, 25% and 0% of historical result in the average flow at Delta to be increased 2550 AF/mo, 5100 AF/mo, 7632 AF/mo and 9271 AF/mo, respectively with corresponding reductions in $X_{0.85}$ of [Se] at Delta of 1.9 μg/l, 4.1 μg/l, 6.3 μg/l and 17.0 μg/l, respectively (with reductions of 9%, 19%, 29% and 79% from the baseline, respectively). The predicted average selenium load at Delta for these four simulations show reductions of 256 lbs/yr, 939 lbs/yr, 1793 lbs/yr and 5804 lbs/yr, respectively. These management changes are predicted to reduce the constituent loads to canals by 652 lbs/yr, 1118 lbs/yr, 1482 lbs/yr and 1934 lbs/yr, respectively for selenium and 53,369 tons/yr, 102,439 tons/yr, 142,407 tons/yr and 181,032 tons/yr for salt. The most drastic change involving total removal of all irrigated land on the east side (18,538 acres in Mancos Shale). This measure is predicted to reduce the selenium concentrations in the river below the 4.6 μg/l standard while reducing the total salt load from the basin by 20,290 tons/yr.

Land retirement in the Loutsenhizer and Cedar Creek sub-basins would be most beneficial to overall water quality, as these regions contribute the highest combined selenium and salt loads estimated from the baseline model simulation on an average annual load per acre basis (refer to Table 5.8). Therefore decisions on retiring lands in these areas would be highest priority for reducing constituent loading for standards compliance.

6.5 Treatment Options

These simulations involve no water management changes, but rather implement a reduction in selenium in return water by water treatment. Water treatment options are available (e.g., Chow et al. 2004), but may not be feasible given the magnitude and timing of return flows. Many of the treatment methods involve batch treatment of water similar to what is often performed to reduce concentrations of toxics in mining leachate. The effectiveness of these treatments is highest at extremely high concentrations (above 10,000 μg/l dissolved selenium) and multi-stage treatment would be required to obtain water "clean" of selenium at the 0.5 μg/l concentration (James J. Gusek, Golder Associates, personal communication). However these simulations are presented in order to demonstrate the magnitude of reductions that would be required for strict water quality compliance.

Three treatment simulations are performed, to clean the outlet water from the Loutsenhizer Arroyo, clean both the Cedar Creek and Loutsenhizer Arroyo outlets and finally to clean all sub-basin outlets. These options are assumed to not alter flows anywhere in the basin. The changes in predicted concentrations are presented in Figure 6.6.

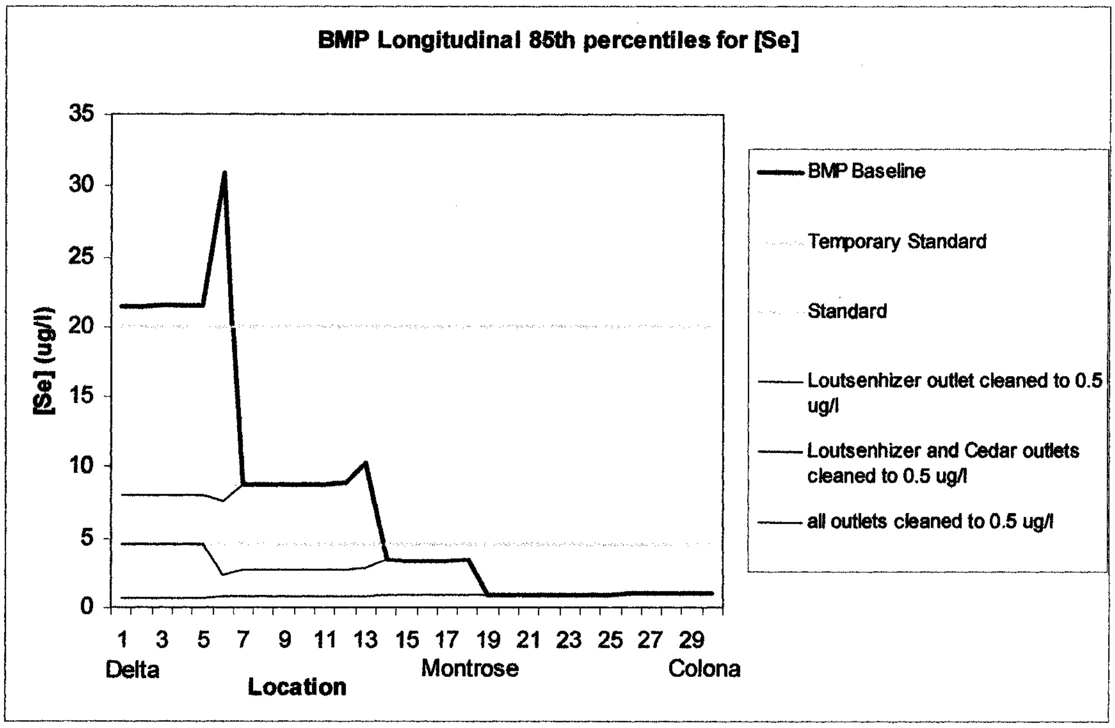


Figure 6.6. Changes in [Se] predicted by treatment BMP's

By cleaning the highest contributing sub-basin, the Loutsenhizer, to a constant concentration of 0.5 μg/l dissolved selenium does not fully bring the reach into compliance. The influence of the Cedar Creek is very apparent, driving the concentrations in the river to 8.8 μg/l for $X_{0.85}$ of [Se]. By reducing the concentrations of the return water from both the Loutsenhizer and the Cedar Creek, the river is predicted to be in compliance with the 4.6 μg/l concentration. Again the Dry Creek is the driver of the downstream concentration, but this still allows for compliance. By reducing the concentration in all sub-basin outlets, a concentration of 0.6 μg/l is maintained, where the outlets are now diluting the 1 μg/l upper basin inflow water.

6.6 Combined Changes in Management

This scenario involves combining a reasonable level of management practices in an attempt to meet strict water quality standards. For this simulation return flows from the east side are curtailed through piping all canal and laterals, lining all ponds and reducing irrigation deliveries to 50% of the historic levels to the current acreage. The transfer of water from the Loutsenhizer arroyo outlet to the Garnet Canal is also removed. Diversion to the Ironstone Canal is reduced to 50% and the diversion to the Garnet Canal is removed. These changes in diversion at the downstream portion of the river will reduce dewatering in the area with the highest return flow loading. The predicted water quality conditions for this complex management scenario are presented in Figure 6.7.

The combined effect of these management changes is predicted to increase the average discharge at Delta by 8017 AF/mo on average and reduce the selenium concentrations at Delta by 13.6 μg/l. The elevated concentration just below the Loutsenhizer Arroyo inflow is drastically reduced in this case through a combination of reduced loading through return flow reduction and higher volumes of receiving water in the river. While the model predicts that concentrations are above the 4.6 μg/l strict standard, this large reduction is a big step forward still allows for large-scale crop production in the Basin. The influence on the Gunnison River water quality is shown in Figure 6.8. The range of [Se] in the Gunnison downstream of the Uncompahgre influence is always below 6 μg/l and for this simulation, has an $X_{0.85}$ for [Se] of 4.7 μg/l.

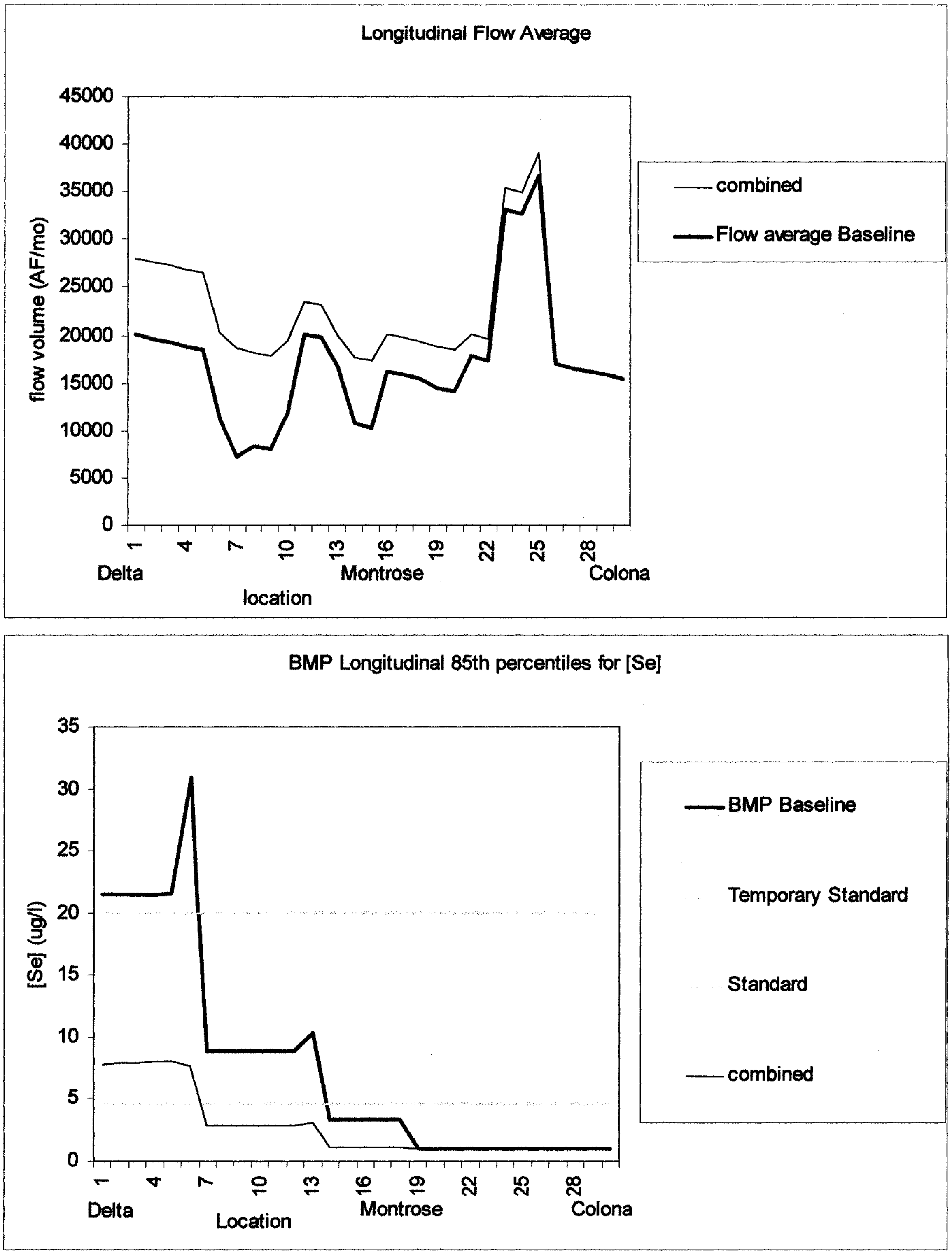


Figure 6.7. Water quality predictions for the reasonable combined management scenario

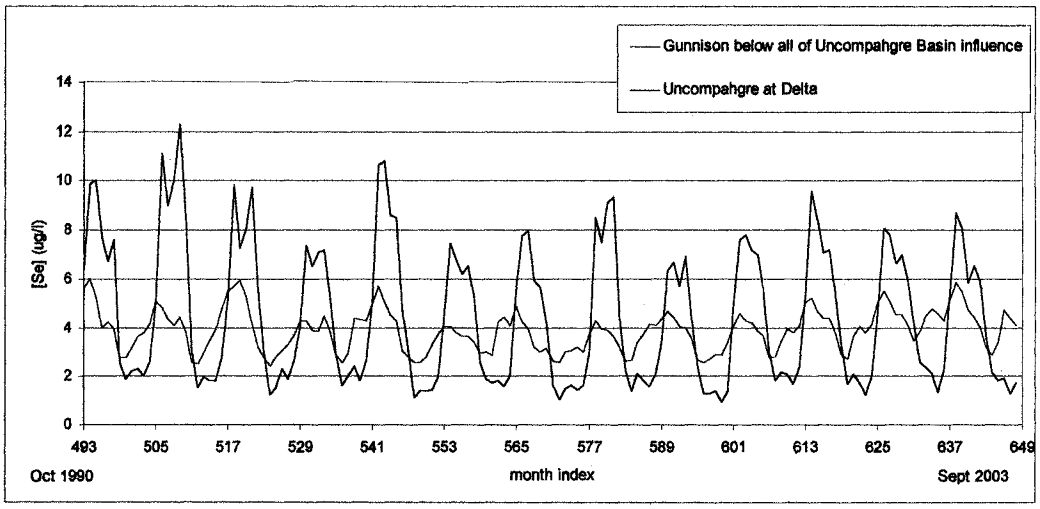


Figure 6.8. Uncompahgre and Gunnison River monthly selenium concentrations as predicted for the combined management scenario

6.7 Natural Conditions

This simulation is not a management change per se, but a modeling simulation created in an attempt to recreate natural conditions before basin-wide irrigated agriculture. The results from this simulation act as a "best-case scenario" and a set of water quality conditions that shouldn't be expected to be improved upon by any water management scenario. In this simulation, the flow from the Gunnison tunnel is set to zero, baseflow is set to zero (baseflow is assumed to be a combination of groundwater and surface flow from small tributaries or return flows from smaller diversions not specifically modeled and provides no additional selenium load), and all diversions and crop consumptive uses are set to zero. Precipitation is the only source of water to sub-basins and provides a small volume of return flow. This return flow is mixed with the water that naturally flowed into the basin at Colona to drive concentrations in the reach of interest. In this simulation, sub-basin representative average groundwater concentrations are set to be the same as the current calibrated model conditions. These concentrations could be similar to long-term, steady-state concentrations seen in groundwater when natural precipitation conditions exist. Under natural conditions, the groundwater is recharged only by precipitation, resulting in lower volumes of flow compared to the current irrigated conditions. One simulation is performed to present the lower bound of possible conditions under the baseline level of precipitation. The flow and water quality predictions are presented in Figure 6.9.

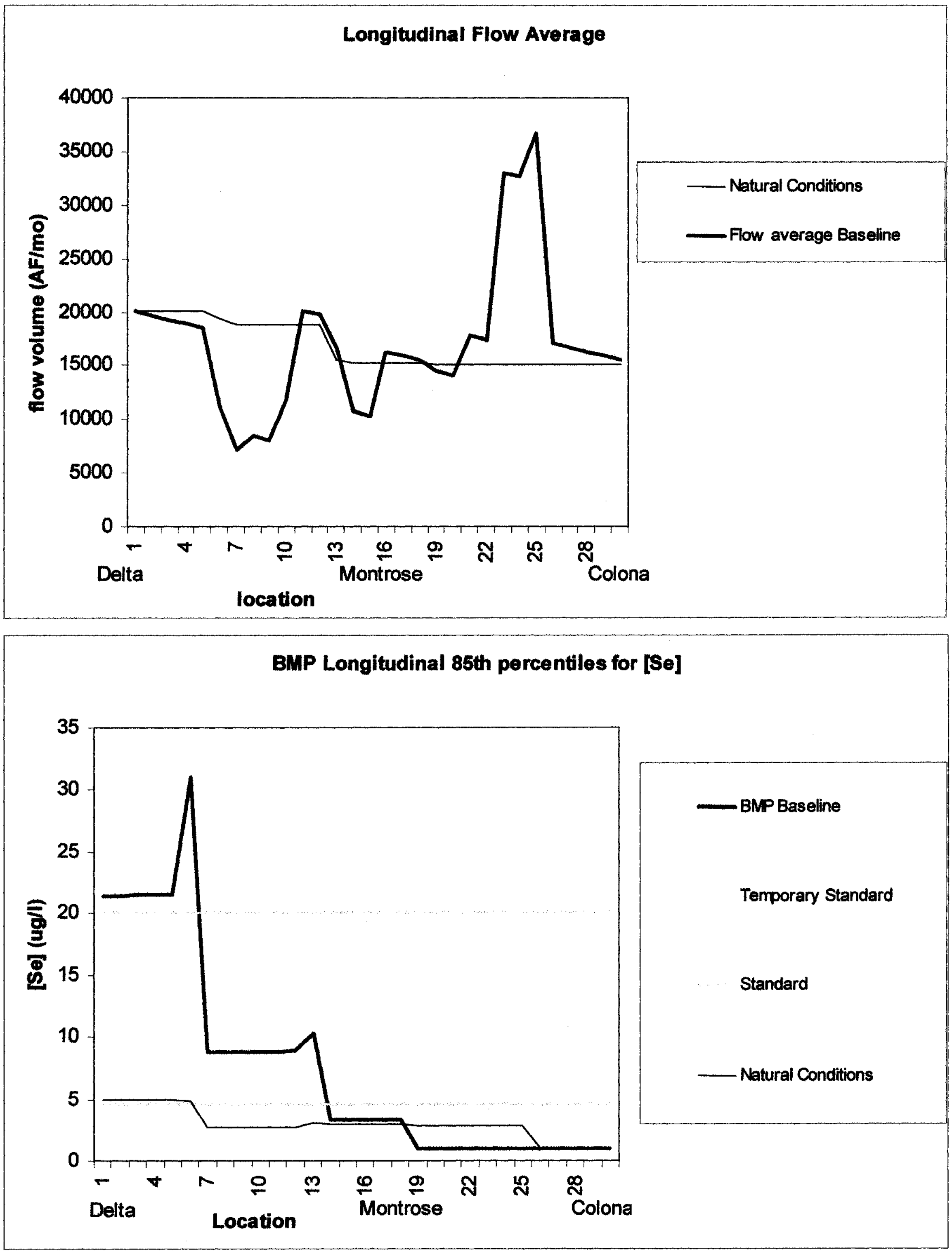


Figure 6.9. Natural conditions water quality simulation output

The model predicts that under natural conditions prior to development, dissolved selenium concentrations were likely to be within the water quality compliance limits set forth by the state. The influence of tributary inflows is apparent in changing concentrations as water moves downstream. Most inflows are predicted to increase concentrations slightly even when only driven by natural precipitation. Based on these model predictions, the 4.6 mg/l standard for selenium may just barely have been met in the Uncompahgre River prior to the Gunnison Tunnel and the extensive irrigation in the Uncompahgre Basin. The reduction in selenium concentration is also predicted to occur with little if any change in average flow at Delta. The influence on the Gunnison River under natural conditions is presented in Figure 6.10. In this scenario, the Gunnison River downstream from the full influence of the Uncompahgre Basin also shows greatly reduced selenium concentrations rarely greater than 3 μg/l. The Uncompahgre River concentrations are driven solely by groundwater seepage served by the baseline level of precipitation, and based on the sub-basin surface to sub-surface flow partitions and representative groundwater concentrations of the calibrated model. If pre-irrigation groundwater flow process and representative groundwater concentrations were significantly different, the in-river concentrations could have been different. This simulation is most likely conservative and presents the lower bound of in-river conditions before large-scale irrigation in the Uncompahgre Basin.

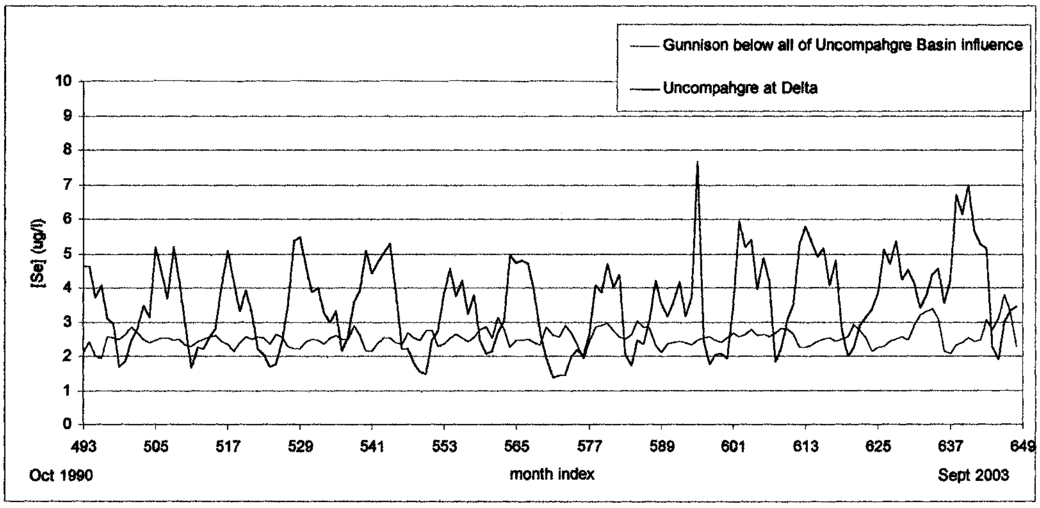


Figure 6.10. Uncompahgre and Gunnison River monthly selenium concentrations as predicted for the natural conditions scenario

6.8 Groundwater Variability in the Context of Sub-basin Average Conditions

The conceptual model used in this study assumes that the sub-basin outlet conditions represent the average set of conditions at the outlet as a result of variability and complexities throughout the sub-basin. Hence, variability in soil chemistry, while not specifically modeled, is included in the outlet conditions. For example, one sub-basin wide groundwater concentration is used per sub-basin. From sampling data inside the sub-basins, both higher and lower concentrations in selenium and salts have been found in seeps, possibly as a result of locally higher concentrations "hot spots" and locally lower concentration "cold spots" throughout the sub-basin. The overall influence of these hot and cold spots on outlet water quality is portrayed by the model. Using sampling data for seeps in sub-basins, ranges of possible groundwater concentration are found. By comparing the maximum and minimum concentrations to the sub-basin average used in the model, a weighted average representation can be built to define fractions of sub-basin seepage at those high and low concentrations that could exist while still satisfying the overall sub-basin average.

For example, in the Loutsenhizer sub-basin, USGS sampling data for dissolved selenium concentrations range between 0.5 μg/l and 5450 μg/l. The sub-basin average groundwater quality used in the model (based on winter concentration sampling data at the sub-basin outlet), is 170 μg/l. Based on the range of concentrations and the outlet average, only about 3% of the groundwater can be of the high concentration of 5450 μg/l and still allow for an average of 170 μg/l (170 = 0.5 * 0.969 + 5450 * 0.031).

A similar comparison of concentrations is seen in the Cedar Creek sub-basin. In the Montrose Arroyo piping study (Butler, 2001), a groundwater concentration for localized seepage reduced by piping was calculated to be 98 μg/l. The sub-basin average outlet concentration for the Cedar Creek sub-basin used in the model (and based on winter sampling data at the outlet) is 40 μg/l. Locally, a higher groundwater concentration exists, but through mixing and variations the sub-surface concentration seen at the outlet is less as a result of groundwater from high concentration "hot spots" and lower concentration "cold spots" mix before they reach the outlet.

The result of this observation and conceptualization of variability is that the modeled BMP impacts shown above that reduce seepage probably predict an overall mean sub-basin load reduction. If a BMP is implemented in the field, a locally higher or locally lower load reduction may be seen. However, the load reductions predicted by the model are the average reductions that should be expected for a sub-basin region.

6.9 Economic Impact of BMP Implementation

As mentioned previously, BMP implementation such as large-scale changes in irrigation or the retirement of cropland in the Uncompahgre Basin may result in a loss of profit to individual farmers. Several questions arise: "If BMP implementation negatively impacts the local agricultural economy, why do it? What is the incentive for farmers to implement BMP's?" In the context of the current situation of voluntary water quality standards compliance, the answers to these questions lie in benefits beyond the scope of the Uncompahgre Basin. Salinity reductions will most likely follow as by-product of a selenium reduction BMP. Increased crop yield may be realized through reduced salinity (e.g., Francois, Grieve and Maas, 1994), resulting in basin-wide and downstream benefits to many users. A direct comparison of farm profit losses with the combined benefits of reduced salinity downstream and the corresponding selenium concentration reductions preserving aquatic life is a difficult research topic. Combining land retirement with crop changes to higher value crops (and combining with irrigation efficiency changes) may help offset profit loss while enhancing water quality.

6.10 Summary of BMP Results

The BMP results presented above demonstrate the magnitude of a management change that might be required to reduce selenium concentrations to the strict 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 best benefit of canal lining is predicted to be within the Loutsenhizer Arroyo sub-basin area, given the highest overall groundwater concentrations seen there. Even a tripling of the current irrigation efficiency throughout east side of the valley still is predicted to have limited benefit. Management changes on the order of full retirement of land on the east side are predicted to be required if the 4.6 μg/l concentration standard is to be met. Drastic reductions in the return flow (or loads through treatment) from the Cedar Creek and Loutsenhizer Arroyo sub-basins is predicted to be required to meet the standard for in-river concentrations. A combined management plan can be predicted by the model and the benefit of canal seepage reduction, enhanced efficiency and reduced diversions show promise. The natural state of the basin has been estimated to be in compliance with the standard, so through management changes the model predictions show that is it possible to reach this goal.

Chapter 7

SUMMARY, DISCUSSION AND CONCLUSIONS

This chapter reviews the research goals of the study, the methods employed and the most significant findings.

7.1 Summary of Problem and Solution Approach

One objective for this study was 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 parameters to simulate a change in water management. The benefits of various management changes were quantified as changes in outflow load from the basin and ability to meet water quality concentration criteria.

Water quality sampling and analysis performed by the USGS was extensive in both temporal and spatial scales. The measurement of instantaneous flows as well as analysis for concentrations of selenium, total dissolved solids and electrical conductivity in water samples were very valuable and allowed for the investigation of total loads and relationships between water quality parameters.

Investigation into the details of the STATEMOD model for the Gunnison basin provided a valuable overview of the general water movement throughout the Basin and complexity of the irrigation system. However, the details of the network, while sufficient for flow forecasting for water rights by the State Engineer's office, did not describe enough of the details of the physical system of return flows in the basin to be extended to include water quality, as was first envisioned. The monthly flow data, irrigated parcel data and crop consumptive use data used by the STATEMOD model were valuable and used for this study.

Supplied with data describing monthly river flows, diversion volumes, irrigated parcels and diversions serving them and instantaneous measurements of flow and water quality, a systematic method was used to piece together all the knowns and unknowns that describe the influence of irrigation on in-river water quality. The downward approach (Klemes, 1983) was used as a guide for a systematic method that could be used with the application of water and constituent mass balances to describe all the required components of the puzzle. Starting at the basin level and defining the boundary conditions of the Uncompahgre, as described by the flow data and water quality sampling, was valuable to identify the areas of major concern based on high concentrations. Spatial refinement of the basin into tributary sub-basins was key to identifying contributing areas that had sufficient data describing inputs and output to allow a model to be developed. Analysis of the diversion and return flow conditions described by data for these sub-basins led to the creation of the physical building blocks of a model. A water mass balance approach was used to divide the water budget into components with specific agricultural sources. The separation of return flows into two components: surface and sub-surface allowed for the application of general hydrologic modeling for the storage and slow return of flow via convolution. Development of the concept of the two-component mixing model for the uptake of selenium and TDS from groundwater and surface water mixed together led to a physical explanation of the relationship seen in the measured data. The framework for the puzzle was therefore completed: a water balance and use of convolution to predict surface and sub-surface return flows and the application of representative concentrations for the groundwater and mixing these components to produce return flow of varying concentrations.

The method described above could only be applied at the sub-basin level, based mainly on data availability but also based on physical principles. This method assumes that water enters an agricultural sub-basin as canal seepage or field application, some is lost through crop consumptive use and evaporation, but the rest will flow through surface drains and groundwater flow paths and most likely return at or before the natural tributary sub-basin outlet at the river. Therefore, the boundaries are well-defined. This method assumes a general groundwater flow that follows the contours of the land. This assumption allows for a water balance approach to be used instead of implementing a complex two-dimensional groundwater flow model, which would not have been possible in this basin without specifically measuring water table elevations. The scale of the model is therefore defined by the available data and the assumptions used for modeling.

7.2 Results

7.2.1 Summary of Current and Historical Conditions

The modeling method quantified several aspects of current water management on the water quality problem in the basin. Basin water and constituent fluxes such as: inflows, diversions, returns and multiple outflows were quantified as well as contributions from within the basin such as: canal seepage, deep percolation and surface drainage. The calibrated model results show a large uptake of selenium and salt as water moves through the Uncompahgre Basin water distribution system, resulting in elevated selenium concentrations, exceeding the standard and nearly exceeding the temporarily modified standard. Groundwater contributions that enter the river from the east side are the primary drivers that deliver selenium load to the Uncompahgre.

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 area basis were larger than the application water right of 4.76 ft/yr for Mesa soils and 3.97 ft/yr for Adobe soils. Total pond, canal and lateral seepage accounted for a fairly small fraction of the return flow. Deep percolation from fields is 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, and the reduced flow volume in the lower section of the river during irrigation season compounds the elevated concentration problems. 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 irrigation season. The flow from the 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 805 lbs/year and dissolved solids of 137,546 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 each year by the eight major diversion structures for irrigated agriculture on 73,481 acres. This results in volumes of return flows in five major tributaries that comprise 74% of the outflow of the basin at Delta. 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. Return flows load 9,099 lbs/yr of selenium and 316,025 tons/yr dissolved solids to the River on average. Water reuse actually diverts high concentration water for irrigation and results in the loading of 2,561 lbs/yr of selenium and 355,446 tons/yr of salts to irrigated parcels in the basin. The net result of water movement in the Uncompahgre Basin results in an estimated 7,106 lbs/yr of selenium and 314,449 tons/yr of dissolved solids leaving the basin at Delta. An additional 8,320 lbs/yr of selenium and 530,125 tons/yr of dissolved solids are predicted to leave the Uncompahgre Basin to return directly to the Gunnison River. By combining these outflows, a predicted 15,426 lbs of selenium per year and 844,574 tons of dissolved salts are mobilized to the Gunnison River as a result of agricultural practices in the Uncompahgre River Basin.

The agricultural practices result in elevated concentrations in the river, where the concentrations exceed the table value standard of 4.6 μg/l for dissolved selenium. The State of Colorado allows for 15% of samples to be above the standard for compliance (or requires that 85% of sampled concentrations must be below the standard). This computation, the 85th percentile of selenium concentrations is 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.

7.2.2 BMP's

The best management practice simulations offer a view of the magnitude of water quality change that could occur with a change in water management. The scale of the model is admittedly large, and many details and variations are aggregated into a homogenous sub-basin representation. A localized reduction in high concentration seepage could occur as a BMP is implemented in the field; however this is driven by small-scale variations in soil composition or flowpath, and would not be captured by the large scale model predictions. This is a downfall of capturing processes at such a large spatial scale. Given the magnitude of the selenium loading in the basin, this large scale approach is an appropriate first step. The scale of BMP implementation presented here are regional changes, mainly aimed at the reduction in groundwater seepage that might change flows and loads in the large tributaries in the Basin.

The focus from the start of this study has been to study management changes that would directly influence the River. The lateral lining demonstration project (Butler, 2001), while a very valuable study, both in terms of scientific knowledge and public relations for the benefits of canal lining, does not specifically address the impact of this BMP on Uncompahgre River water quality. By not including this and focusing on percentages of selenium and salt removed through lining, the scale of the problem versus the size of the solution is lost. The phytoremediation demonstration project by Fisher, (2004), also falls short of this comparison of scales and impact on the River. In this case the removal of selenium from soils through the uptake by trees and other crops is examined and quantified. The study does show selenium uptake from the soil and is considered a success. However, this uptake of selenium compared to the magnitude of the mass of selenium contained in shale minerals in surface soils and shallow sub-surface aquifer materials basin wide is not emphasized. In this case, no attempt was made to quantify the impact of this field-scale demonstration on changes in quality in drainwater or downstream river water quality.

The best place to test the effectiveness of these BMP's would be in a controlled area where the inflow and outflow conditions are quantified through a rigorously defined sampling plan aimed at a specific target i.e., annual average or irrigation season average. Given comments above on the measurement of impact to the in-river water quality, localized outflow measurements within a tributary and within the River below should be performed to assess the persistence and scope of a BMP impact. An important consideration is the detectability of a change that can be attributed to BMP implementation in the context of natural variability. See details in Gossenauer (2004) regarding specific sampling plans for selenium concentration and load change detection. Therefore the sampling plan used should be built with specific detection limits in mind, possibly using BMP impact results from the simulations in this study.

The following specific results are predicted by the BMP simulations. An estimated selenium load of 5,000 lbs/yr would have to be reduced in order for the concentration at Delta to be within the water quality standard of 4.6 μg/l. Water management practice simulations of canal lining show that large-scale lining projects may be required to meet water quality standards. Lining at the scale of 20 miles of laterals in Cedar creek (as currently planned) is predicted to reduce selenium load at Delta by 89 lbs/yr and total TDS load by 2841 tons/yr. This reduction estimate assumes a uniform groundwater concentration seen overall in the Cedar Creek sub-basin; the influence of soil variability may increase or decrease this average amount for a small-scale change in seepage implemented in the field. Given the magnitude of selenium reduction required to meet the 4.6 μg/l standard, even lining of all canals, laterals and ponds in the Uncompahgre Basin may not be enough of a management change, predicted to reduce selenium load at Delta by only 3,117 lbs/yr and TDS load by 63,995 tons/yr.

Reduction of a majority of return flows from the Cedar Creek and Loutsenhizer Arroyo tributaries shows the most promise to achieve water quality compliance for selenium. This could be performed through large-scale irrigation efficiency changes accompanied by reduction in diversions to the east side of the basin. The total removal of return flows and selenium loads in these tributaries is predicted reduce loading of 5,804 lbs/yr of selenium and 20,290 tons/yr of dissolved solids to the Uncompahgre River. A management change of this scale may be necessary to reduce concentrations in the Uncompahgre and Gunnison Rivers to the 4.6 μg/l standard.

7.3 Applicability And Extension To Other Water Quality Problems, A Recommended Approach

Given the conservative nature of dissolved selenium and salts assumed in this study, the modeling approach is highly applicable to other water quality problems. The nature of this problem is one of describing non-point sources of loading of mass in the context of a river basin. The downward approach used in this study can be quite helpful for tackling a problem like this. This approach is not highly regimented but rather a guide to systematic problem solving that does not involve the application of a standard software package. Based on experience from the present study the following general approach is suggested.

1. A spatially broad analysis of the flow and concentration data is the best first step. This allows for the scope of water quality impairment to be identified and a boundary to the problem defined.
2. Annual loading can be estimated and mass balances for water (first) then the constituent of interest point out the completeness of the sampling dataset to define all sources.
3. A general view of the positive and negative fluxes across the boundary of interest is highly illustrative. These steps to this point define the magnitude of the problem, but do not identify specific sources nor are processes causing these sources identified. Further refinement is necessary for these.

4. The same steps above can be followed in sub-regions within the boundary, to identify fluxes of water and constituent mass.
5. If the contributions of load to a river reach are all that is desired, e.g., for examination of violations of waste permits, refinement can continue to the level of the source or to the level of the data, whichever occurs first.
6. If a process describing that load is desired to be modeled, e.g., irrigation water leaching nutrients to a river, or precipitation leaching metals from tailings, the input and output fluxes to this process need to be identified and quantified.
7. Often a full description results in unknown quantities or fluxes that have not been measured. Specific problems include net precipitation to an area, surface runoff or seepage to a saturated groundwater table. This modeling study has shown that a realistic and plausible description of the balance of these quantities can be built and through estimation of some values, mass balance can be used for solution of unknowns. As is the case in the current study, this method can be used for both water mass and constituent mass. An estimate of an unknown quantity is often required and a good place to start, but this estimate should be checked if possible through the mass balance.
8. Multi-criteria solution methods, such as the use of the Excel solver to minimize a variety of objectives are very helpful for initial and automated calibration of mass balances.

7.4 Further Study

The old adage appears true in this study, "the more research you do, the more research you find there is to do." Additional items of study that were identified during this research should be mentioned here.

The collaborative research into the economic analysis of BMP implementation was not included here. However, specific model outputs including constituent loads to canals and canal water quality have been included to facilitate the study of feedbacks such as: BMP implementation → reduction in selenium concentration, with a corresponding reduction in salinity → improved irrigation water quality for downstream users → crop yield benefit.

A policy study on the ability to change river diversions in the Uncompahgre Basin should be performed. From the modeling results, BMP's that don't somehow change diversions do not seem effective to the level that is required to meet strict standards. The senior water right held by the Uncompahgre Valley Water Users cooperative may require complex judicial efforts to change. The fear would be that if a farmer increases his irrigation efficiency in an effort to reduce seepage, requiring less water, the balance of his original water right volume is now not utilized for a beneficial use. Other farmers can claim this water if it goes unused for several years, possibly negating any reduction in selenium load realized by the farmer who implemented the BMP. A transfer of water right to an in-stream beneficial use will most likely involve the Colorado water courts.

A focused study of the details of the water budget for a sub-basin could prove valuable. Measurements and comparisons of the total water application and total return flow might better quantify the relationship between the fluxes and determine how well the service of water shares to parcels are measured. An identification of the nature and complexity of surface and sub-surface return flow pathways might also yield some interesting water reuse conditions.

7.5 Overall Contribution to the State of the Art

This final section places the modeling effort reported herein within the context of the state-of-the-art as established by the other applications and research studies reviewed earlier. This study presents a new modeling method for water quality compliance evaluation. The 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. Instead of using an off-the-shelf model for water movement by irrigated agriculture or a model for dissolved selenium (for which none were available), a model was conceptualized based on physical principles of mass balanced and observed measurements. In an effort to stay focused on the important aspects of the problem, instead of overwhelmed by the many details, a top-down approach was utilized to break the hydrology and constituent loading into finer and finer temporal, spatial and conceptual details to solve the task at hand. This task: to simulate the impact of agricultural water management changes on water quality, specifically to achieve compliance with a water quality concentration standard. The new academic contributions are 1) use of the top-down method for a water quality application, 2) the development of an accurate loading model for selenium and 3) building a model specifically for standards compliance.

The downward or top-down method has been used before primarily for hydrologic studies, e.g., Klemes (1983), Eder et al. (2003), Sivapalan et al. (2003), Farmer et al. (2003) and Jothityangkoon et al. (2001). This study combines a hydrologic analysis to quantify individual components of the agricultural water balance with representative concentrations of those waters in order to predict the resulting water quality of the surface and sub-surface components at a "watershed" outlet. The top-down approach allowed for a systematic description of the pieces of information required for hydrologic and water quality description for this specific problem. The use of a bottom-up method, starting with a very detailed description of processes, e.g., water movement through the unsaturated zone and complex dissolution of selenium from soil grains, would not have succeeded in this study given the lack of many of the required data. A detailed model, while worthwhile to advance the understanding of chemical processes surrounding water, dissolved selenium and soil in this example, may have been difficult to calibrate without much estimated data and also difficult to scale up to the basin level detail required by the study.

The simple two-component mixing model for selenium and salts for agricultural sub-basins was not found in the studies reviewed. Previous water quality studies, e.g., Borsuk at al (2002), Vieux and Moreda (2003) and Harned at al. (2004), have used relationships between discharge and concentration for rivers and tributaries in water quality studies. These examples use regression techniques to fit equations for the relationship. The mixing model defined here uses physical principles in order to represent the concentration vs. flow relationship seen in the data. The rich water quality sampling dataset from the USGS for this study allowed the development of the accurate relationship. The combined calibration of the hydrologic component models and the constituent uptake models resulted in accurate descriptions of the conditions at each tributary outlet. These loading sources, when combined in a conservative fashion in the river provided a complete picture of the water quality downstream, matching the observed data well. The full loading model for the Uncompahgre Basin provided a picture of the link between irrigated agriculture and in-river water quality.

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. In this case, the details of the standards criteria were known a priori and output from the model ready-built for comparison to the standard via the same method used by the State of Colorado. To be fair, the calculation of the 85^{th} percentile of the monthly mean output from the model (not sampled) is not the same as the 85^{th} percentile of a set of instantaneous random samples, but the model output is designed to make the user think in terms of rank and percentile instead of typical time series output. The model output of constituent loads along with concentrations is easily adaptable for use with an official TMDL study for the basin, where a concentration criterion is examined and the allowable loads from various sources that meet that criteria are developed.

Additional benefit is derived from the model of selenium compliance when simulation of total dissolved solids occurs in tandem. The multiple benefits of selenium concentration reduction and salinity reduction from a BMP can be presented. Economic evaluation of a BMP can be calculated from the model output. A crop yield benefit can be calculated through reduction in salinity of irrigation source water as a result of a BMP implemented for the reduction in selenium. The cost of a BMP that yields a dual benefit of a reduction in both constituent loads can be offset by the benefit in terms of crop yield.

Output from the model describing loading of both constituents to the river as well as loading to the irrigated fields is available by design.

This study has shown the applicability of the downward model design method in building a model that performs well to predict concentrations of selenium and TDS. The model ability has been proven through calibration and validation exercises. The current conditions have been quantified in hopes that they can help identify the inefficiencies in agricultural water management that are causing impairment of the Uncompahgre and Lower Gunnison for selenium and the corresponding high levels of dissolved solids loading. The BMP simulation results have emphasized the magnitude of possible solutions to the water quality problem.

Although changes to water management to meet water quality goals may be great, the benefits may be far reaching: from enhancing the aesthetics of the Uncompahgre Valley area, providing healthier habitat for all aquatic life in the Uncompahgre and downstream, to reducing salinity in the Gunnison River and eventually the Colorado River that serves so many downstream users. It is hoped that these results will assist those who want to make a difference and begin strategies for solution to the selenium problems in the Uncompahgre Basin. There is always room for more study of specific aspects of this problem, but a study of the effectiveness of implemented solutions is perhaps the wisest use of resources. The magnitude of the problem is identified; the magnitude of possible solutions should be realized through this study, hopefully paving the way for implementation.

REFERENCES

Baker, M., 2002, USBR, Personal communication and GIS data sharing.

Bartholow, J., R.B. Hanna, L. Saito, D. Lieberman and M. Horn, 2001, Simulated Limnological Effects of the Shasta Lake Temperature Control Device, Environmental Management, Vol. 27, No. 4, pp. 609 - 626.

Beck, M.B., 1987, Water quality modeling: a review of the analysis of uncertainty, Water Resources Research, 23, 1393-1441.

Beley, D., 2003, 2004, Colorado Department of Public Health, Personal Communications in Oct 2003 - November 2004.

Beley, D., 2004, Colorado Department of Public Health, Presentation to the Statewide Selenium Issues Forum, January, 11, 2005, Denver, CO.

Berthouex, P.M. and L.C. Brown, 1994, *Statistics for Environmental Engineers*, Boca Raton: Lewis Publishers.

Bicknell, B.R., A.S. Donigian and T.A. Barnwell, 1985, Modeling water-quality and the effects of agricultural best management-practices in the Iowa river basin, Water Science and Technology, 17 (6-7): pp 1141-1153.

Borsuk, M.E., C.A. Stow and K.H. Reckhow, 2002, Predicting the Frequency of Water Quality Standard Violations: A Probabilistic Approach for TMDL Development, Environmental Science & Technology, Vol. 36, no. 10, pp. 2109-2115.

Bouzaher, A., P.G. Lakshminarayan, R. Cabe, A. Carriquiry, and P.W. Gassman, 1993, Metamodels and Nonpoint Pollution Policy in Agriculture, Water Resources Research, V. 29, No. 6, p 1579-1587.

Brix, K.V., J.E. Toll, L.M. Tear, D.K. DeForest, and W.J. Adams, 2005, Setting Site-Specific Water-Quality Standards by Using Tissue Residue Criteria and Bioaccumulation Data. Part 2. Calculating Site-Specific Selenium Water-Quality Standards for Protecting Birds and Fish, Environmental Toxicology and Chemistry, Vol. 24, No. 1, pp. 231-237.

Brown, K., 2002, CSU Cooperative Extension Officer, Personal communication.

Brutsaert, W. and H. Stricker, 1979, An advection-aridity approach to estimate actual regional evapotranspiration, Water Resources Research, v15 n 2, pp. 443-450.

Burt, C.M., 1999, Irrigation Water Balance Fundamentals, Proceedings from the Conference on Benchmarking Irrigation System Performance using Water Measurement and Water Balances.

Butler, D.L., W.G. Wright, D.A. Hahn, R.P. Krueger and B.C. Osmundson, 1994, Physical, Chemical and Biological Data for the Detailed Study of Irrigation Drainage in the Uncompahgre Project Area and in the Grand Valley, West-Central Colorado, 1991-92. U.S. Geological Survey Open File Report 94-110.

Butler, D.L., W.G. Wright, K.C. Stewart, B.C. Osmundson, R.P. Krueger and D.W. Crabtree, 1996, Detailed Study of Selenium and Other Constituents in Water, Bottom Sediment, Soil, Alfalfa and Biota Associated with Irrigation Drainage in the Uncompahgre Project Area and in the Grand Valley, West-Central Colorado, 1991-93. U.S. Geological Survey Water Resources Investigations Report 96-4138.

Butler, D.L., and B.C. Osmundson, 1999, Physical, Chemical and Biological Data for the Detailed Study of Irrigation Drainage in the Uncompahgre Project Area and the Grand Valley, West-Central Colorado, 1993-98. U.S. Geological Survey Open File Report 99-453.

Butler, D.L., 2001, Effects of Piping Irrigation Laterals on Selenium and Salt Loads, Montrose Arroyo Basin, Western Colorado, U.S. Geological Survey Water Resources Investigations Report 01-4204.

Butler, D.L. and K.J. Leib, 2002, Characterization of Selenium in the Lower Gunnison River Basin, Colorado, 1988-2000, U.S. Geological Survey Water Resources Investigations Report 02-4151.

Cai, X., D.C. McKinney and L.S. Lasdon, 2003, Integrated Hydrologic-Agronomic-Economic Model for River Basin Management, Journal of Water Resources Planning and Management. Vol. 129, no. 1, pp. 4-17.

Campbell, S.G., R.B. Hanna, M. Flug and J.F. Scott, 2001, Modeling Klamath River System Operations for Quantity and Quality, Journal of Water Resources Planning and Management, Vol. 127, no. 5, pp. 284-294.

Catlin, M. 2004, Water Manager for the Uncompahgre Valley Water Users, Presentation to the Uncompahgre and Gunnison Basin Selenium Task Force, November, 2004.

Chapra, S.C., 1997, *Surface Water-Quality Modeling*, New York: McGraw-Hill Company.

Chiang, P-C. and T.K. Gates, 2004, Strategic River Water Quality Planning Using Calibrated Stochastic Simulation, Journal of Water Resources Planning and Management, 130(3): 215-231.

Chow, A.T., K.K. Tanji and S. Gao, 2004, Modeling Drainwater Selenium Removal in Wetlands, Journal of Irrigation and Drainage Engineering, 130(1):60-69.

Chow, V.T., D.R. Maidment and L.W. Mays, 1988, Applied Hydrology. New York: McGraw-Hill, Inc. 572 pages.

Clemmens, A.J. and C.M. Burt, 1997, Accuracy of Irrigation Efficiency Estimates, Journal of Irrigation and Drainage Engineering, Vol. 123, No. 6, pp. 443-453.

Colorado's Decision Support System (CDSS), 2004a. STATEMOD model and data. On the World Wide Web at http://cdss.state.co.us/ftp/statemod.asp, last accessed 11/10/2004.

Colorado's Decision Support System (CDSS), 2004b. Hydrobase database access for stations and structures. On the World Wide Web at http://cdss.state.co.us/db/index.asp, last accessed 11/10/2004.

Colorado's Decision Support System (CDSS), 2004c. StateCU model and data. On the World Wide Web at http://cdss.state.co.us/ftp/cu.asp, last accessed 11/10/2004.

Colorado's Decision Support System (CDSS), 2004d. GIS data products. On the World Wide Web at http://cdss.state.co.us/ftp/gis.asp, last accessed 11/10/2004.

Colorado Department of Transportation (CDOT), 2004. Geographic data products. On the World Wide Web at http://www.dot.state.co.us/App_DTD_DataAccess/GeoData/index.cfm?fuseaction=GeoDataMain&MenuType=GeoData, last accessed 11/12/2004.

Colorado Water Conservation Board and Boyle Engineering Corp., 1999, Colorado River Decision Support System, Gunnison River Basin Water Resources Planning Model, Final Report.

Colorado Public Health and Environment, 2002, Colorado 303(d) list for 2002. On the World Wide Web at http://www.cdphe.state.co.us/op/wqcc/SpecialTopics/303(d)/combo303dfinal.pdf, last accessed 11/10/2004.

Colorado Public Health and Environment, 2004, Colorado 303(d) list for 2004. On the World Wide Web at http://www.cdphe.state.co.us/op/wqcc/OtherRegs/93-94/Final93.pdf, last accessed 11/10/2004.

Cooley, W., 2004, Colorado State Cooperative Extension, Presentation to the Uncompahgre and Gunnison Basin Selenium Task Force, November, 2004.

Dai, T. and J.W. Labadie, 2001, River basin network model for integrated water quantity/quality management, Journal of Water Resources Planning and Management, Vol. 127, no. 5, pp. 295-305.

Dalzell, B.J., P.H. Gowda and D.J. Mulla, 2004, Modeling Sediment and Phosphorus Losses in an Agricultural Watershed to Meet TMDLs, Journal of the American Water Resources Association, 40(2):533-543.

Dearstyne, D., J. Brummer and J. Fahy, 2003, DRAFT Soils Report on Selenium in the Uncompahgre Valley, Appendix 12.2 of a Summary Report.

de Azevedo, L.G.T., T.K. Gates, D.G. Fontane, J.W. Labadie, JW and R.L. Porto, 2000, Integration of water quantity and quality in strategic river basin planning, Journal of Water Resources Planning and Management, vol. 126, no. 2, pp. 85-97.

de Boise, C.J., H.G. Wind, J.L. Kok and K. Koppeschaar, 2003, Robustness of River Basin Water Quality Models, Journal of Water Resources Planning and Management, vol. 129, no. 3, pp 189-199.

De Marchi, C., P. Ivanov, A. Jolma, I. Masliev, M.G. Smith and L. Somlyody, 1999, Innovative Tools for Water Quality Management and Policy Analysis: Desert and Streamplan. Water Science & Technology, vol. 40, no. 10, pp. 103-110.

Donnelly, J.P. and T.K Gates, 2004, Assessing Irrigation-Induced Selenium and Iron in the Stream-Aquifer System in the Lower Arkansas River Valley, Colorado, Proceedings from AGU Hydrology Days, March 10 – 12, 2004, Fort Collins, CO, pp. 241-251.

Eagleson, P.S., 1978, Climate, Soil, and Vegetation--1. Introduction to Water Balance Dynamics, Water Resources Research, Vol. 14, No. 5, pp. 705-712.

Dudley, S., 2004, The First Five: A Brief History of the Uncompahgre Project (Gunnison). On the World Wide Web at http://www.waterhistory.org/histories/reclamation/Uncompahgre/, last accessed 11/21/2004.

Eder, G., M. Sivapalan and H.P. Nachtnebel, 2003, Modelling water balances in an Alpine catchment through exploitation of emergent properties over changing time scales, Hydrological Processes, 17: 2125-2149.

Elrashide, M.A., D.C. Adriano and W.L. Lindsay, 1989, Solubility, Speciation and Transformations of Selenium in Soils, *Selenium in Agriculture and Environment*, Soil Science Society of America and American Society of Agronomy. Special Publication no. 23.

Environmental Sciences Research Institute (ESRI), 2004. ArcInfo Geographic Information Systems products. On the World Wide Web at http://www.esri.com.

Farmer, D., M. Sivapalan and C. Jothityangkoon, 2003, Climate, soil, and vegetation controls upon the variability of water balance in temperate and semiarid landscapes: Downward approach to water balance analysis, Water Resources Research, 39(2), 1035.

Fio, J.L., 1997, Geohydrological Effects on Drainwater Quality, Journal of Irrigation and Drainage Engineering, vol. 123, No, 3. pp. 159-164.

Fisher, F., 2004, Shavano Soil Conservation District, Presentation to the Uncompahgre and Gunnison Basin Selenium Task Force, November, 2004.

Food Nutrition Board (FNB) and Institute of Medicine (IOM), 2003, *Dietary Reference Intakes: Application to Dietary Planning.* Available on the World Wide Web through the National Academies Press www.nap.edu.

Francois, L.E., Grieve, C.M. and Maas, E.V., 1994, Time of Salt Stress Affects Growth and Yield Components of Irrigated Wheat, Agronomy Journal, 86(1): 100-107.

Fredericks, J.W., J.W. Labadie and J.M. Altenhofen, 1998, Decision Support System for Conjunctive Stream-Aquifer Management, Journal of Water Resources Planning and Management, vol. 124, No. 2, pp. 69-78.

Fujii, R. and S.J. Deverel, 1989, Mobility and Distribution of Selenium and Salinity in the Groundwater and Soil of Drained Agricultural Fields, Western San Joaquin Valley of California, *Selenium in Agriculture and Environment,* Soil Science Society of America and American Society of Agronomy. Special Publication no. 23.

Gardner, R.L. and R.A. Young, 1988, Assessing strategies for control of irrigation-induced salinity in the Upper Colorado River Basin, American journal of agricultural economics, V. 70 (1), p. 37-49.

Gates, T.K., J.P. Burkhalter, J.W. Labadie, J.C. Valliant and I. Broner, 2002, Monitoring and Modeling Flow and Salt Transport in a Salinity-Threatened Irrigated Valley, Journal of Irrigation and Drainage Engineering, Vol. 128, No. 2, pp. 87-98.

Gensemer, R., D. DeForest and J. Toll. Colorado Wastewater Utility Council and Parametrix, Presentation to the Statewide Selenium Issues Forum, January, 11, 2005, Denver, CO.

Gibbons, R.D., 2003, A Statistical Approach for Performing Water Quality Impairment Assessments, Journal of the American Water Resources Association, 39(4): 841-849.

Gilbert, R.O., 1987, *Statistical Methods for Environmental Pollution Monitoring,* New York: Van Nostrand Reinhold.

Goff, K., M.L. Lewis, M.A. Person and L.F. Konikow, 1998, Simulated Effects of Irrigation on Salinity in the Arkansas River Valley in Colorado, Groundwater, vol. 36, No. 1, pp. 76-86.

Gossenauer, M.B., 2004, Selenium Monitoring For Load Estimation, Detectable Change And Standard Compliance In The Uncompahgre River Basin In Western Colorado. Masters Thesis, Department of Civil Engineering, Colorado State University.

Green, G.P. and J.R. Hamilton, 2000, Water allocation, Transfers and Conservation: Links between Policy and Hydrology, Water Resources Development, Vol. 16, No. 2, pp. 197-208.

Gusek, J.J., 2004, Senior Project Manager and geochemist, Golder Associates, Inc., Lakewood Colorado. Personal communication during Uncompahgre and Gunnison Basin Selenium Task Force, November, 2004.

Hanna, R.B., L. Saito, J. Bartholow and J. Sandelin, 1999, Results of Simulated Temperature Control Device Operations on In-Reservoir and Discharge Water Temperatures Using CE-QUAL-W2, Lake and Reservoir Management, no. 2, pp. 87-102.

Hanna, R.B and S. Schaefer, 2000, Analysis of Environmental Monitoring of Selenium Concentrations Throughout the Gunnison Basin, Term Project Report for CE 547, Colorado State University.

Hanna, R.B. and S. Carney, 2002, Spatial Analysis of Irrigation Influence on Selenium Leaching in the Uncompahgre Basin in Western Colorado, Final Project Report for CE 577, Colorado State University.

Hamilton, S.J., K.M. Holley, K.J. Buhl, F.A. Bullard, L.K. Weston and S.F. McDonald, 2002, Toxicity of selenium and other elements in food organisms to razorback sucker larvae, Aquatic Toxicology, 59 (2002), p 253-281.

Harned, D.A., J.B. Atkins and J.S. Harvill, 2004, Nutrient Mass Balance and Trends, Mobile River Basin, Alabama, Georgia and Mississippi, Journal of the American Water Resources Association, 40(3):765-793.

Herr, J.W., C.W. Chen, R.A. Goldstein, RA, R. Herd and J.M. Brown, 2003, Modeling acid mine drainage on a watershed scale for TMDL calculations. Journal of the American Water Resources Association, Vol. 39, no. 2, pp. 289-300.

Hla, A., 2005, Extension Agent, Colorado State University Cooperative Extension, Personal communication.

Hobbins, M.T., J.A. Ramírez, and T.C. Brown, 2001. The complementary relationship in estimation of regional evapotranspiration: an enhanced Advection-Aridity model. Water Resources Research, v 37 n 5, pp. 1389-1403.

Illangasekare, T.H. and H.J. Morel-Seytoux, 1986, A discrete kernel simulation model for conjunctive management of a stream-aquifer system, J. of Hydrology, 85:319-338.

Jolma, A.C., De Marchi, M. Smith, B.J.C. Perera and L. Somlyody, 1997, StreamPlan: a support system for water quality management on a river basin scale, Environmental Modelling and Software, Vol. 12, No. 4, pp. 275-284.

Jothityangkoon, C., M. Sivalalan and D.L. Farmer, 2001, Process controls of water balance variability in a large semi-arid catchment: downward approach to hydrological model development, Journal of Hydrology, 254, 174-198.

Kan, I., K.A. Schwabe and K.C. Knapp, 2002, Microeconomics of Irrigation with Saline Water, Journal of Agricultural and Resource Economics, 27(1): 16-39.

Klemes, V., 1983, Conceptualization and scale in hydrology. Journal of Hydrology, 65: 1-23.

Laronne, J.B., 1977, Dissolution Potential of Surficial Mancos Shale and Alluvium, Ph.D. Dissertation, Colorado State University.

Lee, D.J. and R.E. Howitt, 1996, Modeling Regional Agricultural Production and Salinity Control Alternatives for Water Quality Policy Analysis, American Journal of Agricultural Economics, Vol. 78, pp. 41-53.

Leib, K., 2001, 2002, 2004, USGS, WRD, Grand Junction, Colorado. Personal communication and water quality and GIS data sharing.

Lemly, A.D., 2004, Aquatic selenium pollution is a global environmental safety issue, Ecotoxicology and Environmental Safety, Vol. 59, pp. 44-56.

Lemly, A.D., 2002, A Procedure for Setting Environmentally Safe Total Maximum Daily Loads (TMDLs) for Selenium, Ecotoxicology and Environmental Safety, Vol. 52, no. 2, pp. 123-127.

Lemly, A.D, 1999, Selenium transport and bioaccumulation in aquatic ecosystems: A proposal for water quality criteria based on hydrological units. Ecotoxicology and Environmental Safety, Vol. 42, pp. 150–156.

Lindsay, W.L., 1979, *Chemical Equilibria in Soils*, New York: Wiley. 449 pages.

Loftis, J.C. and R.C. Ward, 1981, Evaluating Stream Standard Violations Using A Water Quality Database, Water Resources Bulletin, Vol. 17, No. 6, pp. 1071-1078.

Loftis, J.C., G.B. McBride and J.C. Ellis, 1991, Considerations of Scale in Water Quality Monitoring and Data Analysis, Water Resources Bulletin, Vol. 27, No. 2, pp. 255-264.

Marsden, W. and T. Wright, 1926, *The Travels of Marco Polo*, New York: Liveright.

McIntyre, N.R., T. Wagener, H.S. Wheater and S.C. Chapra, 2003, Risk-based modeling of surface water quality: a case study of the Charles River, Massachusetts, Journal of Hydrology, 274, pp. 225-247.

McNeal, J.M. and L.S. Balistreri, 1989, Geochemistry and Occurrence of Selenium: An Overview, *Selenium in Agriculture and Environment*, Soil Science Society of America and American Society of Agronomy. Special Publication no. 23.

Medterms.com, 2004, Medical dictionary, On the World Wide Web at www.medterms.com, last accessed 11/20/2004.

Melching, C.S. and W. Bauwens, 2001, Uncertainty in Coupled Nonpoint Source and Stream Water-Quality Models, Journal of Water Resources Planning and Management, Vol. 127, No. 6, pp. 403-413.

Nolan, B.T. and M.L. Clark, 1997, Selenium in Irrigated Agricultural Areas of the Western United States, J. Environ. Qual. 26:849-857.

Novotny, V., 2003, *Water Quality,* second edition, Hoboken: John Wiley and Sons, Inc.

Presser, T.S., and H.M. Ohlendorf, 1987, Biogeochemical cycling of selenium in the San Joaquin Valley, California, Environmental Management, 11:805-821.

Presser, T.S., M.A. Sylvester and W.H. Low, 1994a, Bioaccumulation of Selenium from Natural Geologic Sources in Western States and Its Potential Consequences, Environmental Management, Vol. 18, No. 3, pp. 423-436.

Presser, T.S., 1994b, The Kesterson Effect, Environmental Management, Vol. 18, No. 3, pp. 437-454.

Quinn, N.W., 1989, A screening Study of Management Alternatives for Selenium Drainage Reduction in the San Joaquin Valley of California, *Selenium in Agriculture and Environment*, Soil Science Society of America and American Society of Agronomy. Special Publication no. 23.

Quinn, N.W.T., and J. Karkoski, 1998, Real-Time Management of Water Quality in the San Joaquin River Basin, California, Journal of the American Water Resources Association, Vol. 34, No. 6, pp. 1473-1486.

Reckhow, K.H., and S.C. Chapra, 1999, Modeling Excessive Nutrient Loading in the Environment, Environmental Pollution, 100, p197-207.

Richards, R.P., and G.L. Grabow, Detecting Reductions in Sediment Loads Associated with Ohio's Conservation Reserve Enhancement Program, Journal of the American Water Resources Association, 39(5):1261-1268.

Saito, L., B.M. Johnson, J. Bartholow and R.B. Hanna, 2001, Assessing Ecosystem Effects of Reservoir Operations Using Food Web-Energy Transfer and Water Quality Models, Ecosystems Vol. 4, no. 2, pp. 105-125.

Schuck, E.C. and G.P. Green, 2001, Field Attributes, water pricing, and Irrigation technology adoption, Journal of Soil and Water Conservation, Vol. 56, No., 4, pp. 293-298.

Schuck, E.C., 2002, Assistant Professor, Agriculture and Resource Economics, Colorado State University, Personal communication.

Sexton, A.M., A. Shirmohammadi and H.J. Montas, 2003, Measuring Water Quality Model Uncertainties to Support TMDL Development, A Review of Strategies, Total Maximum Daily Load Environmental Regulations-II, Proceedings of the 8-12 November, 2003 ASCE Conference in Alburquerque, NM.

Smith, R.M.S., and H.S. Wheater, 2004, Multiple Objective Evaluation of a Simple Phosphorus Transfer Model, Hydrological Processes, 18, p1703-1720.

Snyder, W.M. and L.E. Asmussen, 1972, Subsurface Hydrograph Analysis by Convolution, Journal of the Irrigation and Drainage Division.

Sivapalan, M., G. Bloschl, L. Zhang and R. Vertessy, 2003, Downward approach to hydrological prediction, Hydrological Processes, 17: 2125-2149.

Sposito, G, 1994, *Chemical Equilibria and Kinetics in Soils*, New York: Oxford University Press, 268 pages.

Toll, J.E., L.M. Tear, D.K. DeForest, K.V. Brix and W.J. Adams, 2005, Setting Site-Specific Water-Quality Standards by Using Tissue Residue Criteria and Bioaccumulation Data. Part 1. Methodology, Environmental Toxicity and Chemistry, Vol. 24, No. 1, pp. 224-230.

Uncompahgre Valley Water Users' Association, 2003, Personal communication with office staff.

US Environmental Protection Agency, 2004a, Consumer Factsheet on Selenium, On the World Wide Web at http://www.epa.gov/safewater/contaminants/dw_contamfs/selenium.html, last accessed 11/20/2004.

US Environmental Protection Agency, 2004b, Draft Strategy: Proposed Revisions to the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses." Available on the World Wide Web at http://www.epa.gov/waterscience/criteria/aqlife.html, last accessed 11/20/2004.

US Environmental Protection Agency, 2004c, Colorado Water Quality Standards Repository of Documents, On the World Wide Web at http://www.epa.gov/waterscience/standards/wqslibrary/co/co.html. Last accessed 11/20/2004.

US Environmental Protection Agency, 2005, Draft Selenium Aquatic Life Criterion, On the World Wide Web at http://www.epa.gov/seleniumcriteria/. Last accessed 1/18/2005.

U.S. Bureau of Reclamation, 1982, Colorado River Water Quality Improvement Program, Lower Gunnison Basin Unit, Feasibility Report, Appendix B Hydrosalinity.

U.S. Bureau of Reclamation, 1999, Streamflow and Dissolved-Solids Trends, through 1996, in the Colorado River Basin, Colorado, Utah and Wyoming, Water Resources Investigations Report 99-4097.

U.S. Bureau of Reclamation, 2004. National Irrigation Water Quality Program. Information of the World Wide Web at http://www.usbr.gov/niwqp/. Last accessed 1/31/2005.

U.S. Bureau of Reclamation and Natural Resources Conservation Service, 2004. Draft Pond Seepage Study, pp. 10.

U.S. Geological Survey (USGS), 2003, Unpublished spatial data provided by Ken Leib, Water Resources Division, Grand Junction, Colorado.

Van Der Perk, M., 1997, Effect of model structure on the accuracy and uncertainty of results from water quality models, Hydrological Processes, 11: 227-239.

Vieux, B.E. and F.G. Moreda, 2003, Nutrient Loading Assessment in the Illinois River using a Synthetic Approach, Journal of the American Water Resources Association, 39(4):757-769.

Weinberg, M, 1997, Federal water policy reform: implications for irrigated farms in California, Contemporary Economic Policy, Vol. XV, April 1997.

White, A.F., S.M. Benson, A.W. Yee, H.A. Wollenburg and S. Flexser, 1991, Groundwater Contamination at Kesterson Reservoir, California 2. Geochemical Parameters Influencing Selenium Mobility, Water Resources Research, 27: 1085-1098.

Wichelns, D., 2004, New Policies are Needed to Encourage Improvements in Irrigation Management, Journal of Irrigation and Drainage Engineering, Vol. 130, No. 5, pp.366-372.

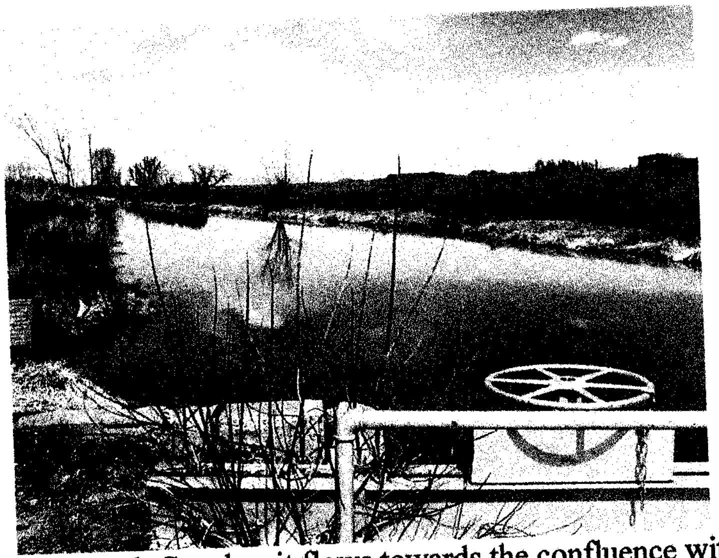
Wichelns, D., 1999, An economic model of waterlogging and salinization in arid regions, Ecological Economics, 30: 475-491.

Wright, W.G., 1999, Oxidation and Mobilization of Selenium by Nitrate in Irrigation Drainage, J. Environ. Q. 28: 1182-1187.

Yates, D.N and K.M. Strezepek, 1998, Modeling the Nile Basin Under Climatic Change, J. of Hydrological Engineering, Vol. 3, No. 2, pp. 98-108.

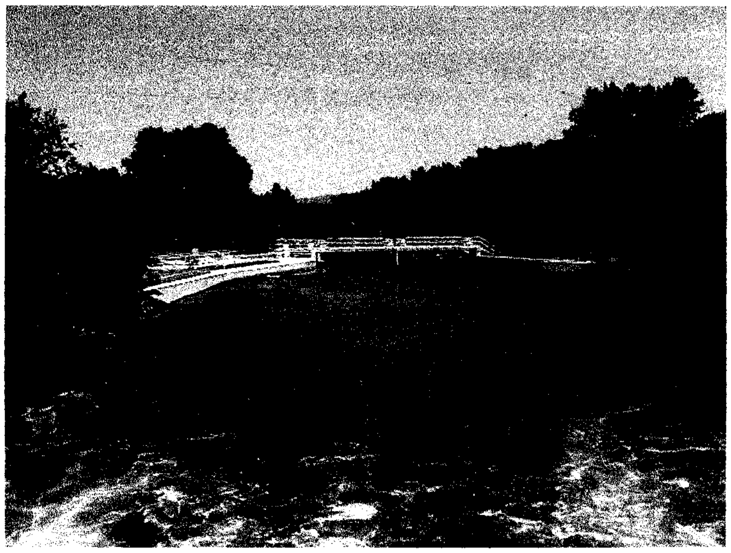
APPENDIX

BASIN PICTURES

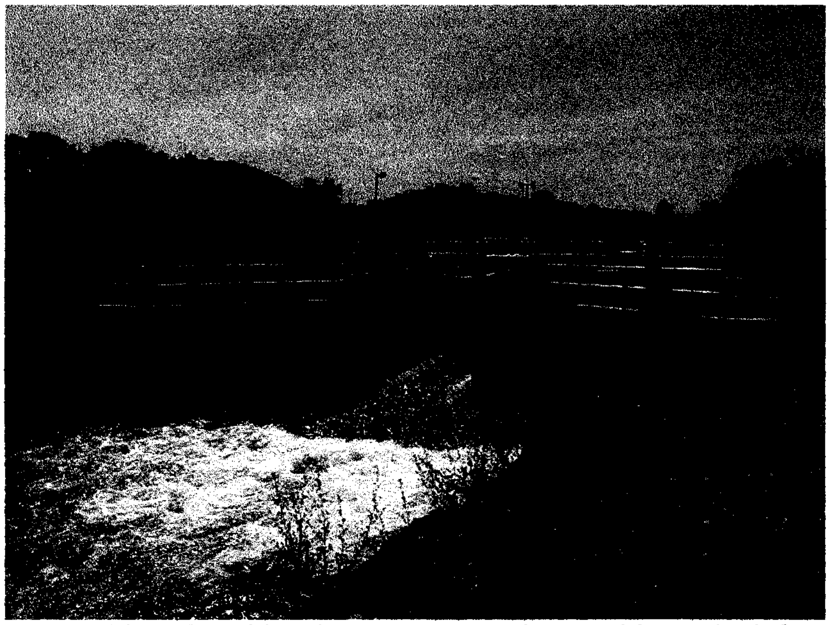


The South Canal as it flows towards the confluence with the Uncompahgre River, photo by Ken Leib, USGS

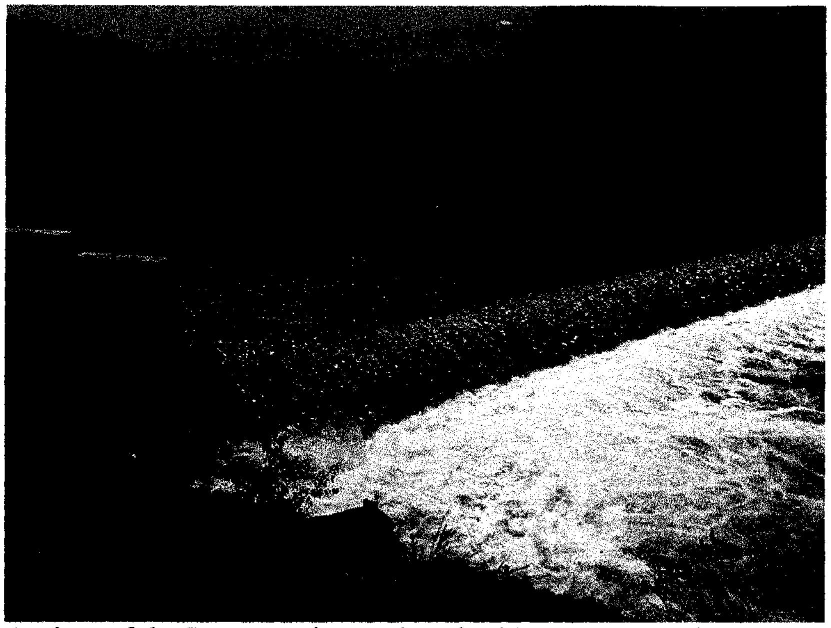
The confluence point of the South Canal as it flows into the Uncompahgre River, just downstream from Colona, photo by Ken Leib, USGS



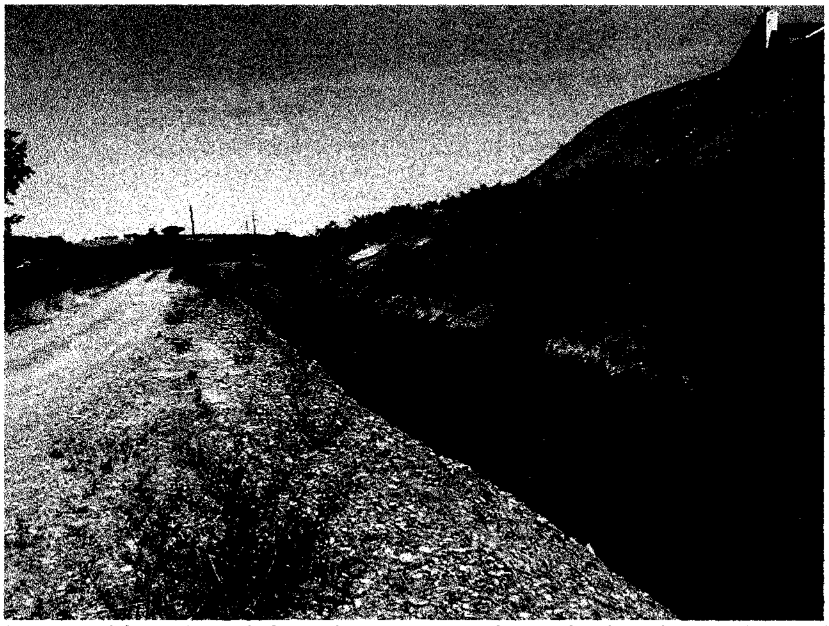
The Montrose and Delta Canal diversion structure taken from a bridge just upstream. The canal headgate is on the left, July 2002



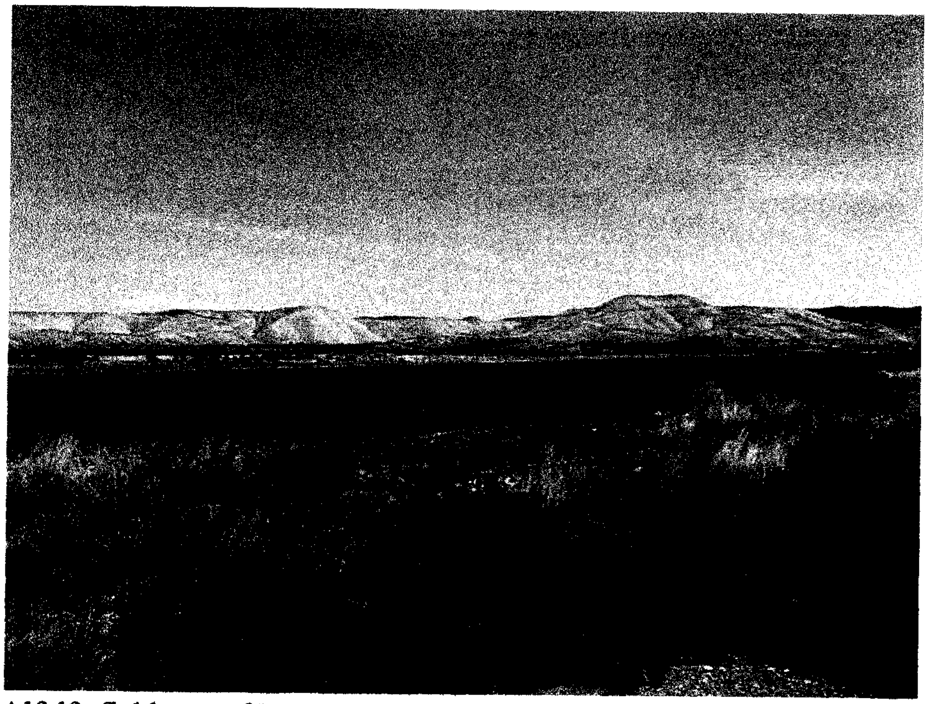
Loutsenhizer Canal headgate structure, the canal is on the left, July 2002



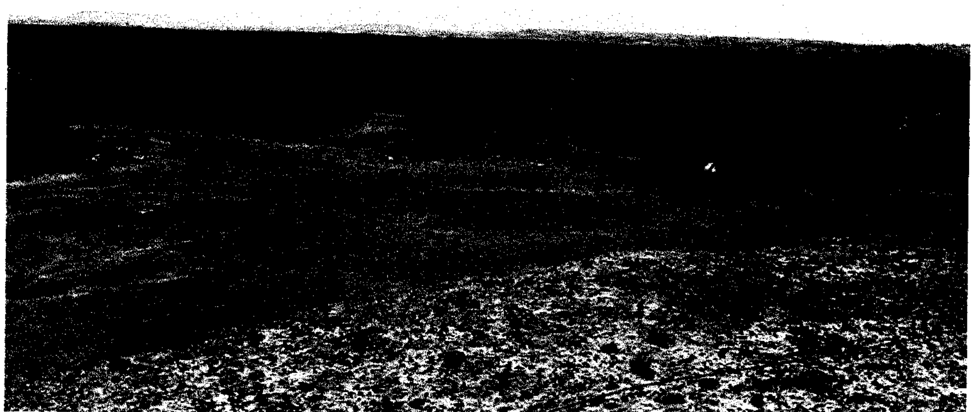
A view of the Uncompahgre River looking upstream from the Loutsenhizer Canal diversion structure. The canal headgate is on the left. July 2002



Loutsenhizer Canal, just downstream from the headgate. Note the house (right) built on the hill of Mancos Shale. July 2002

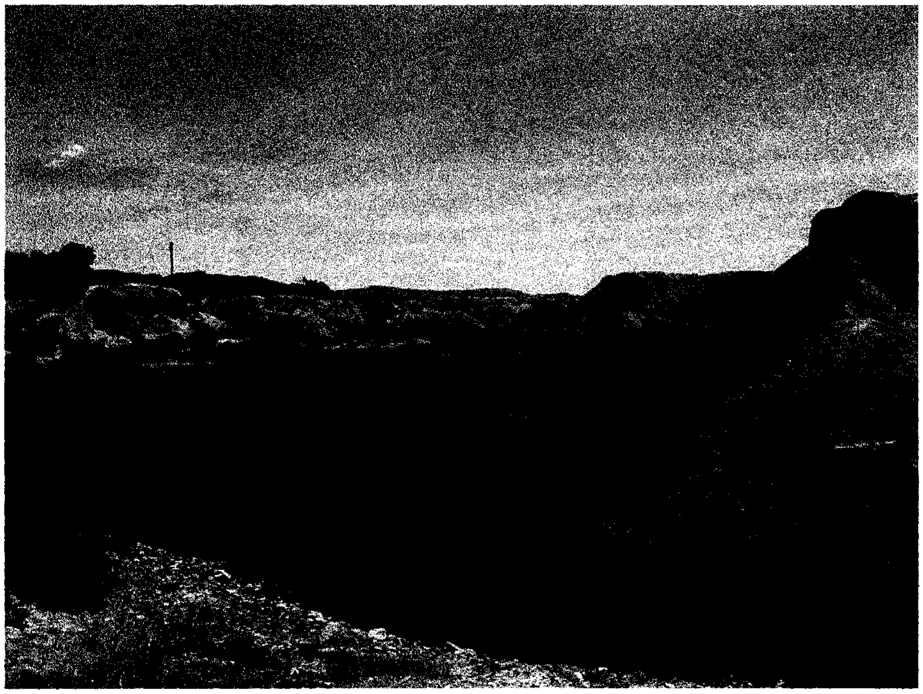


Alfalfa field east of Montrose, Colorado with the Adobe hills (Mancos Shale) in the background, July 2002

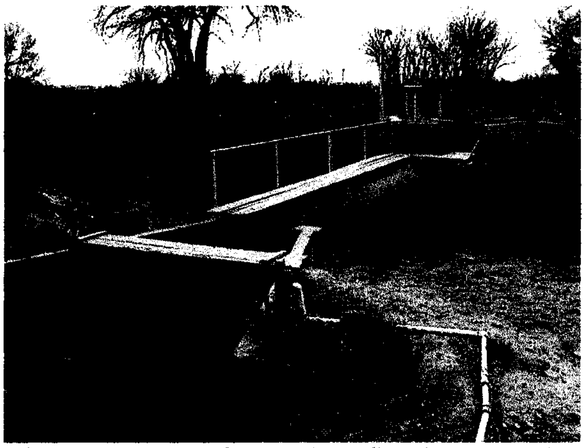


Farmland served by a canal in the Mancos, photo by Luis Garcia

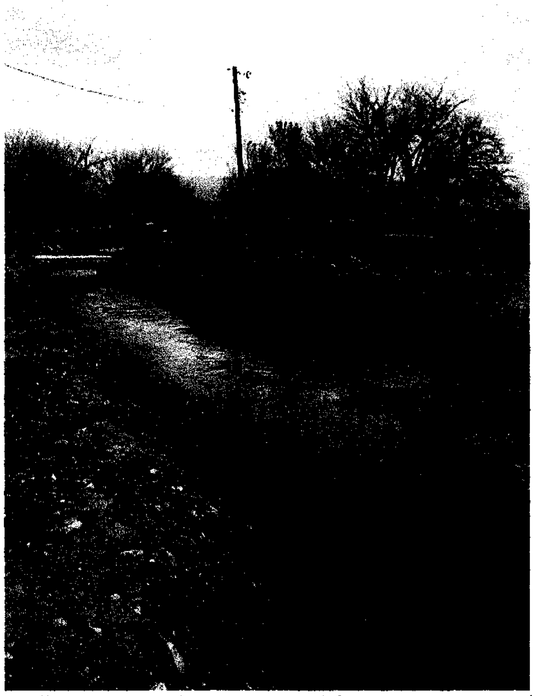
A landscape pond east of the town of Montrose, Colorado, July 2002



The Loutsenhizer Arroyo near Peach Valley Road. The arroyo walls are over 20 feet tall, July 2002

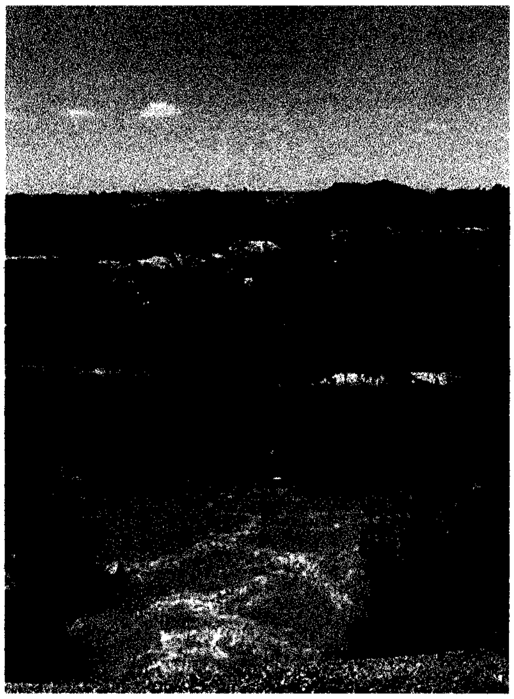


The Garnet Canal aqueduct flowing over the Loutsenhizer Arroyo return, Photo by Ken Leib, USGS



Inflow from the Loutsenhizer Arroyo as it is diverted to flow into the Garnet Canal. The Arroyo flow enters the Canal from the right and flows away from the camera. Photo by Ken Leib, USGS

The Uncompahgre River below all major diversions and above the Loutsenhizer return flow, at Blossom Road, July 2002 (same day as other River photos above)



The Loutsenhizer Arroyo as it passes under Highway 50 north of Banner Road, near Olathe, Colorado, July 2002

The confluence of the Loutsenhizer Arroyo (left) with the Uncompahgre river (background), photo by Ken Leib, USGS

The Devil's Thumb Golf Course north of Delta, Colorado with Mancos Shale in the background, photo by Luis Garcia

Calibration Parameters

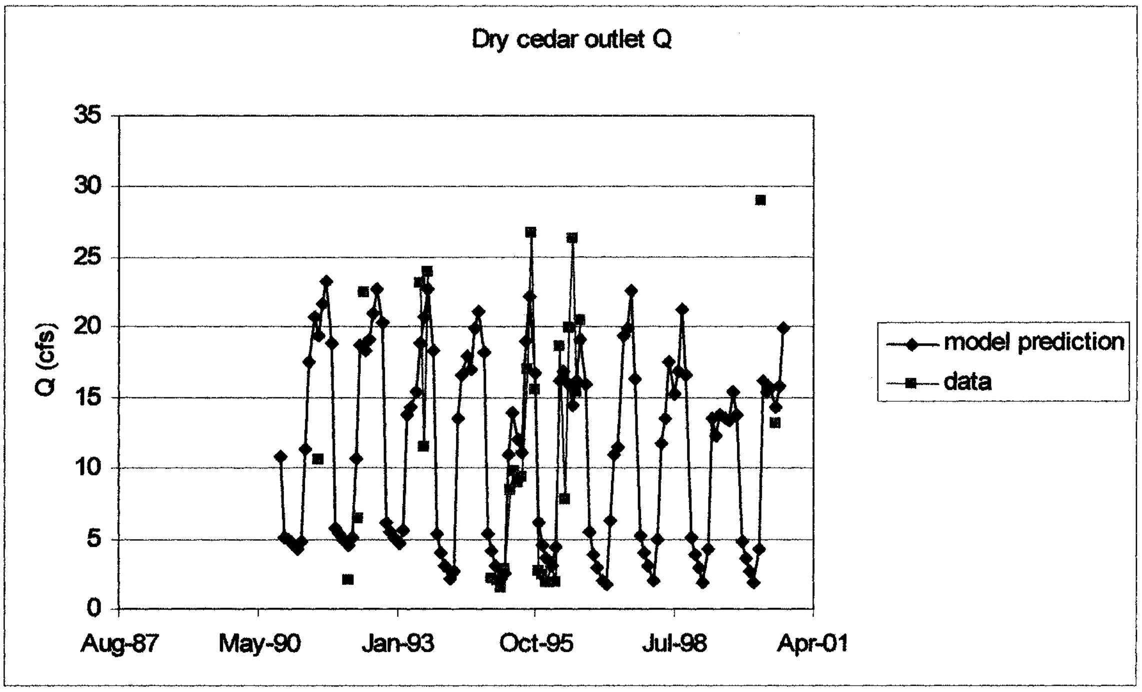
Table A1. Parameter Values for Calibrated Model

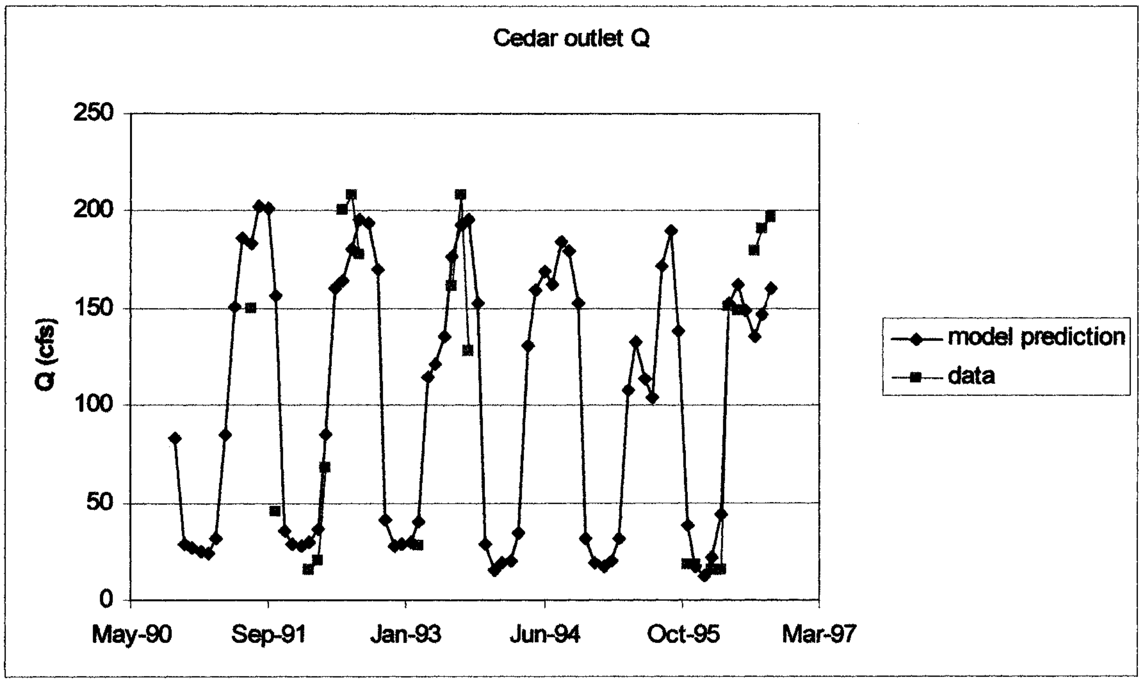
Sub-basin	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry	Out of basin above	Out of basin below
Application Flow Components							
South Canal	0.0889	0.8379	0.03504	0	0	0.0400	0
Loutsenhizer Canal	0.0525	0.5607	0.3642	0	0	0.0225	0
Selig Canal	0	0	0.3236	0	0	0.6763	0
East Canal	0	0	0.1668	0	0	0.8331	0
West Canal	0	0	0	0.3933	0.1126	0	0.4940
M&D Canal	0	0	0	0.2244	0.2905	0	0.4850
Ironstone Canal	0	0	0	0	0.2423	0	0.7576
Surface and Sub-surface Partitioning							
Surface partition	0.90	0.85	0.87	0.35	0.68	0.9	0.9
Sub-surface partition	0.10	0.15	0.13	0.65	0.32	0.10	0.10
Surfacewater Quality							
surfacewater [Se] (µg/l)	0	0	2	0	0	0	0
surfacewater [TDS] (mg/l)	200	200	200	0	300	0	0
Groundwater Quality							
groundwater [Se] (µg/l)	60	40	170	2	9	160	9
groundwater [TDS] (mg/l)	4200	2400	4500	1000	1100	7000	1800
Canal and Lateral Seepage							
seepage rate (ft^3/ft^2/day)	0.25	0.25	0.25	0.25	0.25	0	0
canal wetted perimeter (ft)	14	14	14	14	14	0	0
lateral wetted perimeter (ft)	7	7	7	7	7	0	0
total canal length (miles)	3.5	10.1	26.1	12.2	26.3	0	0
total lateral length (miles)	10.4	33.9	53.0	25.2	62.7	0	0
Pond seepage							
seepage rate (ft^3/ft^2/day)	0.1	0.1	0.1	0.1	0.1	0	0
days per year ponds full	225	225	225	225	225	0	0
seepage fraction that influences river	0.67	0.67	0.67	0.67	0.67	0	0
total area of ponds (acres)	69	69	69	92	92	0	0

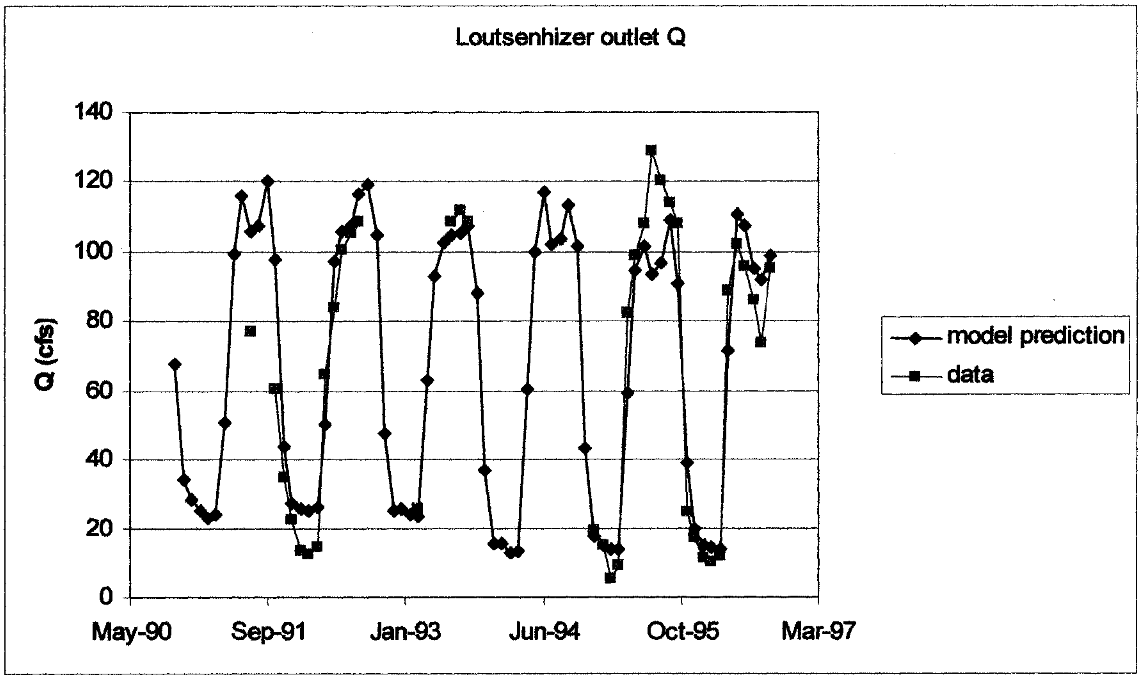
Table A2. Sub-Basin Convolution Parameter Values for Calibrated Model

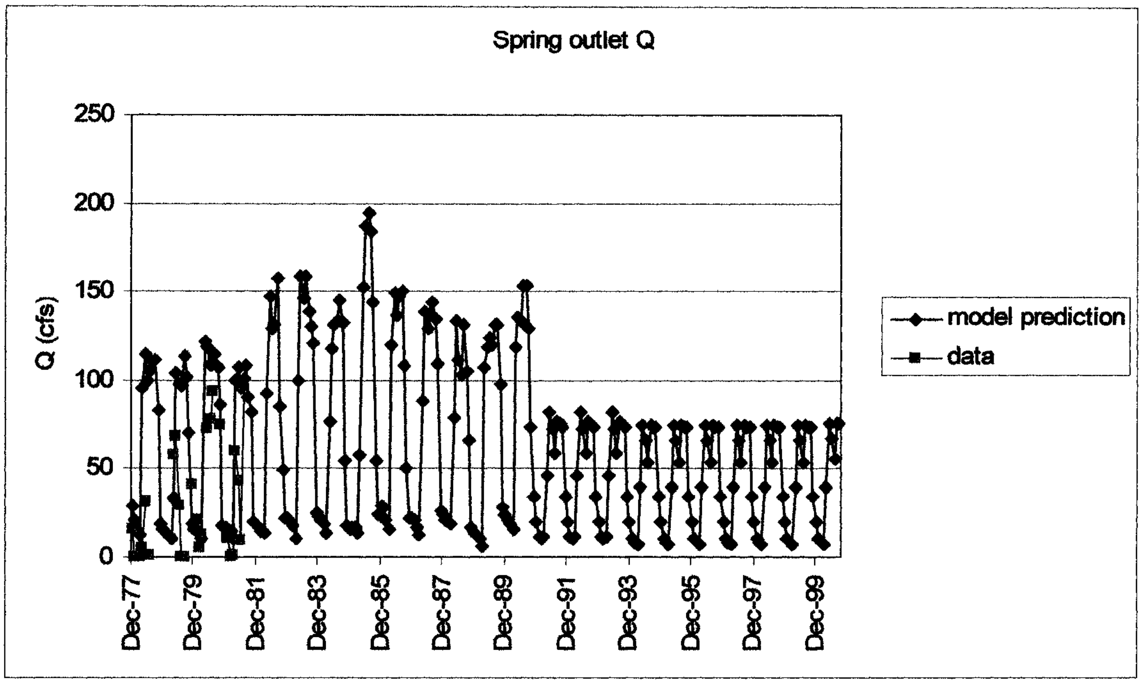
Sub-basin	Dry Cedar	Cedar	Loutsenhizer	Spring	Dry	Out of basin above	Out of basin below
Surface Convolution							
month - 0	0.98	1.00	0.75	0.39	1.00	0.98	0.98
month - 1	0.02	0.00	0.25	0.61	0.00	0.02	0.02
Groundwater Convolution							
month - 0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
month - 1	0.20	0.49	0.36	0.02	0.01	0.20	0.20
month - 2	0.20	0.00	0.00	0.16	0.00	0.20	0.20
month - 3	0.20	0.00	0.11	0.11	0.00	0.20	0.20
month - 4	0.20	0.00	0.00	0.29	0.04	0.20	0.20
month - 5	0.10	0.00	0.00	0.22	0.43	0.20	0.20
month - 6	0.10	0.51	0.53	0.20	0.51	0.00	0.00

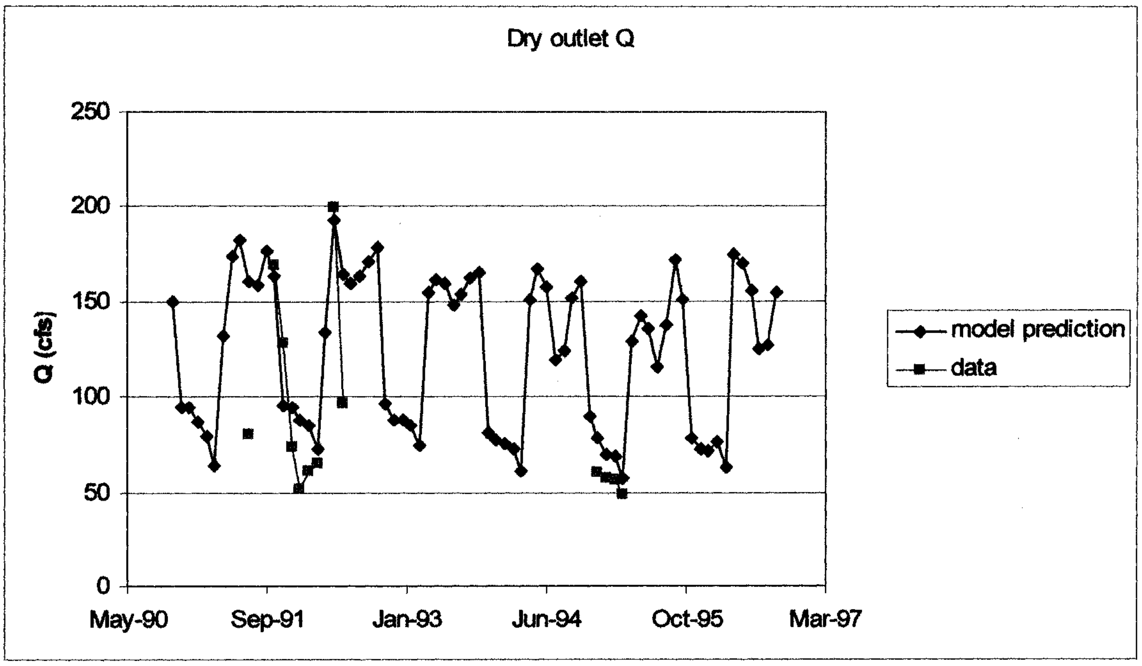
Calibration Comparison Plot Output

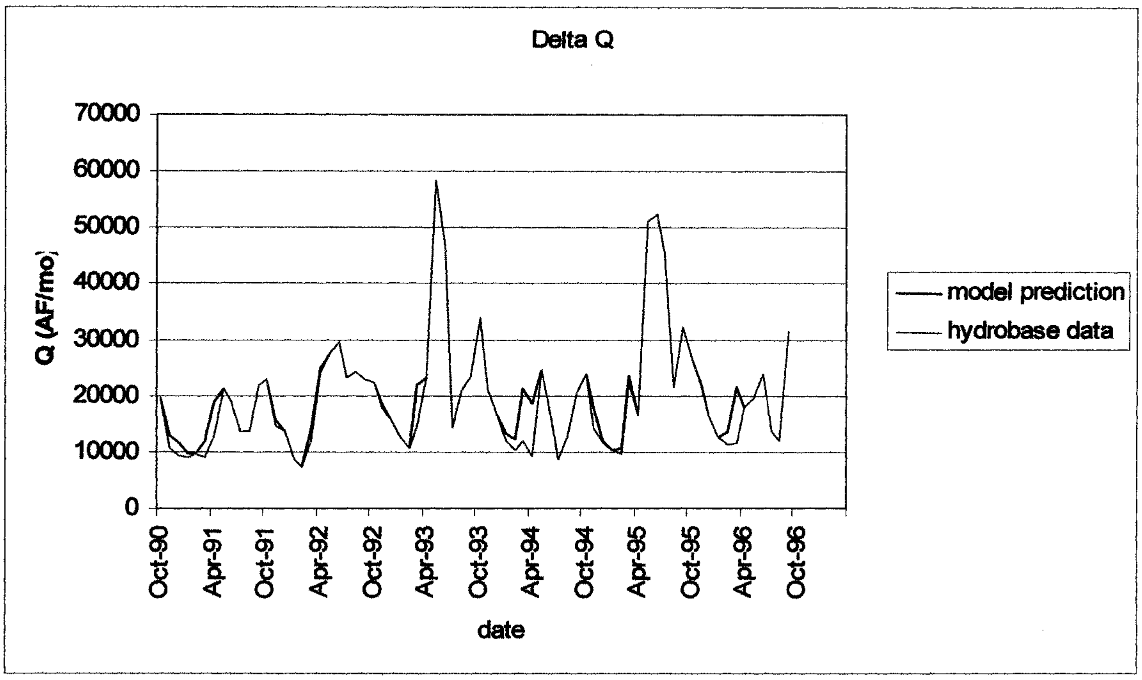


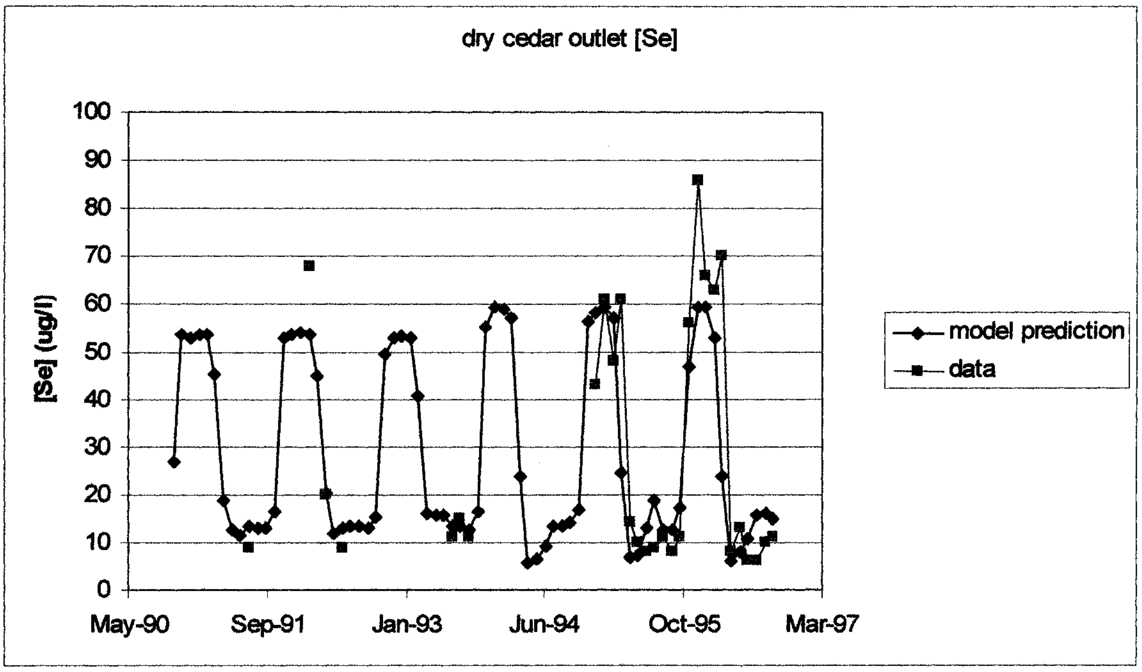

Cedar outlet Q
250
200
150
100
50
0
Q (cfs)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

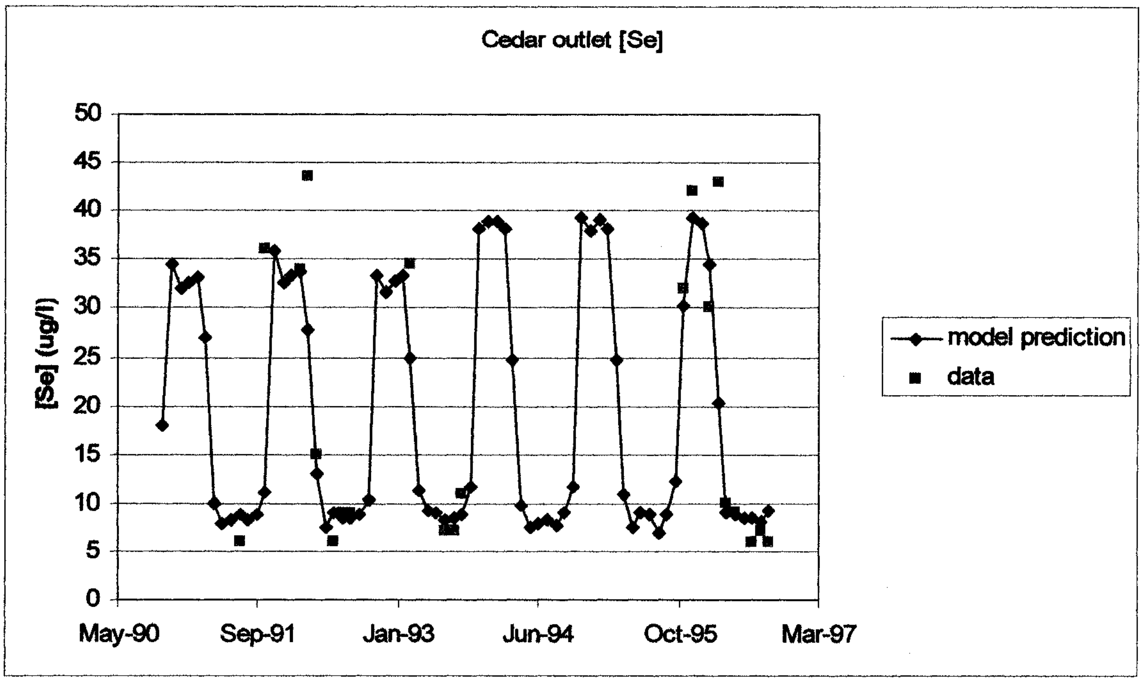

Loutsenhizer outlet Q
140
120
100
80
60
40
20
0
Q (cfs)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

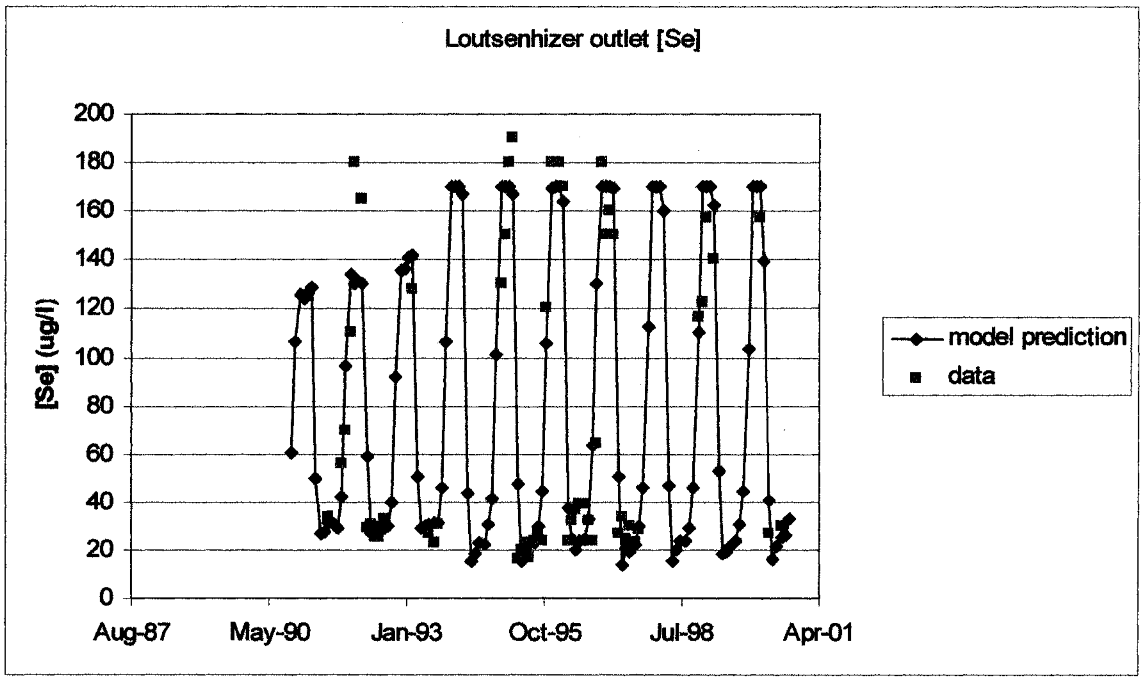

Spring outlet Q
250
200
150
100
50
0
Q (cfs)
Dec-77
Dec-79
Dec-81
Dec-83
Dec-85
Dec-87
Dec-89
Dec-91
Dec-93
Dec-95
Dec-97
Dec-99
model prediction
data

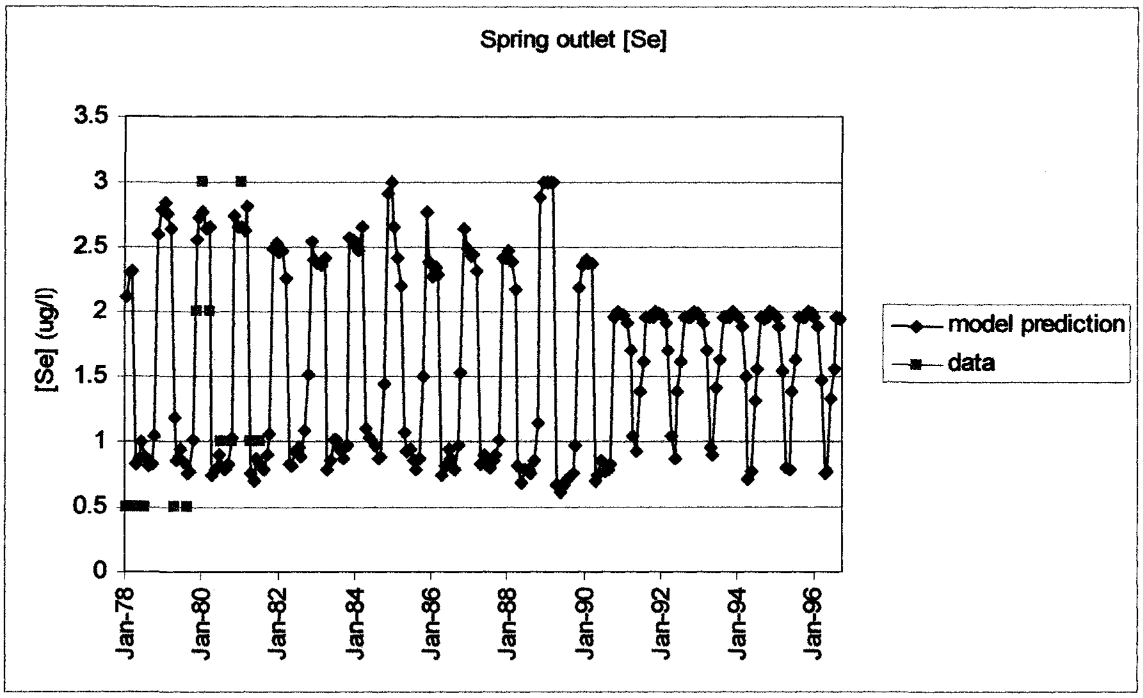

Dry outlet Q
250
200
150
100
50
0
Q (cfs)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

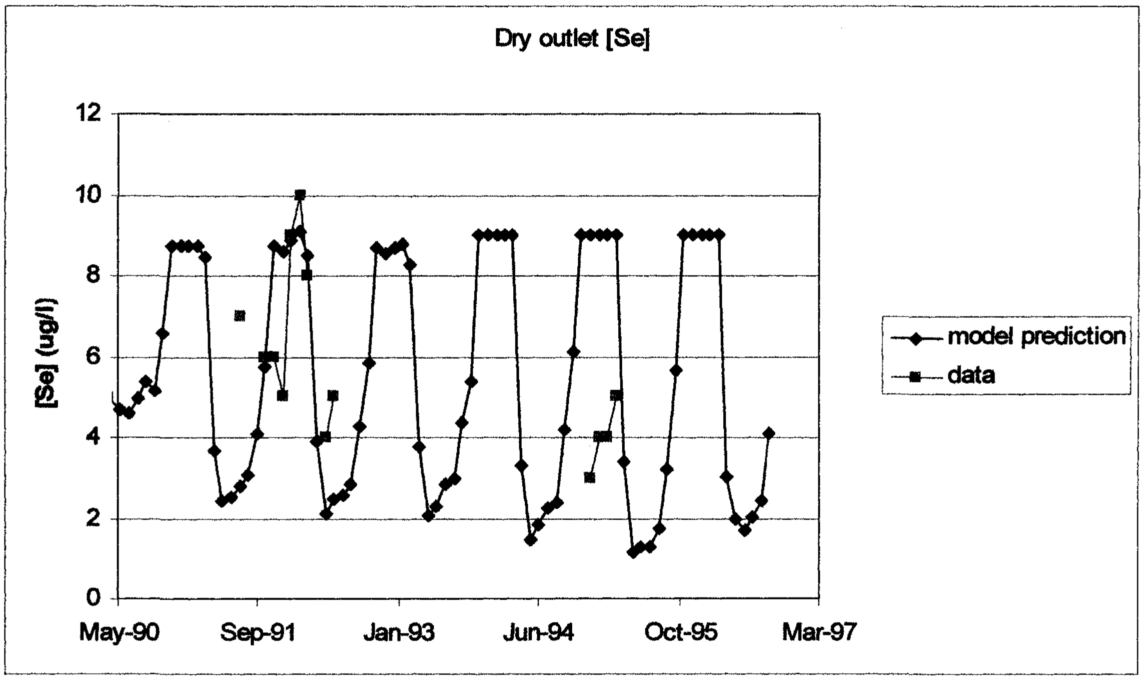

Delta Q
70000
60000
50000
40000
30000
20000
10000
0
Q (AF/mo)
Oct-90
Apr-91
Oct-91
Apr-92
Oct-92
Apr-93
Oct-93
Apr-94
Oct-94
Apr-95
Oct-95
Apr-96
Oct-96
date
model prediction
hydrobase data

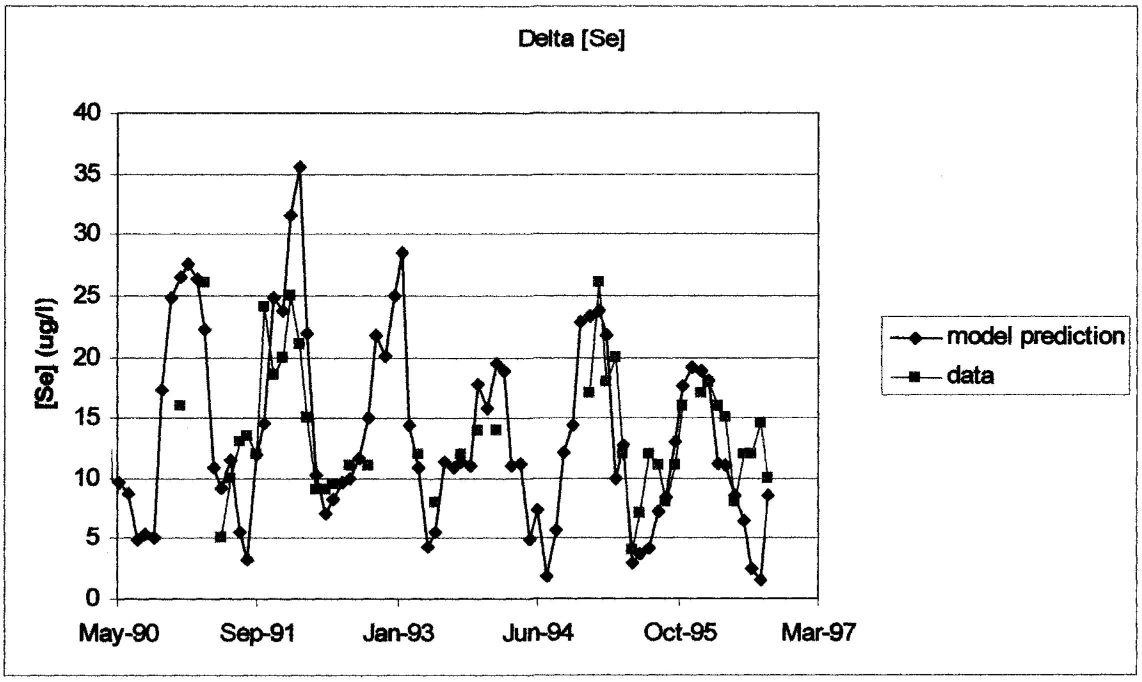

dry cedar outlet [Se]
100
90
80
70
60
50
40
30
20
10
0
[Se] (ug/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

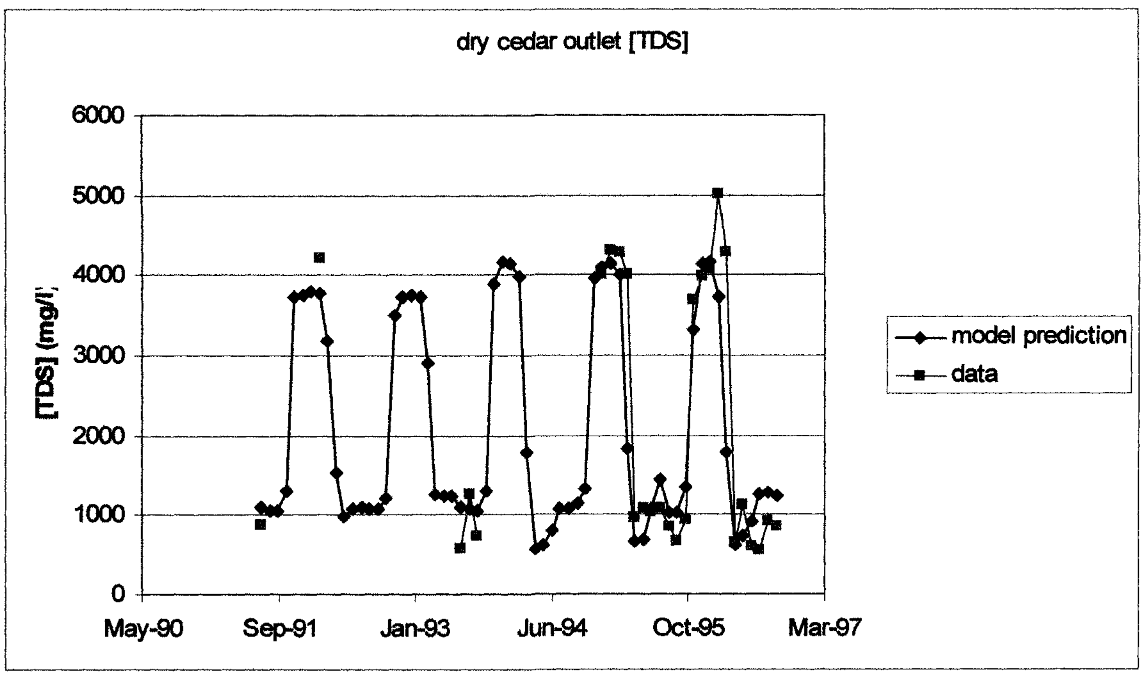

Cedar outlet [Se]
50
45
40
35
30
25
20
15
10
5
0
[Se] (ug/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

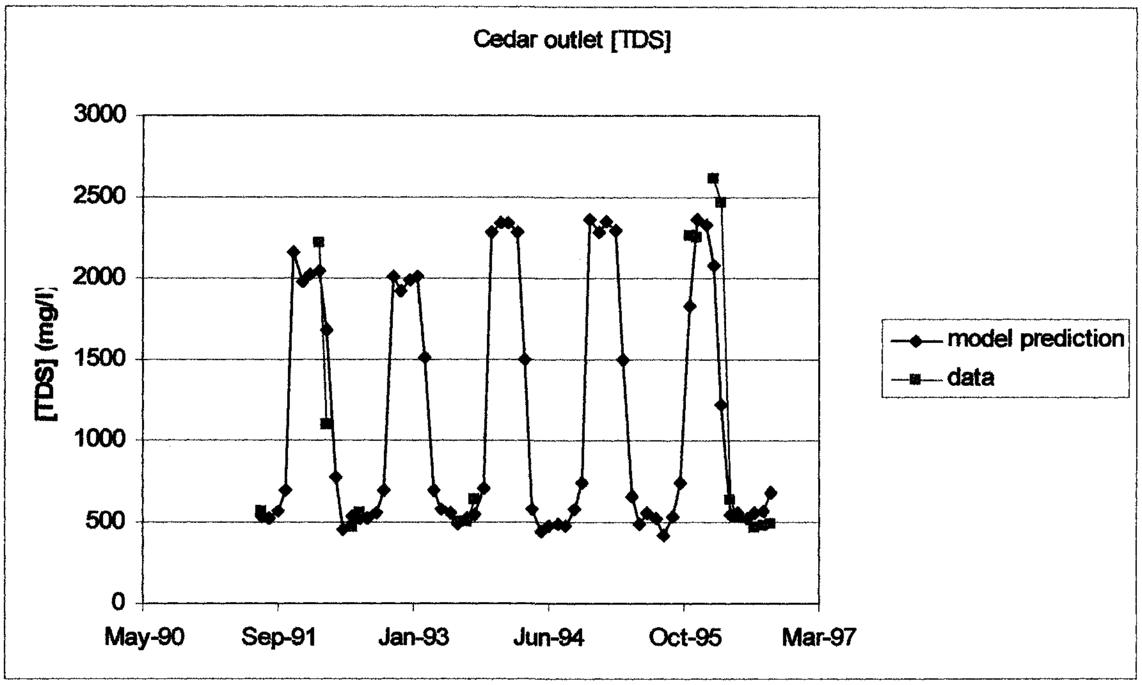

Loutsenhizer outlet [Se]
200
180
160
140
120
100
80
60
40
20
0
[Se] (ug/l)
Aug-87
May-90
Jan-93
Oct-95
Jul-98
Apr-01
model prediction
data

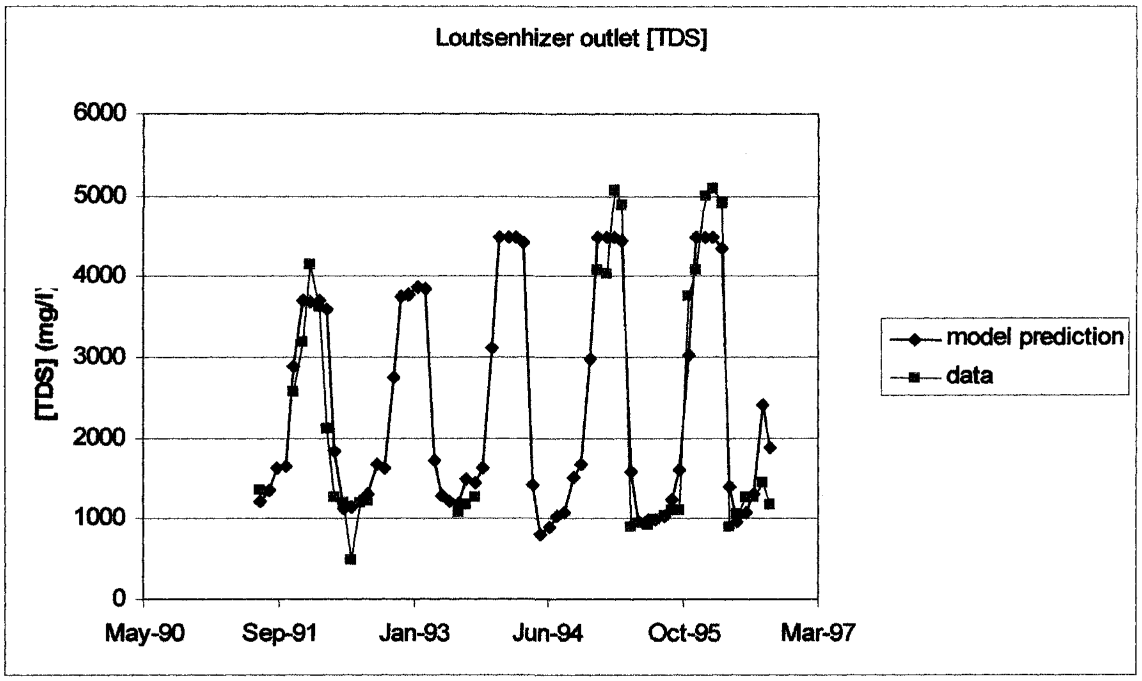

Spring outlet [Se]
3.5
3
2.5
2
1.5
1
0.5
0
[Se] (ug/l)
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
model prediction
data

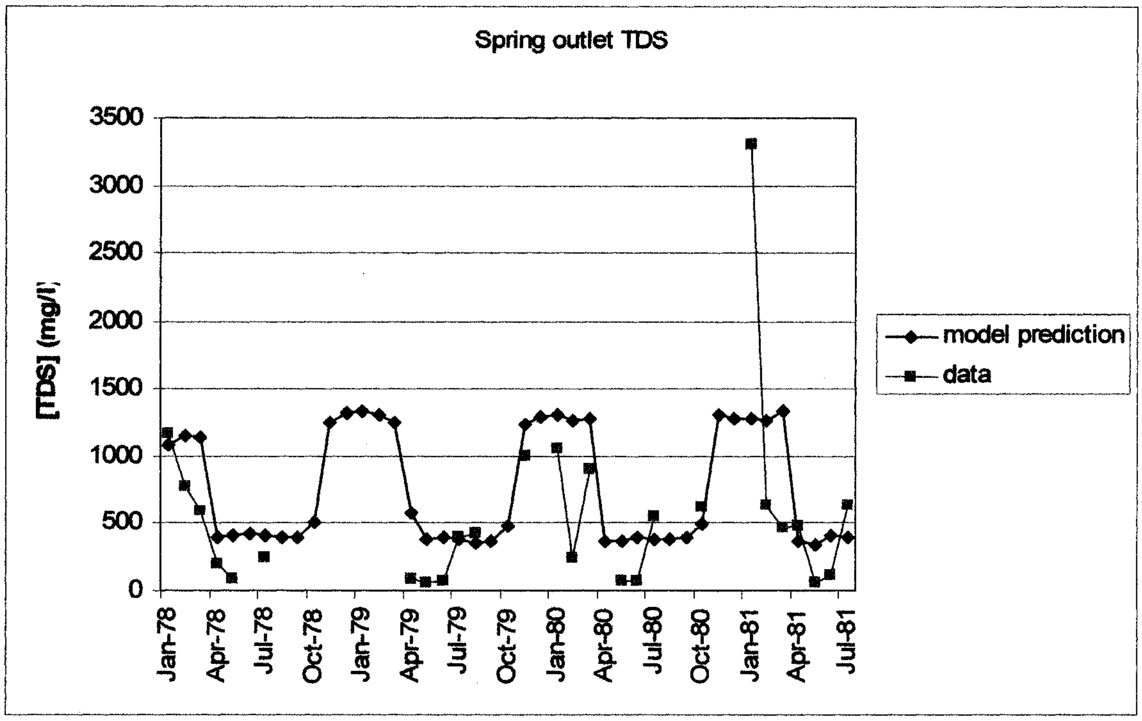

Dry outlet [Se]
12
10
8
6
4
2
0
[Se] (ug/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

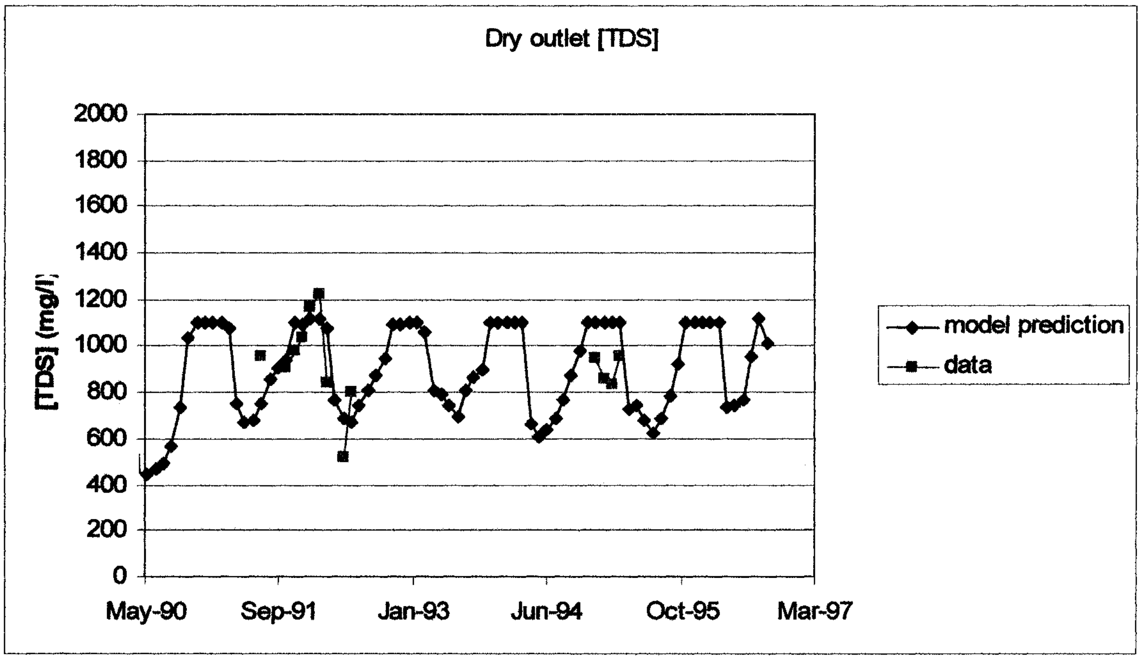

Delta [Se]
40
35
30
25
20
15
10
5
0
[Se] (ug/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

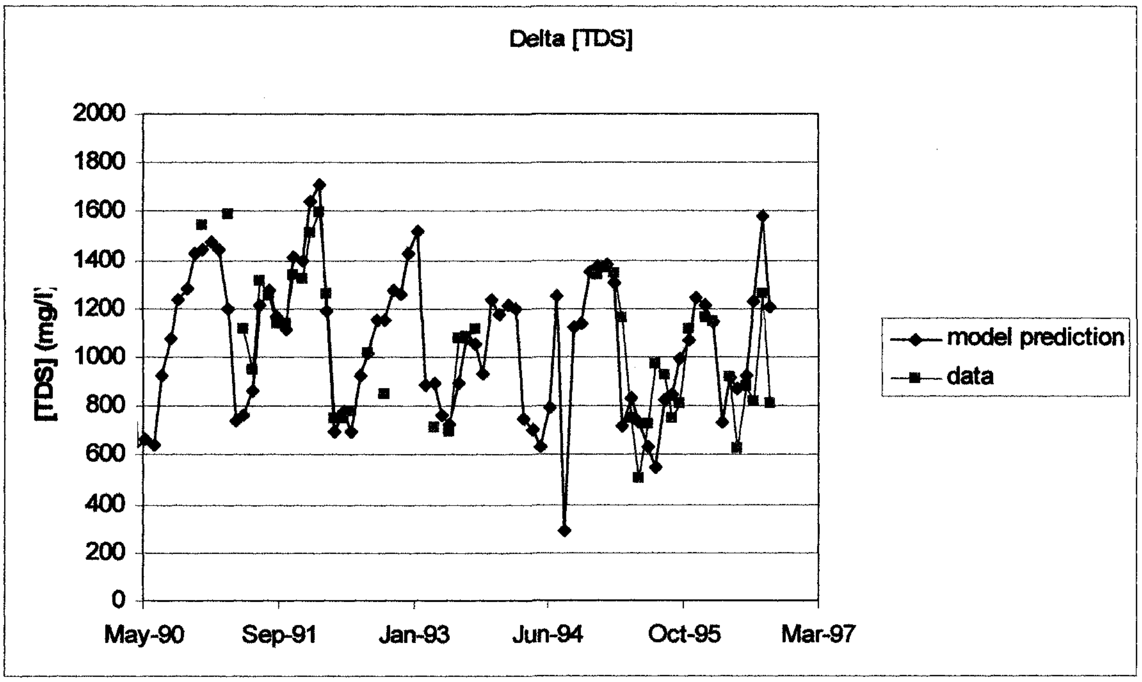

dry cedar outlet [TDS]
6000
5000
4000
3000
2000
1000
0
[TDS] (mg/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

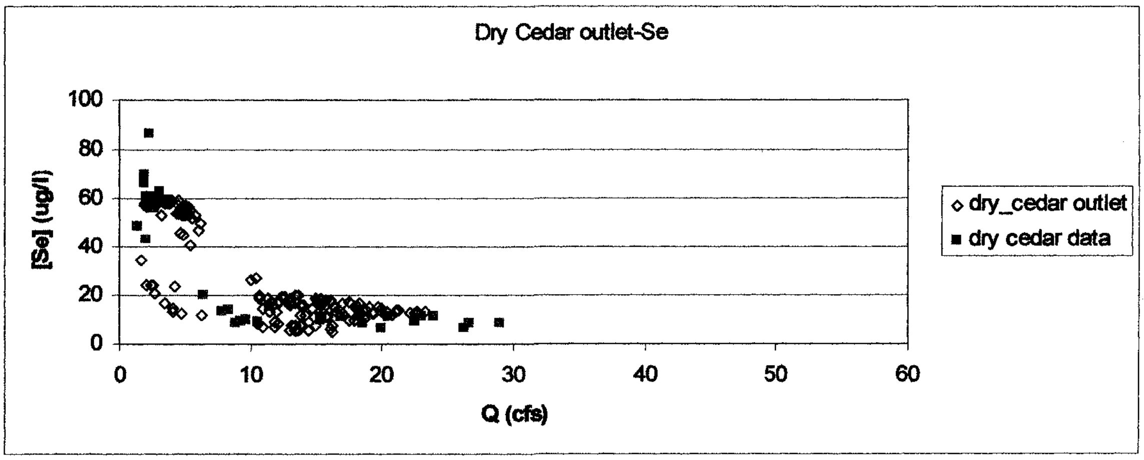

Cedar outlet [TDS]
3000
2500
2000
1500
1000
500
0
[TDS] (mg/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

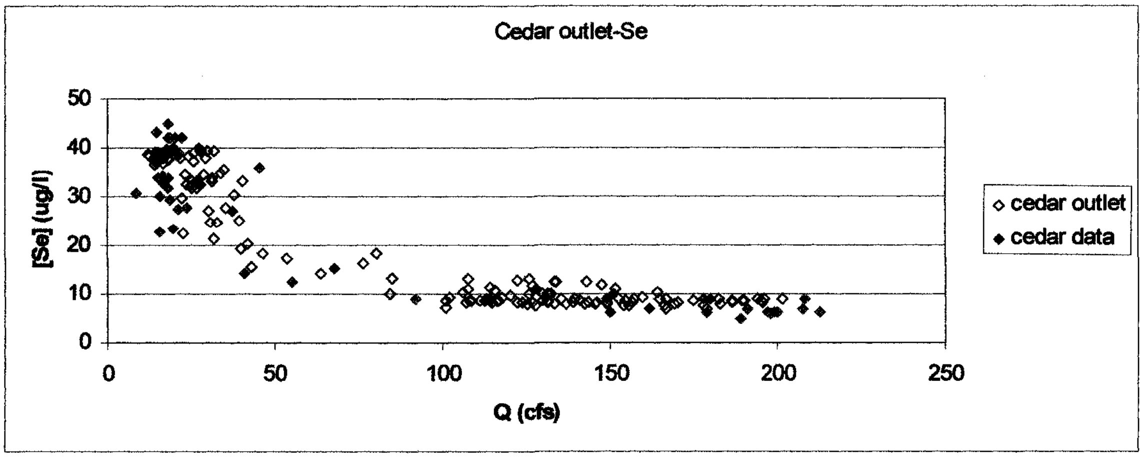

Loutsenhizer outlet [TDS]
6000
5000
4000
3000
2000
1000
0
[TDS] (mg/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

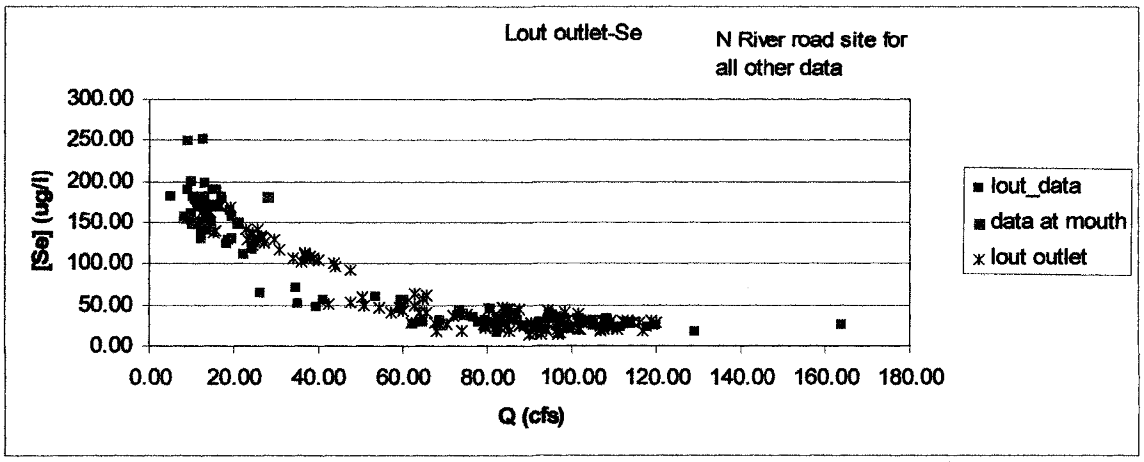

Spring outlet TDS
3500
3000
2500
2000
1500
1000
500
0
[TDS] (mg/l)
Jan-78
Apr-78
Jul-78
Oct-78
Jan-79
Apr-79
Jul-79
Oct-79
Jan-80
Apr-80
Jul-80
Oct-80
Jan-81
Apr-81
Jul-81
model prediction
data

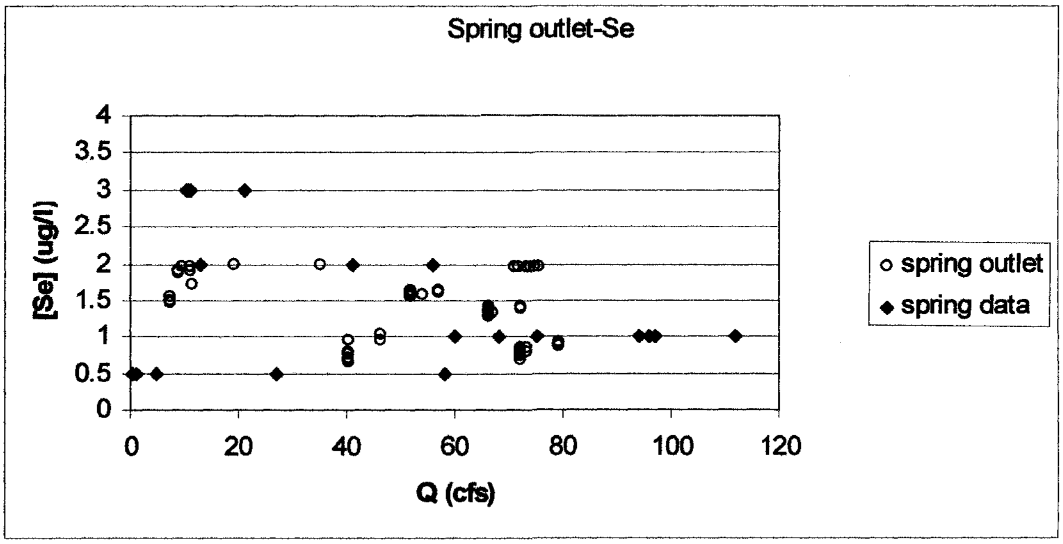

Dry outlet [TDS]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
[TDS] (mg/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

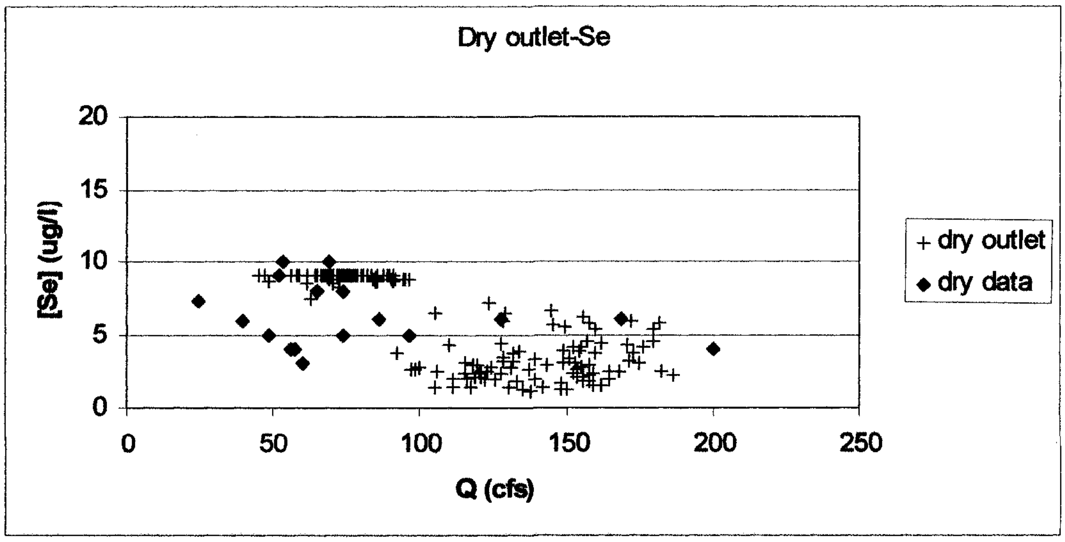

Delta [TDS]
2000
1800
1600
1400
1200
1000
800
600
400
200
0
[TDS] (mg/l)
May-90
Sep-91
Jan-93
Jun-94
Oct-95
Mar-97
model prediction
data

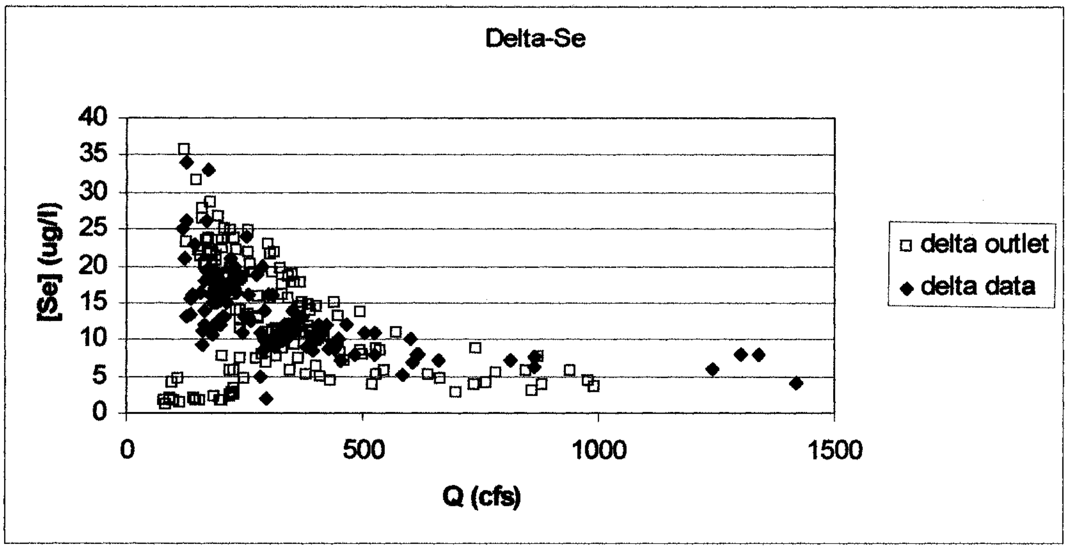

Dry Cedar outlet-Se
100
80
60
40
20
0
[Se] (ug/l)
0
10
20
30
40
50
60
Q (cfs)
dry_cedar outlet
dry cedar data

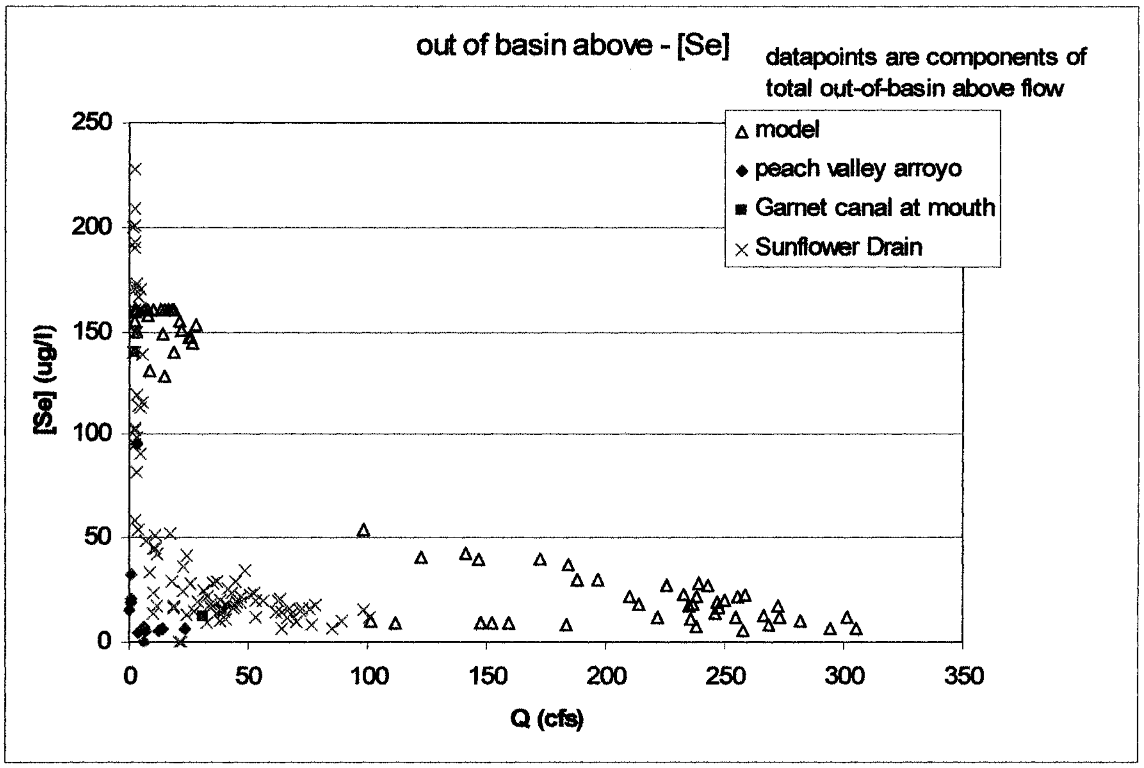

Cedar outlet-Se
50
40
30
20
10
0
[Se] (ug/l)
0
50
100
150
200
250
Q (cfs)
cedar outlet
cedar data

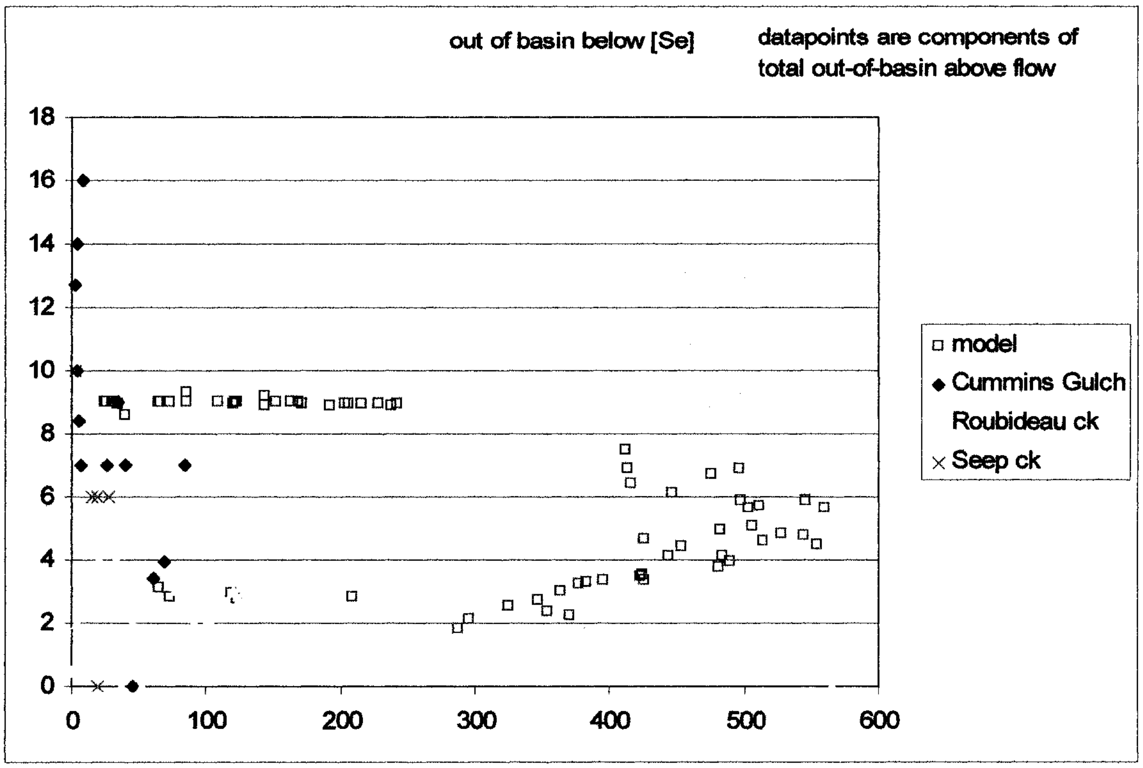

Lout outlet-Se
N River road site for all other data
300.00
250.00
200.00
150.00
100.00
50.00
0.00
[Se] (ug/l)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
160.00
180.00
Q (cfs)
lout_data
data at mouth
lout outlet

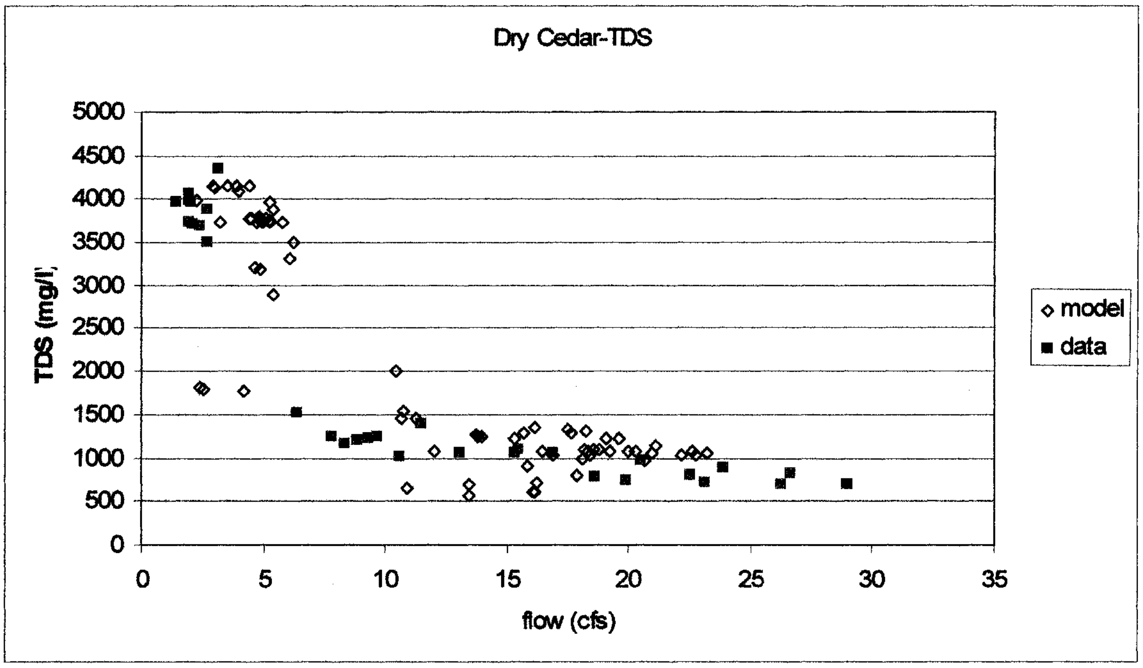

Spring outlet-Se
4
3.5
3
2.5
2
1.5
1
0.5
0
[Se] (ug/l)
0
20
40
60
80
100
120
Q (cfs)
spring outlet
spring data

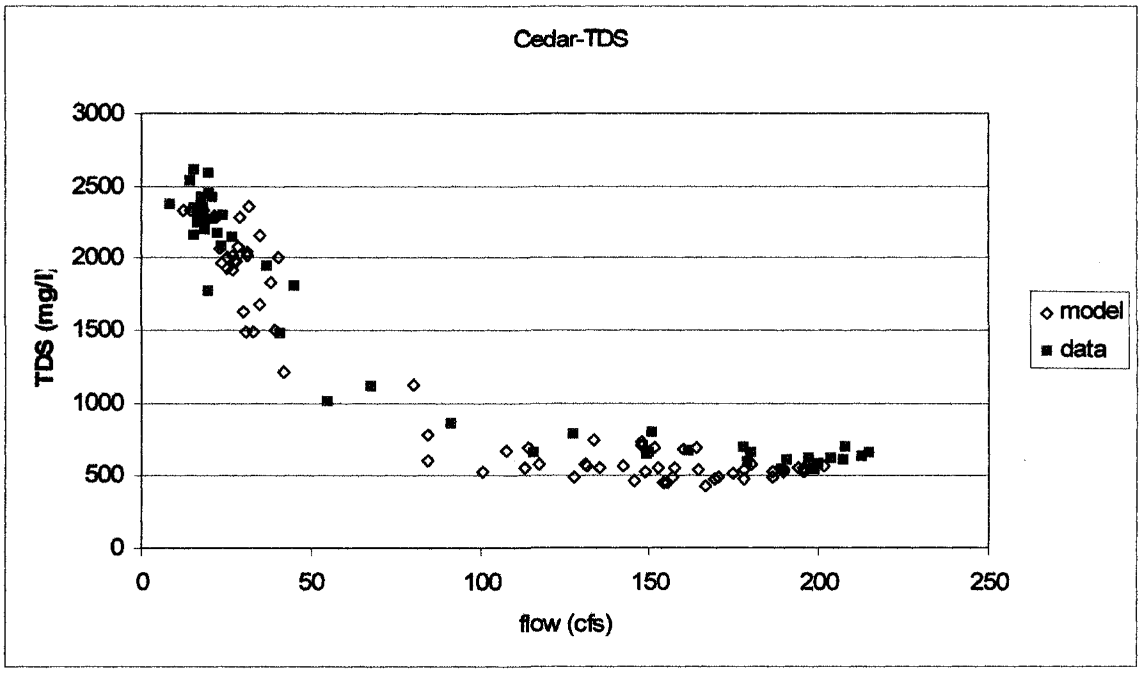

Dry outlet-Se
20
15
10
5
0
[Se] (ug/l)
0
50
100
150
200
250
Q (cfs)
dry outlet
dry data


Delta-Se
40
35
30
25
20
15
10
5
0
[Se] (ug/l)
0
500
1000
1500
Q (cfs)
delta outlet
delta data

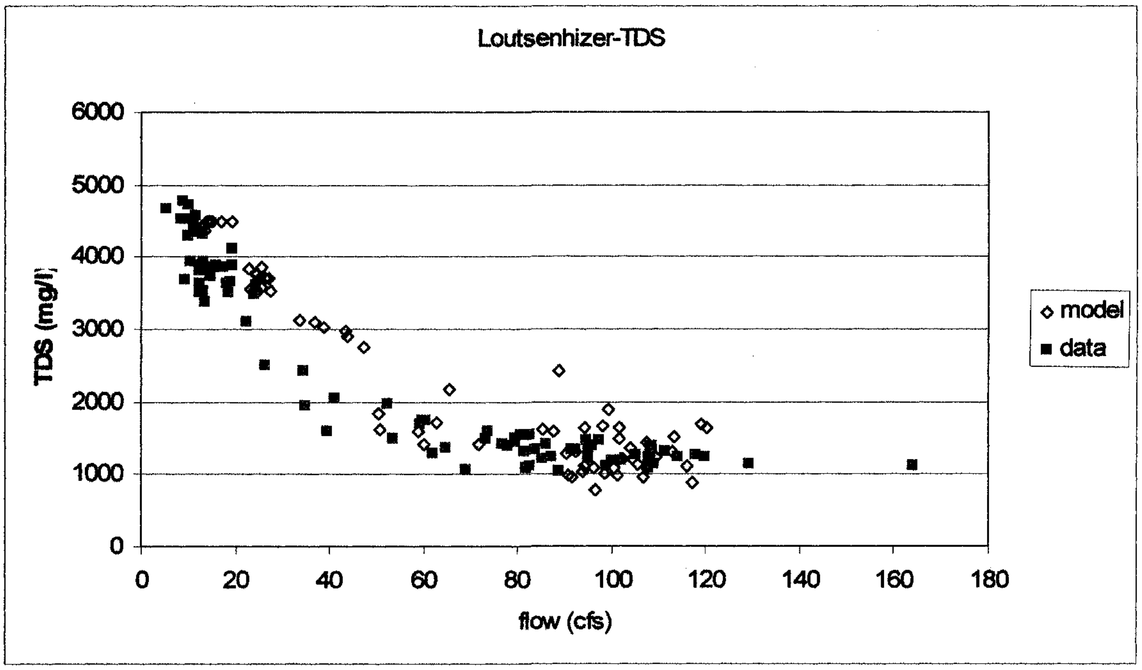

out of basin above - [Se]
datapoints are components of total out-of-basin above flow
model
peach valley arroyo
Garnet canal at mouth
Sunflower Drain
250
200
150
100
50
0
[Se] (ug/l)
0
50
100
150
200
250
300
350
Q (cfs)


out of basin below [Se]
datapoints are components of total out-of-basin above flow
18
16
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600
model
Cummins Gulch
Roubideau ck
Seep ck

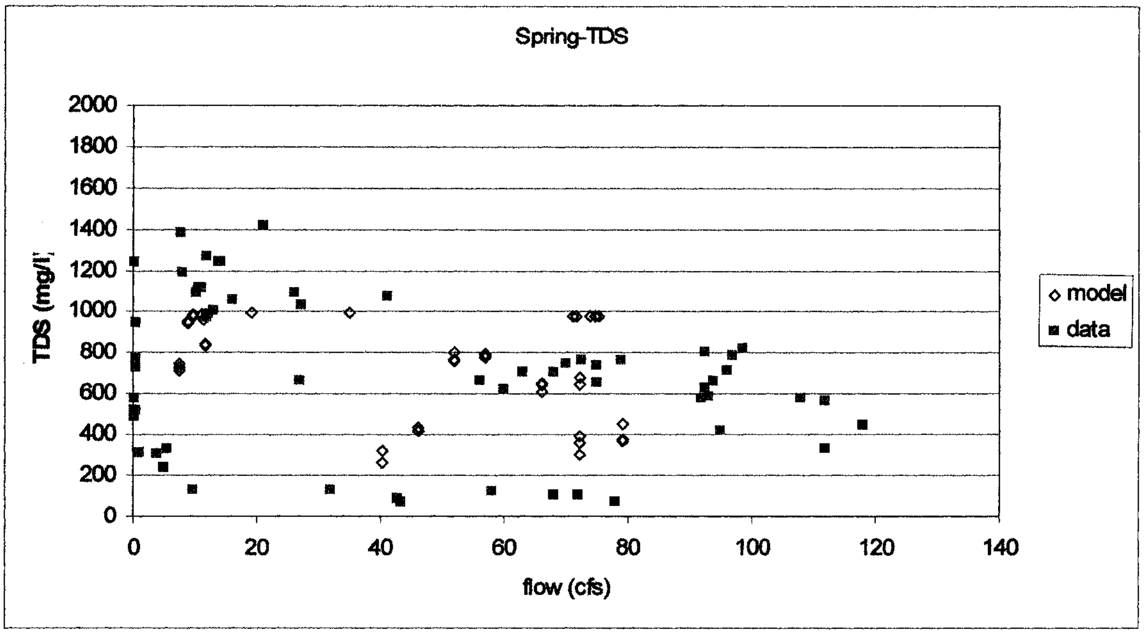

Dry Cedar-TDS
TDS (mg/l)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
flow (cfs)
model
data



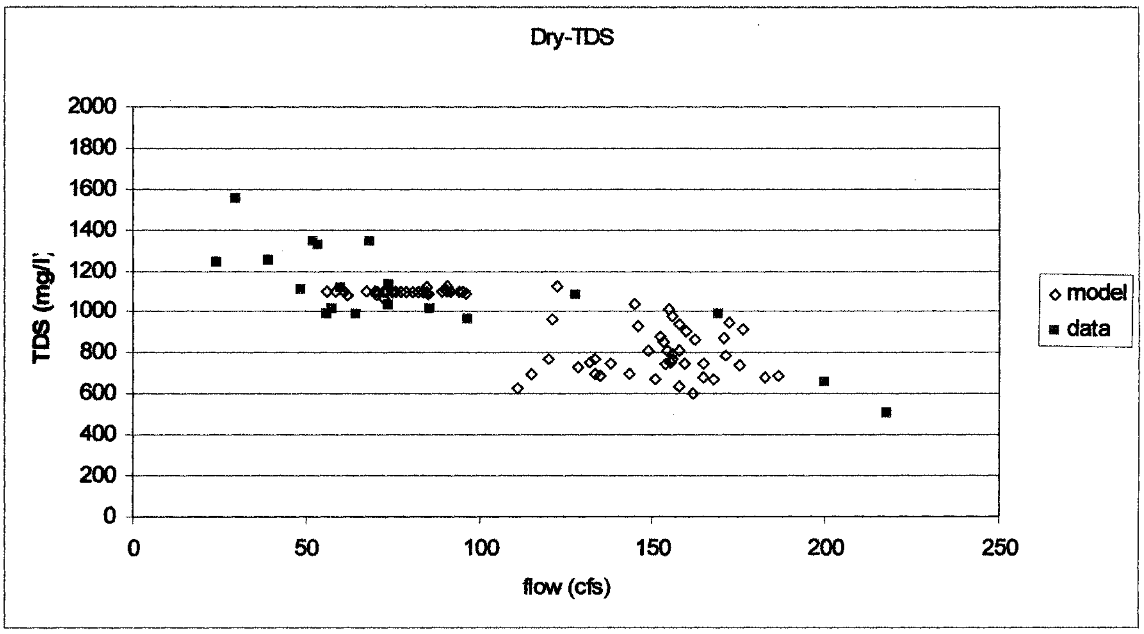
Cedar-TDS
TDS (mg/l)
3000
2500
2000
1500
1000
500
0
0
50
100
150
200
250
flow (cfs)
model
data



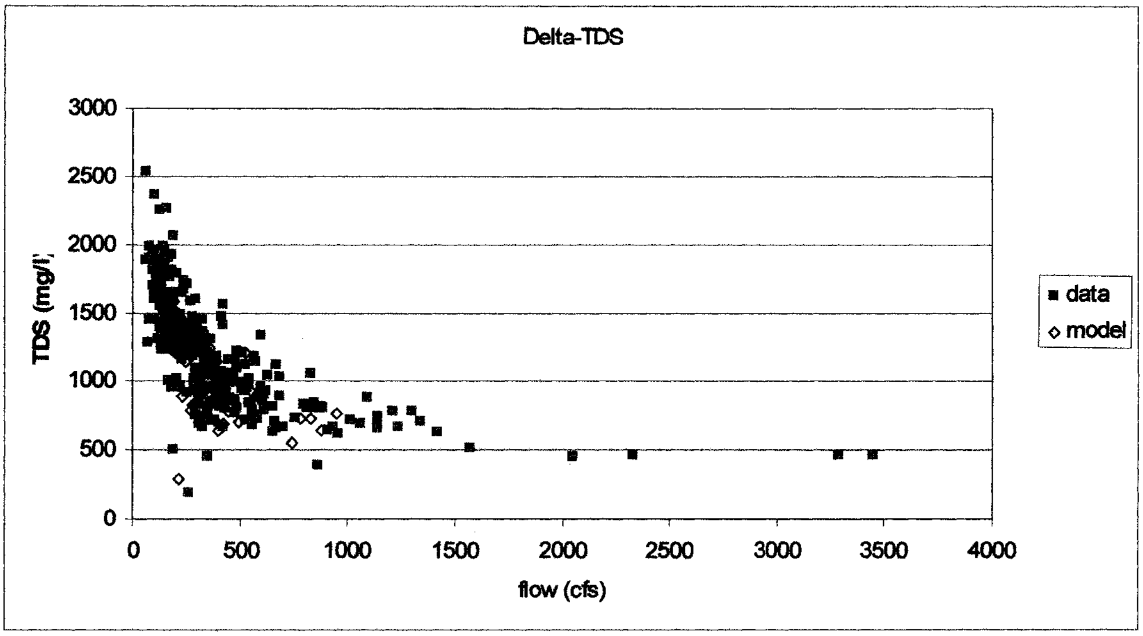
Loutsenhizer-TDS
TDS (mg/l)
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
140
160
180
flow (cfs)
model
data

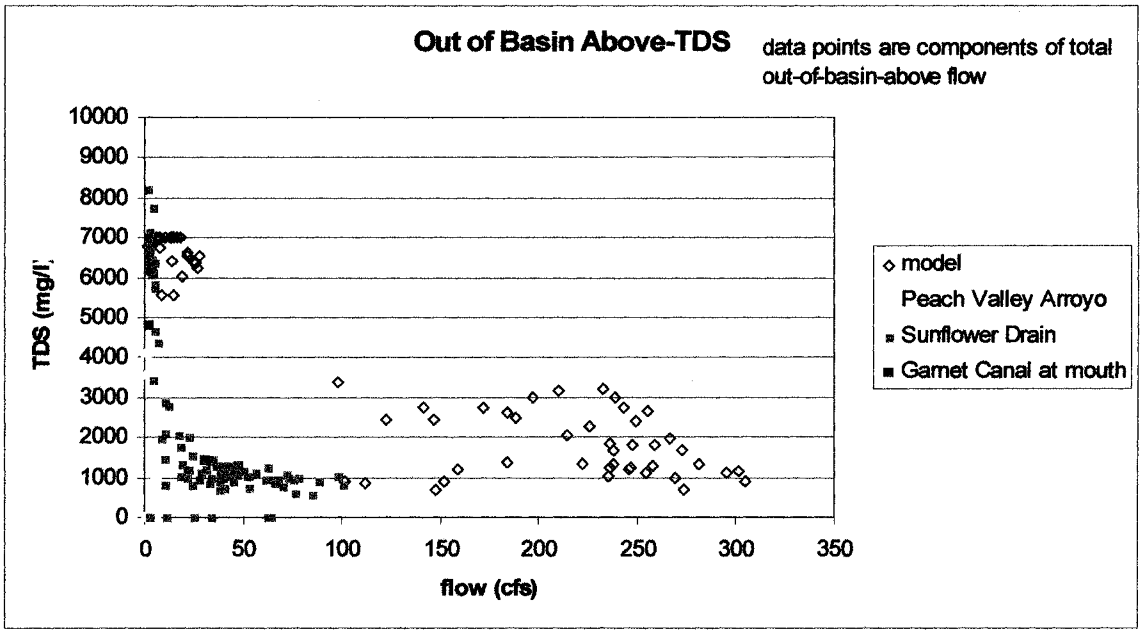


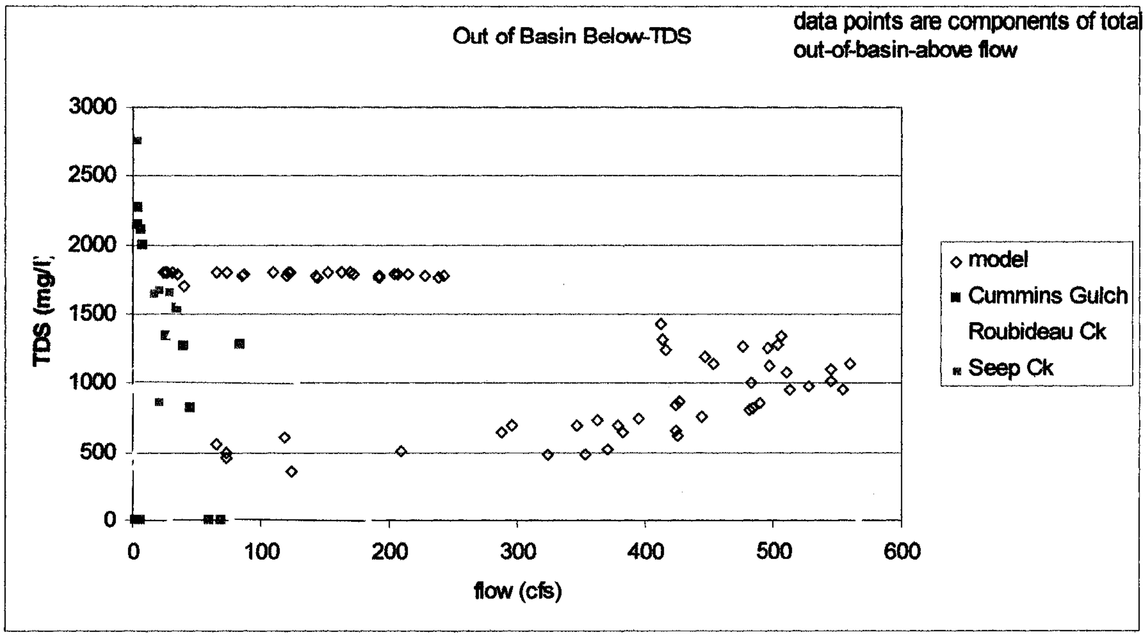
Spring-TDS
TDS (mg/l)
flow (cfs)
model
data



Dry-TDS
TDS (mg/l)
flow (cfs)
model
data


Delta-TDS
TDS (mg/l)
flow (cfs)
0
500
1000
1500
2000
2500
3000
3500
4000
data
model


Out of Basin Above-TDS
data points are components of total out-of-basin-above flow
TDS (mg/l)
flow (cfs)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
50
100
150
200
250
300
350
model
Peach Valley Arroyo
Sunflower Drain
Garnet Canal at mouth



Water Quality Sampling Data

The following data were collected by Marianna French, Chrystine Kessler and Mike Nadiak as part of a cooperative agreement between Colorado State University and Montrose High School, Montrose CO.

Table A3. Sampling locations for CSU/Montrose High School Data collection

Location	Sampling Site Number
Uncompahgre River below South Canal inflow, below West Canal diversion	1
Uncompahgre River above M&D canal diversion	2
Uncompahgre River below Loutsenhizer Canal diversion	3
Uncompahgre River above Selig Canal diversion, above Cedar Creek and Spring Creek inflows	4
Uncompahgre River above Ironstone Canal diversion, below Cedar Ck and Spring Ck inflows	5
Uncompahgre River below East Canal diversion	6
Uncompahgre River at Blossom Rd above Loutsenhizer arroyo inflow	7
Uncompahgre River at B Rd. below Loutsenhizer Arroyo Inflow	8
Uncompahgre River at 1600 Rd below Dry Creek inflow	9

Table A4. Sampling data from CSU/Montrose High School Data collection

Saturday 3/15/2003, 75F partly cloudy			
Brand new Hanna Instruments 8733 multi-range conductivity meter calibrated with Hanna calibration solution to 12.88 mS @25C			
		Conductivity (uS/cm)	Se (ug/l) received from lab 4/11/03
Site 1. Time: 9:30		582	2.2
Site 2. Time: 9:45		528	2
Site 3. Time: 10:00		575	2
Site 4. Time: 10:25		700	3.7
Site 5. Time: 10:40		1002	8.5
Site 6. Time: 11:00		1043	8.5
Site 7. Time: 11:50		1112	9.7
Site 8. Time: 11:35		1412	24
Site 9. Time: 11:20		1396	20
Duplicate Time: 11:50	Dup of Site 7	1067	8.3
Saturday 4/19/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab ~5/13/03
Site 1. Time: 9:42		246	0.73
Site 2. Time: 9:57		250	0.6
Site 3. Time: 10:12		313	0.82
Site 4. Time: 10:30		341	1.5
Site 5. Time: 10:45		522	4.4
Site 6. Time: 11:03		1161	11
Site 7. Time: 11:19		1587	9.9
Site 8. Time: 11:33		1534	19
Site 9. Time: 11:48		1408	12
Duplicate Time 11:55	Dup of Site 9	1390	12
Monday 5/19/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 6/13/03
Site 1. Time: 15:50		302	0.36
Site 2. Time: 16:05		300	0.49
Site 3. Time: 16:40		351	0.55
Site 4. Time: 16:56		488	1.6
Site 5. Time: 17:15		701	4
Site 6. Time: 17:35		767	4.4
Site 7. Time: 18:00		814	4.8
Site 8. Time: 18:16		1056	9.9
Site 9. Time: 18:29		1090	8
Duplicate Time: 16:20	Dup of Site	297	0.57

	2		
Sunday 6/15/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 7/02/03
Site 1. Time: 13:44		392	0.48
Site 2. Time: 13:53		356	0.51
Site 3. Time: 14:06		402	0.7
Site 4. Time: 14:21		491	1.2
Site 5. Time: 14:33		674	3.7
Site 6. Time: 14:43		1260	7.4
Site 7. Time: 14:58		1610	9.2
Site 8. Time: 15:08		1692	17
Site 9. Time: 15:20		1544	11
Duplicate Time: 15:01	Dup of Site 7	1604	9.8
Monday 7/14/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 07/29/03
Site 1. Time: 09:43		481	non-detect
Site 2. Time: 09:51		302	0.55
Site 3. Time: 10:04		336	0.64
Site 4. Time: 10:17		420	0.97
Site 5. Time: 10:30		601	3.4
Site 6. Time: 10:43		762	4.1
Site 7. Time: 10:54		1175	6.9
Site 8. Time: 11:04		1607	15
Site 9. Time: 11:17		1412	9.5
Duplicate Time: 11:04	Dup of Site 8	1609	14
Thursday 8/14/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 09/03/03
Site 1. Time: 12:40		440	0.64
Site 2. Time: 12:51		283	0.47
Site 3. Time: 13:03		366	0.46
Site 4. Time: 13:20		527	1.2
Site 5. Time: 13:31		718	3.7
Site 6. Time: 13:40		912	3.8
Site 7. Time: 13:53		1495	7.8
Site 8. Time: 14:02		1896	16
Site 9. Time: 14:13		1647	10

Duplicate Time: 12:52	Dup of Site 2	283	0.47
Tuesday 9/16/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 10/8/03
Site 1. Time: 15:44		581	0.44
Site 2. Time: 15:52		350	0.45
Site 3. Time: 16:02		413	0.74
Site 4. Time: 16:17		568	1.7
Site 5. Time: 16:30		786	4.1
Site 6. Time: 16:42		837	4.4
Site 7. Time: 16:56		885	4.3
Site 8. Time: 17:07		1182	14
Site 9. Time: 17:18		1107	8.8
Duplicate Time: 16:17	Dup of Site 4	557	1.6
Thursday 10/16/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 11/10/03
Site 1. Time: 15:53		493	0.66
Site 2. Time: 16:02		433	0.58
Site 3. Time: 16:14		503	0.75
Site 4. Time: 16:29		701	2
Site 5. Time: 16:40		876	4.6
Site 6. Time: 16:52		1003	4.5
Site 7. Time: 17:03		1644	11
Site 8. Time: 17:13		1744	31
Site 9. Time: 17:24		1286	11
Duplicate Time: 16:14	Dup of Site 3	502	0.72
Friday 11/14/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 12/04/03
Site 1. Time: 15:36		698	1.4
Site 2. Time: 15:44		620	1.7
Site 3. Time: 15:55		639	1.5
Site 4. Time: 16:11		796	3.4
Site 5. Time: 16:23		1070	7.1

Site 6. Time: 16:35		1096	6.9
Site 7. Time: 16:47		1091	6.7
Site 8. Time: 16:56		1378	20
Site 9. Time: 17:06		1356	16
Duplicate Time: 16:23	Dup of Site 5	1074	7
Sunday 12/14/2003			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 1/2/04
Site 1. Time: 12:26		663	2.3
Site 2. Time: 12:39		621	2
Site 3. Time: 12:52		646	2.4
Site 4. Time: 13:07		760	4.3
Site 5. Time: 13:20		1041	8.5
Site 6. Time: 13:24		1043	8.9
Site 7. Time: 13:46		1054	8.1
Site 8. Time: 13:58		1374	24
Site 9. Time: 14:10		1372	25
Duplicate Time: 12:30	Dup of Site 1	664	2.3
Friday 1/16/2004			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 2/3/04
Site 1. Time: 13:05		692	1.5
Site 2. Time: 13:14		598	1.6
Site 3. Time: 13:24		595	1.7
Site 4. Time: 13:46		742	3
Site 5. Time: 14:01		1019	7.5
Site 6. Time: 14:13		1039	8.3
Site 7. Time: 14:23		1072	8.1
Site 8. Time: 14:33		1377	23
Site 9. Time: 14:43		1355	19
Duplicate Time: 13:46	Dup of Site 4	738	3
Tuesday 2/17/2004			
Conductivity meter recalibrated			
		Conductivity (uS/cm)	Se (ug/l) received from lab 3/4/04
Site 1. Time: 15:44		732	2.1

Site 2. Time: 15:51		647	2
Site 3. Time: 16:04		685	2
Site 4. Time: 16:19		803	3.4
Site 5. Time: 16:31		1095	8.6
Site 6. Time: 16:41		1081	8.3
Site 7. Time: 16:53		1112	9.6
Site 8. Time: 17:02		1417	25
Site 9. Time: 17:12		1396	23
Duplicate Time: 16:04	Dup of Site 3	678	1.9

Table A5. USGS Gage Flows in Uncompahgre Basin on Sampling Days

	Daily average flow from USGS gages bounding basin	
	9147500	**9149500**
Date	**Colona USGS gage (cfs)**	**Delta USGS gage (cfs)**
3/15/2003	49	135
4/19/2003	71	28
5/19/2003	195	320
6/15/2003	421	117
7/14/2003	276	122
8/14/2003	236	109
9/16/2003	117	614
10/16/2003	294	330
11/12/2003	58	322
12/14/2003	54	222
1/16/2003	51	183
2/17/2003	53	144

The following data were collected by Ken Leib, USGS Water Resources Division, Grand Junction, CO as part of a cooperative agreement between Colorado State University and the USGS. This two-part synoptic dataset was designed to characterize longitudinal flow, concentration and loads in the irrigation delivery system in the Uncompahgre Basin as well as provide additional sampling describing inflows and conditions throughout the Uncompahgre mainstem.

Table A6. CSU/USGS Canal Sampling Data

Field ID	**Station Name**	**QA**	**Date**	**Q**	**Specific Conductance**	**TDS**	**Se**	**TDS Load**	**Se load**
			(yyyymmdd)	(cfs)	(uS/cm)	(mg/l = ppm)	(ug/l = ppb)	(tons/day)	(lbs/day)
First Sampling Run									
east side canals in flow order									
S18	Loutsenhizer Canal at Unc. R. Headgate		20030521	108	376	235	0.945	68.5	0.55
S10	Loutsenhizer Arroyo at		20030523	88	439	276	3.01	65.6	1.43

	Hillcrest Rd.								
S8	Selig Canal at Unc. River Headgate		20030515	177	555	356	1.74	170	1.66
S14	Selig Canal at 6400 Rd.		20030513	49.5	554	352	2.51	47.0	0.67
S5	Selig Canal nr. 2100 Rd.		20030512	20.5	567	286	5.0	15.8	0.55
S19	East Canal at Unc. River Headgate		20030515	121	865	586	5.35	191	3.49
S6	East Canal above West Trib.		20030523	124	854	467	6.88	156	4.60
S4	East Canal nr. 2100 Rd.		20030512	97.9	986	670	9.62	177	5.08
west side canals in flow order									
S16	West Canal at HWY. 550		20030520	127	254	153	0.333	52.5	0.23
S11	West Canal Below HWY. 90		20030520	33.5	266	160	0.426	14.5	0.08
S11	West Canal Below HWY. 90	X-rep	20030520	33.5	266	161	0.44	14.6	0.08
S1	CQ Lateral at HWY. 348		20030516	54.6	329	200	0.615	29.5	0.18
S17	Montrose and Delta Canal at Unc. R.		20030521	420	331	204	0.683	231	1.55
S12	C Canal Nr. Franklin Mesa		20030522	337	348	214	0.69	195	1.25
S2	C Canal nr. HWY. 348		20030522	53.3	428	263	0.93	37.8	0.27
S7	Ironstone Canal at Unc. River Headgate		20030515	147	763	501	4.68	199	3.71
S3	Ironstone Canal nr. HWY. 348		20030522	132	637	412	2.46	147	1.75
Inflows									
S15	South Canal at Unc. River near Colona		20030522	600	229	138	0.334	224	1.08
S22	Spring Creek at Jay-Jay Rd.		20030520	95.4	705	467	1.09	120	0.56
S13	Last Ditch nr. Red Rock Canyon Cr.		20030513	2.21	1035	703	28.25	4.2	0.34
S9	AB Lateral at Landfill Rd.		20030513	2.93	343	210	1.27	1.66	0.02
Mainstem									
S21	Unc. R. above Loutsenhizer		20030514	6.48	1867	1400	12.6	24.5	0.44

	Arroyo								
S21	Unc. R. above Loutsenhizer Arroyo	X-blank	20030514	NA	2.5	NA	<.50	NA	NA
S23	Unc. R. below Loutsenhizer Arroyo	X-rep	20030514	12.4	1954	1500	32.1	50.2	2.15
S23	Unc. R. below Loutsenhizer Arroyo		20030514	12.4	1954	1500	31.1	50.2	2.08
S20	Unc. River below Selig Canal		20030515	0.4	555	356	1.74	0.4	0.00
Second Sampling Run									
east side canals in flow order									
S18	Loutsenhizer Canal at Unc. R. Headgate		20030820	75.1	389	246	0.65	49.9	0.26
S10	Loutsenhizer Arroyo at Hillcrest Rd.		20030822	58	515	330	5.2	51.7	1.63
S8	Selig Canal at Unc. River Headgate		20030820	207	565	364	1.5	203	1.68
S14	Selig Canal at 6400 Rd.	X-blank	20030827	NA	2	NA	<0.5	NA	NA
S14	Selig Canal at 6400 Rd.		20030827	66	662	426	3.2	75.9	1.14
S5	Selig Canal nr. 2100 Rd.		20030819	30.6	885	591	12.6	48.8	2.08
S19	East Canal at Unc. River Headgate		20030826	102	917	613	4.72	169	2.60
S6	East Canal above West Trib.		20030822	150	959	659	6.5	267	5.26
S4	East Canal nr. 2100 Rd.		20030819	141	945	641	6.9	244	5.25
S4	East Canal nr. 2100 Rd.	X-blank	20030819	NA	1.9	NA	<0.5	NA	NA
west side canals in flow order									
S16	West Canal at HWY. 550		20030820	135	242	152	0.37	55.4	0.27
S11	West Canal Below HWY. 90		20030825	35	242	151	<0.5	14.3	
S11									
S1	CQ Lateral at HWY. 348		20030825	68.6	336	204	0.35	37.8	0.13
S17									
S12	C Canal Nr. Franklin Mesa		20030821	297	333	206	0.44	165	0.71
S2	C Canal nr. HWY. 348		20030821	46.6	593	378	1.02	47.6	0.26
S7	Ironstone		20030826	226	833	579	4.76	353	5.80

	Canal at Unc. River Headgate								
S3	Ironstone Canal nr. HWY. 348		20030821	123	842	574	3.2	191	2.12
Inflows									
S15	South Canal at Unc. River near Colona		20030821	700	218	131	<0.5	248	
S22	Spring Creek at Jay-Jay Rd.		20030825	111	796	539	0.943	162	0.56
S13									
S9	AB Lateral at Landfill Rd.		20030820	10.8	235	142	0.296	4.14	0.02
Mainstem									
S21	Unc. R. above Loutsenhizer Arroyo		20030819	27.2	1478	1050	8.49	77.1	1.25
S23	Unc. R. below Loutsenhizer Arroyo		20030819	48.2	1581	1160	16.7	151.0	4.34
S20	Unc. River below Selig Canal		20030820	32.4	565	364	1.5	31.8	0.26
Other									
	Southfork Loutsenhizer Arroyo, near Landfill road		20030827	0.55	4780	3960	389	5.9	1.15
	Montrose and Delta Canal at Unc. R.		20030826	500	324	206	0.54	278	1.46