Project Proposal (NV15-03)

Evaluation of Streamflow Depletion Related to Groundwater Withdrawal, Humboldt River Basin

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BACKGROUND

The Humboldt River Basin (figure 1), in north-central Nevada, is the only major river basin that is entirely within the State. The drainage area of the basin is about 17,000 mi^2 and represents about 15 percent of the total area of the State. Precipitation supplies all the water that enters the basin, consequently the variability in climate has significant impacts on the hydrology of the area. In addition, increased development which has been superimposed on natural climate fluctuations affects the water resources of the basin. Historically, water users relied heavily on surface water and to a lesser extent on groundwater, primarily for agricultural operations. By the 1930's, surface water resources were fully allocated prior to groundwater development. Groundwater withdrawals for irrigation began in the 1950's and gradually increased to more than 150,000 acre-ft/yr by the early 1980s (figure 2; Prudic, 2007). Beginning in the early 1990's, groundwater dewatering, as part of open-pit gold mining, significantly increased total groundwater withdrawals within the middle Humboldt River basin.

Nevada water law is based on two fundamental concepts. Prior appropriation, or "first in time, first in right," ensures senior water users are protected even as new uses for water are allocated. The second concept deals with beneficial use of appropriated water. A water-right permit may only be granted for beneficial uses, which includes irrigation, mining, and municipal uses among others. The Nevada State Engineer is responsible for administering and enforcing Nevada water law. The State Engineer uses the concept of perennial yield to help guide decisions dealing with withdrawal and allocation of groundwater.

Perennial yield is generally defined as the maximum amount of groundwater that can be withdrawn on an annual basis without depleting the groundwater reservoir. In groundwater basins with a flow through river system, like the Humboldt River Basin, perennial yield becomes much more difficult to quantify because base flow may be supported by groundwater, or alternatively, the river may supply water to the groundwater aquifer. Thus, the more recent development of groundwater may be utilizing some of the same water allocated for surface water.

PROBLEM

Continued groundwater withdrawals within the Humboldt River Basin are likely contributing to streamflow depletion of the Humboldt River (figure 2). The timing and magnitude of the effects of groundwater withdrawals on streamflow of the Humboldt River are not well understood.

Although groundwater use in the Humboldt River Basin is primarily for agriculture, a substantial quantity of groundwater has been removed from consolidated rock units and basin fill as part of mining activity in the middle Humboldt River basin. The contribution to streamflow depletion by mine dewatering is currently thought to be relatively small, largely because much of the water was or continues to be returned to the river or to unconsolidated deposits near the river (Prudic, 2007). However, many Humboldt River water rights holders contend that mine dewatering contributes significantly to streamflow depletion.

OBJECTIVES

The objectives of this study are:

- Estimate Humboldt River streamflow depletion caused by groundwater withdrawals within the Humboldt River Basin between Carlin and Imlay streamflow gages (fig. 1) after 10, 25, 50, and 100 years of groundwater withdrawals (Depletion maps).

- Estimate the impact to and response of Humboldt River streamflow for up to 100 years in the future as a result of mine-dewatering operations to date (2015).

- Estimate the effect of cumulative groundwater withdrawals from individual hydrographic areas on Humboldt River streamflow.

Achievement of these objectives will provide the Nevada State Engineer with appropriate information to understand and evaluate the potential effects of groundwater withdrawals on the Humboldt River in order to make informed decisions regarding conjunctive use and possible augmentation of flow to senior water right holders. In addition, this work will provide the State of Nevada an opportunity to inform stakeholders within the Humboldt River Basin about processes related to the interaction between groundwater and surface water.

APPROACH

To evaluate the impacts of groundwater withdrawals on streamflow, three transient, regional-scale flow models will be developed and documented. The three models will represent the upper, middle, and lower Humboldt River Basins, respectively (figure 1). The middle and lower Humboldt River Basin models will be developed by the USGS as part of the scope of work proposed here. The upper Humboldt River Basin (upper HRB) model is being developed separately and simultaneously by the Desert Research Institute. The middle Humboldt River Basin (middle HRB) model will be modified from an existing model developed by Prudic (2007). The lower Humboldt River Basin (lower HRB) model will be developed as part of this project and may incorporate major elements of an existing model for Paradise Valley (Prudic and Herman, 1996). The two models will be linked sequentially (in upstream to downstream order) in order to simulate the extent and magnitude of stream depletion caused by groundwater withdrawals on downstream water deliveries as observed at the Imlay streamgage (Figure 1).

General Model Construction

Both USGS models will be developed similarly and will use similar boundary flow processes. The models will be constructed using MODFLOW-NWT (Niswonger and others, 2011) which is the Newton formulation of MODFLOW 2005 (Harbaugh, 2005). The Newton formulation extends the applicability of MODFLOW 2005 to solve non-linear problems representing unconfined aquifer conditions and evapotranspiration of groundwater as well as wetting and drying of cells related to surface water and groundwater interactions.

The simulated Humboldt River streamflow at the outlet of the middle HRB model will be passed as inflow to the lower HRB model, which is approximately coincident with the streamflow gage at Comus. Initially, groundwater movement (subsurface flow) between the two model areas will be assumed negligible in comparison to streamflow. However, subsurface flow between the models may be simulated as generalized flow using head-dependent boundary conditions, if necessary for ensuring model accuracy.

Hydrogeologic frameworks will be represented differently between the middle and lower HRB models. Mine dewatering is being simulated only in the middle HRB model so the middle HRB model will need to simulate groundwater flow within consolidated rock units whereas the lower HRB model will only represent basin-fill aquifer units. This is because it is assumed groundwater flow in consolidated rock units in the lower basin are insignificant in comparison to basin-fill aquifer units and effects of mine dewatering in the consolidated rock units of the middle HRB model are separated from the lower HRB model by no-flow boundaries.

The models will vary stresses on a semi-annual basis to coincide with irrigation and non-irrigation seasons and will simulate conditions using monthly time steps.

The active model boundary perimeter will mostly be along hydrographic divides and designated as no-flow boundaries, except where groundwater flow through the boundary is known or assumed, such as beneath the Humboldt River near the middle and lower HRB model interface. Where necessary, subsurface inflows and outflows through the boundaries will be simulated using head-dependent boundaries in MODFLOW-NWT. Humboldt River streamflow will be simulated using the Streamflow Routing Package (SFR; Prudic and others, 2004; Niswonger and Prudic, 2005). Humboldt River inflows entering the middle HRB model domain at the Carlin streamflow gage (figure 1) will be specified based on historic streamflow data. Inflow of the Humboldt River into the lower HRB model domain near the Comus streamflow gage will be specified during calibration based on historic streamflow data, but will be simulated output from middle HRB model for scenario simulations. Major perennial tributaries to the Humboldt River will be represented using specified head boundaries upstream of streamgages closest to confluence with Humboldt River. Below the streamgages closest to confluence with Humboldt River, perennial tributary flow will be specified using historically observed streamflows.

Surface-water diversions from the Humboldt River will be simulated using the Streamflow Routing Package, similar to how diversions were handled in lower Walker River basin model (Allander and others, 2014). Seasonal diversion rates for each ranch will be specified based on the median right in priority for the season and Humboldt River priority tables (Hennen, 1964b) for each irrigation season for model calibration. When the models are used to evaluate streamflow depletion, seasonal surface-water diversions will be demand driven based on median priority dates as determined from simulated Humboldt River flows at Palisade gage and water distribution tables by Hennen (1964b). The consumptive use portion of diversions will be removed from the model (i.e., is not simulated as evapotranspiration) and the remaining water will be evenly recharged to groundwater beneath fields served by irrigation to represent irrigation return flows. Consumptive use and recharge from diversions will be determined according to project efficiencies for each diversion. Project efficiency is defined here as the ratio of crop consumptive use to total diversion at point of diversion.

Groundwater withdrawals in the models will be simulated using the well package (WEL) in MODFLOW-NWT. Only individual groundwater withdrawals or aggregated groundwater withdrawals greater than 5 ac-ft/yr will be included in the models. Groundwater withdrawals for domestic, stock water, and other minor uses are considered negligible in comparison with irrigation, municipal, and industrial uses but may be considered if aggregated withdrawals for a particular area exceed 5 ac-ft/yr. Specified rates of groundwater withdrawals for lands irrigated only by groundwater (primary groundwater) will be equivalent to the consumptive use portion for crops being irrigated. When groundwater is used to supplement surface-water use (supplemental groundwater), seasonal groundwater withdrawals will be equivalent to the crop consumptive use less water delivered from surface-water irrigation. For mine dewatering, the non-consumptive portion of withdrawals will be routed either to the Humboldt River or injected into basin-fill sediments according to mine-specific water disposal methods.

The magnitude of precipitation derived groundwater recharge originating within each hydrographic area will be specified in the model using the MODFLOW Recharge package (Harbaugh, 2005). This recharge will be distributed to mountain blocks, mountain fronts, and alluvial fans and valleys similar to methods employed by Halford and Plume (2011). Magnitude of recharge will be allowed to vary from existing estimates during model calibration in areas with sufficient hydrologic data.

Evapotranspiration from groundwater will be simulated in the model using the MODFLOW Evapotranspiration package (Harbaugh, 2005). Evapotranspiration is simulated in the model based on simulated depth to water with groundwater evapotranspiration occurring at a maximum potential rate when depth to water is at land surface, and a linearly decreasing rate with depth until a specified extinction depth is reached in which no evapotranspiration of groundwater occurs. The maximum potential rate of evapotranspiration from groundwater and extinction depths will be determined through model calibration. These estimates will be constrained by new estimates of evapotranspiration discharge being developed by the Desert Research Institute.

Initial hydraulic properties assigned to each model cell will be extracted from existing literature and/or existing calibrated groundwater flow models where available and where properties are reasonable. However, final property values will be determined through calibration procedures guided by all available groundwater head, drawdown, streamflow, and withdrawal data, as well as historic maps of evapotranspiration areas and estimated or measured depths to water. Hydraulic properties of transmissivity and storage will be varied spatially using pilot points and two-dimensional kriging (Doherty, 2008) to allow for spatial heterogeneity of properties.

Middle Humboldt River Basin model

The drainage area of the middle HRB model area is approximately 8,070 mi^2 (figure 1), which is about 50 percent of the total Humboldt River Basin drainage area. The middle HRB model will comprise about 35,000 active grid cells that are 2,500 ft square (area of 6,250,000 ft^2 or about 143 acres per cell). The boundary mainly follows the hydrographic divide downstream of the streamflow gage at Carlin to just downstream of the Comus streamgage. The middle HRB model domain will include major drainages of Pine Creek, Susie Creek, Maggie Creek, Rock Creek, the lower parts of the Reese River Valley, and the upper part of the Little Humboldt River drainage (figure 1). The upstream portion of the Reese River Valley is not included within the model domain because it is assumed Humboldt River streamflow will not be effected by groundwater withdrawals from this area within a 100 year time period. This will be verified by evaluating the

100 year depletion rate near the model boundary in the Reese River Valley. If withdrawals near the model boundary indicate stream depletion within 100 years, then the model boundary will be moved upstream appropriately. The upstream portion of the Little Humboldt River drainage is included in the domain to address potential model limitations associated with boundary effects from simulating dewatering from mines along and near the natural drainage divide (cross-hatched area in figure 1). The simulated groundwater conditions in the Little Humboldt River drainage will mainly be handled with the lower HRB model and will be ignored in the middle HRB model except in evaluation of impact of mine dewatering. Potential limitations associated with simulation of mine-dewatering in the proximity of external no-flow model boundaries will be evaluated to ensure that there are no drawdowns propagating through the boundaries of the upper HRB into the lower HRB models.

The hydrogeologic framework of the middle Humboldt River flow systems will be discretized using a uniform grid and divided into 4 hydrologic model layers. The upper-most model layer represents the Humboldt River flood plain and will include evapotranspiration processes. Layer 1 will be of variable thickness. Model layer 2 represents the basin-fill aquifer system from which irrigation withdrawals occur. Where layer 2 extends to land surface (i.e., in areas where layer 1 is inactive), evapotranspiration will be simulated in layer 2. Layer 3 will represent consolidated rock and includes hydrogeologic units from which mine dewatering takes place. Layer 4 will also represent consolidated rock and will be used as a groundwater storage reservoir.

Formation of pit lakes will be represented in the middle HRB model for the mine dewatering operations listed in table 1 that have or potentially will result in pit lake formation when mine dewatering is stopped. Pit lakes will be simulated using the MODFLOW Lake package (Merritt and Konikow, 2000) and will occur in the model layer 2 if pit lake occurs in basin fill or from layer 3 if pit lake is formed in consolidated rock unit. Simulation of filling of pit lakes will result from groundwater inflow to lakes from adjacent aquifer material as well as from direct precipitation and any surface runoff contributions that are specified. The Lake package simulates lake evaporation from and precipitation onto lake surface area that is related to simulated lake depth. Lake evaporation and precipitation rates are specified and will be based on existing estimates of open water evaporation and precipitation rates.

Lower Humboldt River Basin model

The drainage area of the lower HRB model area is approximately 3,030 mi^2 (figure 1), which is about 20 percent of the total Humboldt River Basin drainage area. The lower HRB model will be comprised of about 38,000 active grid cells that are 1,500 ft square (area of 2,250,000 ft^2 or about 52 acres for per cell). The boundary mainly outlines the basin-fill aquifer from near the Comus streamgage to the Imlay streamgage and includes major tributary drainages of the Little Humboldt River, Martin Creek, and Pole Creek (figure 1).

The hydrogeologic framework of the middle and lower Humboldt River flow systems will be discretized using a uniform grid and divided into 2 to 3 hydrologic model layers. The upper-most model layer represents the Humboldt River flood plain and will include evapotranspiration processes. Layer 1 will be of variable thickness. Model layer 2 will represent the basin-fill aquifer system from which irrigation withdrawals occur. Where layer 2 extends to land surface (i.e., in areas where layer 1 is inactive), evapotranspiration will be simulated in layer 2. Layer 3 will also represent the basin-fill aquifer system in places where its saturated thickness is greater than the extent of layer 2. This model will not simulate groundwater flow in consolidated rock units as there is no mine dewatering occurring within this model domain and it is assumed groundwater flow is negligible in comparison to the basin-fill aquifer.

Model Calibration

The middle and lower Humboldt River Basin models will be calibrated through coupled steady-state and transient simulations. Steady-state calibration and simulation will represent hydrologic conditions observed prior to 1961. Transient calibration will simulate hydrologic conditions observed over the 55-year period from 1961 through the end of 2015.

Model parameters will be calibrated by minimizing a weighted composite, sum-of-squares objective function through nonlinear regression using PEST (Doherty, 2008), an automated parameter estimation routine. The objective function represents the differences (residuals) between observed and simulated hydrologic observations. Tikhonov regularization (Doherty, 2008) will be used in the automated calibration process to constrain parameter estimates within reasonable ranges in areas in which estimates are insensitive to observation data.

Reference scenario for evaluating streamflow depletion and impact from groundwater pumping

Evaluating Humboldt River streamflow depletion resulting from groundwater withdrawals requires some reasonable assumptions related to the future stresses and streamflows entering the middle HRB model at the Carlin streamgage. Future stresses and streamflows are associated with natural future climate variations within the Humboldt River Basin that are unknown. A common approach for simulating future stresses and streamflows is to repeat historical climate conditions (Allander and others, 2014; Prudic, 2007). Future stresses and stream inflow at the Carlin streamgage will be specified in the calibrated transient models by repeating the stresses specified in the calibrated model for the 50-year period from 1966 to 2015. This 50-year period will be repeated in order to simulate conditions 100 years into the future. This reference scenario is hereafter referred to as the “**historical reference scenario**”.

An alternative reference scenario will be developed that will simply repeat the mean annual conditions during the historical reference scenario. This alternative reference scenario is hereafter referred to as the “**mean historical reference scenario**”. This alternative reference scenario may be desirable for use with the streamflow depletion analysis as it will generate smooth results that are not directly influenced by interannual climate variability. The mean annual stresses and stream inflow at the Carlin streamgage will be repeated over 50- and 100-year simulations. Results from historical and mean historical reference scenarios will be compared and if found to be similar, the mean historical reference scenario will be used for evaluating streamflow depletion and developing streamflow depletion maps.

Data required to support model development and calibration

A variety of data are needed for model development and to constrain model calibration. Most of the required data is available and will require some level of quality assurance, compilation, formatting, and incorporation into the model input data sets. These data types include hydrogeology, streamflows, groundwater levels, evapotranspiration discharge, water budgets, diversion rates and priorities, and groundwater withdrawal records. However, some pertinent data will need to be collected in order to fill gaps in available data and provide altitude control and stream-channel geometry.

Hydrogeology

Existing hydrogeologic frameworks will be used to define hydrogeologic units with similar hydraulic properties and to inform and guide model parameter calibration. The middle HRB model will use the hydrogeologic framework described by Plume and Ponce (1999). The lower HRB model will rely on hydrogeologic frameworks developed by Bredehoeft (1963), Cohen (1963), Prudic and Herman (1996), and Maurer and others (2004). In addition, hydrogeologic framework information from non-USGS flow models will be reviewed and evaluated for inclusion, if available.

Streamflow data

Streamflow data along the Humboldt River and some of the major tributaries is available from long-term streamflow gages. The streamflow data will be obtained from the USGS National Water Information system (NWIS). Streamflow data from the Carlin gage will be specified inflow to the middle HRB model for calibration and subsequent model scenarios. Streamflow data from the Comus gage will be specified inflow to the lower HRB model only for calibration. For scenario models, simulated stream outflow from the middle HRB model will be used as inflow to the lower HRB model. Data from other Humboldt River gages within the model domains will be used during the calibration process to help guide determination of hydraulic properties in both models.

Groundwater levels

Groundwater-level data are needed to adjust hydraulic properties of transmissivity and storage during calibration of the flow models. Long-term water level data is available throughout much of the developed areas of the Humboldt River Basin. These data will be obtained from the USGS NWIS database and the State of Nevada Division of Water Resources Water Level database. No new water-level measurements are planned as part of this project.

Evapotranspiration discharge

Estimates of evapotranspiration discharge from riparian and phreatophytic areas are being developed for the period of 1985 – 2015 by DRI. These data will be used during model calibration to help constrain parameter estimates for the MODFLOW Evapotranspiration package and will help constrain simulated water budgets.

Water Budgets

Existing water budget estimates for each hydrographic area within the model domains will be used to help constrain estimated model parameters during model calibration. However, areas rich in hydrologic data and knowledge of aquifer properties may suggest revisions to existing water budget estimates are needed (such as groundwater recharge). The quality and/or reliability of existing data used in model calibration will be evaluated to make judgment on the reliability of existing water budget estimates. If hydrologic data and information are sufficient, water budget estimates will be allowed to deviate from existing estimates to improve model calibration. Simulated water budgets for each hydrographic area will be compared with previous estimates and model suggested revisions will be reported.

Diversion rates with rights in priority

Streamflow-diversion rates for each of the major ranches of the Humboldt River are needed to simulate diversions from the Humboldt River. Diversion flow rates for the full distribution of priority rights on the Humboldt River have been reported in Hennen (1964b). Rights in priority are determined according to observed streamflow at the Palisade gage and existing lookup tables used by the Humboldt River Water Commissioners. Spatial datasets of irrigated lands associated with ranches served by diversions will be developed and used to guide determinations of where unused water is infiltrated.

Groundwater withdrawals and priority of wells

Locations of all irrigation primary and supplemental wells, municipal wells, industrial wells, and aggregated domestic and stock water wells withdrawing more than 5 ac-ft/yr are needed along with priority and withdrawal rates. Well location, depth interval of well screen, and priority dates will be compiled to ensure accurate location and simulation of groundwater stresses. Location of fields irrigated by supplemental wells and their ranch affiliation is also needed. This information will all be provided by the Nevada Division of Water Resources.

Pit lakes

Locations of pit lakes and relation of lake surface area and volume to lake depth are needed along with estimates of open water evaporation and precipitation rates and runoff contributions.

Geographic Information System (GIS) Geospatial Datasets

A variety of GIS geospatial datasets will assist in the construction of the flow models. Much of the required datasets currently exist and are available. Those datasets unavailable or not yet developed will be digitized from historic reports and maps. The expected geospatial datasets include; Digital Elevation Model (DEM), National Hydrologic Dataset, agricultural lands subdivided by source of irrigation water (surface water, groundwater, or both), water-table contours and areas of shallow groundwater depicted in historic figures and plates (Cohen, 1963a; Cohen, 1964a; Cohen, 1964b; Cohen, 1964c; Cohen and others, 1965; Eakin and Lamke, 1966; Harrill and Moore, 1970).

Field work required to support model development

Most of the information and data needed to develop and calibrate the flow models are available. However, some additional field data may be needed to achieve acceptable model accuracy. During model development and calibration, the need for additional data, such as more accurate groundwater level altitudes, may become apparent. However, only the data discussed below are required at this time.

Simulation of groundwater and surface-water interactions requires relatively accurate estimates of groundwater-level altitudes and stream-level altitudes. Stream level, or stage, is simulated in SFR based on Manning’s equation (Prudic and others, 2004) which requires stream-reach altitudes, slopes, cross-sectional channel geometry, and Manning’s roughness coefficient. Most streamflow gages in the Humboldt River Basin have an established datum within acceptable accuracy and do not require additional surveying. However, some streamflow gages have datums determined from maps with high uncertainties and require more accurate determination. A survey grade GPS system will be used to determine altitudes of uncertain gage datum, stream-channel bottoms and cross sections. Cross sections will be collected at all existing streamflow-gage sites along the Humboldt River within the model domain, at tributary inflows, and at slope breaks in the Humboldt River stream profile. Separate Manning’s roughness coefficients will be assigned to both active (main channel) and inactive (flood plain) stream-channel cross sections and will be determined from existing streamflow measurements at streamflow gages, and through model calibration to match existing stage and discharge relations.

Development of Streamflow Depletion Maps

Streamflow depletion maps (generically known as capture maps) are a mapping tool designed to help characterize the effects of groundwater withdrawal on the timing and rates of streamflow depletion (Leake and others, 2010, Barlow and Leake, 2012). Depletion maps are created through repeated simulations of a calibrated groundwater flow model, where each simulation computes the streamflow depletion as a result of pumping at varying locations over time. The middle and lower HRB models will be used in sequence to evaluate streamflow depletion based on changes in streamflow at the Imlay gage caused by upstream groundwater withdrawals. The time periods proposed for evaluating Humboldt River streamflow depletion are current depletion (2015), and depletion after 10, 25, 50, and 100 years of pumping starting from pre-development conditions in 1961. Locations of groundwater withdrawals will be restricted to basin-fill aquifer units, and consolidated rock units where mine dewatering is or has occurred.

The complexity of the Humboldt River Basin flow system may present unique challenges that can limit the practicality and accuracy of direct interpretation of streamflow depletion from standard streamflow depletion map analysis. This is due to nonlinearities introduced by other head-dependent flow processes, in particular evapotranspiration of shallow groundwater from phreatophytic areas away from the river (this does not include riparian ET), and simulation of unconfined aquifer conditions. Depletion maps are developed by simulating withdrawals in only one model cell at a time. Because of this, depletion maps are likely to represent more efficient capture of groundwater evapotranspiration and less efficient capture of streamflow than is realized by the combined influence of all pumping from areas in which evapotranspiration is a component of the overall capture. This limitation pertains more to areas distant from the Humboldt River and in particular, to areas with shallow groundwater and groundwater evapotranspiration discharge between pumping locations and the river.

One approach for addressing this limitation is to evaluate and present the bias associated with estimation of streamflow depletion from the developed depletion maps. This is done by estimating streamflow depletion for existing distribution of pumping using the streamflow depletion maps and comparing with the streamflow depletion determined from the calibrated model. The difference between these two methods of determining streamflow depletion is the bias associated with use of a non-linear model to develop the depletion map. This bias is a function of the aquifer properties, depth to water table, and distribution of actual pumping. It is anticipated that the overall bias associated with use of non-linear models to develop streamflow depletion maps will be relatively small (<10%). However, this is an area of active research and therefore will be further researched and documented as part of this project.

The bias associated with use of non-linear flow models in determination of streamflow depletion will be researched in collaboration with the Desert Research Institute using a variety of test models that have similar representation to many of the valleys within the Humboldt River system. The test models will simulate groundwater flow in systems containing rivers (and/or streams), groundwater evapotranspiration from shallow groundwater areas adjacent to rivers (riparian ET) and away from rivers (phreatophyte ET) and a variety of pumping distributions and rates. Bias associated with use of streamflow depletion maps to estimate streamflow depletion will be summarized and then methods applied in a real-life example using an existing model of the Fernley area in Nevada. The Fernley area groundwater flow model was developed and documented by the Desert Research Institute in Stevick and others (2005).

Effect of mine dewatering on Humboldt River streamflows

The impact of existing large-scale mine dewatering that has occurred through 2015 on Humboldt River streamflows will be evaluated using the middle and lower HRB models. Because future mine-dewatering is not known, this evaluation will only be for the impact of historical and current mine-dewatering activity on Humboldt River streamflow. The point of this scenario is to evaluate the long-term impact and recovery from the mine-dewatering that has occurred to date (2015). All mine dewatering is within the domain of the middle HRB model. The lower HRB model will be used to translate the impacts simulated in the middle HRB model to the Imlay gage.

The calibrated middle HRB model will simulate mine dewatering that has occurred from initiation of dewatering around 1990 through the end of the calibration period (end of 2015) for dewatering operations that have pumped greater than an annual average of 1,000 acre-ft for 5 or more years. Starting in 2016, mine dewatering will be specified as 0 over a prediction period of 100 years to evaluate the response and recovery of the hydrologic system. Simulated mine dewatering activities include groundwater withdrawal rates and amounts from dewatering mine locations in the Humboldt River basin, the discharge of this water to areas of use for irrigation, injection as aquifer storage, and/or discharge to streams, and formation of pit lakes after mine dewatering has discontinued. The impact of mine dewatering on Humboldt River streamflow at Imlay gage will be evaluated as the simulated difference in streamflow at the Imlay gage between the calibrated models with reference projection (with mine dewatering simulated) and the same models with mine dewatering not simulated. Results will be presented as cumulative plots of change in streamflow as a result of mine dewatering activity individually for mine operations listed in table 1 as well as in aggregate. It is anticipated that plots will show substantial increase in flows during early periods of mine dewatering when much of the water was being discharged to the Humboldt River or tributaries of the Humboldt River followed by a period of depleted flows as mine dewatering is discontinued and groundwater removed from storage is replenished. Cumulative plots of streamflow accretion and streamflow depletion will be presented separately.

The effect of evaporation from pit lakes will be briefly evaluated. This will be done by creating a scenario in which evaporation from pit lakes is not simulated and calculating the difference in streamflow from the model that simulates evaporation from pit lakes.

Table 1. List of mining operations included in analysis of individual mine-dewatering impacts on Humboldt River streamflows.

Fig. 1 No.	Mine Operation	Basin	2015 Mine status
M1	Lone Tree	Clovers	Inactive

M2	Carlin South Operations	Maggie Creek	Active
M3	Cortez Operations	Crescent Valley	Active
M4	Goldstrike Operations	Boulder Flat	Active
M5	Carlin North Operations	Boulder Flat	Active
M6	Twin Creeks	Kelly Creek	Active
M7	Phoenix	Buffalo Valley	Active
M8	Turquoise Ridge	Kelly Creek	Surface Inactive, Underground Active
M9	Cove-McCoy	Lower Reese River Valley	Inactive/Exploration

Effect of groundwater withdrawals from individual hydrographic areas on Humboldt River depletion.

The cumulative and annual effect of groundwater withdrawals from each hydrographic area on Humboldt River depletion will be evaluated and summarized. This evaluation will be done by taking the difference in simulated streamflow at Imlay gage between the calibrated models – with and without simulated groundwater withdrawals. Groundwater withdrawals will be removed from model simulations one hydrographic area at a time. The major purpose of this evaluation is to estimate the relative impact of groundwater withdrawals from each hydrographic area on the Humboldt River streamflow. This evaluation will also provide a measure of the relative connection of the groundwater systems within each of the hydrographic areas to the Humboldt River.

Predictive Uncertainty

Uncertainty of model predictions will be evaluated through an analysis of sensitivity of response variables to variability in estimates of model parameters (sensitivity analysis). In particular, the sensitivity of estimated Humboldt River depletion to uncertainties of transmissivity and storage properties, maximum groundwater evapotranspiration rate and extinction depth, streambed conductance, and reductions in groundwater recharge and streamflow entering the model domain at Carlin gage as results of potential future climate change, will be evaluated for select locations of groundwater withdrawals. Select locations will be at varying distances from Humboldt River based on existing areas with groundwater withdrawals. The sensitivity of the estimated effect of mine dewatering on Humboldt River streamflow to uncertainty of model parameters will also be evaluated.

QUALITY ASSURANCE

Only minimal field work is planned as part of this project. The field work planned will mainly be survey grade Global Navigation Satellite System (GNSS) work and leveling surveys of stream channel cross sections. All survey data and computations will be reviewed for accuracy. All field data collected as part of this project will be managed according to USGS Nevada Water Science Center Data Management plan.

Modeling activity will be quality assured through project reviews as well as through a model review process. An initial project review at the very onset of the project will be provided by the USGS Office of Groundwater and one or more Water Science Field Team Groundwater specialists during the triennial review of the Nevada Water Science Center groundwater technical program in September 2015, and again during the evaluation phase of the project sometime during early 2018. Additional Water Science Center project reviews will occur annually or more frequently as needed throughout the life of the project.

Adequacy of model design and calibration will be evaluated collaboratively with hydrologists from Nevada Division of Water Resources and Desert Research Institute. Once Nevada Water Science Center and Nevada Division of Water Resources are satisfied with model design and calibration, the model will undergo additional review by technical experts within the USGS to ensure the model is sufficient for addressing the objectives of this proposal and to ensure the model is defensible.

The models will be archived according to USGS policies and will also be provided through electronic report appendix. Reports will be peer-reviewed and will follow USGS fundamental science practices.

PRODUCTS

Two products are planned for this project. The first product will be a journal article written in collaboration with the Desert Research Institute to develop and document methods and results for evaluating bias associated with use of non-linear groundwater flow models in determination of streamflow depletion. This article will be published in a peer-reviewed journal such as Groundwater, Water Resources Research, Journal of Hydrology, or Hydrogeology Journal.

A single four chapter professional paper report with electronic appendices is also planned. Chapter one will provide introduction, problem, purpose, objectives, and overview of approach. Chapter two will provide background, description of hydrologic system, and document construction, calibration, and results of middle HRB model. Chapter three will provide background, description of hydrologic system, and document construction, calibration, and results of lower HRB model. Chapter four will document effects of groundwater withdrawals, mine dewatering, and existing groundwater withdrawals from individual hydrographic areas on Humboldt River streamflow at Imlay and will include depletion map analysis and figures. The middle and lower HRB model archives will be provided as an electronic appendix. A simple executable tool that queries the depletion map datasets for estimated streamflow depletion based on location will also be provided as an electronic appendix.

PROJECT SCHEDULE

The 4.25 year study is planned to start during summer of 2015 and be completed by the end of September 2019. Table 2 below provides a general timeline for the major tasks of the study.

Table 2. Project schedule for completion of major study tasks.

[Quarters are based on Fiscal Federal Year. 1st quarter is Oct-Dec, 2nd quarter is Jan-Mar, 3rd quarter is Apr-Jun, and 4th quarter is Jul-Sep. **Abbreviations**: **PP**, Professional Paper; **HA**, Hydrographic Area; **NSE**, Nevada State Engineer]

Task	FY15	FY16				FY17				FY18				FY19			
	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Field work		■				■											
Develop model input datasets	■	■	■	■	■	■	■										
Model calibration						■	■	■	■								
Journal Article draft			■	■	■												
Journal Article Acceptance									■								
PP Chapters 1 - 3 draft			■	■	■	■	■	■	■								
PP chapters review and processing										■	■	■	■				
Depletion map development										■	■						
Mine dewatering evaluation											■	■					
HA evaluation											■	■					
PP Chapter 4 draft										■	■	■	■				
PP Ch 4 report review and processing														■	■	■	
Final PP report publication																	■
Quarterly progress reports to NSE		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Annual progress update to stakeholders		■				■				■				■			■

PERSONNEL

Project personnel consist of a 0.5 Full Time Equivalent (FTE) senior hydrologist/modeler and project chief (Allander; GS13), 1 part-time USGS emeritus (Prudic, retired), 1 FTE modeler (GS12), 0.5 FTE code writer/developer (GS11), 0.25 FTE GIS analyst (GS11), and a 0.06 FTE field technician (GS9).

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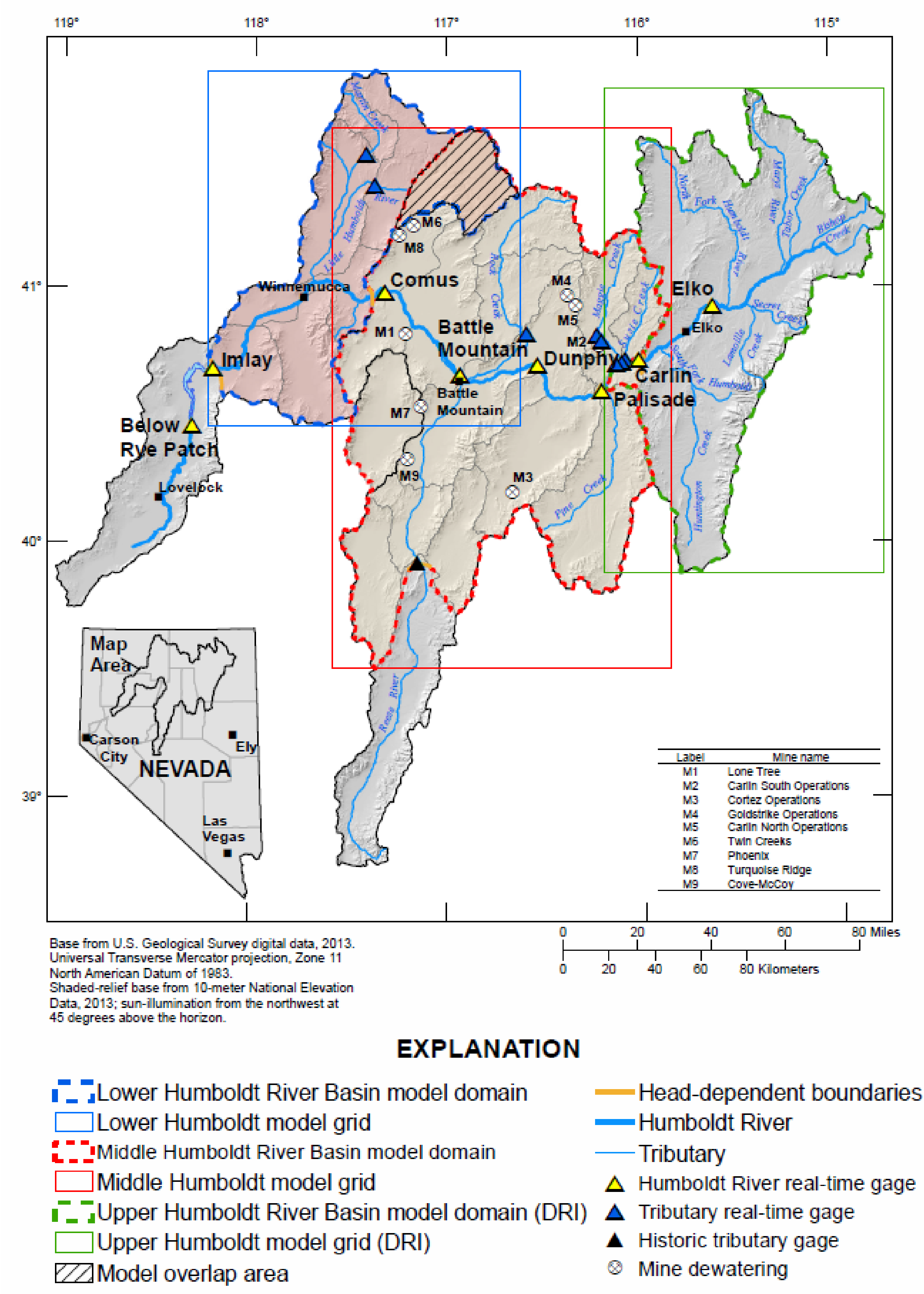
119°
118°
117°
116°
115°
41°
40°
39°
Winnemucca
Comus
Imlay
Below
Rye Patch
Lovelock
Battle
Mountain
Dunphy
Carlin
Palisade
Elko
M1
M2
M3
M4
M5
M6
M7
M8
M9
Map
Area
Carson
City
Ely
NEVADA
Las
Vegas
Label
Mine name
M1 Lone Tree
M2 Carlin South Operations
M3 Cortez Operations
M4 Goldstrike Operations
M5 Carlin North Operations
M6 Twin Creeks
M7 Phoenix
M8 Turquoise Ridge
M9 Cove-McCoy
0 20 40 60 80 Miles
0 20 40 60 80 Kilometers
Base from U.S. Geological Survey digital data, 2013.
Universal Transverse Mercator projection, Zone 11
North American Datum of 1983.
Shaded-relief base from 10-meter National Elevation
Data, 2013; sun-illumination from the northwest at
45 degrees above the horizon.
EXPLANATION
Lower Humboldt River Basin model domain
Lower Humboldt model grid
Middle Humboldt River Basin model domain
Middle Humboldt model grid
Upper Humboldt River Basin model domain (DRI)
Upper Humboldt model grid (DRI)
Model overlap area
Head-dependent boundaries
Humboldt River
Tributary
Humboldt River real-time gage
Tributary real-time gage
Historic tributary gage
Mine dewatering

Figure 1. Location, extent, and boundary conditions for the middle and lower Humboldt River Basin models, central Nevada and extent of upper Humboldt River Basin model.

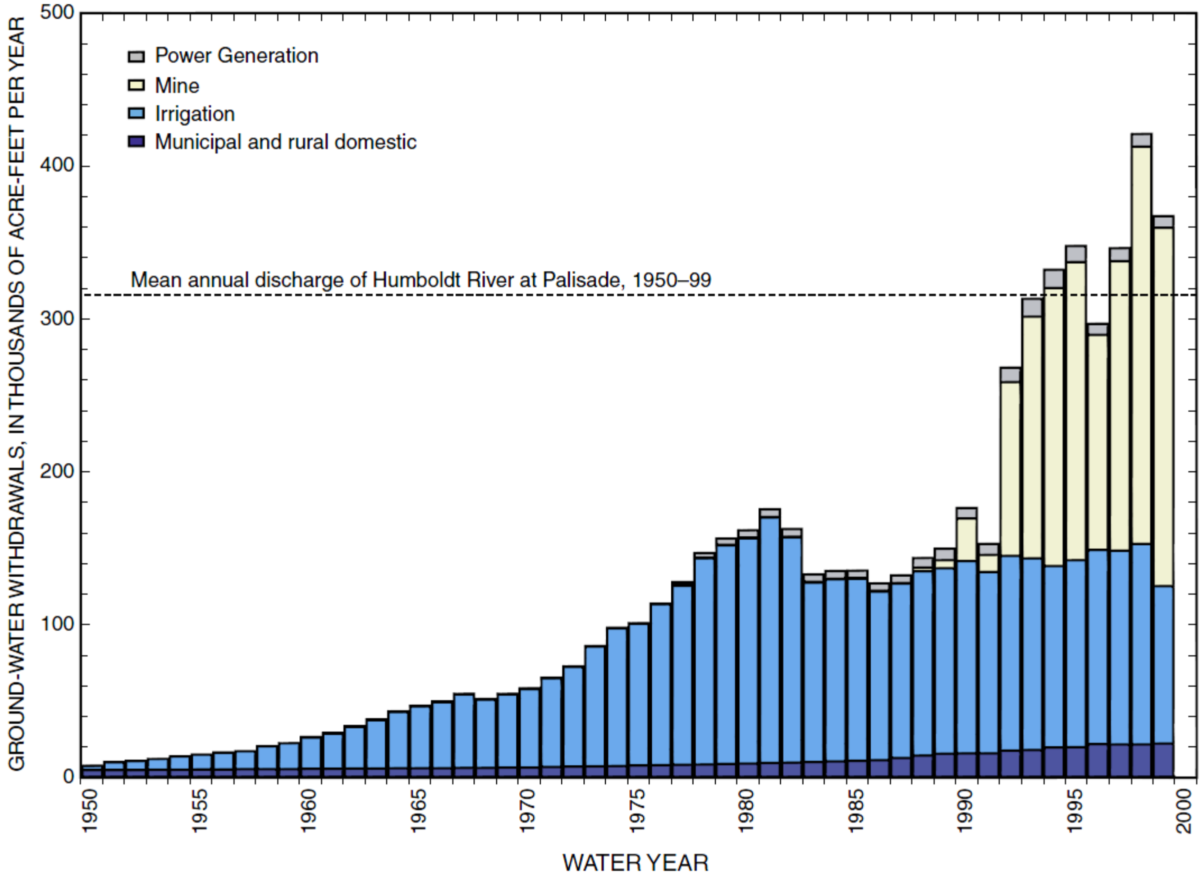

Figure 2. Estimates of total annual groundwater withdrawals (consumptive and non-consumptive use) in the Humboldt River Basin above Rye Patch Reservoir, 1950 – 99 (from Prudic, 2007).