Mine Water Environ (2015) 34:153–161
DOI 10.1007/s10230-014-0294-4

TECHNICAL ARTICLE

# Integrating Less Common Data Sources to Improve Groundwater Model Calibration

**Keith Thompson · Sonya Cadle · Gaius Roemer**

Received: 6 December 2013 / Accepted: 14 July 2014 / Published online: 25 October 2014


**Abstract** MODFLOW-SURFACT was used to create and calibrate a three-dimensional groundwater flow model to simulate the effects of Nevada Copper Corporation's proposed Pumpkin Hollow mining project on the local and regional hydrogeologic system. This groundwater flow model relied not only on standard data sources but also on less-common and frequently-overlooked sources that enhanced the knowledge base that supported the model. Heavily investing in the knowledge base skews the model development process toward the front end but results in sound model construction and allows model calibration to proceed quickly and efficiently. This example illustrates the value of: (1) incorporating existing accepted models, where possible, (2) using anecdotal evidence in conjunction with hydrogeological data to guide model construction, (3) using GIS and database tools to streamline the process of incorporating both public and site-specific data, and (4) employing automated calibration tools to make the process more efficient and effective.

**Keywords** Groundwater · MODFLOW · Modeling · Dewatering

**Electronic supplementary material** The online version of this article (doi:10.1007/s10230-014-0294-4) contains supplementary material, which is available to authorized users.

K. Thompson (✉)
Tetra Tech, Inc., 3801 Automation Way, Fort Collins, CO, USA
e-mail: keith.thompson@tetratech.com

S. Cadle · G. Roemer
Tetra Tech, Inc., 363 Centennial Parkway, Suite 210, Louisville, CO, USA

## Introduction

When beginning a regional-scale groundwater modeling project, little data may be available from the client regarding regional hydrogeologic conditions. However, public data sources often can provide information for model construction and calibration. Public databases can sometimes present an overwhelming amount of data, some of which will be apparently conflicting, and most of which can be extraneous to the modeling effort. Consequently, these data sources may not be utilized because of the time and cost to confirm and organize the data. For example, separate governmental agencies may have different data records for the same well, but under different names and with different estimated coordinates. Collating and correlating these data sources can be a daunting task. However, with the aid of databases, spreadsheet tools, and GIS, the data manipulation can ultimately reduce the time and cost of model construction and calibration while improving the model's accuracy and lending additional credence and defensibility to the model.

Particularly on mining projects, where resource evaluation requires intense exploration, additional insight into the local and occasionally the regional hydrogeologic conditions can be gained through discussions with exploration personnel. Although numerical data preferred for groundwater model development may not be available from such sources, anecdotal evidence provided by observations made during drilling and by interpretation of exploration data can support the addition of important details to the model, thereby increasing model accuracy.

Nevada Copper Corporation's (NCC) proposed Pumpkin Hollow mining project in west-central Nevada, USA, provides a case study in which numerous public data

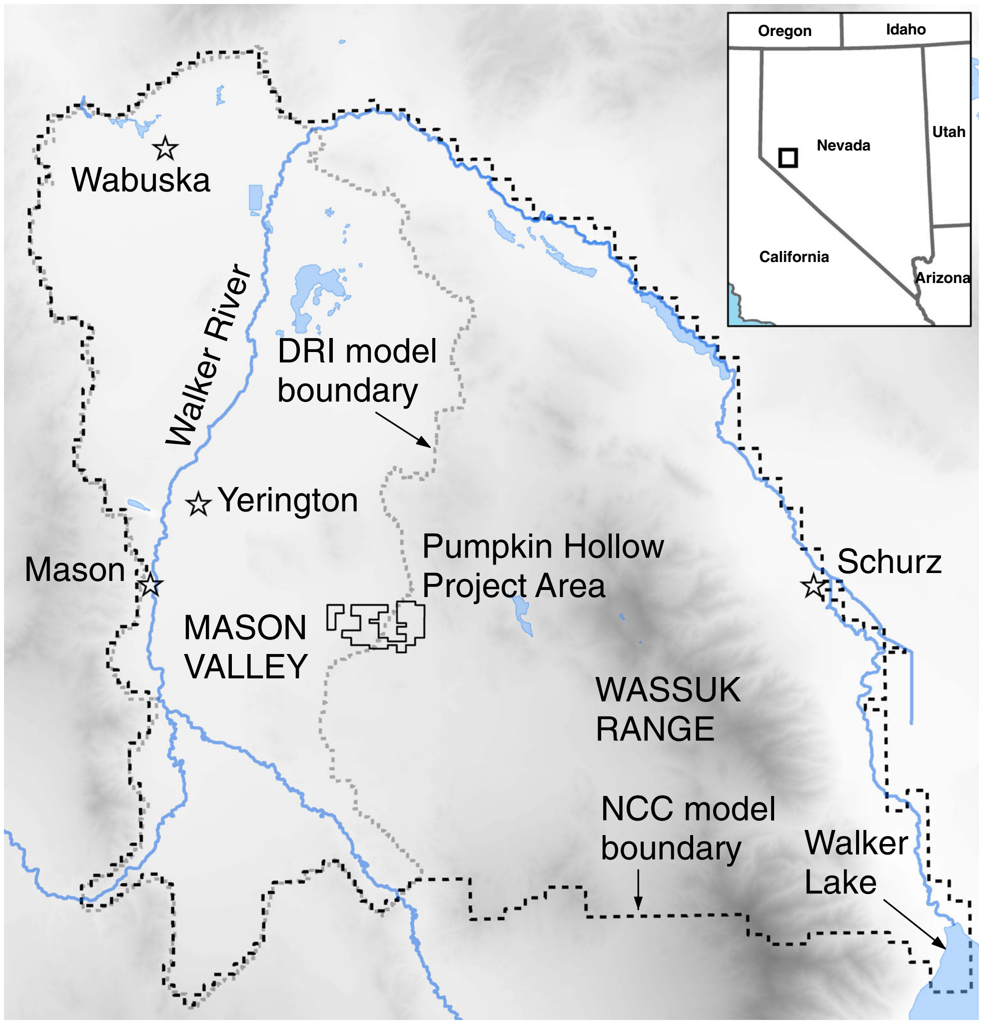


**Fig. 1** Model location map

sources were combined with site-specific data and anecdotal information to create a well-calibrated regional groundwater flow model (NCC model). Figure 1 provides a site location map for the modeled area.

One of the concerns with the proposed mining project was the potential to impact water supplies in the nearby Mason Valley, an intensively developed agricultural area that relies on irrigation from groundwater and surface water sources. An additional concern was the project's location within the Walker River Basin. Walker Lake, the terminus of the Walker River, is a closed-basin lake that has experienced more than 45 m of water level decline since 1882 as a result of agricultural diversions. Consequently, prediction of potential impacts from the project was critical, and the goal during model development was to create a well-calibrated model based to the extent possible on publicly available data that had undergone thorough quality assurance review.

## Methods

At the start of the project, in conjunction with review of data provided by the client, a detailed literature review and data search was conducted to identify publicly available data sources. Public data sources included:

- An integrated surface water and groundwater model of Mason Valley, constructed and calibrated by the Desert Research Institute [DRI] (Carroll et al. 2010; Collopy and Thomas 2010),
- U.S. Geological Survey (USGS) digital elevation model (DEM),
- Geologic maps (Bingler 1978; Proffett and Dilles 1984),
- Geologic data sets in GIS format from Nevada Bureau of Mines and Geology (NBMG),
- Quaternary fault and fold database (USGS and NBMG 2011),

- Hydrogeologic data sets in GIS format from the USGS (Maurer et al. 2004),
- USGS and DRI studies compiling well pumping records (Carroll et al. 2010; Collopy and Thomas 2010; Huxel and Harris 1969; Lopes and Allander 2009a, b; Schaefer 1980),
- Nevada Division of Water Resources (NDWR) well permits and point-of-diversion (POD) information,
- U.S. Dept of Agriculture (USDA) National Agricultural Statistics Service vegetation maps (2009),
- Groundwater elevation and stream flow data from the USGS, and
- USDA National Agricultural Imagery Program (NAIP) 2006 orthophotos.

Many of the data sets necessary for model construction were accumulated by downloading data from the internet. Some well and geologic data were hand-entered or digitized from the associated studies and maps. Most of the DRI model electronic files were obtained by requesting them from DRI directly, but for confidentiality reasons, not all files could be provided. Those files that could not be directly provided were summarized numerically by DRI in such a manner that confidentiality was preserved while data integrity was maintained.

## Numerical Model Construction

After all data sets were obtained, significant formatting, generalization and correlation had to be performed to create a unified MODFLOW-SURFACT model. The DRI model of the Mason Valley formed the western half of the NCC model. The DRI model discretization was generalized laterally to fit the scale of the NCC model, but the estimates and distributions of all of the water balance components were retained from the DRI model. The NCC model grid was selected to be more refined in the proposed mine area (100 m by 100 m) and telescoped out to 500 m elsewhere. GIS was used to generalize the DRI grid from its original uniform 100 m by 100 m to the new, variable grid.

The vertical discretization was designed to accommodate the proposed mining plan. The NCC model has 22 layers, which are for the most part flat and extend far below DRI's original two layers (Fig. 2). This construction greatly simplified the incorporation of both regional and local geologic information, but resulted in a cube with inactive (no-flow) cells representing the elevations above ground surface. This complicated the incorporation of DRI's top model layer, which had variable elevation. Irrigation wells, streams, ditches, and evapotranspiration had to be assigned to the correct layers. This was accomplished using a combination of GIS and database processing to match the elevations of the features to the correct model layer.

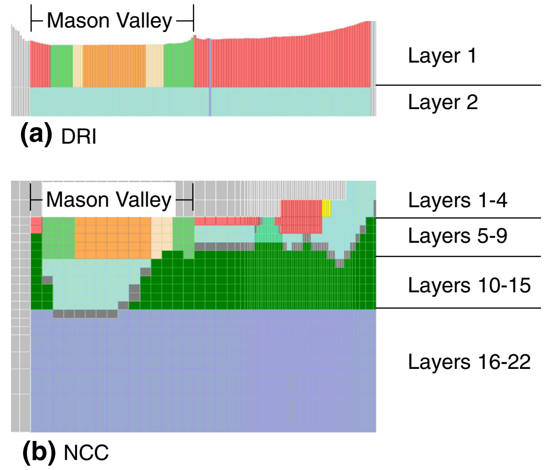


**Fig. 2** Comparison of vertical layering in DRI and NCC models; *grey coloration* represents inactive cells, while colored cells represent hydraulic conductivity zones

GIS was also used to generalize or aggregate (if applicable) all of the other DRI model inputs including stream flow routing, ditch flows and PODs, evapotranspiration, irrigation-related recharge, hydraulic conductivity, and mountain block recharge to match the NCC model grid. The seasonal component of DRI's model was averaged to represent steady-state conditions, since the NCC model covered a multi-decade time frame.

A brief summary of the model boundary conditions is useful to provide context for the discussion of less-common data sources. Like the DRI model, the NCC model includes MODFLOW no-flow boundaries, general head boundaries (GHBs), streams, and wells. The NCC model also included horizontal flow barriers (HFBs). The following sections briefly summarize the usage of these boundary conditions and elaborate on the ways less-common data sources were used in specifying the boundary conditions. Figure 3 provides a generalized conceptual diagram of these boundary conditions. The actual boundary locations vary by layer due to ground surface elevation changes and fault geometries.

### *No-flow Boundaries*

No-flow cells were used to define the horizontal and vertical extents of the NCC model. Specifically, the DRI model's north, south, and west no-flow boundaries (outlined in Fig. 1) were retained, but the DRI model's east no-flow boundary bisected the NCC model and was not retained. No-flow cells were also employed east and north of the Walker River, reflecting that the Walker River is expected to constitute a groundwater sink toward which groundwater flow converges. Finally, no-flow cells were used to represent the estimated location of the groundwater divide associated with the Wassuk Range to the south.

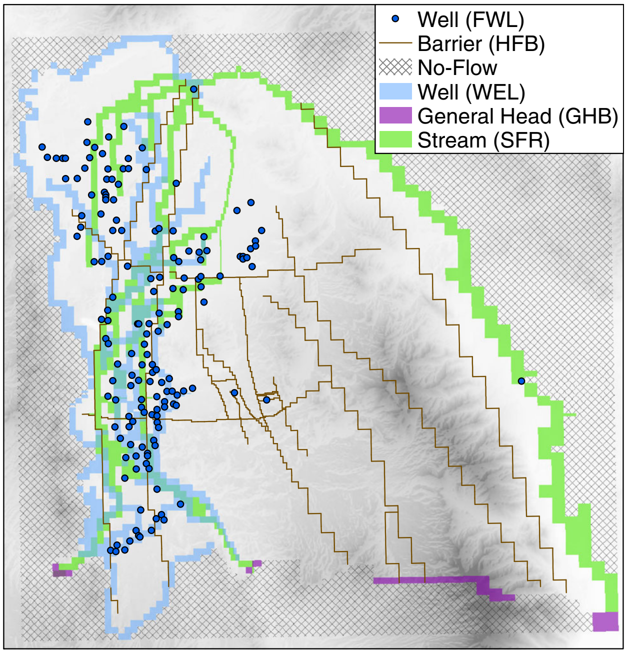


**Fig. 3** Summary of model boundary conditions

*General Head Boundaries*

General Head Boundaries (GHBs) were used for several purposes in the NCC model. First, as in the DRI model, GHBs were used to set the potentiometric heads where the East and West Forks of the Walker River enter the southwestern portion of the NCC model. The DRI model's values (Carroll et al. 2010; Collopy and Thomas 2010) were used to guide the GHB elevations. Second, the central portion of the Wassuk Range does not represent a groundwater divide at the location of the model boundary; rather, there are higher-elevation mountains to the south that drive groundwater flow into the model. Hence, GHBs were used to simulate groundwater flow into the model from the higher-elevation portion of the Wassuk Range to the south. Finally, GHBs were used in the southeast corner of the model to simulate drainage toward Walker Lake, which is not explicitly represented in the model.

*Horizontal Flow Barriers*

HFBs were used to represent the more significant faults (both normal and strike-slip) in the NCC model. The general locations and associated strike and dip information for these faults were identified from published geologic maps (Bingler 1978; Proffett and Dilles 1984), public databases (USGS and NBMG 2011) and Nevada Copper geologic documents. Figure 3 indicates the general fault locations; however, the fault locations migrated somewhat between model layers because of fault dips. The faults were modeled with hydraulic conductivities that were generally lower than the adjacent rocks, resulting in HFBs that impede but do not block groundwater flow across the faults.

*Streams*

Streams were represented using the MODFLOW-2000 stream flow routing (SFR) package. DRI expended significant effort in matching their model's representation of the Walker River to reality and had the benefit of numerous additional data sources (such as field observations of diversion and return flow rates) that are typically not available. Hence, DRI's representation of the Walker River was incorporated as closely as possible into the NCC model.

- Stream bed elevations and characteristics—In the DRI model, the streams were all in the top layer, which had a variable top elevation to represent the actual ground surface. However, the NCC model's generally flat-layer construction resulted in the ground surface occurring in several layers. A combination of GIS and database processing was used to identify the correct NCC model layer to which each stream bed elevation in the DRI model corresponded. The stream bed characteristics in the NCC model were set to mimic those in the DRI model. Outside the Mason Valley, USGS topographic information and stream gage data were used to estimate stream bed elevations, and stream bed characteristics were assumed to be consistent with those in Mason Valley.
- Stream routing and lengths—GIS was used as the processing tool to accurately assign DRI model segments and reaches to the appropriate NCC model cells and to re-calculate stream reach lengths where cell boundaries did not correspond between the two models. Outside the Mason Valley, stream routing and reach lengths were determined from aerial photography.
- Stream inflows—The USGS stream gages near Hudson (#10300000) and above Strosnider Ditch (#10293500) were used to calculate the average stream flows entering the model from the West Walker River and the East Walker River, respectively. Other inflows to the streams included irrigation return ditches. The DRI model used a complex FORTRAN code to calculate the amount of water that would flow off the irrigated fields and into the ditches, but this level of complexity was not necessary for the NCC model. Rather, the NCC model was allowed to calculate return flows to the river from the irrigation return ditches. No information regarding irrigation return flow was available outside the Mason Valley, so no return flows were simulated for that area.
- Stream outflows—Numerous PODs exist, from which water is removed from the Walker River via diversion ditches and used for irrigation. Exact matching of these

flows was not possible in the NCC model because DRI used confidential information to determine the diversion ditch flow rates. However, the POD locations were publicly available from the NDWR and DRI's two model reports, and DRI was able to provide averaged ditch leakage rates by location during the growing season. These information sources were combined to estimate ditch flow rates as an average over the year, rather than just the growing season. The estimated ditch flows were accurate enough to allow NCC model calibration. Outside the Mason Valley, the only diversion that could be represented was above Little Dam near Schurz; no other diversion data were publically available.

### *Wells*

Three different types of features were represented as wells in the NCC model. The MODFLOW well (WEL) package was used to represent mountain block recharge on the north, south, and west sides of the Mason Valley, as well as diversion ditch leakage. MODFLOW-SURFACT's fracture well (FWL) package was used to represent irrigation pumping wells and the test pumping wells at the proposed mine site.

The DRI model represented mountain block recharge entering the Mason Valley from all sides by injecting that recharge directly into the subsurface (Carroll et al. 2010; Collopy and Thomas 2010). The NCC model retained this representation of mountain block recharge on the north, south, and west sides of the Mason Valley (but not on the east side of the valley), as shown on Fig. 3. The rate of mountain block recharge was obtained by using GIS to aggregate the rates applied by the DRI model to account for the larger cell sizes in the NCC model. The wells were aggregated such that each mountain block recharge cell had only one well which represented the sum of the flows from the DRI wells that would fall in that cell.

Both the DRI model and the NCC model represented leakage from diversion ditches using the WEL package. The diversion ditch leakage wells were aggregated using GIS in much the same way as were the mountain block recharge wells: each NCC model cell affected by ditch leakage was assigned one aggregate well which applied the sum of the flows from all the DRI model diversion ditch leakage wells present in that cell. In the transient DRI model these ditches flow during the irrigation season, which is approximately 245 days per year (Carroll et al. 2010; Collopy and Thomas 2010). For the NCC model, however, the ditch leakage was represented by annual average values applied continuously.

Irrigation wells were represented using the WEL package in the DRI model (Carroll et al. 2010; Collopy and Thomas 2010), with all irrigation wells screened in uppermost model layer. However, DRI model's uppermost layer was subdivided into numerous layers in the NCC model, so it was necessary to identify the depth and approximate screened interval for each irrigation well in order to assign it to the correct NCC model layer(s).

Because many irrigation wells also had hydraulic head observation data associated with them, and hydraulic head observation targets also require accurate layer assignment, the identification of observation and irrigation well screened intervals was done in tandem. The well locations were compared to NDWR's well and POD database, the USGS well database, and well information provided by DRI as part of their model files. However, the identification of the wells represented a significant challenge, because many of the wells were represented in several different databases that sometimes used different coordinate systems or estimated coordinates, as well as different identifiers for the wells. The following procedure was used:

- All the observation and irrigation well data for the region were imported into a single database and, where necessary, location data were converted to a single coordinate system. Wells represented using the Public Land Survey System (PLSS) were assigned coordinates using GIS based on the centroid of the PLSS polygon.
- The database was used to match up wells based on database information such as application, permit, or well log number. When a match was found, the depths and screened intervals from the database were assigned to the MODFLOW irrigation or observation well.
- After as many matches as possible were made and the matched wells were combined, all well data were imported into GIS for spatial evaluation. If wells were within about 100 m of each other, they were examined to see if they might be the same well. Additional wells were then matched based on spatial proximity combined with depth, installation date, or other criteria, as available.
- Depth information was necessary for hydraulic head target and irrigation well pumping layer assignment. If no depth information was available from any database for a particular well, estimated depths and screened intervals were assigned based on other wells spatially near that well. The assumption was that nearby wells would likely screen similar productive zones.

## Geologic Model Construction and Analysis

The hydraulic property distribution was assigned based on regional and local geology and USGS divisions of hydrogeologic units in Nevada, for which a GIS dataset was available (Maurer et al. 2004). Geologic cross-sections were used to generalize the regional lithologic units into

Quaternary alluvium, Tertiary volcanics and sediments, Mesozoic intrusives, and Mesozoic volcanics and sediments. A three-dimensional geologic model was created from these cross-sections and other available geologic information, such as well logs and surface geologic maps. Mine site geologists had created a separate three-dimensional solid model using GEMS (GEOVIA GEMS™) software to represent the generalized regional lithologic contacts. This three-dimensional solid model was transferred to Mining Visualization System (C Tech's MVS software) with cooperation from Tetra Tech and NCC geologists with detailed knowledge of the local geology. The geologists felt that the boundary zone between the Tertiary and Mesozoic units (likely erosional or faulted) should be called out as a separate unit, based on anecdotal evidence from resource drilling that suggested it was more highly fractured, potentially causing the unit to be more transmissive. The regional lithologic units were used where the DRI model was not present, but DRI model lithologic units were used wherever they were present.

The DRI model's second layer, representing the deeper alluvium in the Mason Valley, was flat-bottomed, which was an appropriate conceptualization for the shallow subsurface focus of the DRI model. However, the NCC model was intended to represent potential hydrogeologic effects of alluvial interaction with underlying and adjacent bedrock units. Hence, it was necessary to more accurately represent the topography of the bedrock-alluvial interface in the Mason Valley (Fig. 2). Since the MVS three-dimensional solid model's basin bottom morphology was based on geologic cross-sections and additional well lithologic logs, the MVS model was used to guide the Mason Valley's lower bedrock-alluvial contacts.

Limited aquifer testing data were available, particularly with respect to the large fault structures that cross the model domain. Anecdotal evidence and numerous cross-sections provided by NCC geologists were crucial in incorporating both the faults and the extensive geologic information near the proposed mine site. As a result, in the immediate vicinity of the mine, a number of previously unmapped faults and additional lithologic units such as hornfels and endoskarn were included. The various faults and a hydraulically significant lithologic contact were incorporated into the model sequentially during the initial calibration process. First, mapped regional faults, such as those bounding the Wassuk Range and the central portion of the Mason Valley, and major faults in the project area were added in configurations consistent with those presented in published literature and NCC documents. Subsequently, smaller mapped faults and the hydraulically significant lithologic contact at the project site were added. After each addition, the model calibration was checked for potential improvement. The major faults were simulated as HFBs with lower hydraulic conductivities than the surrounding rock, which limited but did not prevent groundwater flow across the faults. Individual fault conductances were adjusted during calibration.

A graben structure crosses north–south through the approximate center of the project site. Various lines of evidence indicated that the portions of the project site east and west of the graben might exhibit different hydraulic properties. The evidence included:

- Exploration drilling that showed that the ore bodies east and west of the graben had different styles of mineralization.
- NCC geologists had observed greater drilling fluid loss and more instances of lost circulation in exploration holes west of the graben compared to holes east of the graben.
- Monitoring wells west of the graben were said to be more productive than wells east of the graben when pumped for water-quality samples.
- Water-level responses associated with a 7-day pumping test conducted east of the graben in 2010 indicated relatively low hydraulic conductivities and suggested that at least the eastern graben-bounding fault acted as a low-permeability feature.

As few quantitative hydraulic conductivity data were yet available west of the graben, these qualitative contrasts resulted in a recommendation for a long-term pumping test west of the graben. That test confirmed the existence of much greater hydraulic conductivities for the hornfels and endoskarn lithologic units and in a small zone encompassed by three wells. It also showed the existence of low-permeability features that were interpreted as corresponding to the west graben-bounding fault and a clay-rich lithologic contact on the north side of the project site.

*Precipitation*

Two methods were used to estimate precipitation-related recharge from the mountains in the model. For the portions of the model that corresponded to the DRI model's north, west, and south boundaries, the DRI mountain block recharge values were represented as below-ground injection wells, mimicking the DRI method. For the area where the DRI model connected to the Wassuk Range near the proposed mine site, recharge was represented using MODFLOW's recharge package. The Precipitation Zone Method (PZM) of the USGS (Lopes and Medina 2007) was used to estimate average annual precipitation on the Wassuk Range. The elevation-based precipitation zones were calculated from the USGS DEM. Then, the calculated precipitation was converted to estimated recharge using the elevation-based Maxey–Eakin recharge categories (Maxey and Eakin 1949). The portion of recharge that would flow out of the Wassuk Range and into the Mason Valley was compared to the DRI estimate for recharge in that same area, and the calculated recharge was adjusted using a multiplier to match the calibrated DRI mountain block recharge. That multiplier was applied to the calculated recharge for the portion of the Wassuk Range that fell within the model boundaries. DRI's values for irrigation-related recharge in Mason Valley were incorporated directly into the NCC model.

#### *Evapotranspiration*

Evapotranspiration estimates for the NCC model were taken from two sources. In the Mason Valley, the DRI model's evapotranspiration estimates were used to generate the NCC model evapotranspiration estimates. DRI had used three categories of vegetation—wetlands vegetation, phreatophytes, and riparian vegetation—to assign evapotranspiration. To assign evapotranspiration to NCC model cells, GIS was used to calculate the weighted average evapotranspiration for each NCC model cell, based on the vegetation types that DRI had assigned. For the eastern portion of the NCC model outside the Mason Valley, publicly available vegetation maps (USDA National Agricultural Statistics Service 2009) were used to identify the vegetation types and group them by evapotranspiration rate.

Because the top NCC model layer did not always contain the uppermost active cell, it was necessary to define not only the lateral distribution of the evapotranspiration, but the vertical distribution. GIS was used to identify the uppermost active cell and associated ground surface elevation to which the evapotranspiration would be applied. This information was used to generate the necessary evapotranspiration arrays for the NCC model.

### Model Calibration Targets

The steady-state hydraulic head target data set was constructed using a combination of publicly available groundwater elevation data from the USGS and water level measurements collected by NCC. A total of 357 separate wells were used as steady-state calibration targets. The procedure described above for identifying irrigation well depths and screened intervals was also applied to observation wells, and the target layer was identified based on the center of the screened interval. Duplicate target locations were screened out using a combination of visual and database analysis, as described above. Where multiple water level data were available for a single location, the average value was used. Finally, a weighting scheme was employed for the observation data set to incorporate the uncertainties due to missing information.

In addition to the steady-state hydraulic head observation targets, the model was calibrated to steady-state stream flow and transient drawdown data. Stream flow targets were obtained by downloading the data for USGS stream gages within the model domain from the National Water Information System (NWIS) website. An average stream flow was calculated for each gage to use as a steady-state stream flow target.

Transient drawdown targets were created by calculating the drawdown over time from two long-term pumping tests conducted at the proposed mine site. The first long-term pumping test was conducted in stages; well WW10-01 was pumped for approximately 3 days, allowed to recover for 5 days, then pumped for a week and allowed to recover. During the second pumping test, well WW11-01 was pumped for 29 days and allowed to recover. During both tests, pressure transducer data and manual water level measurements were collected during drawdown and recovery phases. Because the model was intended to simulate effects of dewatering during proposed mining, long-term aquifer pumping tests in the vicinity of the proposed mines were a reasonable choice for transient calibration targets.

The steady-state model and transient model were calibrated in tandem using PEST model-independent parameter estimation software (Doherty 2010), an automated calibration tool to improve the efficiency and accuracy of the calibration process. Supplemental Figure 1 (which accompanies the on-line version of the journal) shows the locations of the observation points that served as targets for steady state and transient calibration.

## Results

The incorporation of DRI's model materially improved the NCC model's representation of Mason Valley. Initial model simulations indicated that the DRI portion of the model was already well calibrated due to scrupulously maintaining DRI's calibrated input parameters to the maximum extent possible. Hence, the DRI parameter zones were excluded from any adjustments, greatly simplifying the remaining calibration effort.

The use of PEST in the NCC model calibration significantly reduced the time necessary to complete calibration. PEST was first used to identify the parameters to which the calibration was sensitive. Then, PEST was used to optimize those parameter values, and the results were assessed for reasonableness and consistency with available data. Insensitive parameters were not subjected to optimization, but were fixed at reasonable values based on available data.

The final calibration statistics for the steady-state hydraulic heads, transient drawdowns, and steady-state stream flow data sets are shown in Table 1. The steady-state model was calibrated to within about 5 % of the

**Table 1** Final calibration statistics for NCC model, 2013

| Residual statistics by data set | Hydraulic head (m) | Drawdown (m) | Stream flow ($m^3$ per day) |
|---|---|---|---|
| Mean | 3.62 | −0.061 | −96,654 |
| Absolute mean | 7.43 | 0.61 | 98,359 |
| SD | 24.78 | 0.91 | 105,636 |
| Number of data points | 357 | 6,371 | 11 |
| SD/range | 0.054 | 0.087 | 0.18 |
| Absolute mean/range | 0.016 | 0.059 | 0.17 |
| Range of calibration data | 461.47 | 10.42 | 584,737 |

standard deviation divided by the range and the transient model to within about 9 %. The steady-state stream flow targets were primarily used qualitatively, since the actual magnitude and location of diversions inside Mason Valley was confidential and very little information was available regarding diversions downstream in the Walker Valley. Also, DRI used a complex FORTRAN code to determine return flows back into the Walker River; the NCC model simply simulated the return-flow ditches as streams draining excess water. The NCC model was expected to over-predict stream flow as a result, particularly outside the Mason Valley where diversions were not well-characterized. However, despite the uncertainties regarding stream flow, the numerical match was within 4 % in the Mason Valley and within 18 % overall. Figure 4 is a plot of the measured versus simulated steady-state hydraulic head targets, and Figs. 5 and 6 illustrate the measured versus simulated drawdown in the two pumping tests.

On Fig. 4, the close fit to the 1:1 line and lack of excessive scatter indicate that the model is well-calibrated. Layers 3 and 4 have the most deviation from the 1:1 line, possibly because the targets had only one data point apiece, the most recent of which was from 1965. It is probable that conditions have changed since that date. Also, those were the uppermost points in the model and were near the top of the Wassuk Range. Because of the high gradients between the summit and foot of the mountains, such data points are difficult to match.

On Fig. 5, the first pumping test calibration is visually good for wells NC07-19, NC10-GT02, and NC07-26. However, NC08-MW03 showed an unusual lack of recovery in the observed data, while the modeled drawdown data show typical drawdown and recovery behavior. There appears to have been a localized factor influencing drawdown at the well, since it would ordinarily be expected to recover after cessation of pumping. NC08-MW03 is screened in welded tuff and volcanics, which generally comprise the uppermost saturated zone in that area but have limited fracture connectivity and relatively low hydraulic conductivity. Approximately 10 m of drawdown occurred

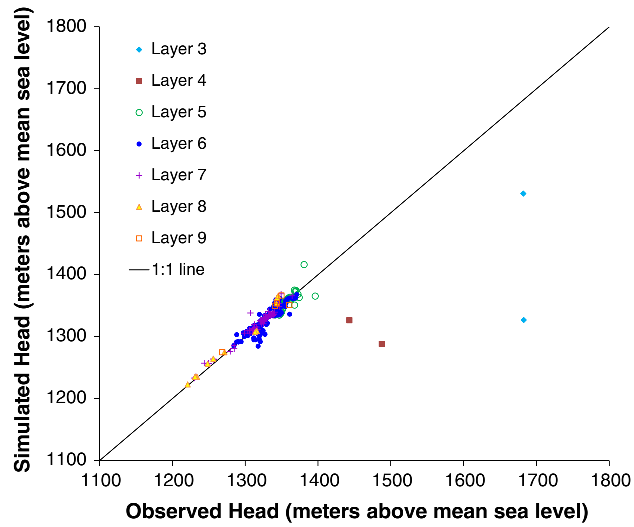


**Fig. 4** Observed versus model-simulated steady-state hydraulic heads

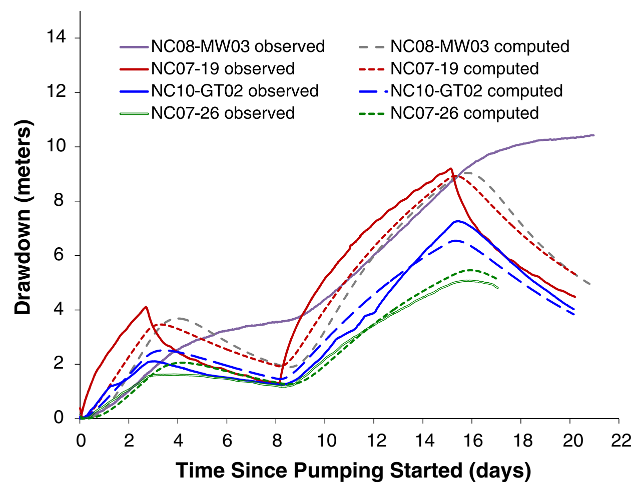


**Fig. 5** NCC model observed versus simulated drawdown for first pumping test data set

during the test. One likely explanation for the lack of recovery is that the fractures that remained saturated in that area were too poorly interconnected to allow recharge to occur during the monitored recovery period. Without further information, the model could not include this local influence and would not be expected to reproduce the unusual recovery pattern observed in that well.

The calibration results for the second pumping test are shown on Fig. 6. Again, the matches were quite good overall, but an unusual fracture-related effect was observed in a set of three wells (NC11-46, USS-85, and MW10-01). Those wells had similar drawdowns even though they varied in distance between 28 and 203 m from the pumped well. The pumped well and those three monitoring wells are located in an area of extremely complex geology

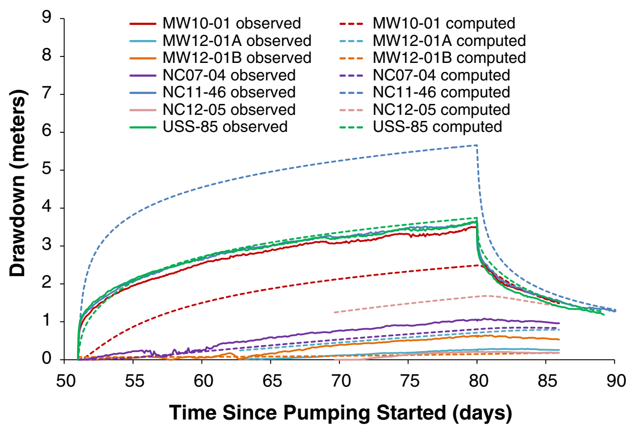


**Fig. 6** NCC model observed versus simulated drawdown for second pumping test data set

including faulting, metamorphism, and igneous intrusions. Local geology and the results of the aquifer test suggest the presence of a small-scale, highly fractured zone in the vicinity of these wells. However, this could not be accurately represented without greatly reducing the model cell size and performing additional geologic characterization. The model cell size of 100 m by 100 m in that area was chosen to allow representation of a large proposed open pit mine in a regional-scale model, rather than to simulate small-scale features in great detail. Furthermore, because the area in question is located in the footprint of the early stages of mining and will be excavated early in the mine life, detailed fracture characterization did not seem warranted. An equivalent porous medium model such as this regional-scale finite-difference model cannot reasonably incorporate these small-scale fracture-related effects.

## Conclusions

The NCC model incorporated a number of data sets not commonly used in other modeling efforts. These included publicly available irrigation well and water level data sets that are not often used due to the time and expense necessary to reconcile inconsistencies between data sets. In addition, the existing DRI model was a rarely-available and highly useful data source. Finally, the extensive field investigation conducted at the site and close communication with the client's geological and other staff provided valuable anecdotal evidence regarding the local geology and faulting, which informed and greatly improved the geological representation in the NCC model. Substantial emphasis on building the knowledge base for the model skewed the modeling task heavily toward model development. However, the investment provided ample return in the form of a sound and easily defensible model and rapid, efficient model calibration. The use of the DRI model, the estimates of fault and aquifer properties based on anecdotal information, and the use of GIS, database tools, and PEST resulted in a well-calibrated and defensible MODFLOW-SURFACT model that can be used to support engineering and permitting activities for the project, such as mine dewatering design and geochemical assessment of post-mining pit lake formation. Incorporating such less-commonly-used data sources can ultimately reduce the costs and improve the quality of a groundwater flow model.

**Acknowledgments** Both the model and the extensive field work that went into gathering the data to create and calibrate the model were supported financially by Nevada Copper Corp. The authors wish to thank Nevada Copper Corp., and in particular Greg French and Tim Dyhr, for significant and insightful review, comments, and discussion provided during model development, calibration, and revision.

## References

Bingler EC (1978) Geologic map of the Schurz quadrangle, Nevada. Nevada Bureau of Mines and Geology Map 60, scale 1:48000

Carroll RWH, Pohll G, McGraw D, Garner C, Knust A, Boyle D, Minor T, Bassett S, Pohlmann K (2010) Mason Valley groundwater model: linking surface water and groundwater in the Walker River Basin, Nevada. J Am Water Resour As 46(3):554–573. doi:10.1111/j.1752-1688.2010.00434.x

Collopy MW, Thomas JM (eds) (2010) Restoration of a desert lake in an agriculturally dominated watershed: the Walker Lake Basin. Prepared by Desert Research Institute and Univ of Nevada, Reno

Doherty J (2010) PEST model-independent parameter estimation user manual, 5th edn. http://www.simulistics.com/files/documents/pestman.pdf

Huxel CJ, Harris EE (1969) Water resources development in Mason Valley, Lyon and Mineral Counties, 1948–65. Nevada Div of Water Resources Bull no. 38

Lopes TJ, Allander KK (2009a) Hydrologic setting and conceptual hydrologic model of the Walker River Basin, west-central Nevada. USGS Scientific Investigations Report 2009-5155

Lopes TJ, Allander KK (2009b) Water budgets of the Walker River Basin and Walker Lake, California and Nevada. USGS Scientific Investigations report 2009-5157

Lopes TJ, Medina RL (2007) Precipitation zones of west-central Nevada. J Nev Water Resour As 4(2):1–19

Maurer DK, Lopes TL, Medina RL, Smith JL (2004) Hydrogeology and hydrologic landscape regions of Nevada. USGS Scientific Investigations Report 2004-5131

Maxey GB, Eakin TE (1949) Groundwater in White River Valley, White Pine, Nye and Lincoln Counties, Nevada. Nevada State Engineer, Water Resources Bull 8

Proffett JM, Dilles JH (1984) Geologic map of the Yerington District, Nevada. Nevada Bureau of Mines and Geology Map 77

Schaefer DH (1980) An appraisal of the water resources of the Walker River Indian Reservation, Nevada. USGS Open-File Report 80-427

US Dept of Agriculture National Agricultural Statistics Service (NASS) (2009) Vegetation Indices. http://www.nass.usda.gov/research/Cropland/SARS1a.htm. Accessed 9 Feb 2011

USGS (US Geological Survey) and Nevada Bureau of Mines and Geology (2011) Quaternary fault and fold database of the United States. http://earthquake.usgs.gov/hazards/qfaults/. Accessed 24 May 2011