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Technical Review:

**TWO-DIMENSIONAL STEADY-STATE MODEL
OF GROUND-WATER FLOW,
NEVADA TEST SITE AND VICINITY
NEVADA-CALIFORNIA**

(By Richard K. Waddell-USGS WRI 82-4085)

Reviewed by: M.E. Campana
Water Resources Center
Desert Research Institute
University of Nevada System

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The Nevada Agency for Nuclear Projects/Nuclear Waste Projects Office was created by the Nevada Legislature to oversee federal high-level nuclear waste activities in the state. Since 1985, it has dealt largely with the U.S. Department of Energy's siting of a high-level nuclear waste repository at Yucca Mountain in southern Nevada. As part of its oversight role, NWPO has contract for studies of various technical questions at Yucca Mountain.

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TWO-DIMENSIONAL, STEADY-STATE MODEL OF GROUND-WATER FLOW, NEVADA TEST SITE AND VICINITY, NEVADA-CALIFORNIA

By Richard K. Waddell

Abstract

A two-dimensional, steady-state, finite-element model of the ground-water flow system of the Nevada Test Site and vicinity in Nye and Clark Counties, Nevada, and Inyo County, California, was developed using parameter-estimation techniques. The model simulates flow in an area underlain by clastic and carbonate rocks of Precambrian and Paleozoic age, and volcanic rocks and alluvial deposits of Tertiary and Quaternary age. Normal Basin-and-Range faulting and both right- and left-lateral strike-slip faults have caused the juxtaposition of rocks of differing hydraulic conductivities.

Characteristics of the flow system are principally determined by locations of low-hydraulic-conductivity rocks (barriers); by amounts of recharge originating in the Spring Mountains, Pahranagat, Timpahute, and Sheep Ranges, and in Pahute Mesa; and by amount of flow into the study area from Gold Flat and Kawich Valley. Discharge areas (Ash Meadows, Oasis Valley, Alkali Flat, and Furnace Creek Ranch) are upgradient from barriers. Analyses of sensitivity of hydraulic head with respect to model-parameter variations indicate that the flux terms having the greatest impact on model output are recharge on Pahute Mesa, underflow from Gold Flat and Kawich Valley, and discharge at Ash Meadows. The most important transmissivity terms are those for rocks underlying the Amargosa Desert (exclusive of Amargosa Flat area), the Eleana Formation along the west side of Yucca Flat, and the Precambrian and Cambrian clastic rocks underlying the Groom Range.

Sensitivities of fluxes derived from simulated heads and head sensitivities were used to determine the parameters that would most affect predictions of radionuclide transport from a hypothetical nuclear repository in the southwest quadrant of the Nevada Test Site. The important parameters for determining flux through western Jackass Flats and Yucca Mountain are recharge to and underflow beneath Pahute Mesa; and transmissivities of the Eleana Formation, clastic rocks underlying the Groom Range, tuffs underlying Fortymile Canyon, and tuffs beneath Yucca Mountain. In the eastern part of Jackass Flats, the important parameters are transmissivities of the Eleana Formation; clastic rocks underlying the Groom Range; transmissivity of tuffs beneath

Fortymile Canyon; and recharge or discharge terms for Pahute Mesa, Ash Meadows, and the Sheep Range. Transmissivities of rocks beneath the Amargosa Desert are important for flux calculations there.

Introduction

The disposal of high-level radioactive wastes produced by commercial nuclear reactors is an aspect of the nuclear fuel cycle that currently (1982) has high national interest. The Nevada Nuclear Waste Storage Investigations, funded by the U.S. Department of Energy under Interagency Agreement DE-AI08-78ET44802, are designed to appraise the Nevada Test Site for potential repository sites. These investigations include non-site-specific experiments on various rock types, and regional and site-specific geologic, geophysical, and hydrologic investigations.

One of the more probable mechanisms for transport of radionuclides from a repository to the biosphere is transport by ground water. This report documents results of an investigation of the regional hydrology of the Nevada Test Site and vicinity, which was conducted using computer-simulation techniques. Analyses of effects near the potential repository site in the southwest quadrant of the Nevada Test Site and of transport of radionuclides are aspects of the hydrologic investigations planned for future work.

The Nevada Test Site is located in Nye County, Nevada. The study area of about 18,000 km^2 (square kilometers), however, encompasses parts of Clark, Nye, and Lincoln Counties, Nevada, and Inyo County, California. The study area's boundaries are determined by areal distribution of precipitation or lithology. Altitudes range from greater than 3,600 m (meters) in the Spring Mountains (Charleston Peak) to below sea level in Death Valley. Climatic conditions vary with altitude; precipitation ranges from less than 50 mm/yr (millimeters per year) in Death Valley to greater than 700 mm/yr in the Spring Mountains.

The goals of this investigation were: (1) to estimate ground-water fluxes for use in predictions of transport of radionuclides; and (2) to study the effects of uncertainty in model parameters on these estimates. An understanding of the regional flow of ground water near a repository site is essential before risk analyses can be completed for that site. Both regional and repository-scale models need to be used to estimate the transport of radionuclides in ground water over long distances. These models require specification of realistic boundary conditions that can be provided best from regional studies.

The following methods were used in this study:

1. Comprehensive review of published and unpublished geologic and hydrologic data for the study area;
2. Design of a conceptual model of the regional flow system and development of a mathematical description of that model;
3. Solution of the equations describing ground-water flow, based on the mathematical description of the conceptual model, using finite-element techniques;
4. Refinement of the conceptual model based on the results of the computer simulations, geologic and hydrologic knowledge, and sensitivity analysis;
5. Repetition of steps 3 and 4 until satisfactory agreement of simulated and measured values was obtained; and
6. Examination of results.

Details of these methods are provided in a later section of this report.

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Technical Review by M. E. Campana

Introduction

R.K. Waddell's numerical groundwater flow model is a quantification of the conceptual model of regional flow presented by Winograd and Thordarson (1975) in U.S. Geological Survey Professional Paper 712-C. His model is but a first approximation to a complex groundwater flow system; indeed, the author scatters caveats throughout the publication. He documents the major assumptions of the model on pages 28-29 and the uncertainties in the conceptual model on pages 20-21. With regard to the proposed repository, the last paragraph of the document is pertinent, particularly the first sentence: "Estimates of rates of transport of radionuclides should not be made using the regional flow model." However, this comment contradicts one of the stated goals of the investigation (page 4): "To estimate groundwater fluxes for use in predictions of transport of radionuclides", a goal that is apparently reinforced in the section 'Calculated Fluxes' (page 43). In this section, Waddell states: "One of the prime reasons for modeling groundwater flow near the Nevada Test Site is to predict movement of radionuclides from a repository. These predictions can be done only through transport modeling, which requires estimates of flux. The flow model provides these flux estimates; some results are given in table 4."

Major Assumptions of the Model

The assumption of steady-state flow conditions, which the author states is known to be violated by the natural system, may be especially poor given the 'planning horizon' involved. Under certain conditions (i.e., water resource evaluation), a steady-state assumption would probably be fine since the planning horizon for such circumstances would be short (30 years or so). However, in the case at hand, the 'planning horizon' extends over thousands of years and encompasses such things as climatic changes (changes in recharge, etc.) which dictate transient groundwater flow conditions. Although the author acknowledges that the steady-flow assumption is not good, it is undoubtedly worse than he says simply because the long-term behavior of the system is of concern.

The assumptions of isotropy (with respect to the hydraulic conductivity) and homogeneity within each zone are also made in the model. These two assumptions are commonly made in groundwater flow models, since data are often not available to do otherwise. The isotropy assumption is particularly troublesome since it dictates that the velocity vectors are orthogonal to equipotentials, which will not be true in the natural (anisotropic) system.

The lack of vertical flow in the model (two-dimensional plan view) obviously breaks down in recharge and discharge areas. In other regions, this may not be a bad assumption. The author's rationale for assuming horizontal flow appears specious. Although areas of significant vertical flow (i.e., recharge/discharge areas) may in fact occupy relatively small areas, they are extremely important with respect to radionuclide transport. Recharge areas provide the source areas for groundwater and discharge areas are regions where radionuclides can be discharged to the outside environment. In addition, contrary to what Waddell states on page 28, recharge may be occurring in Jackass Flats (Blankennagel and Weir, USGS Professional paper 712-B, 1973, page B21). Vertical flow is also occurring in Frenchman and Yucca Flats, not to mention other regions as well (e.g., Pahute Mesa).

In addition to providing no information on vertical flow, the two-dimensional model provides no information on the depth of flow (by definition). However, the presence of the third (vertical) dimension is implied since the model uses transmissivities instead of hydraulic conductivities. This approach is common, but it would have been instructive if the author had estimated the depth of flow (i.e., the approximate 'thickness' of the model). Does the flow pattern inferred from Figure 3 exist to a depth of 1000 meters? 1500 meters? In summary, more information on the thicknesses of the various zones would be useful, although the model is explicitly two-dimensional. This simply illustrates the difficulty of modeling a decidedly three-dimensional system as a two-dimensional one. The author is certainly not at fault since he is correct when he states that data for the construction of a three-dimensional model throughout most of the study area do not exist.

Conceptual Model

The conceptual model used by Waddell to develop his numerical model is based heavily upon the conceptual model of Winograd and Thordarson; it is therefore not surprising that many of the results only substantiate conclusions that can be obtained from the aforementioned conceptual model (page 65). Referring to his model, Waddell states (page 43):

> "The model is not unique; other combinations of zones representing different conceptual models could result in similar solutions and matches to the measured heads. Certain aspects of any conceptual model would not be different. Presence of the barriers and large transmissivity of the carbonates are well-documentd. Correlation between altitude and precipitation is well-established, even though correlation between altitude and recharge is tenuous. Locations of discharge points are well-known; measurements of discharge are generally good. Models probably would differ in locations of zones and zonal boundaries, and locations of outer boundaries of the model. Because of known constraints on the system, any type of model probably would yield similar results."

Granted, the model is not unique and certain aspects of any conceptual model would be unchanged. Discharge points may be well-known, but even Waddell admits (page 21) that discharge rates may be poorly known:

> "Discharge areas are generally well-known, but rates of discharge may be poorly known. It is difficult to obtain accurate estimates of discharge where numerous small springs and seeps occur, as they do near Furnace Creek Ranch and Oasis Valley. In Alkali Flat, discharge is by evapotranspiration; estimates of this discharge potentially contain larger errors. Simulated hydraulic heads, and determination of transmissivities and recharge rates, will be affected by errors in discharge rates."

In addition, estimates of underflow from one region to another, when based upon water budget approaches, may be highly inaccurate. For example, Waddell states (page 13) that the underflow estimate to eastern Pahute Mesa from Gold Flat and Kawich Valley is partially based upon earlier estimates of recharge to these valleys. These recharge estimates, based upon the use of isohyetal maps for estimating recharge, may be subject to large errors (see bottom of page 12 and top of page 13). Since estimates of recharge and discharge by evapotranspiration may be subject to large errors, underflow estimates based upon water budgets or recharge estimates may themselves be quite inaccurate.

Waddell is of the opinion that any type of model would probably yield similar results, as he states on page 43: "Because of known constraints on the system, any type of model would yield similar results." This statement may or may not be true; as long as one starts with a conceptual model vaguely resembling that of Winograd and Thordarson the results may be similar to those of Waddell. However, if one decides to use more latitude in the specification of a conceptual model and hence, numerical model, then the results may be quite different. The argument is somewhat academic without actually conducting another modeling effort. The term 'known constraints' is somewhat vague; perhaps constraints are not so 'known' after all. It has already been shown that recharge and some discharge estimates are not very good. In addition, the boundaries of the various groundwater basins comprising the model are not well-known (see bottom of page 13). In short, perhaps more latitude (freedom? creativity?) is needed in the development of regional groundwater flow models in the Nevada Test Site - Yucca Mountain area. In particular, the use of different zonations should be addressed, since zonation can determine the model results.

General Comments

On several occasions, Waddell mentions the importance of low-K zones in the overall flow system. Examples can be found on pages 6-10 regarding the upper and lower clastic aquitards and related lithologies and the 'barrier zones' (3, 5, 10, 11, 14, 16, 18, 21, and 23 on Figure 2), which are discussed on page 25. In fact, on page 25 he states that these zones (barriers) 'greatly affect the flow field'. Despite these admissions, observations of heads within these low-K zones were not used in the model. The rationale for their exclusion is as follows: since head gradients are steep within these barriers because of the low hydraulic conductivities, the potential for large residuals (i.e., errors) is great since barrier geometry must be well-known (see pages 27-28). The solution algorithm has difficulty providing tenable solutions in these regions since it cannot alter the zonation. This seems like a poor approach, given the admitted importance of these low-K regions in affecting the overall head distributions and the location of discharge areas. This essentially means that the model was calibrated by neglecting existing head information in regions of great importance, which leads one to question the validity of the model (other assumptions aside). Waddell did include one barrier data point -- well UE25a-3 in the Calico Hills, which did not result in unrealistic solutions. However, he also states (pages 27-28) that attempts to decrease the residual for this observation by modifying zonal geometry were generally unsuccessful because of the lack of data between Calico Hills and Timber Mountain, and the possible effects of structural features underlying Topopah Wash. This statement tends to leave the impression that even if the solution method could alter zonal boundaries in low-K regions, the residuals (errors) would still be unacceptable.

Head residuals were also large in Pahute Mesa and Jackass Flats and attempts to reduce them were unsuccessful (page 35). These areas, along with the aforementioned Calico Hills, are important vis-a-vis the proposed Yucca Mountain repository site, yet the model performs poorly in these regions. The alteration of zonal boundaries near Timber Mountain and Yucca Mountain failed to improve results in Jackass Flats. The poor results for Pahute Mesa are attributed to the presence of vertical flow (page 35), which is not considered by the 2-D model. These large residuals occur in an area that, according to Waddell, is 'well-known hydrologically' (page 35).

One of the quirks of the approach used is that variables with few data available to allow them to be estimated were held constant. This would indicate that the least-known quantities 'remain' the least-known even at the end of the modeling exercise because their residuals cannot be quantified. Thus, the transmissivities of zones 10, 11, and 14 (representing the upper clastic aquitard) cannot be estimated using the inverse procedure. The zone (23) responsible for producing the discharge area at Ash Meadows could not have its transmissivity estimated by the inverse procedure; neither could the fluxes across the Resting Springs and Pahranagat Ranges (page 30).

Sensitivy Analyses

Analyses of head sensitivities with respect to model-parameter variations showed that the flux terms having the greatest effect on model output were Pahute Mesa recharge (poorly known)/underflow from Gold Flat and Kawich Valley (poorly known, as it was determined as the residual from a water-budget analysis), and Ash Meadows discharge (reasonably well-known). It should be noted that the Pahute Mesa recharge/underflow term had a small coefficient of variation (see page 42). Transmissivity terms having the greatest impact on model output are those found in zones 8 (beneath Amargosa Desert), 5 (Eleana

Formation on the west side of Yucca Flat) and 3 and 18 (clastic rocks beneath the Groom Range). The initial estimates of transmissivities in zones 3, 5, and 18 had high coefficients of variation (Table 2, page 32). The transmissivity variables used in the simulation had lower coefficients of variation (see Table 3, page 38-39).

Flux sensitivities derived from simulated heads were used to assess the parameters that would most affect radionuclide transport from a repository in the southwest quadrant of the Nevada Test Site. Waddell found that for fluxes through western Jackass Flats - Yucca Mountain, the most important parameters are recharge to and underflow beneath Pahute Mesa (discussed above), transmissivities in zones 3 and 18 as well as the transmissivities of the Eleana Formation and the tuffs underlying Fortymile Canyon and Yucca Mountain. It should be remembered that the flux sensitivities were derived from simulated heads and that the model performed poorly in Pahute Mesa and Jackass Flats.

When interpreting the results of the sensitivity analyses, one must also remember all the assumptions, limitations, and uncertainties of both the numerical and conceptual models. No sensitivity analysis of model nodal spacings was performed.

Concluding Statement

The conclusions reached by Waddell (pages 65-67) are reasonable if one remembers the assumptions made to develop his model. His statement regarding the non-necessity of collecting more data on the Ash Meadows flow system in order to evaluate repository potential in western Jackass Flats or Yucca Mountain may be true only in the context of a two-dimensional flow model. Would this statement be true in the context of a more realistic three-dimensional flow model? Perhaps not. However, his statement that one should not use the model to predict radionuclide transport cannot be overemphasized enough. This is a regional model, and an approximate one at that, not a site-specific model.

In summary, Waddell's model represents a reasonable first approximation to a highly complicated regional flow system. It can be criticized because, like any model, it makes a lot of assumptions regarding the nature of the real system, some of which may seem reasonable to some and unreasonable to others. However, there are a number of flaws in the model. It is by no means unique (as the author readily admits), but it is possible that another flow model, built upon a somewhat different conceptual model than that of Winograd and Thordarson, could yield quite different results. For example, more latitude is needed in specifying the zonation. Additionally, the assumption of two-dimensional flow is poor in a number of areas, although data deficiencies throughout much of the study area restricted the modeling effort to a two-dimensional one.