WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

WDOT-Skokomish Site near Potlatch

Volume 2.
Groundwater Mounding Analysis

December 2000

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WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

WDOT-Skokomish Site near Potlatch

Volume 2.
Groundwater Mounding Analysis

by
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Olympia, Washington 98504-7710

December 2000

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Abstract

A hydrogeologic study was conducted at the Washington Department of Transportation Skokomish site near Potlatch, Washington. The study was conducted to determine the suitability of the site for construction and operation of a rapid infiltration system, and if possible, identify critical design constraints for the system location.

The study findings are presented in a two-volume report: Volume 1 (Carey, 2000) presents a description of site hydrogeologic and soil conditions, and Volume 2 (this report) presents the results of a modeling analysis used to estimate the mounding potential of the aquifer. The *Executive Summary* below describes the results of the entire study.

Using simplified assumptions about site hydrogeologic conditions, both analytical and numerical modeling methods were used to develop predictions of the mounding response of the local water table to the proposed rapid infiltration system discharge volume. Using an average-maximum, steady-state discharge condition of 500,000 gal/day, modeling suggests that the water table directly beneath an infiltration system constructed in the south-central portion of the site will not breach the ground surface in the vicinity of the system. The numerical model does predict that the mounding response of the aquifer could reach the local wetland downgradient of the infiltration area, potentially raising the water table above the ground surface in low-lying areas. The lower permeability character of the sediments in the far-western portion of the site could cause the water table mound to breach the site surface if the system is centered in this area.

Recommendations are provided regarding additional field efforts that could reduce the uncertainties in the predictions described in this report.

Acknowledgements

I would like to thank the following individuals for their contribution to this study:

- ◊ Denis Erickson for providing technical peer review and guidance that led to significant changes to the original draft of this report.
- ◊ Barb Carey for sharing much of the field data that was used for this report and for providing peer review comments.
- ◊ Dale Norton for providing editorial comments.
- ◊ Joan LeTourneau for final editorial review and formatting of the report.

Executive Summary

A hydrogeologic study was conducted at the Washington State Department of Transportation's Skokomish site near Potlatch, Washington. The purpose of the study was to evaluate the suitability of the site for a rapid infiltration system. A rapid infiltration system is needed to distribute effluent discharge from a proposed wastewater treatment facility serving the Skokomish Tribe and local residents.

The study results are described in two volumes. Volume 1 (Carey, 2000) presents a preliminary characterization of the hydrogeology of the site, including descriptions of soil and vadose zone conditions. Volume 2 (this report) describes a modeling analysis conducted to estimate the mounding potential of the unconfined aquifer.

The primary findings of the hydrogeologic characterization (Volume 1) are:

- Test pit observations indicated that native soils are mainly composed of sand and gravel with cobbles and boulders. There was no evidence of fine-grained layers or obstacles to downward flow of water in the native soil test pits.

- Percolation rates were less than one minute/inch in the native soils and roughly eight hours/inch in the landslide debris soils.

- Based on soil types, grain size distributions, inspection of test pits, field tests of percolation, and the rapid water table response to recharge, the native soils appear suitable for rapid infiltration. However, the imported landslide debris soils are not suitable.

- A low permeability layer identified above the water table in the western portion of the site could obstruct downward flow if effluent were applied in this area or similar areas where finer deposits exist above the water table.

- Little, if any, additional treatment can be expected for effluent percolating through the permeable native soil.

- The site has a relatively thick vadose zone (15-28 feet). The range in water table fluctuation was 1.5-3.6 feet over one year.

- Based on specific capacity testing, permeability estimates for the coarse, outwash material found in the central and eastern portions of the site are in the range of 350-400 feet/day. The permeability estimate for the finer sand found in the western portion of the site is roughly 60 feet/day.

- Low-permeability layers may be present at 15 feet below ground surface (bgs) at well Skok-2 and less possibly at 5 and 25 feet bgs at Skok-3. The limited density of samples over the site and the small volume in the samples collected make it impossible to determine the extent of these layers. If extensive, these layers could obstruct downward flow of effluent infiltrated nearby causing effluent to surface before reaching the water table.

- Groundwater flows from northwest to southeast. The horizontal flow gradient between well Skok-1 and the other monitoring wells is 0.2-0.3. The flow gradient between the other three wells is 0.0004-0.003.

- The area near well Skok-4 and test pit TP-1 appears to be the most favorable for infiltration, as long as sufficient distance is maintained from the contact with finer grained material represented in Skok-1. This area is most favorable, because there is no evidence of a fine-grained layer above the water table from test pits or split spoon samples, the unsaturated zone is the thickest observed, and the percolation rate and hydraulic conductivity estimates were high.

- Water quality results for nitrate+nitrite-N, chloride, specific conductance, and total dissolved solids were far below maximum contaminant levels and similar to background concentrations in Mason County.

- No hydrocarbons were found in the one sample collected from the monitoring well downgradient of the abandoned maintenance building. However, this basic screening does not preclude the need for further site investigation of the impacts of past practices at the site.

- Impacts on the wetland downgradient and across the highway from the study site were not analyzed.

The primary findings of the mounding analysis (Volume 2) are:

- A mounding analysis was performed to estimate the potential response of the site unconfined aquifer to the introduction of treated wastewater via a rapid infiltration system.

- The mounding analysis was conducted using simplified assumptions about site hydrogeologic conditions. The analysis assumed that infiltration through the site vadose zone is not a limiting factor for the operation of a rapid infiltration system.

- Both analytical and numerical models were used to estimate the mounding potential of the aquifer. Wet season conditions were assumed for modeling. Modeling scenarios were constructed assuming the discharge system was centered in the south-central portion of the site (Skok-4 area).

- Using a steady-state, average-maximum system discharge rate of 500,000 gallons/day, the modeling results indicate that the water table will not rise to the base of the infiltration system. The analytical modeling results indicate that the water table response to an assumed peak flow rate of 700,000 gal/day would be only slightly greater than predicted under average maximum conditions.

- The numerical modeling results suggest that, under the average maximum discharge rate, the mounding response could reach the downgradient wetland, potentially raising the water table above the ground surface in low-lying areas.

- The analytical modeling results suggest that, under the stated discharge rate, a water table mound may breach the site surface if infiltration is centered over the lower permeability material found in the western portion of the site (Skok-1 area). Likewise breaching could occur if infiltration is centered over native soils where aquifer hydraulic conductivity is significantly lower than that adjacent to well Skok-4 or if hydraulic conductivity is reduced over time by plugging.

On the basis of the above findings, the following activities are recommended:

- Additional subsurface investigation should be considered in the area between wells Skok-1 and Skok-4 to better characterize the depth and eastern extent of the lower permeability sediments encountered in Skok-1. Without further investigation, it is recommended that the infiltration area be centered away from the far-western half of the site.

- On the basis of the permeable soils, deep unsaturated zone, and distance from the landslide debris, the area near well Skok-4 and test pit TP-1 is the most favorable location for the rapid infiltration system. Care is needed even here to avoid the fine-grained material observed in well Skok-1 just west of this area.

- Do not construct the infiltration area in the landslide debris soils.

- A pilot-scale field test is recommended prior to full system construction to minimize the uncertainties of the mounding analysis. Water levels should be closely monitored in the vicinity of the test area to confirm that the aquifer responds as predicted. Monitoring of water levels in areas predicted by the analysis to be at risk for near surface water table rise should also be considered.

- Characterize in detail the soils in the proposed infiltration area to detect any potential obstacles to infiltration, especially areas of low permeability above the water table. If such areas are discovered in the proposed construction area, their vertical and lateral extent should be determined and their impact on downward percolation of water analyzed. (If appropriately designed, a pilot-scale test may preclude the need for detailed soil characterization.)

- Survey monitoring well elevations to 0.01 foot to verify the groundwater flow direction.

- Appropriate operation and maintenance procedures should be implemented to minimize aquifer plugging and ensure that aquifer transmissivity does not diminish over time.

- A professional wetlands scientist should evaluate the consequences of a water-table rise adjacent to or within the wetland.

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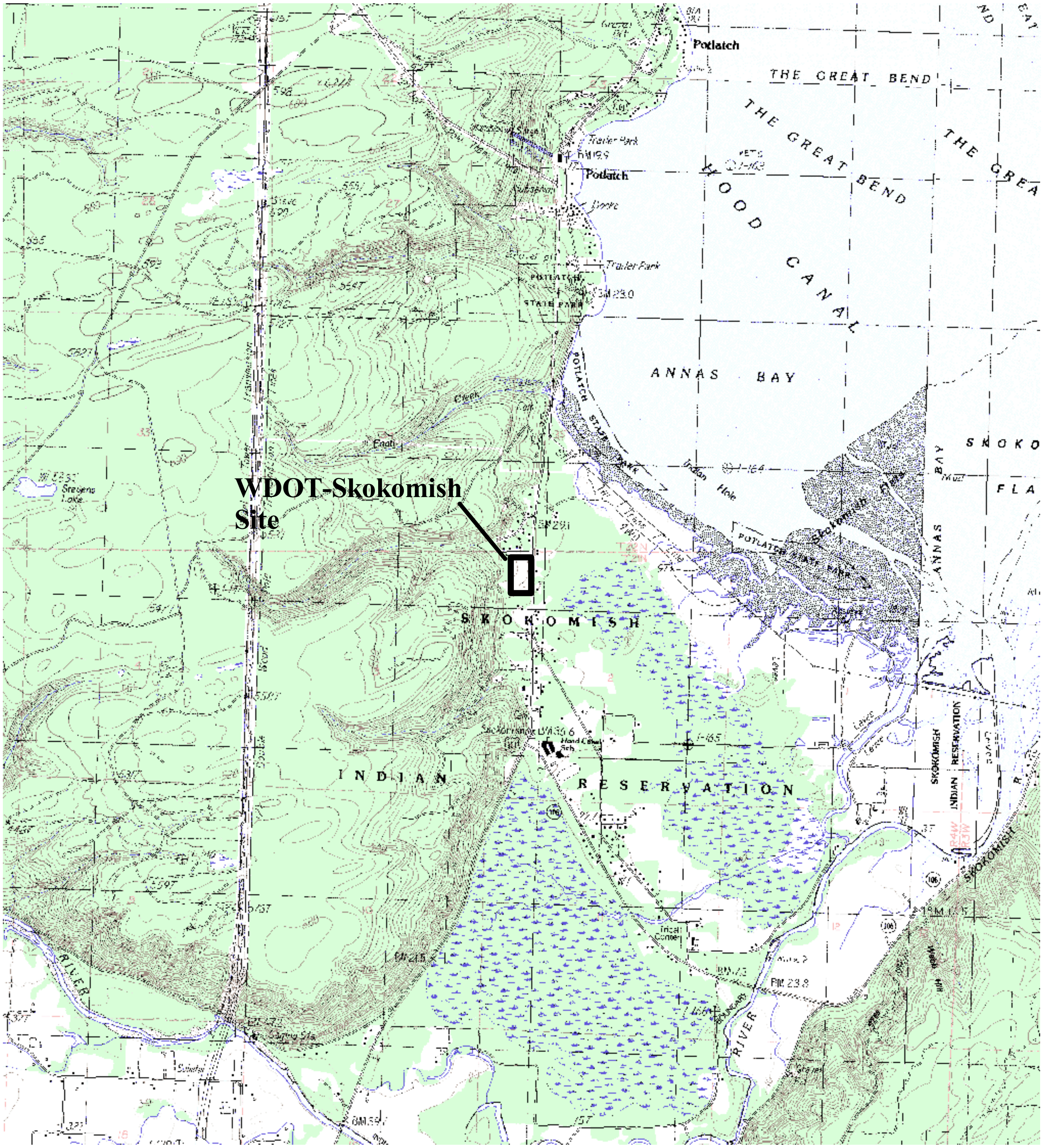
Introduction

This report presents final results of a groundwater mounding analysis conducted in support of site characterization activities at the Washington State Department of Transportation (WDOT)-Skokomish site (Figures 1 and 2), near Potlatch, Washington. The site is under consideration as the future location of a wastewater treatment plant for the Skokomish Indian Reservation. The proposed disposal method for treated water from the plant is via a rapid infiltration system discharging into site soils. Due to future land-use considerations, the discharge system would preferably be located within the western half of the site.

Much of the site characterization data summarized and used by this report is presented in detail in Volume 1 of this study (Carey, 2000), including an analysis of the infiltration capacity of the site vadose zone. Detailed descriptions of the sampling and analysis methods employed during site investigations are provided in that report.

This study (Volume 2) assumes that the infiltration capacity of the site vadose zone is not a limiting factor for discharge. This report does not discuss any issues pertaining to water chemistry or treatment.

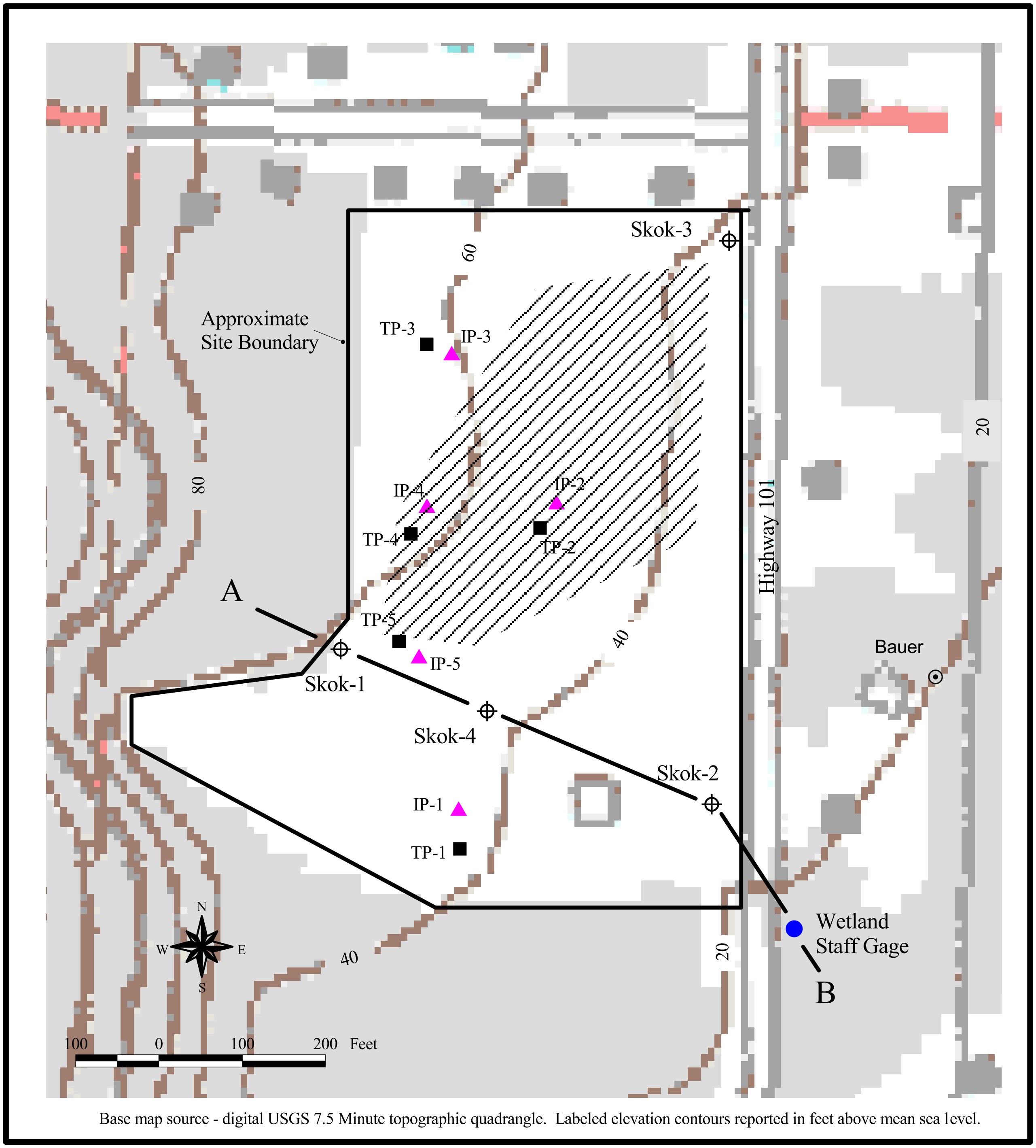


Base map source - digital USGS 7.5 minute topographic quadrangle

N
W E
S

2000 0 2000 4000 Feet

Figure 1
Site Location Map



Legend

▲	Infiltration Test Pit	■	Test Excavation
⊙	Domestic Well	▨	Approximate Extent of Imported Material
⌖	Site Monitoring Well	A—B	Figure 3 Cross-Section Trace

Figure 2
WDOT-Skokomish
Site Map

Purpose and Objectives

The purpose of the study was to determine if the proposed discharge of wastewater to the site's unconfined aquifer would cause excessive mounding of the water table. The main objectives of the study were to develop predictions of the head response of the water table to the proposed infiltration rate and, where possible, identify critical hydrogeologic design constraints for the location of the rapid infiltration disposal system.

Site Conditions

The WDOT-Skokomish site is located adjacent to Highway 101, several miles south of Potlatch State Park, on the lowlands southwest of Hood Canal (Figures 1, 2). The site is situated on a fan terrace of recessional outwash deposited in the late Pleistocene, as part of the Vashon Drift sequence (Molenaar and Noble, 1970; Carson et al., 1975). The terrace is bounded to the west by a steep hillside rising to a till-capped upland plateau. To the east, the site is bounded by a low-relief, forested wetland developed on the Skokomish River floodplain. The wetland ultimately drains to Hood Canal. Annual precipitation in the study area averages approximately 70-80 inches/year (in/yr). The annual recharge rate for the area has previously been estimated during a regional-scale study at 27-36 in/yr (Vaccaro et al., 1998).

Figure 2 identifies the location of ten test excavations and four monitoring wells that were completed during field investigations. The descriptions and interpretations of the site-specific hydrogeology are based on the information collected at these locations. Grain-size analyses of samples of the recessional outwash deposits indicate a highly permeable unit composed of poorly-sorted sandy gravel and cobbles, fining downward to poorly-sorted gravelly, coarse-to-medium sand (Figure 3)(Carey, 2000). The total thickness of the recessional unit in the area of well Skok-4 is judged to be a minimum of 50 feet. Portions of the northern half of the site have been excavated to an unknown depth during WDOT gravel-mining operations. A significant percentage of the northern half of the site has subsequently been backfilled or overlain by a large volume of landslide excavation spoils imported from offsite by WDOT. The approximate extent of the imported material is shown on Figure 2.

In the western portion of the site, the recessional deposits are interpreted to overlie and ultimately thin out against the Pleistocene Skokomish Gravel unit that comprises the adjoining hillside (Molenaar and Noble, 1970; Carson et al., 1975). Grain size analyses from well Skok-1 indicate an oxidized silty sand containing 25% silt and clay in contact with overlying gravels at approximately 15-20 feet below ground surface (bgs). These deposits grade downward to a well-sorted fine sand (Figure 3) (Carey, 2000). This contact is interpreted as the probable transition between the recessional outwash and deposits of the older Skokomish Gravel unit. Because this transition was not encountered in Skok-4, it is assumed that the contact between these units lies below the base of the well.

The location of the base of the unconfined aquifer is not well understood beneath the site. The base of the aquifer was not encountered during drilling investigations in the site interior. The top of a dry, clay-bearing unit (-3 feet AMSL[1]) recorded on the driller's log for the original WDOT facility well was interpreted for this study as the aquifer base (Figure 3). This well was never field-located, but was reported by WDOT employees to be constructed near the WDOT facility building between wells Skok-2 and Skok-4.

[1] All elevations reported for this study were surveyed or calculated relative to the land surface at well Skok-4. The land surface elevation at well Skok-4 was visually estimated from a U.S. Geological Survey 7.5-minute topographic quadrangle to be 45 feet above mean sea level (AMSL).

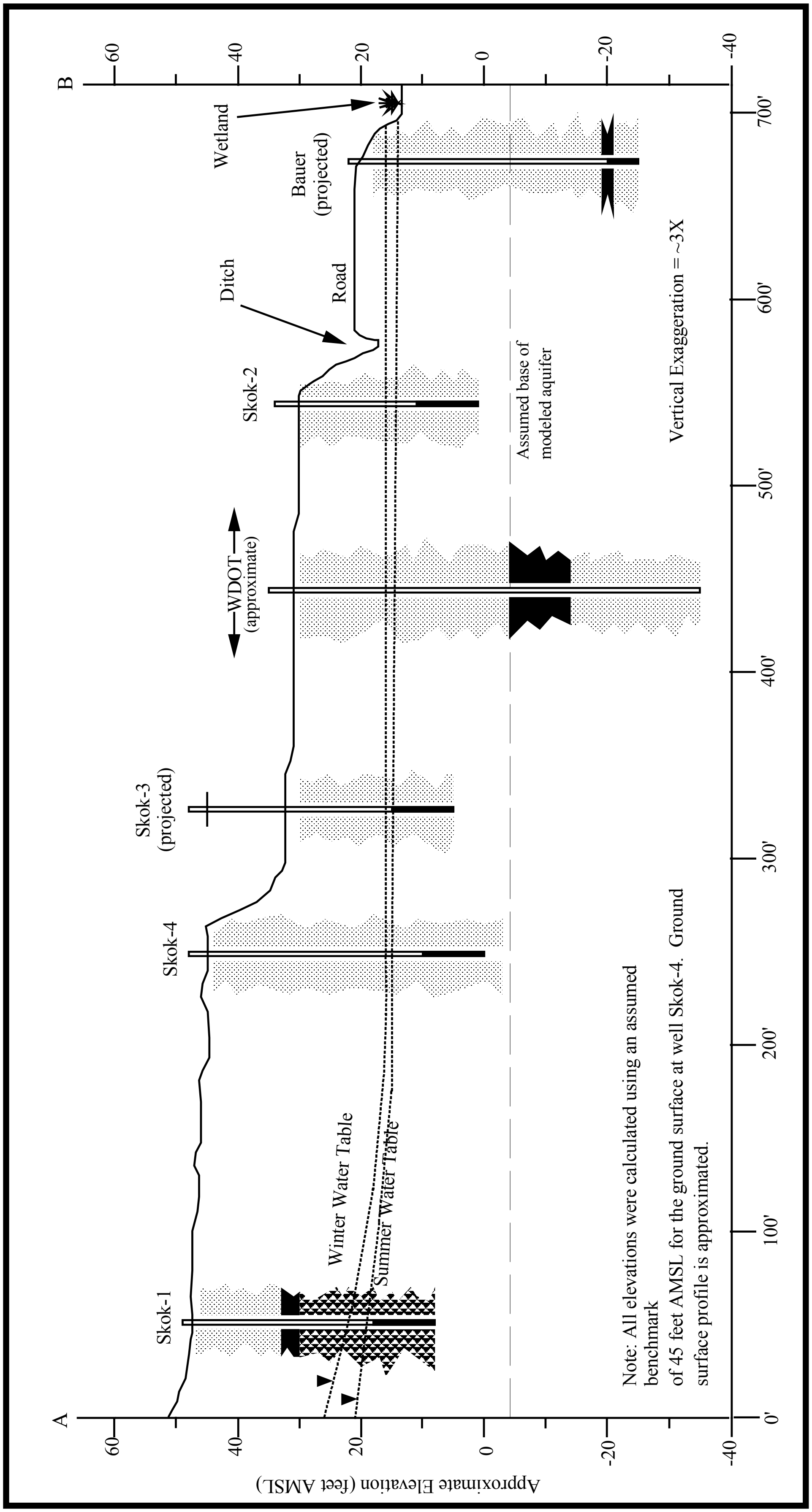


Figure 3
Hydrogeologic Cross Section
WDOT-Skokomish Site

Field measurements of the water-table elevation indicate a near-horizontal gradient over much of the study area, from the wetland to well Skok-4 (Figures 3, 4, and 5). The gradient significantly steepens between wells Skok-4 and Skok-1 (wet-season $dh/dl \cong 0.033$). To supplement measurements collected from the four monitoring wells (Figure 4), static water-level measurements were periodically recorded from a staff gage installed in the wetland southeast of the site (Figure 2). Measurements of daily precipitation for the study period, as recorded at the Hoodsport fish hatchery, are also presented on Figure 4.

To estimate the hydraulic conductivity of the aquifer materials, short-term field tests of specific capacity were conducted during the summer of 1999 on several of the site monitoring wells (Carey, 2000). Specific capacity field data were analyzed using a computer program developed by Bradbury and Rothschild (1985). The program corrects for partial penetration effects and well loss. A well loss correction coefficient of one (1) was used for all tests. Saturated aquifer thickness was estimated using the data and assumptions discussed above. The hydraulic conductivity approximated by the program for the material adjacent to the screened interval of wells Skok-1, Skok-2, and Skok-4 (Figure 3) is 60 ft/day, 350 ft/day, and 400 ft/day, respectively.

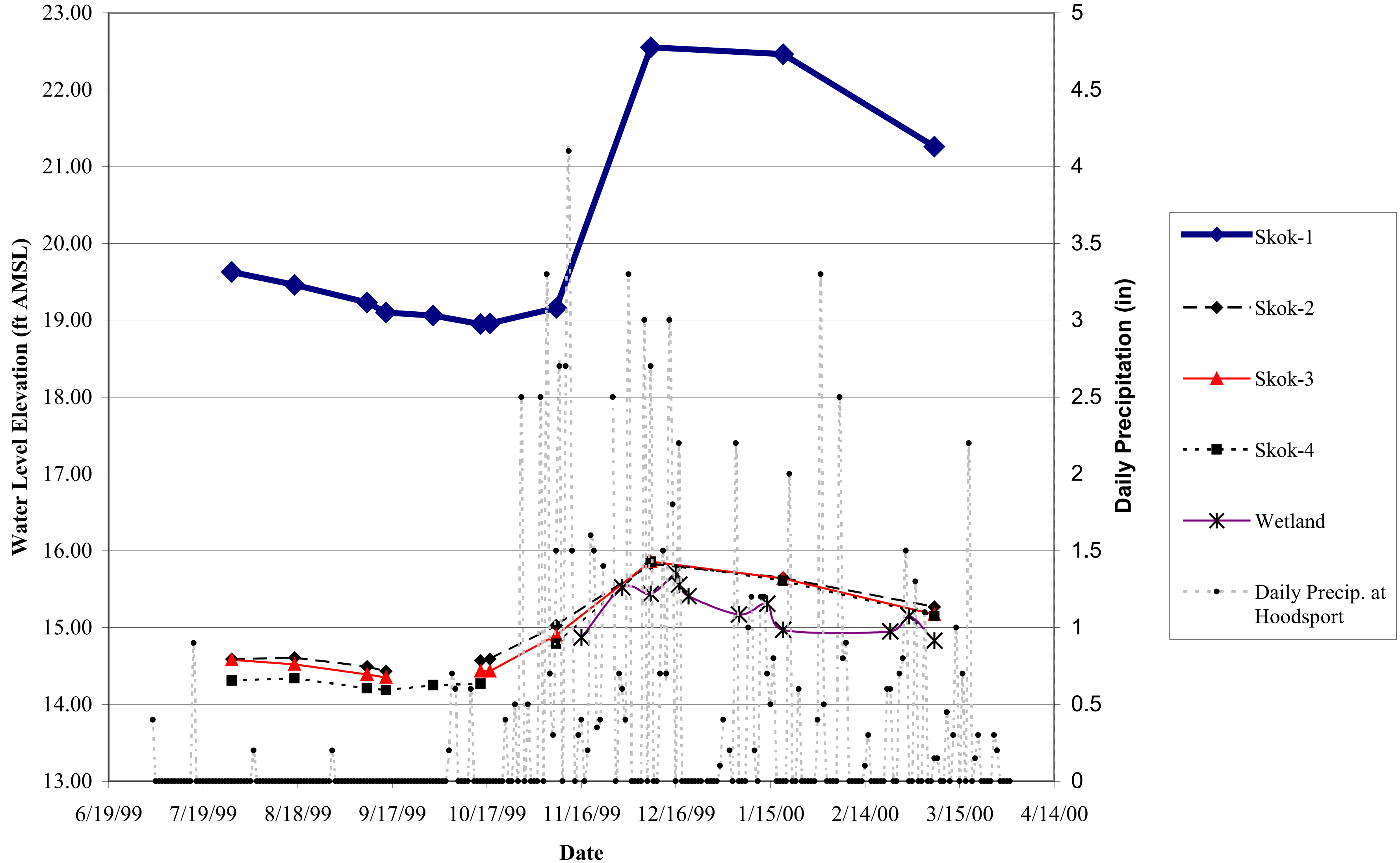


Figure 4
Well and Wetland Hydrographs, and Daily Precipitation
WDOT Skokomish

Mounding Analysis

To develop predictions of the mound geometry that may result below an infiltration system, both analytical and numerical methods were employed. These evaluations were conducted using data gathered in the field during 1999 and early 2000, including monitoring-well installation and testing, water-level measurements, and grain-size analyses of subsurface soils. Many of these data are described in detail under separate cover (Carey, 2000).

Analytical Modeling

Methods

The Hantush analytical method to predict mounding beneath a rectangular infiltration area was applied using a public-domain software program called MOUNDHT (Finnemore, 1995). The Hantush method assumes an infinite, initially near-horizontal saturated zone in an isotropic, homogeneous aquifer, bounded at its base by an impermeable layer (Hantush, 1967; Finnemore, 1993). The method assumes that a constant vertical recharge is applied to a rectangular infiltration area of fixed dimension, and that the water table mound remains below the base of the infiltration area at all times. The solution method is applicable only if the rise of the water table is less than 3.3 times the initial saturated thickness.

Because this method assumes an infinite, near-horizontal, saturated zone as an initial condition (i.e., there is no regional gradient or outflow boundary), it predicts an infinitely increasing mound height with time. If the input variables used appropriately reflect field conditions, this approach provides an upper-bound estimate of the true mound height that will occur in the field. The presence of a regional gradient or a local outflow boundary will limit the field mound height to a value below that predicted by the model. In contrast, a decrease in hydraulic conductivity away from the infiltration area not accounted for by the model may cause a higher mound height than predicted. The idealized conditions of isotropy and homogeneity used by the model are rarely encountered in the field. Therefore an analytical solution such as the Hantush method is considered an approximation of the field response of the water table.

Assumptions and Input Parameters

The hydrogeologic setting and assumptions used for the analytical solutions presented in this report represent conditions interpreted to exist in the south-central area of the site, specifically in the Skok-4 area (Figures 2 and 3). Because subsurface conditions are poorly understood in the area between Skok-4 and Skok-3, and this area is largely covered or backfilled with low permeability imported material, the analysis is not applicable to the northern half of the site. *All model runs were conducted assuming that the point of discharge is constructed in the native soils below or away from any low-permeability, imported material or disturbed soil.* Further, due to future land-use considerations, the placement of an infiltration area in the eastern half of the site was not considered during this study.

For the purposes of the analytical mounding analysis, a variety of infiltration area footprint sizes was evaluated. An average-maximum, steady-state discharge rate of approximately 500,000 gallons/day (gal/day) of wastewater was assumed. The maximum month wet weather flow design rate for the proposed treatment plant is 415,000 gal/day (Munro, 2000). Daily natural recharge was considered a negligible additional contribution and was ignored when establishing the model recharge rate.

On the basis of field observations, grain-size data, and tests of specific capacity from site monitoring wells, a hydraulic conductivity of 350 feet/day (ft/day), and a specific yield of 0.25, was assumed for the receiving aquifer for the analytical solution.

An initial saturated thickness of 19 feet was assumed for the receiving aquifer. This value is based on the difference between the winter water table elevation in well Skok-4 (approximately 16 feet AMSL), and an aquifer base elevation of –3 feet AMSL. This assumption is judged to be the greatest source of uncertainty in the analytical solution, due to a lack of data regarding the true vertical position of the aquifer base in the Skok-4 area (the deepest well installed during the investigation). If the base of the unconfined aquifer were deeper than assumed, the maximum mound height estimates would be smaller than reported here.

A total model run period of ten years was selected as a conservative upper-limit timeframe. It is assumed that in the field, the hydrologic system would equilibrate to a steady-state condition well within the ten-year period.

Results

Appendix A contains detailed model printouts for the various infiltration area designs tested under an assumed discharge condition of 500,000 gal/day. Using the hydrogeologic assumptions described above, the maximum mound height predicted after ten years is less than ten feet above static conditions in all cases. The input parameters and ten-year maximum predicted mound height for these scenarios (Runs 1-5) are summarized in Table 1.

Table 1. MOUNDHT Input Parameter Values and Results

Run	Infiltration Area Width (W) (feet)	Infiltration Area Length (L) (feet)	Initial Saturated Thickness (H) (feet)	Specific Yield (S_y)	Hydraulic Conductivity (K) (ft/day)	Steady-state Recharge Rate (I) (gal/day)	Maximum Mound Height After 10 Years (feet)
1	10	250	19	0.25	350	500,000	7.8
2	5	250	19	0.25	350	500,000	7.8
3	5	500	19	0.25	350	500,000	7.0
4	2	300	19	0.25	350	500,000	7.5
5	1	100	19	0.25	350	500,000	8.8
6	5	250	19	0.25	350	700,000	10.4
7	5	250	19	0.25	35	500,000	39.4

To predict a maximum mound height during peak plant discharge conditions, an additional scenario was modeled, assuming a steady-state flow rate of approximately 700,000 gal/day. The peak instantaneous flow design rate for the proposed treatment plant is 693,000 gal/day (Munro, 2000). Under this scenario, the maximum mound height is predicted to be less than 11 feet above initial conditions after ten years. The detailed model output for this scenario is located in Appendix B. The input parameters and ten-year maximum predicted mound height for this scenario (Run 6) are summarized in Table 1.

To examine the consequences of overestimating the bulk hydraulic conductivity of the unconfined aquifer, and to evaluate the effect of aquifer plugging, an additional mounding scenario was modeled. Using an infiltration area 5 feet by 250 feet in dimension, the hydraulic conductivity of the receiving aquifer was assumed to be one order of magnitude less than the field-estimated value, or 35 ft/day. Under this scenario, the predicted maximum mound height after ten years is approximately 40 feet. The detailed model output for this scenario (Run 7) is located in Appendix C. The input parameters and ten- year maximum predicted mound height for this scenario are summarized in Table 1.

Discussion

- The analytical model is a simplification of the natural system. Idealized assumptions regarding hydrogeologic conditions have been used, introducing uncertainty into the model predictions.
- Assuming an infiltration line was buried four feet below ground surface, approximately 25 feet of unsaturated sediments are available in the Skok-4 area as an initial condition between the line and the water table (Figure 3). Under the assumptions outlined above, the analytical solution indicates that the water table directly beneath an infiltration system built in this area is unlikely to rise to the base of the infiltration line under average-maximum discharge conditions.
- Increasing the total length of the infiltration area decreases the maximum mound height at the water table.
- The ground surface immediately downgradient of well Skok-4 drops approximately 10-15 feet in elevation (Figure 3). While this reduces the effective vadose zone thickness to approximately 13-18 feet in this area, it is still greater than the predicted mound height under assumed average-maximum conditions (<10 feet). While the MOUNDHT program does not provide a three-dimensional description of the geometry of the mound, mound heights are predicted to diminish with distance from the central axis of the infiltration area (Finnemore, 1995; Hantush, 1967). This suggests that the maximum mound height in the eastern portion of the site would be less than the values predicted in Table 1.
- The analysis does indicate that under average-maximum flow conditions a groundwater mound will breach the site surface if the aquifer hydraulic conductivity is significantly diminished over time, or if the infiltration area is centered over sediments with a conductivity significantly lower than that approximated adjacent to well Skok-4.

- As shown on Figure 3, there are significant differences in the subsurface stratigraphy encountered in wells Skok-4 and Skok-1. The highly permeable gravels and sands found throughout the length of Skok-4 only extend to a depth of approximately 15 to 20 feet bgs in Skok-1 (elevation ~30 feet AMSL). At this depth a fine-grained unit (~25% silt and clay) is encountered, grading downward to a lower permeability, well-sorted fine-to-medium sand. The water table lies approximately 25 feet bgs in the Skok-1 area. The analysis suggests that release of the average-maximum discharge volume to the subsurface in the Skok-1 area could result in a groundwater mound breaching the site surface, due to the lower permeability character of the sediments in this area. The presence of a silt- and clay-rich layer within the vadose zone at Skok-1 could additionally act to perch a large volume of rapidly infiltrating water, effectively raising the receiving aquifer base.
- The geometry of the contact between the recessional gravel and the underlying finer-grained material is unknown between wells Skok-1 and Skok-4. If the lower permeability material encountered in Skok-1 extends to the east at a similar elevation, the mound developing beneath an infiltration system centered in the Skok-4 area could potentially breach the site surface. Additional field investigation would be required to characterize the contact geometry in detail.

Numerical Modeling

Methods

To further evaluate the proposed infiltration system, three-dimensional numerical modeling using the U.S. Geological Survey finite-difference MODFLOW model was conducted (McDonald and Harbaugh, 1988). A commercial pre- and post-processor software program, Visual MODFLOW, was used to conduct the modeling (Waterloo Hydrogeologic, Inc., Version 2.7.2, 1997). A simplified representation of the WDOT-Skokomish site and surrounding area was created to: 1) numerically examine the potential maximum mound height beneath the proposed infiltration area, 2) better account for vertical and horizontal changes in hydraulic character of the subsurface sediments, and 3) examine the extent and degree of water table rise downgradient of the infiltration area.

Conceptual Model

The conceptual model of the WDOT-Skokomish site consists of an unconfined aquifer with two main hydrostratigraphic units: the high-permeability recessional gravel, and the lower permeability sand/silt underlying the far-western half of the site. Precipitation derived recharge enters the vadose zone from the site surface and percolates to the water table. Additional water input to the site aquifer occurs from the western margins of the site, where a combination of percolating surface runoff from the hillside and upgradient subsurface inflow sustains a higher head potential. Groundwater flow is dominantly horizontal to the east-southeast, toward Hood Canal. A portion of the underflow moving offsite to the east discharges to the wetland. The base of the unconfined aquifer is assumed to be a flat impermeable surface. Vertical leakage to or from a deeper water-bearing zone is ignored.

Model Construction

A two-layer grid system was constructed to represent the conceptual model of the site. The model dimensions are 900 feet wide by 3500 feet long, with ten-foot by ten-foot cell dimensions (90 cells x 350 cells). Figure 6 shows the model domain and key features in areal view, with the grid framework removed. The principal conductivity tensor direction K_x is approximately aligned with the local groundwater flow direction (Figure 5).

The grid cells along the left model boundary represent the upgradient portion of the site at the base of the hillside. These cells were defined as constant head nodes, with a fixed water table elevation of 31.6 feet (Figure 6). This elevation was determined by extending the gradient measured between wells Skok-1 and Skok-4 to the model boundary, under wet-season water-table conditions (December 8, 1999).

The grid cells along the right model boundary represent the wetland located at the base of the gravel fan. This boundary was constructed as a head dependent flux condition using the MODFLOW drain package. Drain cells allow water to exit the model domain as a function of the modeler-assigned conductance of the cell and the difference between the head in the aquifer and the drain elevation. Water can only exit the model domain if the water level in the cell rises above the base elevation of the drain. The base elevation of the drain cells was established at 14.5 feet AMSL by measuring the ground surface of the wetland in the field. The drain-cell conductance was set through model calibration to match a standing wet-season water level in the wetland of 15.4 feet AMSL (also a field-measured value). All constant head and drain cell nodes are assigned to the lower layer of the model, as shown in a type model cross section in Figure 7.

The model boundaries perpendicular to the direction of groundwater flow were assumed to be parallel to streamlines, and were therefore set as no-flow boundaries. The base of the model grid was established at an elevation of –3 feet AMSL (Figure 7), and is also assumed to be a no-flow boundary. This elevation corresponds with the interpreted base of the aquifer system. The decision to set the base of the model domain at an elevation just below the known limit of the recessional outwash unit provides upper-bound estimates of the mounding response of the aquifer to the infiltration of a large volume of artificial recharge. The deeper the base of the model domain assumed, the smaller the maximum mound height predicted by the model.

The top of the model was established at an elevation of 55 feet AMSL. The base of Layer 1 of the model was established at an elevation of 35 feet AMSL.

Input Parameters

Two conductivity zones were input to represent subsurface conditions. Initial model runs were conducted using values estimated from field observations and testing, and were modified as necessary through successive model runs to improve the model calibration to measured water levels. The majority of the model domain was ultimately assigned a horizontal hydraulic conductivity of 400 ft/day, representing the recessional outwash (Figure 7; K_1). In the upgradient portion of the site, a second conductivity zone (K_2) was established to represent the finer-grained material encountered in the lower portion of Skok-1 (Figure 3 and 7). The horizontal hydraulic conductivity of this unit was established by calibration at ten ft/day. An

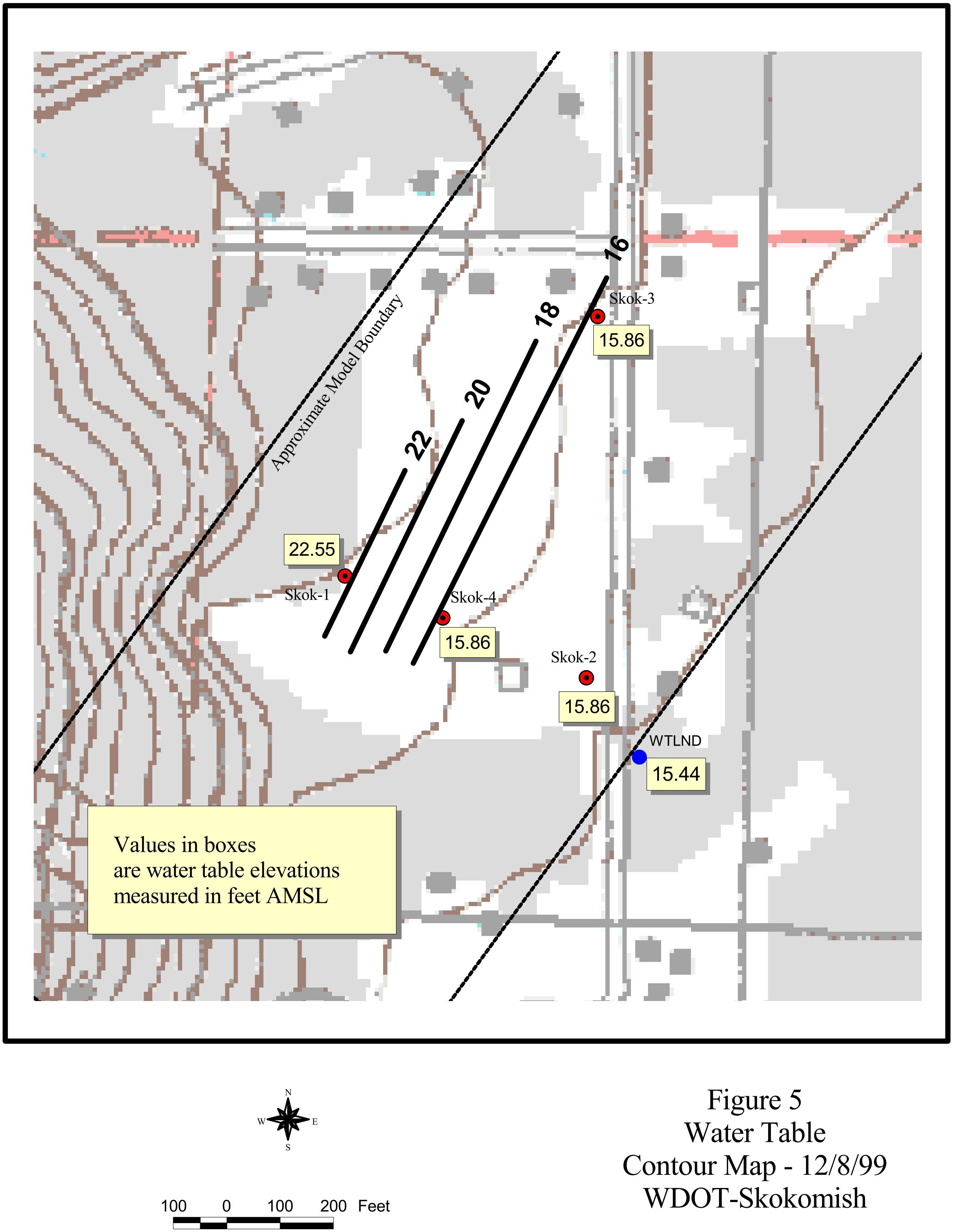


Figure 5
Water Table
Contour Map - 12/8/99
WDOT-Skokomish

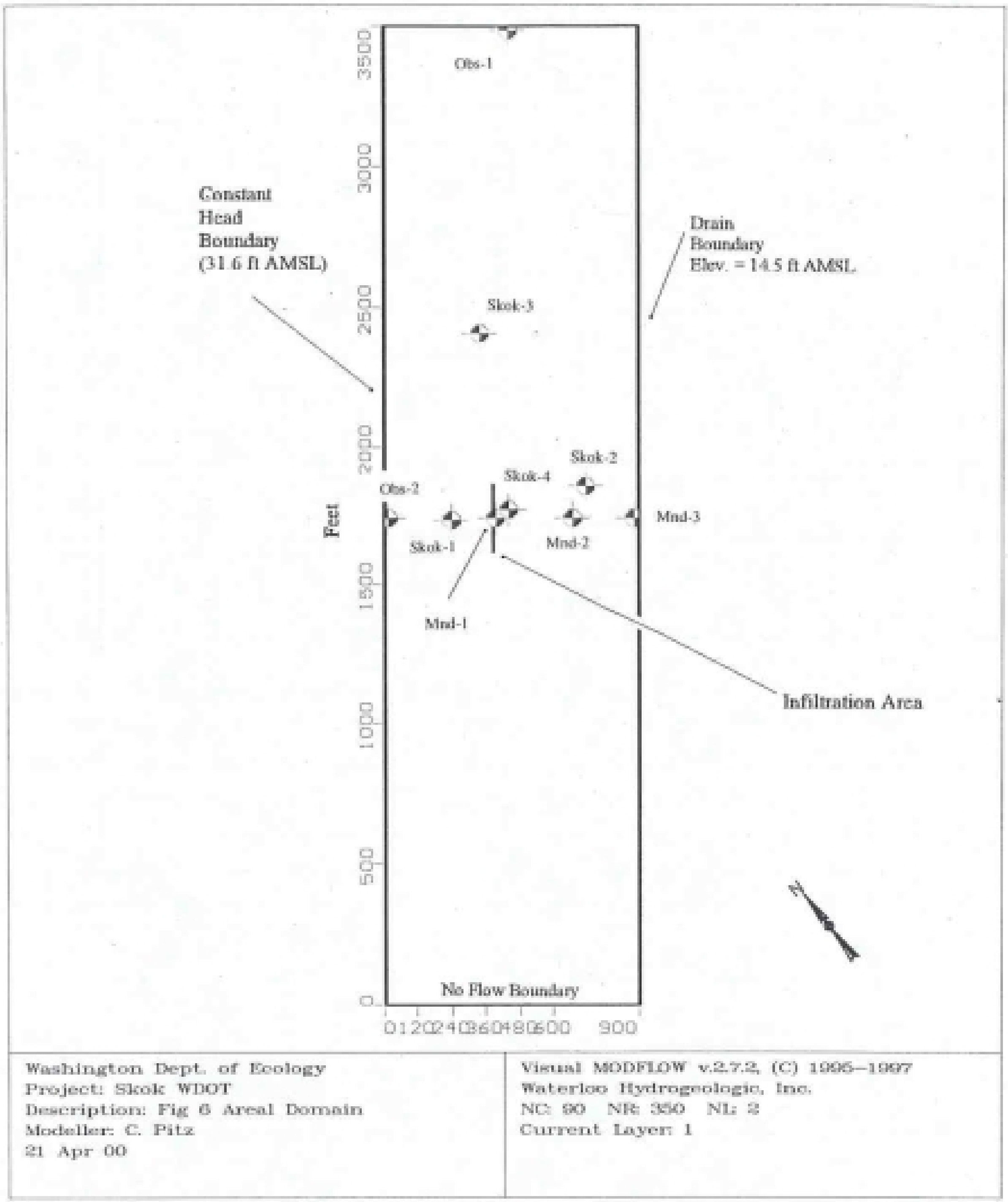


Figure 6
Numerical Model Domain – Areal View

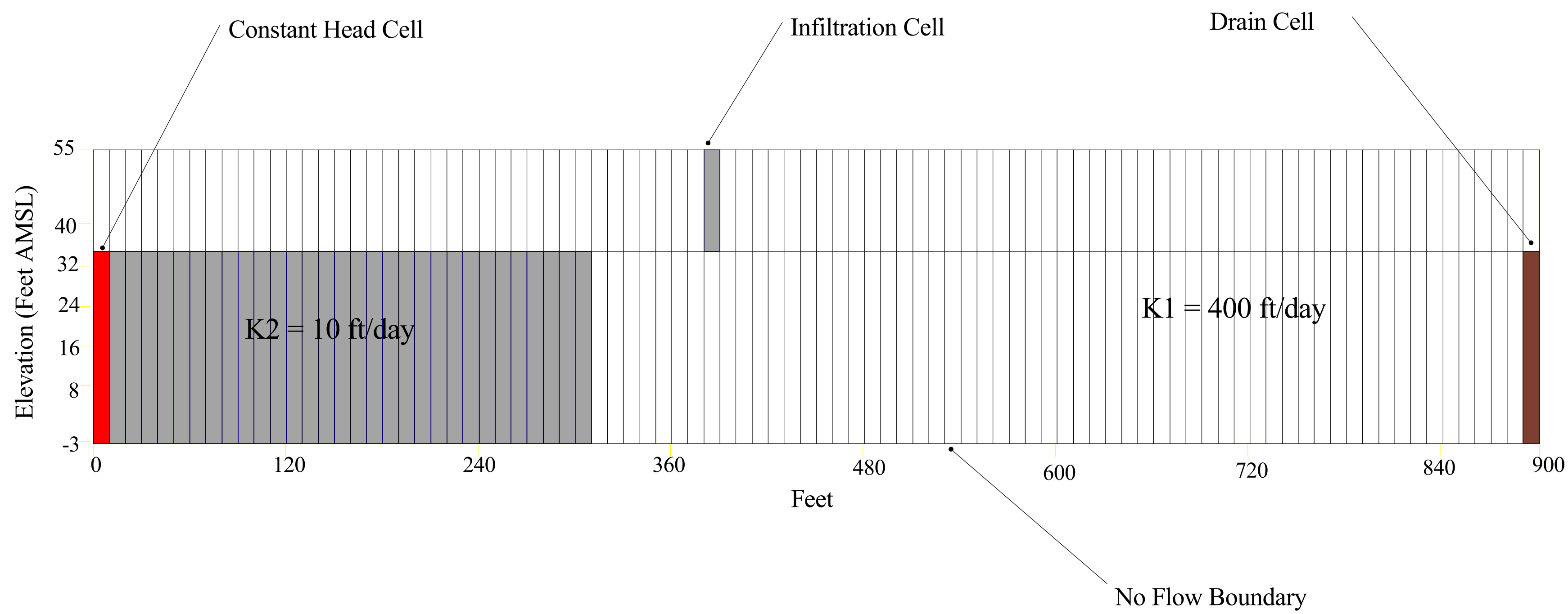


Figure 7
Numerical Model Domain - WDOT-Skokomish
Profile View

assumed horizontal-to-vertical hydraulic conductivity ratio of 10:1 was used throughout the model domain to reflect stratigraphic anisotropy (Anderson and Woessner, 1992).

To calibrate the model and determine initial heads, the model was run as a steady-state solution, using an estimated wet-season recharge rate of 90 in/yr across the entire model domain (*initial condition* scenario). Once a calibrated model was constructed, a second steady-state solution was executed with artificial recharge activated *(stress* scenario). To represent a rapid infiltration system, a 250-foot long infiltration area (25 ten-foot wide cells) was placed near the center of the model, in the vicinity of well Skok-4 (Figure 6). For the stress scenario, the model cells included in this area were assigned equal constant recharge values that collectively represent 500,000 gal/day of treatment plant discharge (the assumed average-maximum discharge condition). The remainder of the model area continued to receive seasonal recharge as described above.

The numerical model ignores the presence of any imported low-permeability material that currently covers large portions of the site, or that was used to backfill excavations created during WDOT gravel mining operations.

Observation Wells

Three mock observation points were included in the model domain to assist in tracking water level changes over time, within and directly downgradient of the infiltration area (Figure 6). These wells, which form a line across the center of the model domain, are called Mnd-1, Mnd-2, and Mnd-3, from northwest to southeast. The site monitoring wells (Skok-1, Skok-2, Skok-3, and Skok-4) are also located within the model domain at the appropriate relative positions.

To track the head response to the applied stress at the model boundaries, two additional mock observation points were included in the model domain. One well, Obs-1, was placed adjacent to one of the boundaries perpendicular to the groundwater flow direction to evaluate the impact of the no-flow assumption on the model predictions (Figure 6). A second well, Obs-2, was placed adjacent to the upgradient constant-head boundary to determine if the applied stress reaches the boundary.

Model Calibration and Verification

To represent wet-season water-table conditions, water-level measurements collected from site monitoring wells on December 8, 1999 were used to calibrate the flow model under steady-state initial conditions.

Various input parameters were adjusted from their initial estimate during the model calibration to achieve the best match between measured and predicted heads. Parameters adjusted included the hydraulic conductivity of the K_1 and K_2 zones, the areal recharge, the drain-cell conductance, and the eastern limit of the K_2 conductivity zone. The model exhibited significant sensitivity to the conductivity and eastern limit of the K_2 zone when attempting to match observed heads. The model was not sensitive to small changes in the areal recharge value, and showed no change in the predicted heads using a model-wide vertical anisotropy factor for conductivity of 100:1. A final conductance value of 300 ft^2/day was assigned to all drain cells through calibration.

Figures 8 and 9 show the model-predicted, steady-state, water-table head distribution under calibrated initial conditions, in areal and profile view. Figure 10 shows the steady-state, initial-condition calibration plot for the site monitoring wells. The root mean squared error[2] between the measured and predicted heads is less than one foot. Figure 11 shows the steady-state, initial-condition calibration plot for the mock wells. The "measured" heads for the mock wells were purposefully matched to the model-calculated heads to allow changes to be accurately tracked between initial and stressed conditions.

As a measure of the model water-balance error, the total simulated inflows and outflows of the initial condition model were compared. The modeling program reported a 0.00% discrepancy between these flows.

To verify the ability of the model to represent natural conditions, an extra model scenario was completed. For this case, the calibrated wet-season model was used to predict steady-state dry-season head values by adjusting the model domain recharge rate to 0 in/yr (vs. 90 in/yr for the wet season). The upgradient constant-head boundary value was changed to 25.7 feet (vs. 31.6 feet) to reflect the change in the dry-season water-table position. This value was estimated by extending the gradient measured in the field during the dry season (September 15, 1999) between wells Skok-1 and Skok-4. All other conditions were left unchanged. The change in the hydraulic head between the wet-season and dry-season model predictions were then compared to changes in head that have been measured in the field. This comparison is shown in Table 2.

Table 2. Comparison of Seasonal Head Change – Field Measurement vs. Model Prediction

Well Name	9/15/99 Water Level Field Measurement (feet AMSL)	12/8/99 Water Level Field Measurement (feet AMSL)	Measured Change (feet)	Dry-season Model Water Level Prediction (feet AMSL)	Wet-season Model Water Level Prediction (feet AMSL)	Predicted Change (feet)
Skok-1	19.10	22.55	3.45	18.03	21.61	3.58
Skok-2	14.43	15.83	1.40	14.97	16.07	1.10
Skok-4	14.19	15.86	1.67	15.26	16.83	1.57

The values presented in Table 2 indicate that the model reasonably predicts the field response to a change in stress. A comparison of the field head measurements to the model predictions indicates that the gradient between Skok-1 and Skok-2 is under-predicted by the model in both the dry (0.010 measured vs. 0.006 predicted) and wet (0.014 measured vs. 0.012 predicted) season. An under-predicted hydraulic gradient would bias the predicted mounding response to be higher.

The calibration error of the numerical model was judged to be within an acceptable limit (<5% of the available wet-season unsaturated zone thickness) for evaluating the likelihood of a

[2] The root mean squared error is the square root of the sum of the square of the differences between the predicted and observed heads, divided by the number of observations.

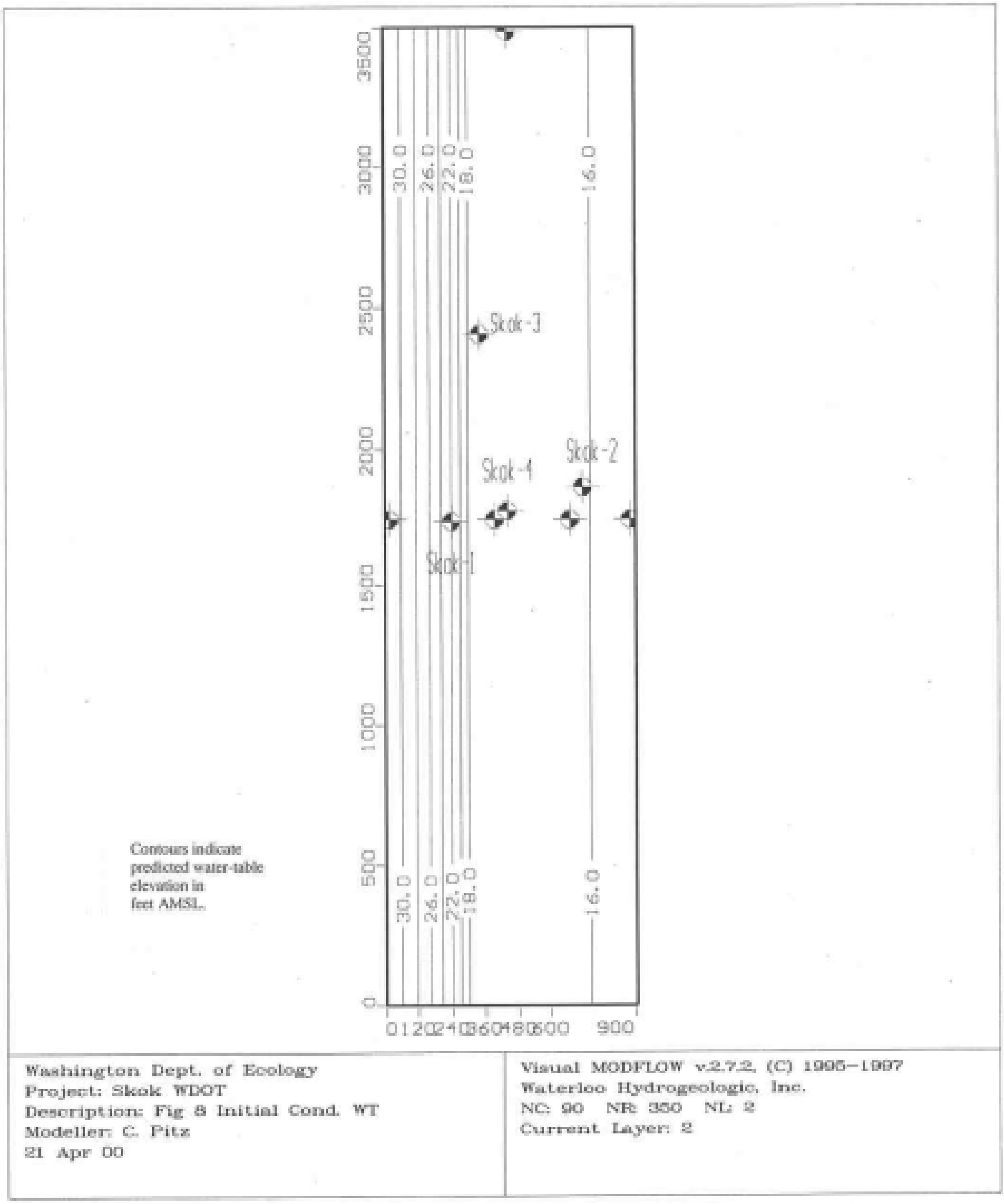


Figure 8
Initial Condition Water Table – Areal View

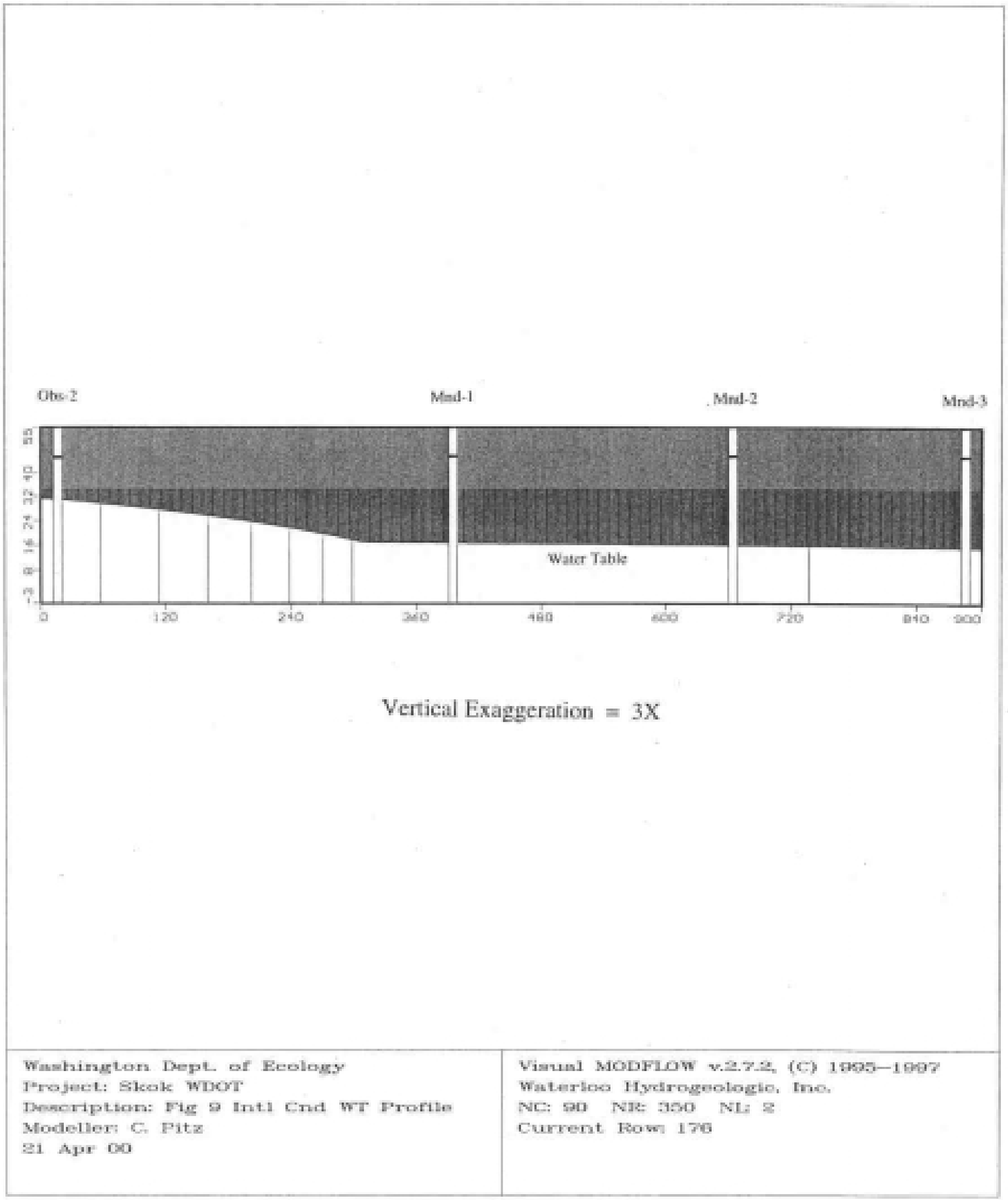


Figure 9
Initial Condition Water Table – Profile View

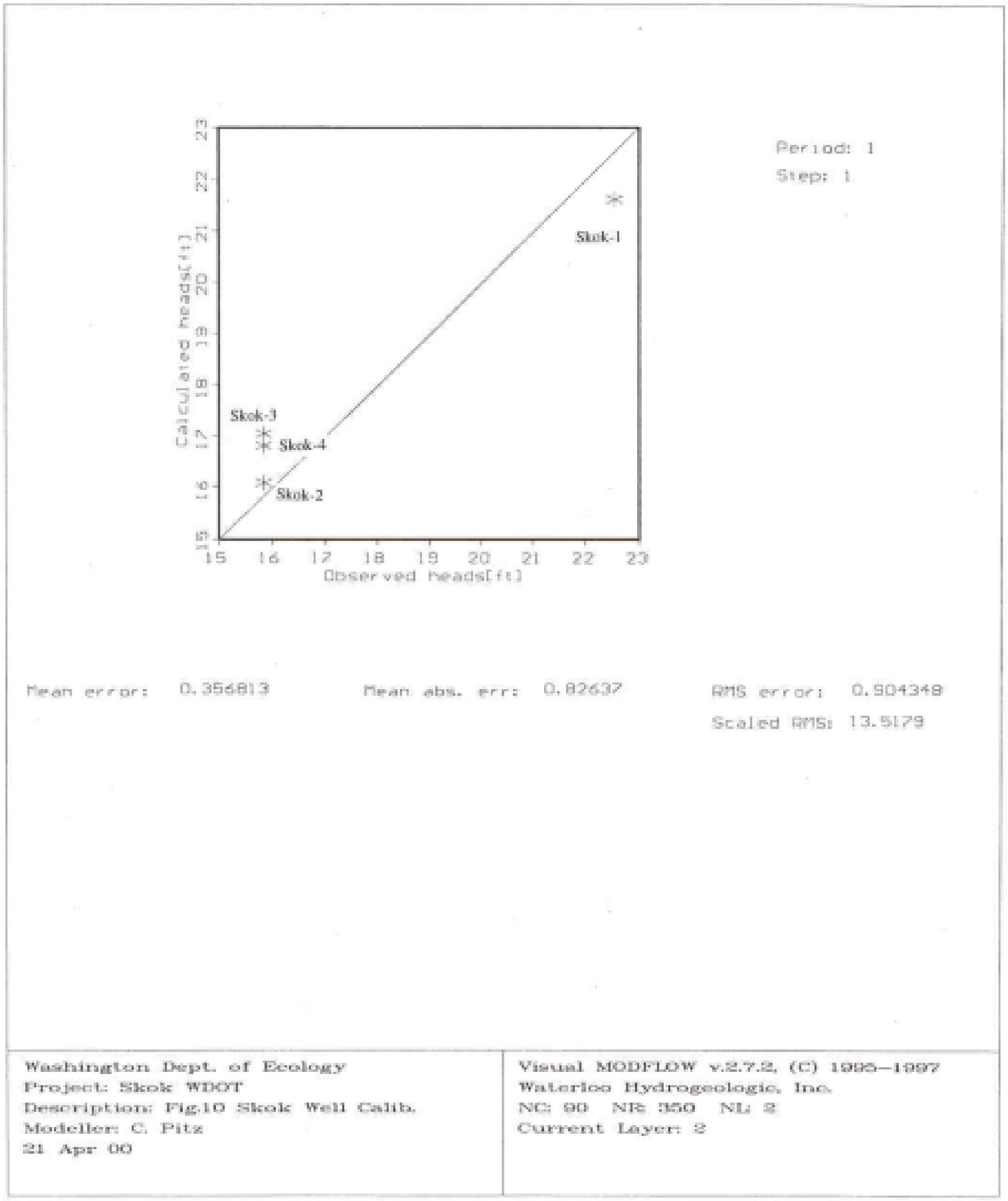
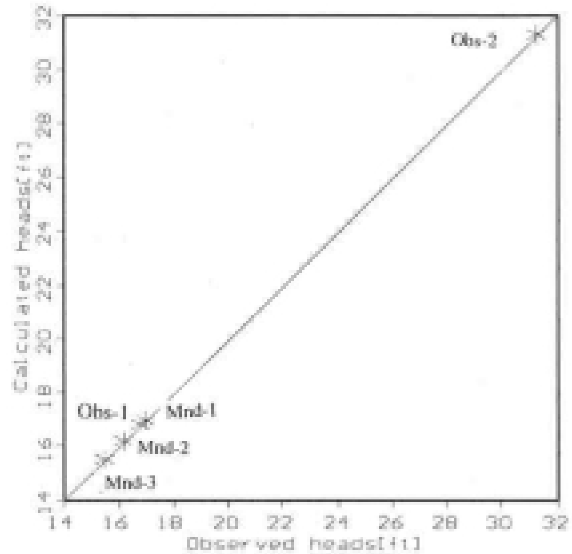


Figure 10
"Skok" Well Calibration Data



Period: 1
Step: 1

Mean error: 0.000111469   Mean abs. err: 0.000264636   RMS error: 0.000328965
Scaled RMS: 0.00207798

Washington Dept. of Ecology Project: Skok WDOT Description: Fig.11 Obs. Well Calib. Modeller: C. Pitz 21 Apr 00	Visual MODFLOW v.2.7.2, (C) 1995-1997 Waterloo Hydrogeologic, Inc. NC: 90 NR: 350 NL: 2 Current Layer: 2

Figure 11
Observation Well Calibration Data

groundwater mound breaching the ground surface beneath the infiltration area. While the model does not necessarily present a unique numerical solution to the site flow field, the ability of the model to closely mimic the aquifer response to changes in the area recharge from summer to winter improves the confidence in the model's ability to represent the natural system.

Results

After construction and calibration of the model under non-stressed conditions, the recharge to the infiltration area cells was increased to the assumed average-maximum discharge condition, and the model was re-run. Table 3 below summarizes the head changes recorded between the initial-condition and stressed model runs. The table results are graphically summarized in Figure 12. Figure 13 shows a contour map of the model-predicted, steady-state, water-table head distribution under stressed conditions, in areal view.

Table 3. Summary of Head Change by Well – Initial Condition vs. Stress Condition

Well Name	Initial Condition Water Level (feet AMSL)	Stress Condition Water Level (feet AMSL)	Change (feet)
Skok-1	21.61	24.96	3.35
Skok-2	16.07	18.35	2.28
Skok-3	17.05	18.49	1.44
Skok-4	16.83	21.51	4.68
Mnd-1	16.94	22.43	5.49
Mnd-2	16.23	18.90	2.67
Mnd-3	15.48	16.91	1.43
Obs-1	31.31	31.41	0.10
Obs-2	16.83	17.15	0.32

Figure 14 shows a contour map of the model-predicted hydraulic-head change in response to the recharge stress. The maximum head increase (~5.5 feet), as expected, was observed directly adjacent to the infiltration area, in well Mnd-1.

The model predictions suggest that the head response in the area downgradient of the infiltration cells diminishes with distance. The model predicts that the water-table elevation will rise more than one foot in the mock observation well (Mnd-3) immediately adjacent to the wetland boundary (Figure 14).

Small responses to the imposed stress were exhibited in both of the boundary observation wells (Obs-1: ~0.3% of the initial condition; Obs-2: ~1.9%). However, the magnitude of response suggests that the model boundaries did not introduce significant error into the predictions in the model interior. The modeling program reported a water balance error discrepancy of 0.00% for the stress condition run.

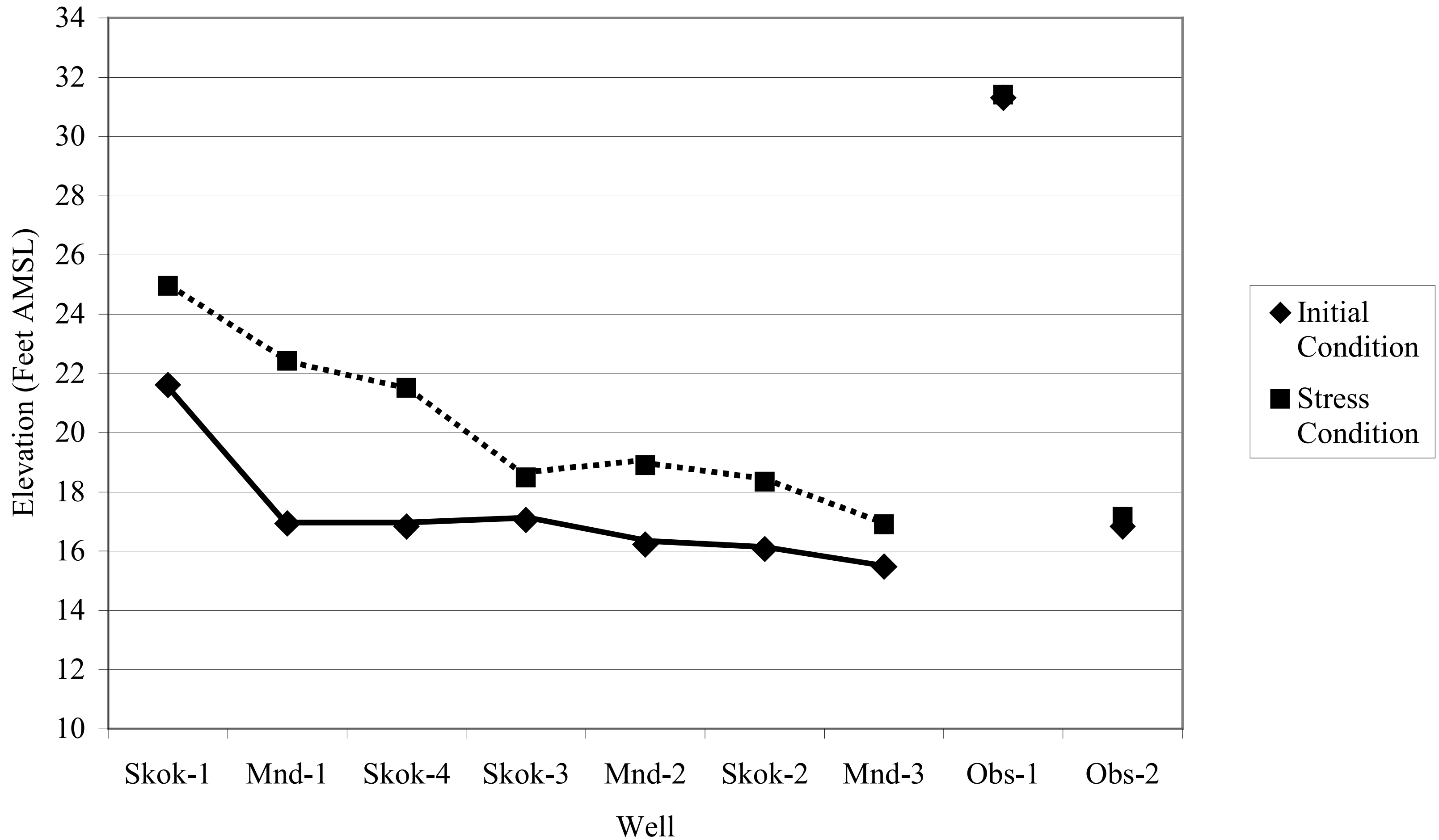


Figure 12
Head Response by Well - Initial Condition vs. Stress Condition
WDOT-Skokomish

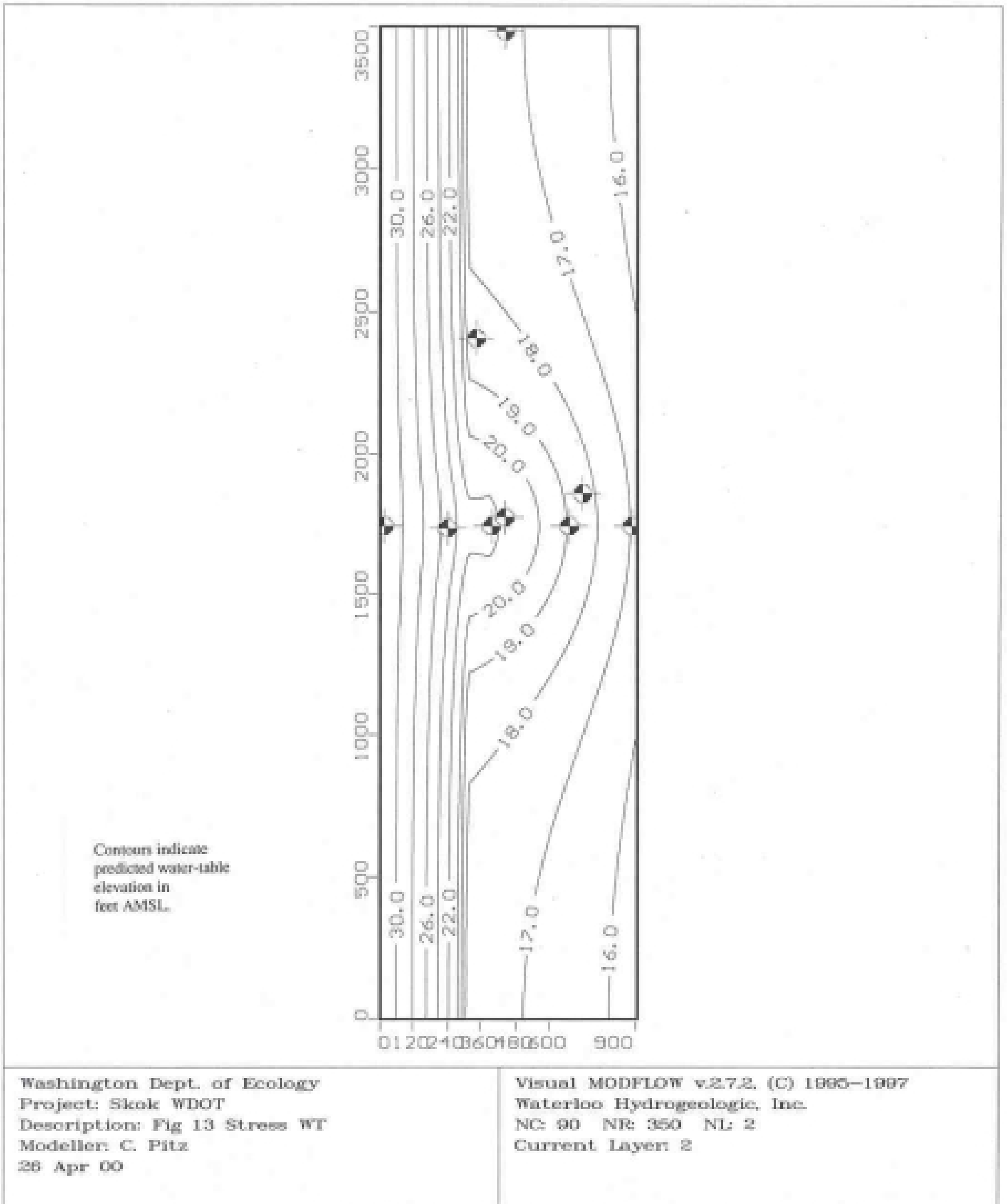


Figure 13
Stress Condition Water Table Contour Map

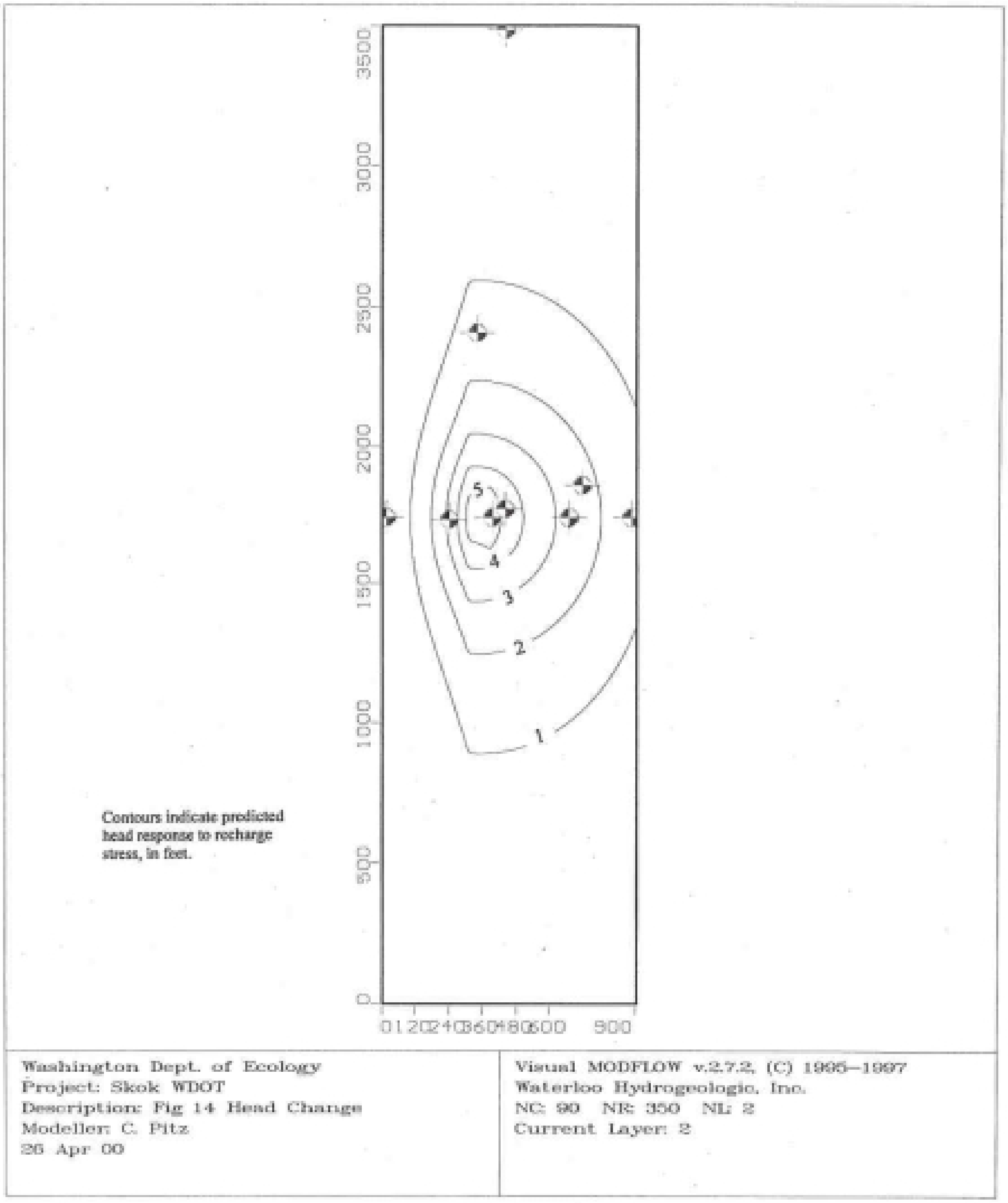


Figure 14
Head Change Contour Map – Initial Condition vs. Stress Condition

Discussion

- The numerical model is a simplification of the natural system. To construct the model with limited available field data, point measurements of hydraulic properties and hydrogeologic conditions have been extrapolated throughout the model domain. This approach introduces uncertainty into the model predictions. The potential error increases with distance from the known field measurement points, including uncertainty regarding the influence of hydrogeologic boundaries beyond the site area that are not incorporated into the model.
- The numerical model predictions are only applicable to *average* maximum steady-state conditions. The numerical model does not provide information on the aquifer response to transient flows higher than 500,000 gal/day.
- As expected, the numerical model predicts a maximum water-table response to the recharge stress that is less than that predicted using analytical methods. The smaller stress response in the numerical model is primarily due to the presence of a hydrologic boundary downgradient of the infiltration area that allows groundwater to exit the modeled aquifer. Calibrating the numerical model to measured heads also suggests that the bulk hydraulic conductivity of the recessional gravels in the field may be higher than used for the analytical solution. Both methods indicate that under the described assumptions, infiltration of the average-maximum water volume will not cause a groundwater mound to breach the site surface in the near vicinity of the infiltration area.
- The model predicts that the water-table rise under average-maximum discharge conditions will reach the wetland located on the east side of Highway 101. While the model error is too great to allow a prediction of the exact magnitude of the rise of the water table in the vicinity of the wetlands, the results suggest this rise could be more than one foot in elevation. This rise could potentially change the hydrodynamic cycle of the wetland. The hydraulic character (and impact on the local flow field) of the material underlying or composing the Highway 101 roadbed immediately upgradient of the wetland is unknown.
- A detailed comparison of the predicted water-table response to the surface topography of the site and surrounding area was beyond the scope of this project. However, field measurement of the base elevation of the ditch on the western (upgradient) side of Highway 101 (Figure 3) suggests that under wet-season conditions, the head response to the average-maximum discharge could bring the water table above the base of the ditch. The ditch elevation in the vicinity of well Skok-2 and the wetland staff gage lies between 14 to 23 feet AMSL. The model predicted water table elevation directly downgradient of Skok-2 under the stress condition is approximately 18 feet.
- As constructed, the numerical model cannot be used to examine the impact of recharge from an infiltration system centered on the western side of the site. Additional field borings and wells upgradient of Skok-1 would need to be completed to construct a model to examine this scenario. The sensitivity of the model predictions to the eastern limit of the K_2 zone suggests that additional investigation of the geometry of the contact between the recessional gravels and the underlying finer-grained material between Skok-1 and Skok-4 may be beneficial.

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Conclusions

Both analytical and numerical modeling methods were used to predict the mound geometry that may develop in the unconfined aquifer beneath a proposed rapid infiltration system. It was assumed that the infiltration capacity of the site vadose zone is not a limiting factor for the discharge of treated water. The mounding analyses were conducted assuming that the infiltration system would be located in the south-central area of the site near well Skok-4, away from any imported or disturbed material. A steady-state, average-maximum treatment plant discharge rate of 500,000 gal/day was used for the analyses, and wet-season initial conditions were assumed.

With these assumptions, the *analytical model* predicts that:

- The maximum head change expected beneath the infiltration area is less than ten feet after ten years under average-maximum discharge conditions, significantly less than the wet-season condition thickness of the vadose zone in the well Skok-4 area.
- Only a small additional water-table response to peak flow (700,000 gal/day) is predicted.
- A water-table mound could breach the site surface if the aquifer hydraulic conductivity is significantly reduced over time by plugging, or the infiltration system is centered over sediments with a conductivity significantly lower than that approximated adjacent to well Skok-4.

If the assumptions stated in the report reasonably reflect site conditions, the analytical predictions are upper-bound estimates.

The *numerical model* predicts that:

- Under the proposed average-maximum daily discharge conditions, the maximum head change predicted beneath an infiltration area centered near Skok-4 is less than six feet, indicating that the water-table mound is unlikely to reach the base of the infiltration system.
- The water table adjacent to and within the wetland could rise in response to artificial recharge.
- A comparison of the surface topography to the predicted head response to stress suggests that the water table could rise above the base of the ditch located west of Highway 101.

The predictions in this report only apply to the assumed conditions. Predictions are made on the basis of relatively limited field data that have been extrapolated over large areas.

Recommendations

The predictions presented in this report are only valid for the stated discharge rates. Any proposal to increase this rate should be accompanied by additional mounding analysis.

It is recommended that an additional investigative boring be considered in the area between wells Skok-1 and Skok-4 to confirm assumptions about the elevation of the upper surface of the finer-grained unit. Without further detailed investigation and analysis, it is recommended that the infiltration area be centered away from the far-western half of the site. On the basis of the data collected to date, the area in the vicinity of well Skok-4 is currently the most suitable infiltration area to minimize water-table mounding.

A pilot-scale field test is recommended prior to full system construction to minimize the uncertainties discussed in this report. Correspondingly, water levels should be closely monitored during the start-up phase of any infiltration system constructed at the site to confirm that the aquifer responds as predicted. These efforts should include monitoring water levels in areas predicted by this report to be at risk for a water table rise near or above the ground surface.

Appropriate operation and maintenance procedures should be implemented upon plant start up to minimize aquifer plugging over time, to ensure the aquifer transmissivity is not significantly diminished.

The consequences of a water-table rise adjacent to or within the wetland should be evaluated by a professional wetlands scientist.

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Appendix A

Analytical Solutions for
Maximum Mound Height –
Average-Maximum Flow Condition

APPENDIX A

```
Ver. 1.1                    MOUNDHT                    April 1994

Accurately computes the maximum height of a ground-water mound
 forming on an extensive and initially near-horizontal saturated
 zone beneath a rectangular recharge area.  Uses the method of
 Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234)
 (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

           Originally developed in 1992-93 by
               Professor E. John Finnemore
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               Tel: 408-554-4924,   Fax: 408-554-5474

           Assisted in programming by Jennifer Fong

Caution:  Such prediction methods need to be used with judgement by
          experienced engineers who are aware of their limitations.
                **  No guarantees are expressed or implied  **
```

Run 1

```
DATA ENTERED:

   Recharge area width,             W =   10.0    ft
   Recharge area length,            L =  250.0    ft
   Saturated depth of aquifer,      H =   19.0    ft (no mound)
   Specific yield of aquifer,      Sy =     .250
   Aquifer hydraulic conductivity, K =  350.000  ft/day
   Constant rate of recharge,       I =   27.0000 ft/day
   Input mound-growth time,       TYR =   10.00   years
   Name of file written               =  d:\MoundHT\Skok1

COMPUTED RESULTS:

Example of calculation accuracy:
```

NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	9.27450
2	1.4627519837	7.81175
3	-.0056543012	7.81741
4	-.0000000890	7.81741

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
10.0	7.817	4	.41144	1
.1	4.998	4	.26306	1
.2	5.443	4	.28650	1
.5	6.020	4	.31684	1
1.0	6.447	4	.33934	1
2.0	6.868	4	.36145	1
5.0	7.413	4	.39014	1
10.0	7.817	4	.41144	1
20.0	8.216	4	.43242	1
50.0	8.734	4	.45969	1
100.0	9.120	4	.47998	1

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims

Ver. 1.1 MOUNDHT April 1994

Accurately computes the maximum height of a ground-water mound forming on an extensive and initially near-horizontal saturated zone beneath a rectangular recharge area. Uses the method of Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234) (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

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Run 2

DATA ENTERED:

```
Recharge area width,            W =    5.0    ft
Recharge area length,           L =  250.0    ft
Saturated depth of aquifer,     H =   19.0    ft (no mound)
Specific yield of aquifer,     Sy =     .250
Aquifer hydraulic conductivity, K =  350.000  ft/day
Constant rate of recharge,      I =   54.0000 ft/day
Input mound-growth time,      TYR =   10.00   years
Name of file written              =  d:\MoundHT\Skok2
```

COMPUTED RESULTS:

Example of calculation accuracy:

NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	9.29956
2	1.4698997442	7.82966
3	-.0057173767	7.83537
4	-.0000000911	7.83537

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
10.0	7.835	4	.41239	1
.1	5.018	4	.26412	1
.2	5.463	4	.28754	1
.5	6.039	4	.31786	1
1.0	6.466	4	.34033	1
2.0	6.886	4	.36243	1
5.0	7.431	4	.39110	1
10.0	7.835	4	.41239	1
20.0	8.234	4	.43336	1
50.0	8.751	4	.46060	1
100.0	9.137	4	.48088	1

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims

Accurately computes the maximum height of a ground-water mound forming on an extensive and initially near-horizontal saturated zone beneath a rectangular recharge area. Uses the method of Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234) (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

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Run 3

DATA ENTERED:

Recharge area width,	W =	5.0	ft
Recharge area length,	L =	500.0	ft
Saturated depth of aquifer,	H =	19.0	ft (no mound)
Specific yield of aquifer,	Sy =	.250	
Aquifer hydraulic conductivity,	K =	350.000	ft/day
Constant rate of recharge,	I =	27.0000	ft/day
Input mound-growth time,	TYR =	10.00	years
Name of file written	=	d:\MoundHT\Skok3	

COMPUTED RESULTS:

Example of calculation accuracy:

NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	8.19243
2	1.1665472872	7.02588
3	-.0033644457	7.02925
4	-.0000000289	7.02925

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
10.0	7.029	4	.36996	1
.1	4.114	4	.21653	1
.2	4.575	4	.24081	1
.5	5.172	4	.27223	1
1.0	5.615	4	.29551	1
2.0	6.049	4	.31837	1
5.0	6.612	4	.34799	1
10.0	7.029	4	.36996	1
20.0	7.440	4	.39158	1
50.0	7.973	4	.41965	1
100.0	8.370	4	.44051	1

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims

Accurately computes the maximum height of a ground-water mound forming on an extensive and initially near-horizontal saturated zone beneath a rectangular recharge area. Uses the method of Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234) (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

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Run 4

DATA ENTERED:

Recharge area width,	W =	2.0	ft
Recharge area length,	L =	300.0	ft
Saturated depth of aquifer,	H =	19.0	ft (no mound)
Specific yield of aquifer,	Sy =	.250	
Aquifer hydraulic conductivity,	K =	350.000	ft/day
Constant rate of recharge,	I =	111.0000	ft/day
Input mound-growth time,	TYR =	10.00	years
Name of file written	=	d:\MoundHT\Skok4	

COMPUTED RESULTS:

Example of calculation accuracy:

NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	8.90155
2	1.3593030214	7.54225
3	-.0047893068	7.54704
4	-.0000000622	7.54704

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
10.0	7.547	4	.39721	1
.1	4.736	4	.24927	1
.2	5.180	4	.27264	1
.5	5.755	4	.30290	1
1.0	6.181	4	.32533	1
2.0	6.600	4	.34738	1
5.0	7.144	4	.37598	1
10.0	7.547	4	.39721	1
20.0	7.944	4	.41813	1
50.0	8.461	4	.44530	1
100.0	8.845	4	.46551	1

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims

Ver. 1.1 MOUNDHT April 1994

Accurately computes the maximum height of a ground-water mound forming on an extensive and initially near-horizontal saturated zone beneath a rectangular recharge area. Uses the method of Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234) (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

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Assisted in programming by Jennifer Fong

Caution: Such prediction methods need to be used with judgement by experienced engineers who are aware of their limitations.
** No guarantees are expressed or implied **

Run 5

DATA ENTERED:

Recharge area width,	W =	1.0	ft
Recharge area length,	L =	100.0	ft
Saturated depth of aquifer,	H =	19.0	ft (no mound)
Specific yield of aquifer,	Sy =	.250	
Aquifer hydraulic conductivity,	K =	350.000	ft/day
Constant rate of recharge,	I =	670.0000	ft/day
Input mound-growth time,	TYR =	10.00	years
Name of file written	=	d:\MoundHT\Skok5	

COMPUTED RESULTS:

Example of calculation accuracy:

NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	10.71246
2	1.8938582669	8.81861
3	-.0101286707	8.82873
4	-.0000003114	8.82873

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
10.0	8.829	4	.46467	1
.1	6.146	4	.32350	1
.2	6.568	4	.34571	1
.5	7.116	4	.37451	1
1.0	7.522	4	.39590	1
2.0	7.922	4	.41696	1
5.0	8.442	4	.44432	1
10.0	8.829	4	.46467	1
20.0	9.210	4	.48474	1
50.0	9.706	4	.51085	2
100.0	10.076	5	.53030	2

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims

Appendix B

Analytical Solution for Maximum Mound Height – Peak Flow Condition

APPENDIX B

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Ver. 1.1                    MOUNDHT                    April 1994

  Accurately computes the maximum height of a ground-water mound
  forming on an extensive and initially near-horizontal saturated
  zone beneath a rectangular recharge area.  Uses the method of
  Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234)
  (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

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Run 6

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 DATA ENTERED:

    Recharge area width,             W =    5.0    ft
    Recharge area length,            L =  250.0    ft
    Saturated depth of aquifer,      H =   19.0    ft (no mound)
    Specific yield of aquifer,      Sy =     .250
    Aquifer hydraulic conductivity, K =  350.000  ft/day
    Constant rate of recharge,       I =   75.0000 ft/day
    Input mound-growth time,       TYR =    3.00   years
    Name of file written               =  d:\MoundHT\Skok6

 COMPUTED RESULTS:

 Example of calculation accuracy:
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NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	11.56539
2	2.1181688396	9.44722
3	-.0125939470	9.45982
4	-.0000004820	9.45982

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
3.0	9.460	4	.49789	1
.1	6.739	4	.35468	1
.2	7.317	4	.38509	1
.5	8.061	4	.42427	1
1.0	8.611	4	.45320	1
2.0	9.150	4	.48156	1
5.0	9.846	4	.51820	2
10.0	10.361	5	.54533	2
20.0	10.868	5	.57199	2
50.0	11.524	5	.60652	2
100.0	12.011	5	.63216	2

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims

Appendix C

Analytical Solution for Maximum Mound Height – Low Permeability Condition

APPENDIX C

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Ver. 1.1                    MOUNDHT                    April 1994

  Accurately computes the maximum height of a ground-water mound
  forming on an extensive and initially near-horizontal saturated
  zone beneath a rectangular recharge area.  Uses the method of
  Hantush (Water Res. Research, vol. 3, no. 1, 1967, pp. 227-234)
  (see Ground Water journal, vol. __, no. _, 1994, pp. _______)

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Run 7

DATA ENTERED:

Recharge area width,	W =	5.0	ft
Recharge area length,	L =	250.0	ft
Saturated depth of aquifer,	H =	19.0	ft (no mound)
Specific yield of aquifer,	Sy =	.250	
Aquifer hydraulic conductivity,	K =	35.000	ft/day
Constant rate of recharge,	I =	54.0000	ft/day
Input mound-growth time,	TYR =	10.00	years
Name of file written	=	d:\MoundHT\Skok7	

COMPUTED RESULTS:

Example of calculation accuracy:

NO. OF N-R ITERATION	LAST HEIGHT CORRECTION (FT)	MAX MOUND HEIGHT (FT)
1	99.0000000000	74.39759
2	37.7568031376	36.64079
3	-2.6929784194	39.33377
4	-.0297588202	39.36353
5	-.0000033840	39.36353
6	.0000000000	39.36353

Mound height results:

YEARS	MAX MOUND HEIGHT (FT)	# N-R ITERS	Z/H	ACCURACY RANGE
10.0	39.364	6	2.07176	2
.1	24.954	5	1.31338	2
.2	27.425	5	1.44341	2
.5	30.496	5	1.60505	2
1.0	32.692	5	1.72063	2
2.0	34.793	5	1.83121	2
5.0	37.443	6	1.97070	2
10.0	39.364	6	2.07176	2
20.0	41.219	6	2.16942	2
50.0	43.583	6	2.29382	2
100.0	45.310	6	2.38474	2

Accuracy ranges:

RANGE	Z/H	SOURCE	ACCURACY
1	0 - 0.5	Rao & Sarma (1980)	To 2%
"	"	Hantush (1967b)	To 6%
2	0.5 - 3.3	Rao & Sarma (1980)	To 2%
3*	> 3.3	None	No claims