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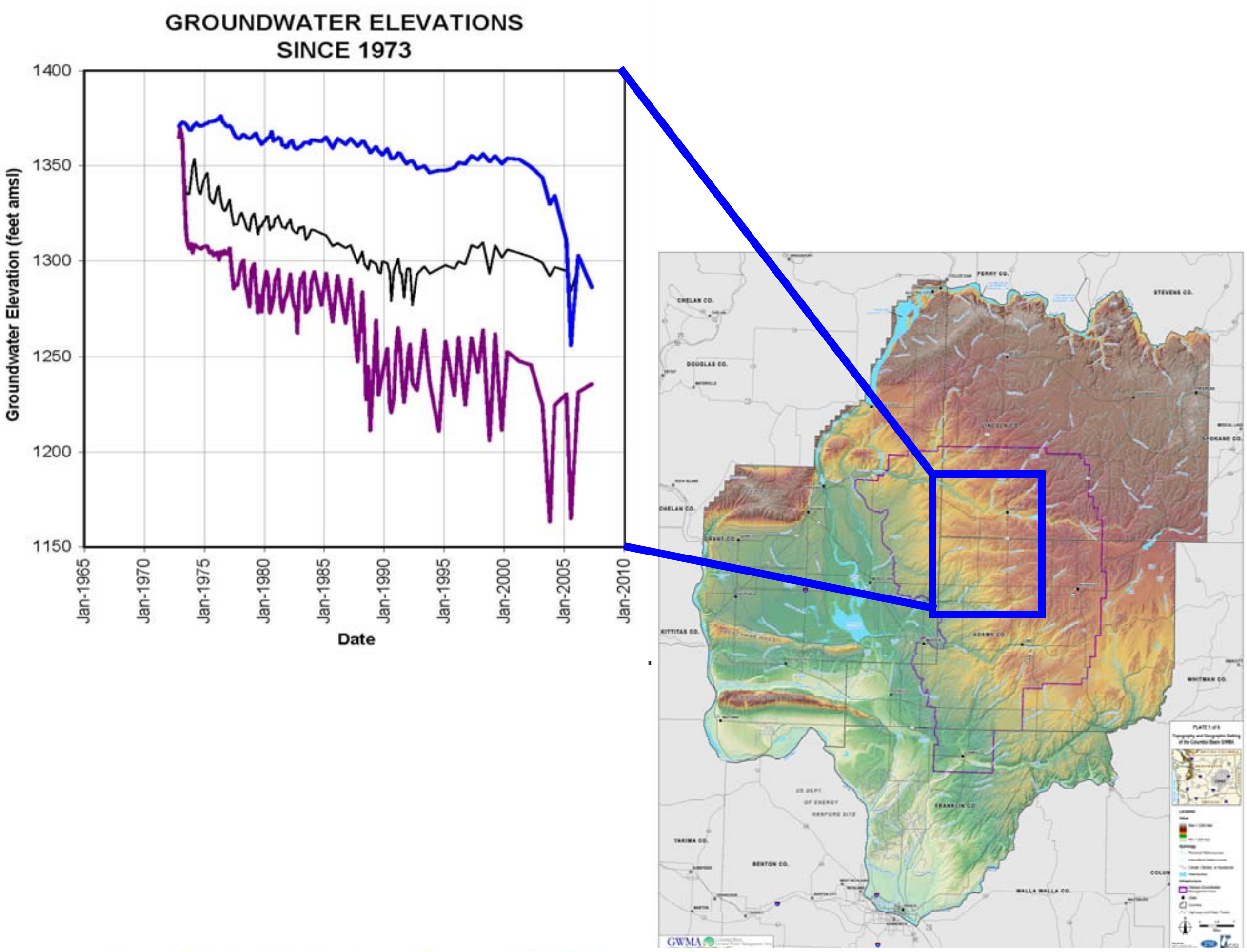
Groundwater Level Declines in the Columbia River Basalt Group and their Relationship to Mechanisms for Groundwater Recharge: A Conceptual Groundwater System Model

Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties June 2009



GWMA Columbia Basin Ground Water Management Area

OF ADAMS, FRANKLIN, GRANT AND LINCOLN COUNTIES

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GROUNDWATER LEVEL DECLINES IN THE COLUMBIA RIVER BASALT GROUP AND THEIR RELATIONSHIP TO MECHANISMS FOR GROUNDWATER RECHARGE: A CONCEPTUAL GROUNDWATER SYSTEM MODEL, COLUMBIA BASIN GROUND WATER MANAGEMENT AREA OF ADAMS, FRANKLIN, GRANT, AND LINCOLN COUNTIES

JUNE 2009

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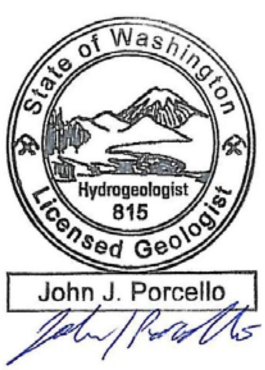

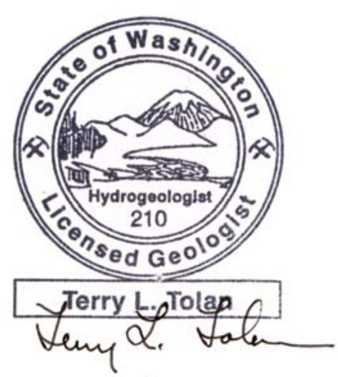

ACRONYMS AND ABBREVIATIONS

af	acre-feet
BWIP	Basalt Waste Isolation Project
CBIP	Columbia Basin Irrigation Project
Ca	calcium
cfs	cubic feet per second
Cl	chloride
CFCs	chlorofluorocarbons
CO2	carbon dioxide
CRBG	Columbia River Basalt Group
Ecology	Washington Department of Ecology
Fe	iron
GIS	Geographic Information System
gpm	gallons per minute
GWMA	Columbia Basin Ground Water Management Area
HCO3	bicarbonate
Ma	millions of years ago
mg/L	milligrams per liter
mi^2	square miles
Mg	magnesium
Na	sodium
NRC	National Research Council
pg	page
PCA	Principal Components Analysis
RASA	Regional Aquifer System Analysis
T, R	Township, Range
USDOE	U.S. Department of Energy
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WSB	Water Supply Bulletin

EXECUTIVE SUMMARY

The Columbia River Basalt Group (CRBG) hosts a regional aquifer system that is the primary, and in many cases the only, water supply for numerous communities, small water systems, individual homes, industry, and agriculture in east-central Washington. In this central portion of the semi-arid Columbia Plateau, primarily in Adams County and southern Lincoln County, the CRBG aquifer system has experienced significant water level declines and does not appear to receive significant, if any, natural recharge. The occurrence of groundwater declines within the CRBG aquifer system is a significant concern to water resources managers in the region.

The Columbia Basin Ground Water Management Area (GWMA) has conducted a Subsurface Geologic Mapping and Hydrogeologic Assessment project to complete subsurface geologic mapping in Lincoln County and develop a conceptual model of the groundwater flow system. The conceptual model evaluates several key aspects of the regional groundwater resources, including the potential for natural recharge to be occurring from the Lake Roosevelt Pool and from other nearby surface water bodies; the age of CRBG groundwater and the potential for modern recharge to be occurring naturally; and the degree of interconnection between the different parts of the CRBG aquifer system, both horizontally and vertically. The conceptual model is thus a working description of how water recharges the CRBG aquifers, how groundwater moves through these aquifers, and how groundwater discharges from these aquifers. While the focus of the conceptual model is on understanding conditions in the areas of the historically steepest water level declines (in the Odessa Groundwater Management Subarea), the conceptual model is a regional-scale framework for describing groundwater conditions in and beyond this area. The local and regional scales of the conceptual model provide a comprehensive analysis of the mechanisms and locations for groundwater recharge and discharge to be occurring under natural conditions, as well as providing a framework for evaluating future groundwater management strategies, such as artificial recharge.

This project and numerous previous studies have found that the CRBG aquifer system resides in sediments that lie on top of the CRBG basalt flows, and also in thin interflow zones that are situated between layers of dense, massive, low-permeability basalt flows. Within the CRBG, groundwater is present primarily in thin, discrete zones that are hydraulically separate from each other in most areas, except near recharge areas on the periphery of GWMA. Many such water-bearing interflow zones exist in the CRBG, but their compartmentalized nature results in little direct connection between individual zones. Connection occurs primarily where uncased (open-borehole) water supply wells artificially cross-connect multiple zones. This artificial cross-connection has been prevalent in Lincoln and Adams Counties for many years and has been noted by this project and previous studies to have resulted in passive downward drainage of groundwater from relatively shallow basalt zones to deeper zones over long periods of time. This phenomenon and the continuation of pumping and well deepening practices during the past 2 to 3 decades are the principal causes of the significant declines in groundwater yields and groundwater levels in these two counties.

The occurrence and movement of groundwater in the CRBG is governed by 1) its geologic features (lithology, folding, faulting, the areal extent of individual interflow zones [including lateral pinchouts], the presence of buried structures [granitic bedrock or vertical basalt dikes], and the presence of erosional features [coulees]); and 2) its exposure to surface water sources (lakes, rivers, streams, canals, irrigation). The recent subsurface geologic mapping conducted for this project shows that with the exception of areas along the Snake River in eastern Franklin County, the deep (Grande Ronde Basalt) aquifers have little exposure at the ground surface and thus receive very little recharge that flows into the interior of GWMA. This finding is consistent with the results of geochemical and age dating studies, which indicate that groundwater in the Grande Ronde Basalt is pre-Holocene in age (i.e., greater than 10,000 years old). Shallower water-bearing zones (in the Wanapum Basalt) receive some recharge from precipitation runoff in the floors of coulees; however, because of groundwater pumping and the prevalence of uncased boreholes that drain water into deeper zones, streamflows and groundwater elevations in the Wanapum Basalt have not recovered to pre-development conditions.

For both the shallow (Wanapum Basalt) and deep (Grande Ronde Basalt) aquifers, the recent subsurface geologic mapping work indicates that the Lake Roosevelt pool and other reaches of the Columbia River and the Spokane River do not recharge any of the basalt aquifers in GWMA. Additionally, subsurface inflow of groundwater into GWMA from adjoining areas appears to occur only along the Adams/Whitman county line. However, this inflow may be limited in magnitude, particularly in the Grande Ronde Basalt, as indicated by geologic evidence (the suspected presence of a buried dike system along the Cow Creek drainage, and buried structures in Whitman County and southern Spokane County) and geochemical analyses of groundwater samples. Consequently, the subsurface geologic mapping, the long-term record of groundwater elevation trends in GWMA, and the geochemical and age-dating studies together indicate that in Adams County and southern Lincoln County, the existing groundwater supplies in the Grande Ronde Basalt are ultimately not reliable or sustainable in the long-term under current water management programs. Deepening wells is only a temporary solution to mitigating declining groundwater levels and well yields; the recent increase in pumping from the Grande Ronde Basalt is tapping ancient sources of water that receive little if any recharge near groundwater pumping centers or at the margins of GWMA. While the long-term outlook for Grande Ronde Basalt water supplies in this portion of GWMA is not promising, restoration of historical groundwater supplies in the Wanapum Basalt via artificial recharge may be possible in this same area because of the prevalence of Wanapum Basalt exposures in coulee floors and the northern channeled scablands of northern Lincoln County.

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INTRODUCTION

The Columbia Basin Ground Water Management Area (GWMA) of Adams, Franklin, Grant, and Lincoln Counties encompasses approximately 8,300 square miles in south-central Washington (see Figure 1 and Plate 1). This report is one in a series of four reports prepared by GWMA in 2009 that presents the results of a comprehensive study of the portion of the Columbia Basin groundwater system underlying GWMA. The study, which is called the Subsurface Geologic Mapping and Hydrogeologic Assessment Project, was funded by the Washington State Legislature for the 2007-2009 biennium and builds on previous studies of the regional groundwater systems that lie in the four-county GWMA area. The Subsurface Geologic Mapping and Hydrogeologic Assessment Project was conducted for the purpose of developing a framework for understanding and describing groundwater occurrence and flow, groundwater quality, and the relationship between groundwater and surface water within GWMA. Specific objectives for the study were to: 1) refine and upgrade the GWMA geologic database and geographic information system (GIS), 2) complete the subsurface mapping project (primarily in Lincoln County), and 3) use the data from this study to test and refine one or more conceptual models of the groundwater flow system and the relationship between groundwater and surface water.

This and previous studies for GWMA have been conducted because of concerns about the continued decline of groundwater levels in the basalt aquifers that lie beneath portions of GWMA. In particular, GWMA stakeholders have recognized the need for study efforts that focus on identifying the aquifers contributing groundwater to production wells, the extent of those aquifers, and the recharge sources (if any) for these aquifers. Productive aquifers are found in the Columbia River Basalt Group (CRBG) in three formations (from youngest to oldest, the Saddle Mountains Basalt, Wanapum Basalt, and Grande Ronde Basalt), as well as in interstratified sediments (Ellensburg Formation) that are present in some areas. In the CRBG, productive aquifers are present in thin, discrete zones that are separated by thick sequences of dense, massive basalt rock that yields negligible amounts of water, if any.

The legislative directive that accompanied the 2007-2009 biennium funding requested that the study address the following issues:

1. The potential recharge, or lack of recharge, of the GWMA CRBG aquifers by the Lake Roosevelt pool
2. The potential for recharge of the GWMA CRBG aquifers by other surface water bodies found around the edge of the GWMA
3. The age of CRBG aquifer groundwater and the potential for modern recharge of the basalt aquifers
4. The degree of interconnection between the different parts of the CRBG aquifer system, both horizontally and vertically

5. A review of GWMA's conceptual model of how water recharges the CRBG aquifers, how groundwater moves through these aquifers, and how groundwater discharges from these aquifers

Understanding these questions, as we now do, provides GWMA stakeholders with a powerful tool box to use in monitoring the different portions of the groundwater system; devising strategies to mitigate against further groundwater level decline and the associated reductions in groundwater supplies; and building groundwater models which can be used to study the impacts of different actions, including artificial recharge.

The focus of this report is the Odessa Groundwater Management Subarea (herein referred to as the Odessa Subarea) and nearby areas to the north (Plate 1). This focused study area encompasses the portions of Lincoln, Adams, and Franklin counties that lie east of the East Low Canal, which conveys agricultural irrigation water from Lake Roosevelt to the Columbia Basin Irrigation Project (CBIP). Groundwater declines are largely concentrated in the Odessa Subarea because groundwater pumping is the sole source of water in this area; CBIP water is not available in the eastern portion of GWMA for irrigation use. This report focuses on describing the degree of horizontal and vertical interconnections between the various CRBG aquifers that are present in the Odessa Subarea, and the locations and relative significance of recharge sources to the various CRBG flows. The interpretations and findings on this subject have been derived in part from examining the temporal trends in water levels that have been measured during the past three to four decades in production wells and in non-pumping observation wells. However, the interpretations and findings in this report are also heavily derived from the subsurface geologic mapping work and the resulting improvements in the geologic conceptual model of GWMA that have also occurred under this study.

This report is the fourth in a series of reports documenting the Subsurface Geologic Mapping and Hydrogeologic Assessment Project. The four project reports are as follows:

- GWMA, 2009a, A summary of Columbia River Basalt Group geology and its influence on the hydrogeology of the Columbia River Basalt aquifer system, Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington: Consultant report prepared for Columbia Basin GWMA, prepared by GSI Water Solutions, Inc., June 2009.
- GWMA, 2009b, Geologic framework of selected sedimentary and Columbia River Basalt Group units in the Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington, Edition 3: Consultant report prepared for Columbia Basin GWMA, prepared by GSI Water Solutions, Inc., and the Franklin County Conservation District, June 2009.
- GWMA, 2009c, Groundwater geochemistry of the Columbia River Basalt Group aquifer system – Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington: Consultant report prepared for Columbia Basin GWMA, prepared by S.S. Papadopoulos and Associates, Inc., and GSI Water Solutions, Inc., June 2009.

- GWMA, 2009d, Groundwater level declines in the Columbia River Basalt Group and their relationship to mechanisms for groundwater recharge: A conceptual groundwater system model for the Columbia Basin Ground Water Management Area of Adams, Franklin, Grant, and Lincoln Counties, Washington: Consultant report prepared for Columbia Basin GWMA, prepared by GSI Water Solutions, Inc., June 2009.

The primary objective of this report (GWMA, 2009d) is to document new and previous geologic analyses and interpretations, groundwater level records, and geochemical analyses for the purpose of improving the understanding of groundwater occurrence and movement, groundwater recharge and discharge, and the degree and locations of hydraulic interconnection (particularly vertical connection) between the different groundwater-bearing zones that lie at multiple depths throughout the CRBG. A particular focus of this report is to describe the mechanisms by which recharge occurs to shallow and deep water-bearing zones alike, both currently and historically. A secondary objective of this report, and its companion reports (GWMA, 2009a, 2009b, 2009c), is to create an updated conceptual hydrogeologic model that 1) can provide insights as to the long-term reliability of groundwater supplies, particularly in the Odessa Subarea; and 2) facilitate future evaluations of various water management strategies, including artificial recharge projects.

To meet these objectives, the remainder of this report summarizes the nature of the current groundwater availability concerns, and then describes the historical studies of the aquifer system and the declining groundwater levels. The report then discusses the salient geologic features that have a direct controlling effect on the occurrence and movement of groundwater in the basalt aquifers, including discussions of how those features facilitate or impede groundwater recharge and groundwater movement. This understanding of the geologic system is then used to interpret the available water level and geochemical data, with an emphasis on identifying the nature and relative significance of current and historic recharge to the various basalt aquifers that are present beneath GWMA. The report concludes with a summary of the principal observations and conclusions from this evaluation, including interpretations about groundwater recharge that have been newly developed under the Subsurface Geologic Mapping and Hydrogeologic Assessment project. These descriptions thus constitute a conceptual model of the hydrogeology of the CRBG aquifer system. The conceptual model is largely descriptive and qualitative in nature and provides a working framework for future monitoring and management of the regional groundwater resource, including the formulation, analysis, and implementation of resources management strategies.

NATURE OF THE PROBLEM

Groundwater is an important source of water to meet agricultural, industrial, and municipal water demands in GWMA, and groundwater is the only source of water supply in the eastern portion of GWMA. The Subsurface Geologic Mapping and Hydrogeologic Assessment project was funded by the Legislature during the 2007-2009 biennium because of growing concerns by GWMA and local groundwater users about continued declines in groundwater levels in the Odessa Subarea and the corresponding implications of these declines for the long-term sustainability of deep aquifer production wells and groundwater supplies.

Little was written about the hydrogeology of the area encompassed by GWMA prior to 1968. A statewide study of the occurrence of flowing artesian wells noted the occurrence of two wells in eastern GWMA with discharges of 300 gallons per minute (gpm) or greater (Molenaar, 1961). The study identified a 300-gpm flowing artesian well in the southeastern corner of Adams County near the Palouse River and the mouth of Cow Creek (in Township 15N, Range 37E, Section 34C1 [T15N, R37E, 34C1], owned by the Oregon-Washington Railroad and Navigation Co., and measured in December 1949). The study identified a 570-gpm flowing artesian well about 5 to 6 miles north of the Town of Odessa in Lincoln County (T22N, R33E, Section 4F1, owned by L.J. Bonney and measured in September 1956).

The first publication from the scientific and regulatory community to comprehensively identify and discuss the occurrence of groundwater level declines in the eastern portion of GWMA was conducted by the state's former Department of Water Resources and was published as Washington Water Supply Bulletin (WSB) 31 (Garrett, 1968). As described in WSB-31, settlement began in the Odessa area in the 1880s, accompanied by the development of dry-land wheat farming. During the early 1960s, wheat growers found that markedly greater crop yields could be obtained by applying supplemental water through the use of sprinkler irrigation systems. In much of Lincoln and Adams Counties, landowners east of the Columbia Basin Irrigation Project (CBIP) service area turned to groundwater from the regional CRBG aquifer system for their source of irrigation water. WSB-31 noted that many of these early wells were being drilled to depths of 1,000 feet or more, though some wells also obtained large amounts of water from shallow alluvial deposits lying in the floors of local coulee systems. WSB-31 identified rapid rates of groundwater usage in the early 1960s, including a doubling of the annual groundwater pumping volume from 1963 to 1965 within this study area, which occupies southwest Lincoln County and northwest Adams County. This and surrounding areas were designated by the State of Washington as the Odessa Groundwater Management Subarea. Implementation rules for the Odessa Subarea were developed by the Washington Department of Ecology (Ecology) in 1973, in the form of Washington Administrative Code (WAC) Chapters 173-128A and 173-130A. In particular, WAC 173-30A specified that aquifers in the Odessa Subarea could not decline more than an average of 30 feet every 3 years before regulatory action would be taken.

Records maintained by Ecology show that the number of water wells drilled or deepened in an individual year increased gradually from the 1960s through the early 1970s, increased dramatically in the mid-1970s (when Ecology revoked a 1968 ban on groundwater withdrawals and started issuing new water right permits), and has also increased over time since the mid-1980s (Figure 2). In Lincoln County, the annual number of installations and deepenings for water supply wells (both small- and large-capacity) has increased each year since 1990.

The study by Garrett (1968) was the first of several studies by the former state DWR and by other agencies that documented the continuing lowering of regional groundwater levels east of the CBIP service area. Garrett measured as much as 20 feet of lowering during the one-year period from late 1964 through December 1965. He also noted that comparatively shallow domestic wells had seen water level declines of 1 to 2 feet at locations that were as much as several miles away from centers of heavy pumping by deep wells. The next study of the area (Luzier and Burt, 1974; WSB-33) noted that pumping in the Odessa Subarea increased from 16,000 acre-feet (af) in 1963 (from 85 wells) to about 74,000 af in 1968 (from 169 wells), with groundwater levels declining at rates of 2 feet per year to more than 10 feet per year between 1965 and 1968. Luzier and Burt (1974) predicted continued declines at rates of between 8 and 18 feet per year in the Odessa Subarea if annual pumping were to be maintained at 1967 rates. Later, a U.S. Geological Survey (USGS) study (Cline and Collins, 1992) noted that in 1984, 75 percent of the groundwater pumping in the State of Washington occurred in the four counties that today comprise the Columbia Basin GWMA. In addition to the historical record of increased pumping and continued lowering of groundwater levels, local landowners also have reported that streamflows began decreasing in certain drainages in northern Lincoln County (particularly Sinking Creek and Lake Creek) after regional groundwater development began for agricultural irrigation purposes (Wildrick, 1982; Wildrick, 1991).

PREVIOUS STUDIES OF GROUNDWATER LEVEL DECLINES AND CRBG HYDROGEOLOGY

A large number of hydrogeologic studies of the CRBG have been conducted over the past 50 years. Some studies have been regional in nature, covering large areas in Washington and Oregon where the CRBG is present. Others have been focused on conditions in local groundwater basins within the CRBG, such as the Quincy, Pasco, and Walla Walla Basins. Some studies have focused on gathering pumping and water level data, while others have focused on interpreting geologic and hydrologic data for the purpose of characterizing hydrogeologic conditions, including the occurrence of groundwater, the degree of vertical hydraulic interconnection between CRBG water-bearing zones, and the locations and magnitude of groundwater recharge and groundwater discharge from various water-bearing zones in the CRBG. This section surveys key literature references that have preceded, and been utilized during, the Subsurface Geologic Mapping and Hydrogeologic Assessment project.

The first regional-scale study of CRBG groundwater was performed by Newcomb (1959), who published his own observations on groundwater occurrence in the CRBG in Washington and Oregon. This publication examined several important aspects of CRBG hydrogeology, including descriptions of the presence and absence of groundwater in various zones; the mechanisms by which water moves in and between basalt flows; tectonic (structural) controls on groundwater occurrence, movement, and recharge; and the state of development and water quality at the time. His publication built on periodic local basin studies conducted during the prior 60 years, including studies by Russell in southeastern Washington (1897), Smith in Yakima County (1901), Calkins in east-central Washington (1905), Schwennesen and Meinzer in the Quincy Basin (1919), Newcomb in the Walla Walla River Basin (1951), Brown near Pilot Rock, Oregon (1955), Hart and Newcomb in the Tualatin Valley of Oregon (1956), and Hogenson in the Umatilla Basin of Oregon (1957). In his discussion of groundwater occurrence, Newcomb (1959) noted that groundwater is present in separate, compartmentalized zones in the CRBG, with little vertical connection between any two water-bearing zones that are separated by an individual basalt flow:

> "The completely massive lava flow and the flow whose center part is massive do not commonly allow water to pass across them readily in a vertical direction. These tight strata of massive rock commonly form tabular separation between the water-bearing zones. This type of separation of the water-bearing zones is demonstrated by the perched position of some of the groundwater in surficial deposits like the Palouse Formation, and by the "Layered" occurrence of seeps and springs in canyons or hillsides. Water can pass vertically through the cubically fractured "brickbat" type of flow; this is especially evident near the surface, in wells and excavations. Apparently the joints and other fractures, which are partly open in most flows at and near the surface, are at least partly closed deep underground.
>
> The water-bearing zones are commonly identified in wells as more easily drilled parts of the basalt sequence. Changes in the static water levels, as different aquifers are penetrated during the drilling of wells, are further evidence of the tabular separation of the permeable zones in the basalt." [pg 6]

Newcomb (1959) noted that changes in water levels of as much as 100 feet were being commonly observed when drilling over a depth interval of just a few feet. These changes occurred when drilling through the bottom of a massive basalt flow and into the underlying interflow zone. Newcomb noted that in some cases the water level rose, sometimes to artesian conditions. He concluded that the increases in the static water level indicated that the massive basalt flow interiors were acting as confining layers for groundwater in the underlying interflow zone. Newcomb stated that the occurrence of confining conditions is in part "an expression of the resistance to percolation" into a given water-bearing zone from overlying or underlying water-bearing zones.

In his 1959 publication, Newcomb also noted that long fracture zones transecting the basalt section could be acting as effective groundwater barriers because of slippage, shearing, and the resulting formation of clayey gouge along fault planes. Newcomb concluded that "the fundamental pattern of aquifers in the Columbia River basalt is that of separate tabular zones, each of which is interrupted in many places but nevertheless is of rather widespread lateral extent." [pg 7] Soon after this publication, the USGS published a more detailed study of the influence of subsurface structures on groundwater movement in basalt (Newcomb, 1961). This study noted that high-yielding basalt wells were being found in structurally down-warped portions of the CRBG, including at Walla Walla, Cold Creek, and Ephrata in central and eastern Washington. Newcomb (1961) observed that these wells were situated on the upgradient side of fault zones, and he concluded that the faults were acting as barriers and subsequently creating "reservoirs" of groundwater that were supporting groundwater pumping from high-yielding wells. While this study did not examine conditions within the Odessa Subarea, because of the lack of deep irrigation wells at the time, it was the first study to observe that geologic structures can influence groundwater occurrence significantly at both the local and regional scale.

Six years after publication of the first focused study of the Odessa Subarea (Garrett, 1968, WSB-31), two subsequent studies were conducted cooperatively by the State and the USGS to update the status of groundwater level conditions and further examine the hydrogeologic mechanisms controlling groundwater yields and water level trends in the region (Luzier et al., 1968, WSB-36; Luzier and Burt, 1974, WSB-33). Key topics and findings discussed in these studies, particularly in WSB-33, were as follows:

- The studies concluded that the major CRBG aquifers in east-central Washington, including in the Odessa-Lind area, are present in the interflow zones and that groundwater in these aquifers is normally confined by dense basalt of low permeability. The study authors also noted that the direction of groundwater movement (generally from the northeast to the southwest) coincides with, and is controlled by, the regional dip of the basalt flows.
- The study authors prepared groundwater contour maps for shallow and deeper basalt aquifer zones, from which they identified the presence of localized areas where the horizontal hydraulic gradient is steep, with flatter gradients immediately upgradient to the east (see Figures 3, 4, and 5). Referring to similar studies elsewhere in the CRBG by Newcomb (1961, 1969), Luzier and Burt (1974) concluded that buried, subsurface structural features likely exist at the location of the steep gradient, and that such structures, while not identifiable from drilling or borehole geophysical logs, are acting as “groundwater dams” that limit the amount of groundwater that can continue moving to the west, as reflected by marked changes in the hydraulic gradient over short distances. They estimated that a groundwater dam, or series of dams, was present along a northwest-southeast trending line just east of the East Low Canal. After mapping the amount of groundwater level declines and the amount of pumping in both the shallow and deeper zones throughout the Odessa-Lind area, Luzier and Burt (1974) found that the measured annual rate of water level decline in the deep zones from 1965 through 1969 closely coincided with the rate predicted from theoretical calculations that assume a groundwater dam is present just east of the canal.
- Luzier and Burt (1974) also noted that many anecdotal reports in the Odessa-Lind area, along with data from a number of borehole geophysical logs, showed the occurrence of downward cascading groundwater in wells that were open (uncased) through multiple basalt layers. Luzier and Burt (1974) concluded that while some natural connection may exist vertically between various aquifer zones in the CRBG, the amount of natural vertical connection is insignificant compared with the artificial vertical connection created by the presence of uncased boreholes. They referred to this artificial vertical connection as a “short circuit” between aquifer zones and also noted that downward drainage via uncased wells continues from shallow zones regardless of whether or not a well is actively

pumping at any given time. In their conclusions, Luzier and Burt (1974) stated that “the short-circuiting effect of deep wells is the rule rather than the exception” [pg 50]. Additionally, from an examination of hydrographs in wells constructed only in the shallow zones, Luzier and Burt (1974) observed that the large number of open boreholes and “short circuits” was causing steady declines in shallow zone groundwater levels, and that this could create “acute” problems for shallow domestic and stock wells, many of which they noted had already gone dry. Luzier and Burt (1974) also expressed concern about the potential for reduced streamflows; they noted that data from a stream gage on Crab Creek (at Irby) was suggesting that such depletion might have already begun at that time.

- Luzier and Burt (1974) also predicted that the continuation and expansion of pumping in the Odessa-Lind area would likely cause declines in groundwater levels nearby, including in the Canniwai Creek drainage and near the towns of Wilbur and Ritzville. They concluded that groundwater withdrawals in the Odessa-Lind area at that time were already outpacing the rate of natural recharge, and that the initially high yields of the basalt aquifers was fostering over-development and depletion of the regional CRBG groundwater resource in the area. Their report expressed concern that communities, irrigators, and industries were becoming committed to, and dependent on, the CRBG groundwater resource and would eventually feel the long-term effects of overpumping.

Brown (1978, 1979, and 1980) reviewed geophysical logs and water level data from a State network of observation wells and concluded that the CRBG groundwater flow system could be conceptualized as essentially a two-layer groundwater flow system, rather than several separate confined aquifer systems. Brown (1978) stated that along the southwest side of the Odessa-Lind area, he could not find evidence of the groundwater dams described by Luzier and Burt (1974) because he found it possible to correlate basalt flows on each side of the location where the dams were thought to be present (Brown, 1978, page 31). However, he acknowledged that there was good hydrologic evidence of the presence of the dams, despite the difficulty obtaining direct geologic evidence. Brown (1978) also stated that correlation of basalt flows over large areas was only possible in the deepest basalt flows, and not in shallower flows, which he concluded must have significant vertical hydraulic interconnection because of their discontinuous nature horizontally. He concluded that the controlling factors for groundwater occurrence and movement therefore “may not be wholly stratigraphic.” (Brown, 1980, page 17.) Yet he also stated that the study left no doubt that understanding basalt stratigraphy is necessary in order to understand basalt hydrology. In the third report, Brown (1980) called for further research, including packer tests, geochemical analysis, and age dating, to better understand the controlling factors. These research activities were later conducted in the Pasco Basin at the Hanford Site, as part of hydrogeologic characterization studies for the proposed Basalt Waste Isolation Project (BWIP) (Gephart et al., 1979; Myers and Price, 1979, 1981; Price, 1982; Graham et al., 1984; USDOE, 1988) as well as later research efforts at Hanford (Spane and Webber, 1995; Newcomer et al., 2002; Reidel et al., 2002). The findings of those studies are discussed below in the section of this report titled “Geologic Controls on Groundwater Occurrence and Movement”.

The next set of studies in the eastern half of GWMA was conducted by Ecology in the Sinking Creek watershed of northern Lincoln County, beginning in the early 1980s. The study, which initially produced four reports (Wildrick, 1982, 1985, 1990, and 1991), examined potential causes for decreased streamflows in Sinking Creek, focusing in particular on whether CRBG groundwater pumping was responsible for the decreases. After reviews by Ralston (1991a, b), Ecology conducted a more detailed study of possible pumping effects on spring flows feeding the creek (Covert, 1995). Together, these studies identified an apparent response of spring flows and spring water levels to local and regional-scale pumping from deep CRBG aquifer zones. One of the larger springs (Baring Spring) showed apparent flow variations in response to groundwater pumping with a lag of three to four days (Covert, 1995). This included recovery when pumping temporarily stops in the mid-summer during the first wheat harvest of the year, when little if any rainfall is occurring (Covert, 1995, page 10). However, despite this apparent response, long-term monitoring in the Sinking Creek watershed showed no further declines in groundwater levels in the uppermost basalt even though declines continued over time in deeper basalt zones (Wildrick, 1990; Ralston, 1991a). Additionally, Ralston (1991b) expressed a belief that wells distant from this area (for example, near the Town of Wilbur) could potentially be contributing as much to the changes in water levels and spring flows in the Sinking Creek area as the wells close to Sinking Creek.

Cline (1984) conducted an update of pumping volumes and groundwater level declines through 1981. This study evaluated an area roughly four times larger than the area studied by Luzier et al. (1968). Cline concluded that the lack of complete water level recovery in many areas after the irrigation season was an indication that pumping was already exceeding the amount of recharge occurring to the CRBG basalt aquifers. He noted that groundwater levels were declining at a faster rate during the period 1977-1978 than 10 years earlier. He also noted that in some locations, groundwater that had once been in the uppermost aquifers had drained away, as evidenced by the drying up of domestic and stock wells that tapped only these aquifers. While Cline’s analysis was largely focused on quantifying trends in groundwater levels and groundwater pumping volumes, he made two observations that are relevant to understanding the degree of vertical interconnection between different water-bearing zones in the CRBG:

- Cline pointed out a particularly striking example of how deepening a production well can cause a significant change in its static water level as it is penetrated into deeper water-bearing zones in the CRBG. His example was a well in eastern Grant County (T21N, R30E, 3E1) that was deepened from a depth of 451 feet to a depth of 651 feet in 1965, and which subsequently experienced an instantaneous decline in the static water level of approximately 150 feet (see Figure 6).
- Cline also studied the water level data from the installation of nested observation wells installed by the State and the USGS.
    - For the Odessa observation well (T20N, R33E, 16E1-E6), the static water level was at a depth of about 140 feet in the open borehole prior to construction of each individual piezometer. This water level was the

composite of the various water levels from each contributing water-bearing zone over the 750-foot thickness of the open hole. Cline noted that once the five individual piezometers were constructed, the water levels in four of the piezometers were markedly different, while the water level in the fifth piezometer appeared to be similar to that of the open borehole (see Figure 7).

  - At the Basalt Explorer observation well, Cline noted that the piezometers initially showed static water levels that were similar to the water level previously observed in the open borehole. He attributed this similarity to a lack of nearby pumping from each zone being monitored. However, as shown in Figure 8, a steady decline in the borehole water level was observed for 8 years prior to installation of the piezometer network, and this trend continued during the early to mid 1970s in one of the three piezometers, but not in the other two.

From 1982 through the 1990s, under its Regional Aquifer-System Analyses (RASA) program, the USGS estimated groundwater recharge rates and conducted modeling work and other studies to understand the hydrology and water budget for the Columbia Plateau (Bauer and Vaccaro, 1990; Hansen et al., 1994; Vaccaro, 1999; Bauer and Hansen, 2000).

- One of the first publications containing a water budget analysis under this study was by Bauer and Vaccaro (1990), who estimated the average annual groundwater recharge rates for each of 53 subareas within the Columbia Plateau using a deep-percolation computer model. This model estimated deep percolation (groundwater recharge) rates under predevelopment and current land-use conditions. In Lincoln and Adams Counties, their analysis of five separate areas indicated that average annual recharge in eastern GWMA is less than 2 inches and could be as low as 0.13 inches under undeveloped conditions. The study concluded that irrigation had increased deep percolation by 1.1 to 1.6 inches in two areas and may have slightly decreased deep percolation in the other three areas (by 0.06 to 0.33 inches).
- Hansen et al. (1994), Vaccaro (1999), and Bauer and Hansen (2000) presented the final RASA project findings of regional hydrologic conditions in the Columbia Plateau, including the results of numerical model simulations of pre-development conditions and conditions that might occur if the pumping pattern from 1983 through 1985 were to continue into the foreseeable future, with and without expansion of the CBIP. Of particular relevance to the current study of the hydrogeologic system in GWMA were the following observations and conclusions presented in these two reports:
  - Bauer and Hansen (2000) estimated that recharge on non-irrigated lands is zero in low-elevation portions of the Columbia Plateau that receive less than 8 inches of precipitation annually. On irrigated lands, Bauer and Hansen (2000) estimated that annual irrigation recharge to groundwater during the mid-1980s was on the order of 10 inches per year in areas

irrigated with surface water, and 1.5 to 2 inches per year in areas irrigated with groundwater. This difference is likely attributable to the different irrigation practices in use at that time (flood irrigation within the CBIP service area and center-pivot irrigation elsewhere in the groundwater-dependent areas). Much of the CBIP service area has since switched to pivot irrigation, which means current recharge rates are likely lower at this time than at the time of the RASA study.

- The RASA study concluded that the upper portion of the Grande Ronde Basalt is present beneath the Spokane River at the Lincoln/Spokane county line. However, the study noted the occurrence of a groundwater divide south of the river and concluded that any groundwater in the Grande Ronde Basalt just south of the river was moving northwards to the river, rather than moving south from the river into GWMA (Lane and Whiteman, 1989; Bauer and Hansen, 2000).
- The model simulated that as of 1985, the effect of groundwater development (compared with pre-development conditions) had been to decrease groundwater discharges to upper Crab Creek by about 38 cubic feet per second (cfs) while almost doubling the amount of groundwater discharge to lower Crab Creek (from 76 cfs under pre-development conditions to 145 cfs in 1985; Bauer and Hansen, 2000).
- For two of the three CRBG formations (Saddle Mountains Basalt and Wanapum Basalt), the USGS designed the model by lumping all of the individual flows and members of a given CRBG formation into a single hydrostratigraphic unit for simulation purposes. For the deepest CRBG formation (the Grande Ronde Basalt), the model used a similar lumping process, but simulated the Grande Ronde as two systems (shallow and deep). While this “lumping” approach was helpful for simplifying the natural system in a manner that made computer simulations feasible, given the computing power available at that time (the mid-1990s), it resulted in a model design that simulated uniform geologic conditions and hydraulic properties through the full thickness of an individual formation (hundreds, or even a few thousands, of feet) at any given location. As a result, the entire thickness of the CRBG, which is estimated to be as much as 2 miles in southwestern GWMA, was represented with only four model layers, even though it is comprised of more than 300 distinct basalt flows and interflow zones (Tolan et al., 1989).
- The model simulated moderate to significant vertical interconnection between CRBG formations, including an inherent assumption that deeper portions of the CRBG are discharging groundwater to the Columbia River at the center of the basin, where the CRBG is thickest. However, this assumption contradicts the findings of studies conducted at the Hanford Site (USDOE, 1988), which suggest that any such upwards movement of groundwater must be occurring very slowly, as discussed later in this report.

- Over the entire simulation area, the model estimated that the volume of water moving vertically into and out of the upper Grande Ronde Basalt is equivalent to 62 percent of the total recharge to this formation. In the Wanapum Basalt, the model estimated that the total water volume moving vertically to or from adjoining formations is equivalent to 126 percent of its total recharge.
- The use of thick model layers and the assumed strong interconnection to surface water discharge zones (particularly the Columbia River) appeared to cause difficulties calibrating the model. During the process of calibrating the vertical connection between individual basalt layers and between the basalt and surface water bodies, the authors reported considerable difficulty in obtaining reasonable estimates for this connection while also retaining the ability to reproduce field-measured vertical gradients and groundwater elevations (Bauer and Hansen, 2000).
- Another apparent cause of model calibration difficulties was the use of a time-averaged (or "steady-state") approach to running the groundwater model. This approach assumes that groundwater discharge is balanced by groundwater recharge throughout the entire simulation area and in all model layers. While the authors ran the model in a manner that sought to recognize the observed changes in groundwater storage during their calibration period (spring 1983 to spring 1985), they nevertheless encountered calibration difficulties in the Odessa Subarea. In particular, the initial model runs estimated that some portions of the Wanapum Basalt that were still under development were supposedly dewatered by the early 1980s. To correct this problem, the authors concluded that it was necessary to increase the amount of recharge to the Wanapum Basalt beyond the initial estimates reported by Bauer and Vaccaro (1990). Bauer and Hansen (2000) attributed this increased recharge volume to the surface water that is present at times in the coulees crossing this area. However, it is possible that the model's assumption of equal groundwater recharge and discharge rates, which is an inherent assumption in any steady-state model run, was creating an artificial need for more simulated recharge to balance out the simulated pumping rates and storage changes, which were based on historical pumping and water level records.
- Among its many uses, the model was used to estimate the amount of further water level decline that might occur in the Wanapum Basalt under the continuation of the water management practices occurring in 1985, with no expansion of the CBIP. The model estimated that the Wanapum Basalt would become dewatered in localized areas in southern Lincoln County and western Adams County. The model also predicted that large areas in the Columbia Plateau, including some areas in eastern GWMA, would see no more than 10 feet of additional water level decline. Like the model calibration runs, this simulation assumed that the CRBG groundwater system would eventually reach a steady-state condition, in which total groundwater discharge within the model area is the same

> magnitude as groundwater recharge. This simulation therefore assumed that sufficient groundwater recharge would occur on a regional scale to eventually balance the 1983-1985 volume and spatial distribution of pumping, even if this pumping were to continue indefinitely into the future.

In summary, the earliest historical studies of the hydrogeologic system in GWMA and surrounding areas concluded that the CRBG groundwater system is significantly compartmentalized, except where wells artificially cross-connect two or more water-bearing interflow zones. This early view of the hydrogeologic system was derived primarily from inspections of geologic logs and construction diagrams for production wells, and from water level data collected in the 1970s during and immediately after construction of multi-level piezometers for the State observation well network. More recently, numerical models of groundwater recharge and groundwater flow have been developed. These tools have been regional and sub-regional in scale and subsequently have "lumped" many individual CRBG flows into single layers for the purposes of simulating horizontal and vertical groundwater flow in the CRBG, as well as the connection of the CRBG to surface water. This more recent approach to representing the CRBG groundwater system is at odds with the findings from most early studies, as well as local knowledge regarding well and aquifer system responses to well deepenings and continued pumping from the CRBG, particularly in the eastern portion of GWMA. The nature of the vertical interconnection and lateral controls on groundwater occurrence and movement are fundamental to the description and management of CRBG groundwater, especially in the context of understanding its connection to surface water and the mechanisms by which artificial recharge projects could conceivably be conducted in the future. While the purpose of this report is to present and discuss the available water level data in GWMA, and in particular the Odessa Subarea, as well as the interpretations about groundwater conditions that can be derived from those data, such discussions first require a fundamental review of the current scientific understanding of the types of geologic features that control groundwater occurrence and movement, including groundwater recharge and discharge. This topic is discussed in the next section of this report.

GEOLOGIC CONTROLS ON GROUNDWATER OCCURRENCE AND MOVEMENT

As discussed previously, the Subsurface Geologic Mapping and Hydrogeologic Assessment project, of which this report is a part, has been funded by the Legislature for the purpose of describing the dynamic relationship between groundwater and surface water inside GWMA. Evaluating groundwater level trends and connection between aquifers is a key component of this study, and includes significant reliance on the newly-acquired subsurface geologic mapping conducted in Lincoln County under this project. Details regarding the subsurface geologic mapping work conducted under the current study are contained in the companion documents to this report that present the geologic framework within GWMA (GWMA, 2009a, 2009b). The geologic framework has been developed by combining new subsurface mapping work, conducted under the Subsurface

Geologic Mapping and Hydrogeologic Assessment project, with the findings and interpretations of CRBG hydrogeology that have been published in numerous prior studies of CRBG aquifers throughout the Columbia Basin. Prior geologic studies, together with the updated mapping work, provide an understanding of the hydraulic characteristics of the CRBG and allow for development of a geologically-based descriptive model of how various factors (e.g., CRBG flow physical characteristics and properties, tectonic features and properties, erosional features, well construction and pumping influences, etc.) interact to create and govern the basalt groundwater systems. Significant prior geologic studies include, but are not limited to, Hogenson, 1964; Newcomb, 1961, 1969; Brown, 1978, 1979; Gephart et al., 1979; Oberlander and Miller, 1981; Livesay, 1986; Drost and Whiteman, 1986; Lite and Grondin, 1988; Davies-Smith et al., 1988; USDOE, 1988; Burt, 1989; Reidel and Hooper, eds., 1989; Johnson et al., 1993; Hansen et al., 1994; Waitt et al., 1994; Whiteman et al., 1994; Spane and Webber, 1995; Wozniak, 1995; Steinkampf and Hearn, 1996; Packard et al., 1996; and Sabol and Downey, 1997; Reidel, 1998; Vaccaro, 1999; Bauer and Hansen, 2000; Reidel et al., 2002; and Reidel, 2005. One of the overall significant findings that has come out of these studies is the general similarity of the hydrogeologic characteristics, properties, and behavior of the CRBG aquifers across this region. Therefore, much of the general knowledge that has been learned about the characteristics and behavior of the CRBG aquifers is readily applicable to CRBG aquifers throughout the Columbia Plateau.

Of particular importance is the role of geologic features on controlling where CRBG groundwater is present, how it moves, and where it receives recharge. Following are discussions of 1) the general reasons that characterizing geologic controls are important in any aquifer system; 2) CRBG and sediment stratigraphy; 3) the hydraulic characteristics of the CRBG's intraflow structures (the massive basalt rock material separating the discrete water-bearing zones), including the role of secondary controls (faults, folding, jointing, and secondary alteration and mineralization); 4) the role of larger-scale geologic features (stratigraphic, structural, and erosional controls) on groundwater flow; and 5) the role of water well construction on CRBG groundwater movement and occurrence.

Importance of Geologic Controls on Understanding Groundwater Occurrence

Geologic deposits that yield groundwater are called aquifers. The low- to non-yielding deposits that separate an aquifer from overlying or underlying aquifers are called aquitards, a term that reflects the limited occurrence and movement (if any) of groundwater between aquifers. In the CRBG, developing an understanding of the occurrence of groundwater and the influence of geologic controls on its horizontal and vertical movement is critical to understanding the causes of, and potential remedies for, the groundwater level declines that have been historically observed. Freeze and Cherry (1979) state the importance of developing a concise and comprehensive understanding of the geologic controls on groundwater as follows:

> “The nature and distribution of aquifers and aquitards in a geologic system are controlled by the lithology, stratigraphy, and structure of the geologic deposits and formations. … In most regions knowledge of the lithology, stratigraphy, and structure leads directly to an understanding of the distribution of aquifers and aquitards.” [p. 145]

The importance of sufficiently characterizing geology to understand a groundwater resource has been recognized as a core principle in the hydrogeologic profession for over a century. More recently, this principle has also been discussed in professional literature that focuses on the use of applied mathematics to develop numerical models of water, solute, and heat movement in the unsaturated zone and in groundwater. In a publication discussing the scientific and regulatory applications of groundwater models, the National Research Council (NRC, 1990) stated that one governing principal that should apply to the development of any groundwater model is that an evaluation first be conducted of the importance of vertical effects on the groundwater flow system, as arise from “geological stratification, density differences, buried sources, and so on.” The NRC (1990) went on to note that vertical homogeneity should not be assumed without obtaining supporting evidence to document such a condition. Shortly thereafter, in one of the earliest comprehensive textbooks to be published on the groundwater modeling practice and its processes, Anderson and Woessner (1992) noted that it is critical for a groundwater model, and its underlying conceptual model, to be a valid representation of the important hydrogeological conditions governing groundwater occurrence and movement. In particular, Anderson and Woessner (1992) noted that the hydrostratigraphic definition of aquifers and confining beds is a key component of developing a conceptual model:

> “It is critical that the conceptual model be a valid representation of the important hydrogeologic conditions; failure of numerical models to make accurate predictions can often be attributed to errors in the conceptual model.” [p. 28]

Spitz and Moreno (1996) articulated this further by noting that the quality of a numerical groundwater model usually is governed by the physics of the groundwater system, and that this must be understood in order to construct and calibrate a numerical model. They noted that the “gigo” rule (“garbage in, garbage out”) applies to groundwater modeling, and that one of the most important steps in model development is highly dependent on the quality of the conceptual model:

> “Calibration and validation will become meaningless, fail, or yield inadequate results if significant features of the natural system are excluded from the model.” [pp. 21-22]

These principles pertain to the general practices of hydrogeologic characterization and system modeling and apply to all groundwater systems, whether the geologic setting is simple or complex. These principles, therefore, have particular importance in complex and unique geologic settings such as the Columbia Plateau, where groundwater 1) is quite stratified in its occurrence and 2) is particularly challenging to study because most data are obtained from large-capacity production wells that are open to multiple aquifers which have little natural connection vertically. Because of the unique geology of the CRBG, developing a concise understanding of the regional aquifer systems inside GWMA requires careful consideration of available geologic data and interpretations. A concise geologic framework is necessary to interpret short-term and long-term water level and pumping trends in the various CRBG basalt aquifers because these trends are influenced by both the geology and the proliferation of open boreholes (wells) that obtain water from multiple aquifer zones.

Overview of CRBG and Sediment Stratigraphy

The pioneering studies that developed a basic stratigraphic framework for the CRBG that could be correlated and mapped over geographically large areas were conducted by Waters (1961), Mackin (1955, 1961), Wright et al. (1973), and Grolier and Bingham (1971, 1978). Ensuing studies of the CRBG, employing traditional mapping methods coupled with geochemistry and paleomagnetic polarity "tools", demonstrated that mappable units could be uniquely defined throughout the region where the CRBG is present in Washington, Oregon, and Idaho (Swanson et al., 1979a, 1979b, 1980, 1981; Beeson and Moran, 1979). The impetus (and funding) for most CRBG research efforts from the late 1970's to 1988 was the U.S. Department of Energy's (USDOE's) Basalt Waste Isolation Project (BWIP) which examined the suitability of constructing a deep, mined, repository for the final disposal of high-level nuclear waste in the CRBG beneath the Hanford Site in south-central Washington.

A tremendous amount of data and information was produced by BWIP, and its cooperative research partners, on a diverse range of CRBG geology and hydrogeology topics. Results from the BWIP investigations are summarized in the first three volumes of Site Characterization Plan (USDOE, 1988). The Geological Society of America Special Paper 239 (Reidel and Hooper, eds., 1989) presents a comprehensive summary of the results of this period of cooperative research into the regional stratigraphic framework and tectonics of the Columbia River flood basalt province. In the post-BWIP era, much of the efforts in CRBG research has been directed into investigating the emplacement process and history of these huge flood basalt flows (e.g., Reidel and Tolan, 1992; Reidel et al., 1994; Ho and Cashman, 1997; Self et al., 1996, 1997; Reidel, 1998), refining the stratigraphy of the CRBG, and understanding the hydrogeology of the CRBG (e.g., Reidel, 2005; GWMA, 2007, 2009a, 2009b).

CRBG Unit Definitions and Lithology

Collectively the CRBG consists of a thick sequence of more than 300 continental tholeiitic flood basalt flows that cover an area of more than 59,000 square miles (mi^2) in Washington, Oregon, and western Idaho (Tolan et al., 1989). The maximum thickness is estimated to be over 2 miles, occurring in the Pasco Basin area, based on geophysical and deep hydrocarbon exploration well data (Reidel et al., 1982, 1989a, 1989b). As shown by the timeline in Figure 9, CRBG flows were erupted during a period from about 17 to 6 million years ago (Ma) from long (10 to 50 kilometers or more), north-northwest-trending linear fissure systems located in eastern Washington, northeastern Oregon, and western Idaho. Although CRBG eruptive activity spanned an 11 million year period, most (greater than 96 percent by volume) of the CRBG flows were emplaced over a 2.5 million year period from 17 to 14.5 Ma (Swanson et al., 1979a; Tolan et al., 1989).

During CRBG volcanism, most of the flows emplaced were of extraordinary size, commonly exceeding 250 to more than 400 cubic miles in volume, traveled many hundreds of miles from their linear vent systems, and covered many thousands of square miles (Tolan et al., 1989; Reidel et al., 1989b). These gigantic CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history. Figure 10 presents a same-scale comparison between a CRBG flow, the Laki (Skaftar Fires) flow field (the largest basalt eruption in recorded human history; Thordarson and Self, 1993) and the ongoing Pu'u O'o eruption on the Big Island of Hawaii. CRBG flows represent the largest individual lava flows know on the earth (Tolan et al., 1989).

The CRBG has been divided into a host of regionally mappable units (Figure 11) based on variations in physical, chemical, and paleomagnetic properties - in regard to stratigraphic position - that exist between flows and packets of flows (Swanson et al., 1979a; Beeson et al., 1985; Reidel et al., 1989b; Bailey, 1989). The CRBG underlying the Columbia Basin region have been divided into four formations. These formations are, from youngest to oldest, the Saddle Mountains Basalt, Wanapum Basalt, Grande Ronde Basalt, and Imnaha Basalt (Swanson et al., 1979a, 1979b). These formations have been further subdivided into members defined, as are the formations, on the basis of a combination of unique physical, geochemical, and paleomagnetic characteristics. These members can be, and often are, further subdivided into individual basalt flows (e.g., Beeson et al., 1985; Reidel, 2005).

Vertical exposures reveal that CRBG flows all generally exhibit the same basic three-part internal arrangement of intraflow structures (Figure 12). These features originated either during the emplacement of the flow or during the cooling and solidification of the lava after it ceased flowing. These features can be generally divided into flow top, flow interior, and flow bottom. The combination of a flow top of one flow and the flow bottom of the overlying flow is commonly referred to as an “interflow zone”.

- The ***flow top*** is the crust that formed on the top of a molten lava flow. Flow tops commonly consist of glassy to very fine-grained basalt that is riddled with countless spherical and elongate vesicles. Vesicles represent gas bubbles that were trapped (frozen) as the flow solidified. These gasses were originally dissolved within the magma, but reduction in pressure (and subsequent decrease in temperature) as the magma reached the surface allowed these gasses to come out of solution. CRBG flow tops can display a wide range of variation in both their physical character and thickness (USDOE, 1988). The physical character of flow tops falls between two basic end-members, a simple vesicular flow top and a flow top breccia.

- A simple ***vesicular flow top*** commonly consists of glassy to fine-grained basalt that displays a rapid upward increase in vesicle density near the top of the flow (USDOE, 1988; McMillan et al., 1989). Vesicles may be isolated or interconnected, resulting respectively in lower and higher permeability and effective porosity (USDOE, 1988). Tensional cooling joints, related to flow top formation/flow emplacement, can augment the overall permeability of this feature.
- A ***flow top breccia*** consists of angular, scoriaceous to vesicular fragments of basaltic rubble that lies above a zone of non-fragmented, vesicular to vuggy basalt. Flow top breccias can be very thick (over half the flow thickness - more than 100 feet thick) and laterally extensive (USDOE, 1988). Laterally extensive flow top breccias are relatively common features within the CRBG.

- CRBG ***flow interiors*** typically consist of dense, non-vesicular, glassy to crystalline basalt that contains numerous contraction joints (termed "cooling joints") that formed when the lava solidified. CRBG cooling joints most often form regular patterns or styles, with the two most common being entablature-colonnade and columnar-blocky jointing.
  - Columnar-blocky jointing typically consists of mostly vertical-oriented, poorly to well-formed, polygonal columns that can range from 2 feet to greater than 10 feet in diameter. The vertical columns are often cut by horizontal to subhorizontal cooling joints.
  - Entablature-colonnade jointing displays a more complex pattern that forms within a single flow. The entablature portion displays a pattern of numerous, irregular jointed small columns to randomly oriented cooling joints that abruptly overlie a thinner zone displaying well-developed columnar jointing. The transition zone between the entablature and the basal colonnade may be very narrow, generally less than an inch in width. Typically the entablature is thicker than the basal colonnade, often comprising at least two-thirds of the total flow thickness.
- CRBG ***flow bottoms*** have a variety of physical characteristics that largely depend on the environmental conditions the molten lava encountered as it was emplaced (Mackin, 1961; Swanson and Wright, 1978, 1981; USDOE, 1988; Beeson et al., 1989; Reidel et al., 1994; Beeson and Tolan, 1996). If the advancing CRBG lava encountered relatively dry ground conditions, the flow bottom that results typically consists of a narrow (less than 3 feet thick) zone of sparsely vesicular, glassy to very fine-grained basalt. This type of flow bottom structure is very common within the CRBG. However, if advancing lava encountered lakes, rivers, and/or areas of water-saturated, unconsolidated sediments, far more complex flow bottom structures formed (Mackin, 1961; Schmincke, 1967; Bentley, 1977; Byerly and Swanson, 1978; Grolier and Bingham, 1978; Swanson et al., 1979a; Swanson and Wright, 1978, 1981; Bentley et al., 1980; Camp, 1981; Beeson et al., 1979, 1989; Stoffel, 1984; Tolan and Beeson, 1984; Ross, 1989;

Pfaff and Beeson, 1989; Reidel et al., 1994; Beeson and Tolan, 1996). Specifically:

- Where advancing lava encountered standing water, a ***pillow lava complex*** would be created as the lava flowed into the lake. A pillow complex consists of elongate to spherical lobes of basalt (pillows) set in a matrix of glassy basalt fragments (hyaloclastite). The pillows represent subaqueous pahoehoe flow lobes that advanced down the front of the pillow lava delta.
- Where flowing lava rapidly crossed wet sediments, the trapped water within the sediments could be explosively converted to steam, creating ***spiracles***. This type of flow bottom structure is rare, and is an irregular, cylindrical feature that is partially filled with glassy, angular debris (hyaloclastite/breccia). Spiracles can range from 3 feet to more than 50 feet in diameter and can extend upward through CRBG flows for distances of 3 feet to more than 100 feet. Spiracles commonly terminate within the flow, but in rare cases they can pass entirely through the flow. Compared with pillows complexes, which form where there is a high ratio of water to lava, spiracles form where that ratio is much lower.
- A basalt/sediment mixture called a ***peperite*** is present in some locations. This last type of flow bottom structure involves lava/sediment interaction which created a wide range and scale of invasive features. Tongues and lobes of lava emanating from the base of advancing CRBG flows occasionally burrowed into poorly consolidated sediments due to inherent density differences. Where this invading lava encountered water-saturated sediments, phreatic brecciation sometimes occurred, creating the peperite. CRBG flows are known to not only have invaded sediments, but to have been capable of lifting and rafting sediment blocks many miles (Byerly and Swanson, 1978; Swanson and Wright, 1978; Beeson et al., 1979, 1989; Stoffel, 1984; USDOE, 1988; Ross, 1989).

Miocene-Late Pliocene Sediments (Sedimentary Interbeds and Suprabasalt Sediments)

Late Neogene sediments in the Columbia Basin and surrounding region are interfingered with, and overlie the CRBG. The stratigraphic relationships of these sediments with the CRBG provides a natural, mappable subdivision between (1) those sediments intercalated with the CRBG (sedimentary interbeds) and (2) those that overlie the CRBG (suprabasalt sediments). These sediments are present in the Pasco Basin and in the western portion of GWMA (in central and western Grant County), but are generally absent in the eastern portion of GWMA (GWMA, 2007). While not the focus of this paper, a summary of these sediments is presented here. For a more complete discussion of sedimentary interbeds and suprabasalt sediments within GWMA, refer to Smith et al. (1989) and GWMA (2007).

Sedimentary Interbeds. The nature and composition of sediments found interbedded with the CRBG vary greatly, ranging from epiclastic to volcaniclastic in origin. Within the central/western Columbia Plateau region, the sedimentary interbeds within the CRBG are assigned to the Ellensburg Formation (Swanson et al., 1979a; Fecht et al., 1987; USDOE, 1988; Smith et al., 1989). These sediments were deposited by ancient river/lake systems (both channel and overbank deposits) and as air-fall tephras and reworked tephras from Miocene volcanoes active in the Cascade Range and northern Basin and Range. Events controlling the deposition of Ellensburg interbeds (Fecht et al., 1987; Smith, 1988; Smith et al., 1989) include: (1) emplacement of CRBG flows and their impact on paleodrainage systems, (2) synvolcanic sedimentation from Cascadian sources, and (3) local and regional tectonism (uplift/subsidence).

Individual interbeds within the Ellensburg Formation range from less than 3 feet thick to more than 100 feet thick and can be traced laterally over large areas (Mackin, 1961; Schmincke, 1964; Bentley, 1977; Grolier and Bingham, 1978; Swanson et al., 1979a; Fecht et al., 1987; Smith, 1988; DOE, 1988; Smith et al., 1989). Variability in interbed composition directly controls their impact on the hydraulic behavior of CRBG interflow zones (USDOE, 1988). Within the eastern portion of GWMA, these sediments are generally less than 20 feet thick and are not present in much of this area (GWMA, 2009a, 2009b).

Suprabasalt Sediments. The suprabasalt sediments overlie the CRBG and underlie Quaternary-age deposits. These late Miocene- to Pliocene-age suprabasalt sediments generally consist of two basic types:

- Epiclastic sediments derived from the CRBG or from a variety of pre-CRBG rocks. These epiclastic sediments were deposited in a variety of alluvial environments, including streams, floodplains, and lakes.
- Volcaniclastic (non-CRBG) sediments consisting mainly of tuffs derived from adjacent, active volcanic provinces (Cascade Range and northern Basin and Range).

The age of the base of the suprabasalt sediments can vary from 6.5 Ma, where it overlies the youngest basalt formation (Saddle Mountains Basalt), to 15.3 Ma, where it overlies the Frenchman Springs Member of the Wanapum Basalt.

Cataclysmic Floods

Cataclysmic Floods (“Missoula” or “Spokane” Floods) were generated by episodic, cataclysmic releases of huge volumes of water from glacial Lake Missoula that spilled across the Columbia Plateau and through the Columbia River Gorge on their way to the Pacific Ocean. These cataclysmic floods occurred many times during the Pleistocene, between approximately 1,000,000 and 13,000 years ago (Bretz et al., 1956; Baker and Nummedal, 1978; Waitt, 1980, 1985; USDOE, 1988; Kiver et al., 1989; Baker et al., 1991; Waitt et al., 1994). These flood waters scoured and stripped the existing land surfaces, eroding deep channels into the CRBG, giving rise to the "Channeled Scablands" and coulees that reside in the Columbia Plateau (Bretz et al., 1956). These same flood waters also deposited extensive tracts of boulders, gravels, and sands.

The only exit point for these flood waters from the Columbia Plateau was Wallula Gap. This constriction caused the flood waters to hydraulically pond behind Wallula Gap and created a temporary lake that was more than 1,000 feet deep. This temporary lake inundated the Pasco Basin, Yakima Valley and Walla Walla Valley, including much of the central and western portions of GWMA, lying directly on top of CRBG rock exposures (Figure 13). The lake would gradually shrink in size and volume after its initial formation, only to reform with the next release of floodwaters from glacial Lake Missoula. For a discussion of the stratigraphy and hydrogeology of the Cataclysmic Flood sediments within GWMA, refer to GWMA (2007).

Hydraulic Characteristics of CRBG Intraflow Structures

Of particular importance to CRBG hydrogeology in the eastern GWMA is the physical architecture of the basalt flow interiors. This physical architecture is the consequence of the following:

- The mode by which lava flows erupted, and the rate of lava movement across the ground surface upon eruption
- The formation of cooling joints as the lava solidified, followed by changes in cooling joint aperture (secondary alteration and mineralization) over time
- Paleosol development on top of basalt flow tops

Mode and Rate of Emplacement

Rate and volume of lava erupted, lava composition and temperature (rheology), vent geometry, topography, and environmental conditions all play significant roles in the eruption dynamics and overall geometry of individual basalt lava flows or flow fields (Shaw and Swanson, 1970; Reidel and Tolan, 1992; Beeson et al., 1989; Hon et al., 1994; Reidel et al., 1994; Keszthelyi and Self, 1996; Self et al., 1996, 1997; Reidel, 1998). There are two basic types of flow geometries - compound and sheet (Figure 14).

- A compound flow develops when the lava flow advances away from its vent in a series of distinct and separate lobes (flows) of flowing lava. Each lobe is subsequently covered by later lava lobes as the emplacement of lava continues. This results in the accumulation of elongated bodies of basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava.

- In comparison, a sheet flow results when lava is erupted at a high rate and is able to advance away from the vent as a single, uniform, moving sheet of lava. This type of flow consists of a relatively extensive, single layer or "sheet" of lava. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops and flow bottoms (Figure 12).

Two end-member models exist for the emplacement of huge-volume CRBG flows: rapid emplacement - on the order of weeks to months per flow (Shaw and Swanson, 1970; Swanson et al., 1975; Wright et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998) vs. slow emplacement - on the order of many years to centuries per flow (Self et al., 1991, 1993, 1996; Long et al., 1991; Finneamore et al., 1993; Murphy et al., 1997). Field and laboratory evidence to date (Swanson et al., 1975; Mangan et al., 1986; Wright et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Ho and Cashman, 1997; Reidel, 1998; Ho, 1999) appear to favor a rapid, laminar flow model. Evidence supporting the rapid emplacement model is as follows.

- The internal structure of CRBG flows is relatively simple. The slow emplacement model requires low lava discharge that would produce very distinctive flow features such as lava tubes and lava inflation structures that would result in relatively complex internal arrangement of intraflow structures (Chitwood, 1994; Hon et al., 1994; Self et al., 1996). These complex intraflow features are rarely found within a CRBG flow except at the flow's margin. The pervasive presence of simple internal flow structures in CRBG flows supports a rapid emplacement model (Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998).
- Petrographic examination of quenched CRBG lava (e.g., rinds from pillow lava) from medial to distal parts of the flow has shown that the crystallinity is no greater than that of the glassy selvage zone of the feeder dike. This indicates that little or no crystal nucleation and growth occurred from the time the lava was erupted to when it reached it most distal point – distances ranging from 125 to greater than 300 miles (Shaw and Swanson, 1970; Swanson et al., 1975; Mangan et al., 1986; Wright et al., 1989; Ho and Cashman, 1997; Ho, 1999). These observations would not be consistent with a very long duration (slow) emplacement model.
- A basalt glass composition-based geothermometry study has been conducted for the Ginkgo flow (Frenchman Springs Member, Wanapum Basalt) along its 300 mile length to provide a quantitative estimate of heat loss (Ho and Cashman, 1997; Ho, 1999). Results suggest cooling rates of 0.06 to 0.12 ^{o}F per mile for the Ginkgo flow, which are substantially lower than cooling rates observed in active and historic basalt flows (Ho and Cashman, 1997). This data would favor a rapid emplacement model over a slow emplacement model that would require extreme thermal efficiencies to produce these cooling rates (Ho and Cashman, 1997, p. 405).

- The lack of extensive pillow/hyaloclastite complexes along the length of CRBG intracanyon flows favors a rapid emplacement model (Reidel et al., 1994; Beeson and Tolan, 1996). If CRBG intracanyon flows were emplaced over very long periods (years to centuries), dammed-off river(s) would have overtopped the lava dam in a period of a few months and reestablished their presence within their canyon(s) years before the flow reached its most distal point. This situation would result in the river encountering the advancing flow front and consequently the continuous creation of large quantities of hyaloclastic (glassy) debris and pillow lava. Features consistent with this aspect of a slow emplacement model are not found along the length of CRBG intracanyon flows.

In summary, the individual large-volume CRBG flows (especially the members comprising the Grande Ronde and Wanapum Basalt Formations) display characteristics consistent with sheet flows (Swanson et al., 1979a; Tolan et al., 1989; Reidel et al., 1989b, 1994; Beeson et al., 1985, 1989; Beeson and Tolan, 1990, 1996; Reidel and Tolan, 1992; Reidel, 1998). CRBG flows typically only exhibit the complex features associated with compound flows found at their flow margins (Beeson et al., 1989; Reidel and Tolan, 1992; Reidel et al., 1994; Beeson and Tolan, 1996; Reidel, 1998).

Secondary Alteration and Mineralization in Cooling Joints

After the emplacement and burial of the CRBG flows, secondary minerals (e.g., silica, cryptocrystalline quartz, calcite, zeolite, pyrite, clay minerals, etc.) can partially to completely fill existing voids within interflow zones. Processes by which precipitation of these minerals occurs can be very complex and are dependent on a host of variables including groundwater hydrochemistry, groundwater mobility/mixing rates, groundwater residence time, and local geothermal regime (USDOE, 1988). The net effect of secondary mineralization on CRBG interflow zones is a reduction, ranging from slight to total, in the permeability of these zones. This process also is important in sealing cooling fractures in dense flow interiors.

In a detailed analysis of the physical architecture of the basalt flow interiors, Lindberg (1989) examined joint width and the degree of mineral infilling in approximately 3,200 joints in basalt drill core collected at the Hanford Site. He found that while the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints are typically 77 to 99 percent filled with secondary minerals (clay, silica, zeolite). Additionally, the void spaces that do occur are typically not interconnected (USDOE, 1988; Lindberg, 1989). Lindberg (1989) hypothesized that initially, the basalt cooling joints had no infilling in the same way that recent basalt flows in Hawaii have cooling joints with no infilling minerals. Groundwater then begins altering the walls of the joints, and secondary minerals begin to precipitate on the joint walls as water moves through the joints. This reduces the joint aperture and eventually creates only isolated pockets of joints that are not in-filled. Lindberg noted that eventually even the widest joints become highly in-filled too, causing groundwater flow to stop almost completely. Lindberg noted that the narrow width and significant mineral infilling in the cooling joints of the flow interiors gives the flow interiors high strength, rather than low strength. He noted that these very properties are the reason that CRBG exposures are often present as overhanging rock in canyon and valley sidewalls. Over-hangs of CRBG rock outcrops would not be expected to occur if the flow interiors had even modest permeability.

Quantification of Hydraulic Properties

Because of the typical distribution and physical characteristics of CRBG intraflow structures, groundwater primarily resides within the interflow zones (Newcomb, 1969; Oberlander and Miller, 1981; Davies-Smith et al., 1988; Lite and Grondin, 1988; USDOE, 1988; Wozniak, 1995; Tolan and Lindsey, 2000). CRBG interflow zones are tabular, laterally extensive, bodies which clearly have features such as flow top breccias and flow bottom pillow lavas whose physical properties are conducive to forming aquifers.

The physical properties of undisturbed, laterally extensive, dense interiors of CRBG flows make the flow interiors essentially impermeable for all practical purposes (Newcomb, 1969; Oberlander and Miller, 1981; Davies-Smith et al., 1988; Lite and Grondin, 1988; USDOE, 1988; Lindberg, 1989; Wozniak, 1995). While the dense interior portion of a CRBG flow is replete with cooling joints, in their undisturbed state these joints have been found to be typically 77 to 99 percent (or more) filled with secondary minerals (clay, silica, zeolite), and the void spaces that do occur are typically not interconnected (USDOE, 1988; Lindberg, 1989). The fact that CRBG dense flow interiors typically act as aquitards accounts for the confined behavior exhibited by most all CRBG aquifers. Because of this behavior, artesian (flowing) conditions within the CRBG aquifer system have been encountered in many areas around the margins of the Columbia Plateau.

The hydraulic properties of CRBG flow tops, flow interiors, and sedimentary interbeds at the Hanford Site have been tabulated by Strait and Mercer (1987) and discussed and summarized by USDOE (1988). Following are discussions from these and other references of hydraulic conductivity, storativity, specific storage, and effective porosity.

<u>Hydraulic Conductivity and Transmissivity</u>. A range of hydraulic conductivity values are reported for CRBG aquifers:

- At the Hanford Site (USDOE, 1988):
    - The horizontal hydraulic conductivity of CRBG flow tops ranged from 1 x 10^{-6} to 1,000 feet per day and averaged 0.1 feet per day, with flow tops serving as the primary conduit for lateral groundwater flow. The horizontal hydraulic conductivity of CRBG flow tops was estimated to be notably lower in the Grande Ronde Basalt (geometric mean between 1 x 10^{-2} and 1 x 10^{-1} feet per day) than in the Wanapum Basalt (geometric

mean 10 feet per day) and the Saddle Mountains Basalt (geometric mean between 10 feet per day and 100 feet per day).

  - The horizontal hydraulic conductivity of dense basalt flow interiors ranged from 1 x 10^{-9} to 1 x 10^{-3} feet per day, with an average of 1 x 10^{-7} to 1 x 10^{-6} feet per day, which is approximately 5 orders of magnitude less than the average for CRBG flow tops.
  - The vertical hydraulic conductivity of the flow interiors ranged from 1 to 3 times the horizontal hydraulic conductivity determined for flow interiors, or as much as 1 x 10^{-9} to 3 x 10^{-3} feet per day.
  - The mean horizontal hydraulic conductivity of sedimentary interbeds was estimated to be between 1 feet per day and 10 feet per day for interbeds within the Saddle Mountains Basalt, and between 0.01 feet per day and 0.1 feet per day for an interbed (the Vantage interbed) in the Wanapum Basalt.

- Near Lind, measured vertical hydraulic conductivity values ranged from 1 x 10^{-5} feet per day to 1 x 10^{-1} feet per day (Sabol and Downey, 1997).
- The vertical hydraulic conductivity of the flow interior of the Priest Rapids Member of the Wanapum Basalt was estimated to be 1 x 10^{-10} centimeters per second (3 x 10^{-7} feet per day) or less at a site instrumented with numerous piezometers in the Priest Rapids and the overlying Selah Member of the Ellensburg Formation (CH2M HILL, 2006).

<u>Storativity and Specific Storage</u>. At the Hanford Site (USDOE, 1988):

- Four multiple well tests indicated that the storativity of CRBG flow tops ranges from 1 x 10^{-4} to 1 x 10^{-5}, with the corresponding specific storage ranging from 1 x 10^{-5} feet^{-1} to 1 x 10^{-7} feet^{-1}.
- No field tests are known to have been conducted to estimate the storativity or specific storage of CRBG flow interiors. Based on laboratory-derived rock-fluid compressibility and porosity data, USDOE (1988) qualitatively estimated the storativity to likely range between 1 x 10^{-5} and 1 x 10^{-6}, with the specific storage ranging between 1 x 10^{-4} feet^{-1} and 1 x 10^{-6} feet^{-1} for fractured CRBG rocks and 1 x 10^{-5} feet^{-1} to 1 x 10^{-7} feet^{-1} for solid CRBG rocks.
- No estimates of the storativity or specific storage were available for the sedimentary interbeds in either the Saddle Mountains Basalt or the Wanapum Basalt. USDOE (1988) estimated that the storativity is likely to be within the range typical for confined aquifers (between 1 x 10^{-5} and 1 x 10^{-3}).

<u>Effective Porosity</u>. At the Hanford Site (USDOE, 1988):

- Two dual-well tracer tests conducted in an interflow zone in the Sentinel Bluffs Member of the Grande Ronde Basalt indicated that this interflow zone has an estimated effective porosity between 2 x 10^{-4} and 3 x 10^{-4}.

- Laboratory analyses of core samples from the Cohassett and Umtanum flows of the Grande Ronde Basalt indicated that the mean effective porosity of these flow interiors ranged between 1.06 percent and 2.74 percent. However, USDOE (1988) concluded that the representativeness of these laboratory estimates is highly questionable.
- No estimates of the effective porosity were available for the sedimentary interbeds in either the Saddle Mountains Basalt or the Wanapum Basalt.

Stratigraphic, Structural, and Erosional Controls on CRBG Groundwater

Most of GWMA lies within the Palouse Slope structural subprovince of the Columbia Basin (Figure 15). The Palouse Slope is a regional slope that dips gently toward the central portion of the Columbia Basin and is relatively undeformed in comparison to other portions of the Columbia Basin, such as the Yakima Fold Belt (Myers and Price, 1979; USDOE, 1988). Reidel et al. (1989a) noted how the eastern GWMA area has experienced less tectonic activity and deformation than other parts of the CRBG province.

The Palouse slope is the least deformed region in the Columbia Plateau, with only minor faults and low-amplitude, long-wavelength folds. These structures alter an otherwise gently southwestward-dipping paleoslope (Swanson et al., 1980). The Palouse slope has been a relatively stable feature since at least the middle Miocene (Swanson and Wright, 1976). [pg 248]

Reidel et al. (1989a) noted that subsidence was occurring as the CRBG was emplaced, particularly in the southwestern portion of GWMA.

> Subsidence was by far the major tectonic activity in the central Columbia Plateau from early Tertiary through Miocene time. The amount and rate of subsidence in the Miocene, with respect to the relatively stable Palouse slope, can be determined using the thickness of the CRBG. The bulk of the section is represented by the Grande Ronde Basalt, which is about 915 m thicker within the Pasco Basin than compared to the Palouse slope (Reidel et al., 1980, 1987; this volume). The Grande Ronde Basalt was erupted over a 1.0- to 1.5-m.y. period, which indicates that the subsidence rate during this period was about 1.0 to 0.7 centimeters per year. The rate of subsidence decreased with time and was about 0.03 centimeters per year during Wanapum time (15.6 to 14.5 million years ago [Ma]) and about 3 x 10^{-3} centimeters per year during Saddle Mountains time (14.5 to 6 Ma). [pg 253]

Hooper and Conrey (1989) noted that subsidence of the basin was also accompanied by uplift of the granite-cored Idaho batholith to the east. As noted by Reidel et al. (1989), this uplift and the subsidence within the Columbia Plateau kept pace with the rate of emplacement of CRBG flows, giving the Columbia Plateau the appearance of a broad, generally featureless plain with a gentle southwest tilt.

Deformation on the Palouse Slope is primarily characterized by north- to northwest-trending and several east-west-trending folds with little or no apparent topographic expression (Swanson et al., 1980; Tolan and Reidel, 1989). Few faults have been mapped within this region (Tolan and Reidel, 1989), which is consistent with its relatively undeformed nature.

Groundwater flow directions and rates within CRBG aquifers depend not only on the internal features of the CRBG flows and interflow zones, bus also on the presence of external factors – in particular, stratigraphic, structural, and erosional features. These three aspects of the natural system, which are discussed below, are fundamental for understanding the inter-relationship between geology, groundwater occurrence and groundwater movement, as well as interactions with potential sources of surface water recharge.

Stratigraphic Controls

In parts of the Columbia Basin, the terminus of one or more CRBG flows will occur adjacent to one or more of the sedimentary members of the contemporaneous Ellensburg Formation. Where this occurs, the CRBG members will be in local hydrologic connection with each other, and may also be in connection with post-CRBG (suprabasalt) sediments, creating an important groundwater recharge or discharge area for CRBG groundwater.

However, regionally, this control on groundwater movement occurs primarily in the Saddle Mountains Basalt outside of the four-county GWMA area (mostly to the west and south of GWMA). Within GWMA, the subsurface geologic mapping work conducted for this project and in previous studies indicates that the Wanapum Basalt and Grande Ronde Basalt are present throughout most, if not all, of GWMA and do not terminate against Ellensburg sediments in the Odessa Subarea (i.e., in the eastern half of GWMA). Additionally, the mapping work found few deposits of the Ellensburg Formation in GWMA. The oldest named member of the Ellensburg Formation (the Vantage Member) has been mapped in some locations within GWMA, lying between the Wanapum Basalt and the Grande Ronde Basalt. However, in Lincoln and Adams Counties, the Vantage Member is very thin (less than 1 foot thick) in the limited areas where it is present.

A more important stratigraphic control on groundwater movement within GWMA is the occurrence of lateral "pinchouts" of the CRBG basalt flows. From a groundwater standpoint, where the margin of an individual basalt flow is present, the "pinchout" is the juxtaposition of the top and bottom of this flow (and its adjoining interflow zones) with those of the flows above and below this flow. Where a pinchout is present, the overlying flow extends beyond the margin of the terminating flow, and in some cases the underlying flow may also extend beyond the margin of the terminating flow. The geometry of the pinchout and its relationship to groundwater movement is shown schematically in Figure 16. In this example, both the overlying and underlying flows (labeled as Basalt Unit 1 and Basalt Unit 3) are present beyond the margin of the flow that is pinching out (Basalt Unit 2), and the flow that is pinching out (Basalt Unit 2) lies down-dip and downgradient of the locations where it is absent. As a result, in this example, groundwater that is moving towards the pinchout (in the interflow zone between Basalt Units 1 and 3) moves both above and below Basalt Unit 2 once it encounters Basalt Unit 2.

As discussed previously, the emplacement of the basalt occurred simultaneously with the down-warping of the Columbia Basin. Consequently, the Palouse Slope dips from northeast to southwest and the entire basalt sequence dips towards the southwestern corner of GWMA, where the basalt is at its thickest in the Columbia Plateau. Accordingly, the oldest flows (Grande Ronde Basalt) cover the largest area in and outside of GWMA, while younger flows generally are present over slightly smaller areas. For these reasons, and because the Palouse Slope is relatively undeformed structurally, the basalt pinchouts of the geometry shown in Figure 16 are prevalent at and near the outer margins of GWMA. Consequently, the pinchouts play in providing a certain degree of hydraulic interconnection between various basalt interflow zones. The pinchout, in turn, is a highly important geologic control that has direct pertinence to interpreting groundwater elevation data and understanding the means by which various interflow zones are (or are not) interconnected and receive (or do not receive) recharge from a given upgradient source of groundwater recharge. For example, using the example in Figure 16, if two non-pumping observation wells were located downgradient of the pinchout of Basalt Unit 2, with one well screened in the interflow zone above Basalt Unit 2 and one well screened in the interflow zone beneath Basalt Unit 2, then 1) simultaneous measurements in each well might show that the groundwater elevations in the two wells are similar; and 2) if long-term water level records are available, the two wells could be expected to show similar trends if there are not big differences in the locations and magnitude of any pumping that might be occurring from each interflow zone. Such a similarity in water level records would be expected because of the common upgradient zone that provides water to each well. As discussed below, the State observation well network shows several such instances where a group of piezometers shows similar water levels in the upper zones and much different water levels in deeper zones.

An example of the potential importance of pinchouts in understanding groundwater conditions is in the Sinking Creek watershed, where reduced streamflows have been noted since the onset of pumping in the area in the late 1960s. Wildrick (1982, 1990, 1991) and Covert (1995) conducted field tests and reviewed geologic and water level records to examine whether a correlation could be made between groundwater pumping of the local CRBG system (from the Roza Member of the Wanapum Basalt and the underlying Grande Ronde Basalt [Covert, 1995]) and reductions in streamflows and yields to stock wells, domestic wells, and springs completed in the overlying Priest Rapids Member of the Wanapum Basalt. These studies concluded that a relationship between deep groundwater pumping and reduced streamflows was occurring, but neither study could conclusively identify the mechanism for the nature of the connection. The studies by Wildrick noted that the construction of uncased wells was likely an important contributor to the problem, given that these wells allow uncontrolled downward artificial leakage via open boreholes, thereby promoting the drainage of relatively shallow water-bearing zones. However, because water levels in the deeper zones are well below the elevations of the shallower interflow zones, the pumping of the deeper zones does not materially affect the rate of drainage from these shallow zones. Additionally, the water level data indicate that hydraulic gradients between the shallow basalt zones and the deeper basalt zones are strongly downward, as is consistent with the understanding of the dense, massive, low-permeability nature of the basalt flow interiors that separate water-bearing zones. Ralston (1991a, b) noted that the substantial depth to the static groundwater level in the pumped aquifer zones meant that these deep zones were hydraulically uncoupled locally from shallow basalt and surface water, except possibly through the artificial connection provided by uncased boreholes. Ralston (1991a) also pointed out that in the case of a pump test conducted by Wildrick (1982) in a deep basalt irrigation well, no response was measured in shallower basalt zones, which in turn implies that a local connection between the creek and the lower basalt aquifer zones likely does not exist in that immediate area. Yet while he correctly identified this and other hydrogeologic characteristics of the watershed and also correctly refuted certain conclusions stated in the studies by Wildrick, Ralston was nonetheless unable to provide an explanation for the measured and anecdotally observed reductions in streamflows and shallow groundwater resources that had occurred coincident with the onset of groundwater development in the area.

An important clue to understanding this apparent discrepancy between the behavior of the surface water system versus the geologic and groundwater level records is to be found in pumping test observations by Wildrick (1985, 1991) and Covert (1995). Both investigators found that pumping from local basalt production wells caused rapid responses in other irrigation wells located several miles away. Wildrick (1985) observed about 0.1 feet of drawdown more than four miles from a pumping well after just 24 hours of pumping, and the drawdown at this location was nearly 2 feet at the end of the 49.5-hour pumping test. Wildrick (1991) noted that non-pumping observation wells and springs show seasonal water level trends that reflect the seasonality of irrigation and groundwater pumping. Wildrick (1991) also reviewed a 2.5-hour long aquifer test conducted in the Town of Wilbur in 1965, in which a nearby spring showed a rapid drawdown response to irrigation well pumping, with one-half foot of drawdown of the spring level by the end of this short pumping test. Covert (1995) also measured rapid responses of basalt groundwater levels to pumping, but identified a three to four day lag time between groundwater level changes in basalt zones and changes in the water level of a nearby spring (Baring Spring).

The rapid and aerially extensive nature of the observed responses of deep and shallow basalt groundwater zones to pumping is the type of drawdown response that would be expected for highly confined systems. This response indicates that the CRBG groundwater zones have very low storage coefficients and are confined in nature. In confined aquifers, a rapid outward propagation of pressure changes occurs in response to the drawdown of the groundwater level at a pumping well. The drawdown cone around the well continues propagating outward so long as pumping continues, until eventually the pressure changes encounter portions of the groundwater system that have storage capacity and are not confined in nature. In the CRBG, because groundwater is present in thin, highly compartmentalized interflow zones that are overlain by dense low-permeability flow interiors, the interflow zones are commonly confined systems, and are only unconfined close to their local recharge areas. Where a given interflow zone pinches out, groundwater may be present under confined conditions if the adjoining interflow zones are confined. However, an unconfined condition could also exist if the pinched-out interflow and the overlying interflow zone are near a recharge source and are unconfined.

Because Sinking Creek is near the northern limit of GWMA, which is defined by the granitic hills that laterally bound the CRBG and the associated granitic complexes that underlie the CRBG, it is likely that the groundwater in the Sinking Creek area has been recharged by runoff from the hills and deep percolation into the CRBG (where the CRBG laps up against the granitic hills). Along the northern boundary of GWMA, the youngest CRBG flows (the Priest Rapids Member) are in direct contact with the granite and, being the shallowest basalt flows, are the first to receive recharge off the hills. Moving downgradient from this point, the next set of flows (the Rosa Member) appears and also receives some of this recharge. Because of the steepness of the hills and the underlying southward dip of the granitic complex, the various members of the Wanapum Basalt, and perhaps the upper Grande Ronde Basalt (the Sentinel Bluffs Member), receive recharge from these granitic hills, with each water-bearing basalt interflow zone having this common recharge source. The role of pinchouts is thus to distribute this common recharge amongst the various interflow zones that appear as one moves down-dip from the local recharge area. This in turn means that the effect of pumping is to quickly propagate head changes to the lateral boundaries of the flow system, which thereby reduces heads in the recharge areas, which in turn eventually causes heads to decline in shallower zones that are 1) not connected near the pumping centers but 2) are connected at and near the recharge area that is common to each zone. Because of the thin, tabular nature of the interflow zones, confining conditions are prevalent in most CRBG water-bearing zones throughout most of northern Lincoln County, with unconfined conditions present only in localized areas where recharge is occurring (either at flow margins or, as discussed below, at certain locations on the coulee floors).

In summary, the hydraulic and stratigraphic data from the Sinking Creek watershed indicate that basalt pinchouts can play a significant role in providing a common hydraulic connection to multiple CRBG groundwater-bearing zones. Because of the predominantly confined conditions that exist in the CRBG aquifers, pumping from these zones causes a rapid outward propagation of drawdown that can extend up-dip and upgradient to the locations of basalt pinchouts. Downgradient of the pinchouts, the pumped zone has little direct hydraulic connection to overlying and underlying zones, but a direct connection could very well exist at and upgradient (up-dip) of the pinchout. Therefore, groundwater level data collected near a pumping well will often indicate little vertical interconnection between interflow zones at that location, even if data further away indicate that a response is occurring and that an interconnection apparently exists. The presence of pinchouts and their relationship to the interconnection of multiple water-bearing zones at, and upgradient of, the pinchout also is an indication that packages of interflow zones can have a common recharge source.

Structural Controls

This and other studies have identified that groundwater occurrence and movement can be affected by one or more of the following types of geologic structures:

- Faults, which can act as pathways or barriers
- Folds, which can act as pathways or barriers
- Vertical dikes, which generally act as barriers
- Steptoes, which act as local recharge areas but are otherwise barriers to flow
- Incisions by major rivers or coulees, which facilitate groundwater movement

The first four controls are discussed in detail below. While incisions can be partly structural in nature, they are generally erosional in nature inside GWMA and are therefore addressed in a later section of this report.

Faults. Figure 17 shows how faults can alter groundwater flow patterns. Faults have been found to impact the CRBG groundwater system in a number of ways.

- Where a fault acts as a pathway, water levels on each side of the fault would be expected to be similar in a given interflow zone. In these cases, otherwise confined CRBG aquifers can be in direct hydraulic communication, and the fault pathway can expose interflow zones in a manner that creates local opportunities for aquifer recharge and/or discharge.
- In most portions of the Columbia Basin, faults are believed to limit groundwater flow and even act as barriers, creating hydrologically isolated areas within the CRBG. Faulting in the CRBG tends to produce a roughly planer zone composed of coarsely shattered basalt that grades into very fine rock flour. Figure 18 presents a diagrammatic sketch of the typical physical features and terminology for a fault zone cutting CRBG flows. Fault zone shatter breccias often display significant degrees of alteration (clays) and/or secondary mineralization (silica, zeolite, calcite, pyrite). These materials can cement shatter breccias and create rocks that are highly resistant to erosion, even more so than unbrecciated CRBG (Myers and Price, 1981; Price, 1982; Anderson, 1987). In these cases, groundwater levels in a given interflow zone on each side of a fault show markedly different water levels.

An analysis conducted by Johnson et al. (1993) of hydrologic test data collected within the Saddle Mountains, Wanapum, and Grande Ronde Basalts across the Cold Creek fault (west of the GWMA on the Hanford site) appears to support the interpretation that faults generally act as barriers to groundwater flow in the GWMA. Johnson et al. (1993) interpreted the Cold Creek fault to be a barrier to lateral groundwater movement along the axis of the Cold Creek syncline. They interpreted vertical permeability along the fault to be less than horizontal permeability in the upper basalt aquifers, thus producing a constriction in horizontal groundwater movement across the fault. This is the same type of geologic setting seen in the GWMA along the Frenchman Hills and Saddle Mountains.

The ability of faults to affect CRBG groundwater systems in a variety of ways reflects the potential for both lateral and vertical heterogeneities in the physical characteristics of fault zones. For example, the degree of secondary alteration and mineralization along a fault zone may vary. Complete alteration and/or mineralization of fault shatter breccias and gouge zones would "heal" these features and produce rock of very low permeability. Variations in the completeness of this process would produce hydrologic heterogeneities along the trace of the fault. Even if a fault zone is completely healed by secondary alteration and mineralization, renewed movement (displacement) on the fault could produce new permeability within the healed shatter breccia (e.g., USDOE, 1988; Johnson et al., 1993).

<u>Folds</u>. A number of groundwater investigations in the Columbia Plateau area have noted that folds (primarily anticlinal and monoclinal folds) affect the occurrence and movement of groundwater through CRBG aquifers (e.g., Newcomb 1961, 1969; Gephart et al., 1979; Oberlander and Miller, 1981; Lite and Grondin, 1988; USDOE, 1988; Burt, 1989; Packard et al., 1996). In many cases, folds have been identified as groundwater barriers or impediments that either block or restrict lateral groundwater movement through the CRBG aquifer system (e.g., Newcomb, 1969; Oberlander and Miller, 1981; USDOE, 1988). Because most of the folds in this region have genetically related faults, one would initially suspect that the observed impacts of folds on the CRBG groundwater system are caused by related faults. However, the process of folding CRBG can affect the hydraulic characteristics of interflow zones.

Folds can be very important locations for groundwater recharge, especially to deeper water-bearing zones. Figure 19 shows the role of a large, regional-scale anticlinal fold in facilitating groundwater recharge. Folding can expose a deep water-bearing zone by bringing the zone closer to the ground surface than in areas away from the fold. Recharge could occur where the zone has been folded such that it laps up against lower permeability rock that sheds runoff from upland areas, as described previously for the granitic complex that forms the northern boundary of GWMA. Folding also may bring an interflow zone directly to the ground surface, or close enough that it is eventually exposed by erosion of overlying materials. In these cases, where the zone outcrops or is not covered by low-permeability sediments, precipitation and surface water can directly infiltrate to the exposed interflow zone. An example of this is shown in Figure 20, which is a cross-section in western Grant County that looks east through the valley that includes Royal City. This valley is bounded to the north and south by the Frenchman Hills and Saddle Mountains, respectively, which are two large, faulted anticlinal folds within the Yakima Fold Belt. The Royal City municipal supply wells, which are completed in the shallow basalt system (Wanapum Basalt), have apparent radiocarbon ages up to 1,300 years old and also contain detectable tritium, which indicates that part of the groundwater is less than 50 years old. This is direct evidence of a mixture of older water (probably originating as precipitation on the Frenchman Hills) and recent recharge from leakage beneath the nearby Frenchman canal. Static levels in these wells are stable, indicating that the recharge from natural and anthropogenic (canal leakage) sources is sufficient to meet municipal water demands in this part of GWMA. The presence of a mixture of old and young waters indicates that the Frenchman Hills fold is not a barrier to groundwater flow in this area, but instead is an important groundwater recharge feature.

However, in many cases, folds have been identified as groundwater barriers or impediments that either block or restrict lateral groundwater movement through the CRBG aquifer system (e.g., Newcomb, 1969; Oberlander and Miller, 1981; USDOE, 1988). A type of fold that typically acts to restrict groundwater movement laterally is a monocline (also referred to as a monoclinal flexure). A monoclinal flexure zone is characterized by a steep hydraulic gradient across the flexure zone. The steep hydraulic gradient exists because of the dip of the bedding and the reduced permeability caused by the formation of the flexure (Yechieli et al., 2007). The relationship between the physical characteristics of a monoclinal flexure and groundwater conditions on each side of the flexure is shown in Figure 21. As shown in the figure, groundwater elevations in a given CRBG interflow zone will be much different on each side of the flexure. Additionally, the flexure is likely associated with a deep-seated reverse fault; research models for other types of consolidated rock materials indicate that the reverse fault creates a compressional stress field that leads to void closure and permeability reduction during creation of the monoclinal fold (Yechieli et al., 2007). The fault movement that occurs during the process of monoclinal folding causes slippage parallel to the layers (CRBG flows), in part to accommodate the structural shortening associated with the compressional stress field. An analogy for this process is seen when a deck of playing cards is flexed and the individual cards slip past one another to accommodate the flexure. The tighter the flexure of the cards, the greater the “inter-card” slippage. In folds, this type of flexural slip typically occurs within CRBG interflow zones (Newcomb, 1969; Price, 1982; Anderson, 1987), which are the mechanically weakest layers in the CRBG. The effects of this flexural slip on CRBG interflow zones ranges from minor shearing to nearly complete destruction (production of fault shatter breccia/gouge material) and are directly related to the intensity and magnitude of deformation (Price, 1982; Anderson, 1987). This process also impacts the original hydraulic characteristics of interflow zones, reducing or even destroying the permeability of these features (Newcomb, 1969; Yechieli et al., 2007).

As discussed earlier in this report, Luzier and Burt (1974) inferred the presence of a buried structure that appears to limit the amount of westward groundwater flow in the CRBG. The structure was inferred from groundwater elevation contour maps and was estimated to be present near the Adams / Grant County Line, and possibly extending into the southwestern portion of Lincoln County. Subsequent subsurface geologic mapping and aeromagnetic data collection have led to an interpretation during this Subsurface Geologic Mapping and Hydrogeologic Assessment project of the presence of a zone of flexure extending from the Snake River northwesterly through Connell and Warden, and terminating at Crab Creek at a location about midway between Billy Clapp Lake and the Town of Soap Lake. This zone of flexure, whose location is shown in Plate 2, is interpreted to be a monoclinal flexure (fold) of the CRBG and passes through the area where Luzier and Burt (1974) mapped their inferred buried structure. The presence of a monoclinal fold in this location supports the conceptual model of folds being capable of acting as barriers to groundwater movement under certain conditions. The zone of flexure that was first inferred by Luzier and Burt (1974) and has now been identified by the Subsurface Geologic Mapping and Hydrogeologic Assessment Project divides areas of significant groundwater declines (east of the flexure) with areas where little if any decline has occurred.

Vertical Dikes. Road-cut and canyon exposures of the CRBG reveal the presence of vertical dikes extending upwards through portions of the CRBG at various locations. These dikes are the exposed portion of the "plumbing system" of the volcanic vents that erupted a given CRBG flow. Because they contain solidified basalt that originated from the deep magma chambers that feed the vents, they represent buried vertical, tabular structures that consist of dense, non-vesicular basalt having very high density and low permeability. As such, where present, they commonly form barriers to groundwater flow, as shown in Figure 22.

Because dikes represent an opening in older rocks that allowed for the upward movement of magma, they exist in places as a series of multiple dikes that are arranged along a generally linear trace, and fed multiple linear vents. In this case, the dikes form an "en echelon" pattern, where the dike system consists of a series of segmented dikes that are segmented and are not completely joined to one another. In this case, an individual interflow zone may have a somewhat circuitous continuity on each side of the dike, thereby allowing for some migration of groundwater across the dike system. However, the amount of this connection may be minimal, resulting in significant head contrasts on either side of the dike system.

Steptoes. Steptoes are older granitic basement "islands" (hills) that are surrounded by, and rise above, CRBG basalt flows. As shown in Figure 23, steptoes can provide local recharge to the CRBG by shedding surface runoff that can subsequently infiltrate into one or more CRBG interflow zones along the basalt /steptoe contact.

Steptoes are seen predominantly in eastern and northeastern Lincoln County, southwest and southern Spokane County, and the north-central and northeastern portions of Whitman County. As shown in Figure 24, in eastern Lincoln County, these buried hills appear to form barriers to groundwater movement from the higher precipitation areas that lie along the Idaho/Washington border. From the area around Sprague, Washington, and south to the Snake River, the Steptoe system lies just east of GWMA but nonetheless likely is a source of some groundwater movement into the southern portion of GWMA from the east. However, in this southern area, the presence of surface streams (Sprague Lake, Cow Creek, and the Palouse River), along with the young age of groundwater in basalt wells just west of Sprague Lake and the anecdotal comments of local wells owners, indicates that 1) a major basalt dike system may be present in the vicinity of Cow Creek and 2) this dike system may be preventing groundwater from moving west into the central GWMA area.

The granitic hills that are visible as steptoes in northeastern Lincoln County represent the surface exposure of a significant uplifted granitic structure that extends northwesterly from central Whitman County to Sprague Lake and northward to the watershed boundary that divides GWMA from the Spokane River watershed. This basement structure then extends westerly to form the hills lying just south of the Columbia River that are the northern boundary of GWMA. This entire buried ridge lies beneath the CRBG and separates the basalt from the Spokane and Columbia River systems. This feature was suspected by Luzier and Burt (1968) as being a barrier to potential groundwater recharge to the CRBG from the Columbia and Spokane Rivers. This interpretation has been confirmed by the subsurface geologic mapping work conducted under this Subsurface Geologic Mapping and Hydrogeologic Assessment project, which shows that the buried granitic structure provides a physical barrier to recharge of the CRBG aquifers by the Spokane and Columbia Rivers. This relationship is illustrated in Figures 25 and 26, which show that the Lake Roosevelt pool (which has an elevation of 1,290 feet under full-pool conditions) is significantly below the top of the granitic basement rock. As shown in Figure 25, the Lake Roosevelt pool is also below the groundwater elevations on the order of 1,800 feet that have been measured in CRBG wells north of the Odessa Subarea.

Erosional Controls

Incision into CRBG interflow zones, and consequent formation of "erosional windows" into deeper CRBG aquifers, can create recharge/discharge areas into, and from, CRBG aquifers. Throughout the region, erosional windows potentially connecting CRBG aquifers are known to occur, such as in the Channeled Scablands in northern Lincoln County. Erosional windows can be inferred from geologic mapping (see maps by Stoffel et al., 1991; Reidel and Fecht 1994a, 1994b; Schuster et al., 1997; GWMA, 2009b).

Under the Subsurface Geologic Mapping and Hydrogeologic Assessment project, the completion of subsurface geologic mapping efforts in Lincoln County has provided maps that show the important role of the cataclysmic floods in creating erosional windows into the various members of the Wanapum Basalt and into the uppermost members of the Grande Ronde Basalt. Plate 3, a geologic outcrop map for Lincoln County, prominently shows the progression of basalt member exposures in coulee drainages, particularly Crab Creek. The youngest flows (Priest Rapids Member) are present in the upstream reaches of Crab Creek and other drainages. Moving downstream, the basalt rock that outcrops in the coulee floor eventually transitions to the next underlying basalt member, with this pattern continuing down the length of the coulee. As a result, the coulees in Lincoln County contain exposures of each member of the Wanapum Basalt. In western Lincoln County and northeastern Grant County, exposures of the uppermost Grande Ronde Basalt (the Sentinel Bluffs Member) also appear in the coulee floors. Similar patterns are seen in other coulee systems, including Lind Coulee and Rocky Coulee in Adams County, where the outcrops in the coulee floor transition from the Priest Rapids Member in eastern Adams County to the Frenchman Springs Member in western Adams County.

In the uplands of northern and eastern GWMA, which is the upgradient area for the CRBG groundwater flow system, the hydrologic role of the coulees, and particularly the floors of the coulees, is significant with respect to natural recharge and the possibilities for future artificial recharge projects. Figure 27 shows how the coulees interact with groundwater. Groundwater that is present in interflow zones lying above the coulee floor will drain into the coulees where the interflow zone intersects the coulee sidewall. While some of this water likely evaporates or is consumed by vegetation, a portion may move to the sediments occupying the valley floor, particularly where an interflow zone lies at the base of a coulee sidewall. An example of this is shown in Figure 28, which shows a spring in Canniwai Creek, located in northern Lincoln County. The spring has been present at this location for many years and appears to be developed in a shallow interflow zone that receives recharge from the east. Because the rock immediately beneath the interflow zone and the spring consists of a basalt flow interior, the flow of the spring does not immediately infiltrate into the ground nearby, due to the low permeability of the flow interior. Consequently, the spring is present not only because of the outcropping of the interflow zone, which feeds water to the spring, but because the floor of the spring consists of dense bedrock that cannot infiltrate water that is present in the overlying spring.

While the sidewalls of the coulee systems play a role in groundwater movement, of far greater hydrologic significance is the coulee floor, and in particular the occurrence of basalt outcrops in the floor and/or the presence of sediments directly overlying the basalt. Surface water in the coulee floor can infiltrate into the permeable basalt interflow zones wherever those zones are in direct contact with the coulee floor or sediments in the coulee floor.

The significance of the coulees in recharging groundwater is well known anecdotally, particularly from the historical knowledge of local residents living in and near the various tributaries to Crab Creek. Two particularly striking bodies of information are known in the area – in the Sinking Creek watershed and the Lake Creek drainage, which both lie north of Crab Creek.

- In the Sinking Creek watershed, cattle ranchers recall that prior to the beginning of groundwater development in the 1960s, portions of the creek contained pools deep enough for swimming and to sustain native trout (Wildrick, 1991). With the onset of groundwater development, these pools and most of the flow in Sinking Creek began to decline in the late 1960s and eventually disappeared in most reaches of the creek. Additionally, shallow wells and irrigation works yield less, if any, water than occurred prior to groundwater development. Because rainfall is the only source of water to this watershed, and because rainfall amounts have not decreased since the onset of groundwater development, the decrease in surface water and shallow groundwater resources is attributed to the regional lowering of the water table created by groundwater development. The initial lowering of the water table is interpreted by previous researchers (Wildrick, 1982, 1985, 1990, 1991; Covert, 1995) and the GWMA project team to have created a downward hydraulic gradient in the uppermost basalt groundwater zones, allowing surface water to migrate more easily into the permeable interflow zones of the underlying basalt, wherever those zones are in direct contact with the floor of the Sinking Creek coulee system.

- In the Lake Creek drainage, local residents recall that conditions in this drainage were similar to those described by residents in the Sinking Creek watershed. In particular, residents recalls the presence of water in Pacific Lake, and the significant flow of water over a basalt structure at Delzer Falls, located just downstream of Pacific Lake. A recreation facility that included a boat launch was formerly present at Pacific Lake. Since the onset of groundwater development in the Odessa Subarea and other parts of Lincoln County, Pacific Lake has largely dried up (Figures 29 and 30), and Delzer Falls has only small and very infrequent flows. Surface water sources are not available in this area to provide irrigation supply. Consequently, the drying up of the Lake Creek drainage is attributed to lowering of the water table by groundwater pumping and the subsequent recharge of the natural rainfall and snowmelt runoff to the underlying basalt during the early years of groundwater development. The Roza Member of the Wanapum Basalt occupies the floor of Pacific Lake, and the top of the Grande Ronde Basalt is thought to be a few tens of feet to 200 feet below the bottom of the coulee.

  Water has not been present in Pacific Lake or at Delzer Falls for most of the past two decades, except following a significant snowfall / rainfall / runoff event that occurred in late 1996 and early 1997. In February 1995, aerial video films showed flow only in the mid-sections of Lake Creek (Kennedy/Jenks Consultants, 2005). Local residents kept detailed records of water occurrence in Pacific Lake during the 1996/1997 runoff event. These records indicate that a large pool of water appeared in the lake, and then disappeared quickly once the lake level had declined below the point where water could exit the lake at its downstream outlet. Residents who observed the lake during this period recall seeing a whirlpool current in the middle of the lake, where surface water appeared to be infiltrating into the underlying basalt floor of the lake at a high rate.

In these two drainages, the drainage of the uppermost basalt aquifers by regional groundwater pumping has unsaturated these materials and subsequently provided space for surface waters to move rapidly downwards into these basalt aquifers whenever water is present in the floors of these coulees. The coulees therefore are erosional features that create “windows” into the underlying shallow basalt aquifer systems. In the upland areas of GWMA, including the Lake Creek and Sinking Creek drainages and much of Lincoln and Adams Counties, the role of coulees in providing natural recharge of precipitation and runoff to the Wanapum Basalt is significant. Accordingly, the potential for artificial recharge to have a measureable localized influence on the Wanapum Basalt near these drainages is significant. In contrast, because so few outcrops of the Grande Ronde Basalt are present in the interior of GWMA, coulee recharge of the Grande Ronde Basalt is likely to be more limited in areal extent and magnitude, whether occurring naturally (from precipitation runoff) or in the form of future artificial recharge.

Influence of Well Construction on Groundwater Movement and Occurrence

Water wells that are open to more than one CRBG interflow zone act as man-made, vertical pathways that can allow groundwater to migrate between CRBG aquifers having different hydraulic heads (Lite and Grondin, 1988; USDOE, 1988; Wozniak, 1995). In the past the construction of water wells open to multiple CRBG interflow zones (aquifers) has been the norm, rather than the exception. This is due to the fact that the CRBG has been generally treated as a single aquifer instead of a multiple aquifer system. Therefore in regions where groundwater within the CRBG is the primary source of domestic, agricultural, and/or industrial water, the CRBG groundwater system can have significant vertical connectivity on a regional scale because of the large number of water wells that are open to multiple aquifers.

As discussed previously in this report, the early investigations of groundwater level declines in the Odessa Subarea noted the importance of well construction on declining water levels. Luzier and Burt (1974) noted the many anecdotal reports and borehole geophysical logs that showed downward cascading of groundwater in wells that were open (uncased) through multiple basalt layers. Luzier and Burt (1974) concluded that the amount of natural vertical connection between water-bearing zones in the CRBG is insignificant compared with the artificial vertical connection created by the presence of uncased boreholes. They also noted that downward drainage via uncased wells is an ongoing process that does not stop whenever a deep well stops pumping, because the static water level in the well is commonly below the interflow zone(s) contributing cascading water. Luzier and Burt (1974) concluded that the large number of open boreholes and “short circuits” would cause steady declines in shallow zone groundwater levels, and that this could create “acute” problems for shallow domestic and stock wells, many of which they noted had already gone dry. Luzier and Burt (1974) also expressed concern about the potential for reduced streamflows; they noted that data from a stream gage on Crab Creek (at Irby) was suggesting that such depletion might have already begun at that time. Indeed, in later years, both Wildrick (1982, 1985, 1991) and Ralston (1991a, 1991b) identified uncased wells as an important contributor to reduced groundwater levels and streamflows in the Sinking Creek watershed.

Local farmers and ranchers have reported the need to deepen numerous wells as groundwater elevations and well yields have declined over the years in the vicinity of the towns of Odessa and Lind. Water level and well deepening records from an agricultural production well in northwestern Adams County illustrate this trend (Figure 31).The well was deepened just before the 1995 irrigation season. Prior to deepening, the well was 800 feet deep and showed an approximate 40-foot decline in its static (non-pumping) groundwater elevations since the early 1980s. The average rate of decline from the early 1980s to 1995 was about 3 to 4 feet per year. After the well was re-drilled to a depth of 1,100 feet, the static water level initially rose, then in subsequent years began showing a declining trend. In 2005 and 2007, the static water level was approximately 100 feet lower than in the early 1980s and about 60 to 70 feet lower than when it was re-drilled in 1995.

While many production wells are anecdotally known to show similar behavior, the dates of well deepening are often unknown, and a comprehensive set of water level records is not always available. Additionally, detailed geologic and/or geophysical logs of these production wells are not always available. Consequently, while Ecology has measured static water levels at a network of production wells throughout GWMA, few of these wells provide an indication of how the CRBG system functions hydrologically and where, and what rates, it receives recharge from shallower water-bearing zones and/or surface water sources. Instead, the present-day understanding of the CRBG's hydrogeology and recharge has been derived primarily from data provided by a network of non-pumping observation wells, coupled with the detailed subsurface geologic mapping, previous hydrogeologic studies, and the local anecdotal knowledge about groundwater and surface water resources in GWMA. The water level data from the State observation well network and their interpretation are discussed below.

GROUNDWATER ELEVATIONS AND TRENDS

Plate 3 shows the locations of wells where Ecology has measured groundwater elevations over a long enough time period to allow for identification of water level trends. Wells in Plate 3 with the identifier "ERO" are production wells, and wells with the identifier "AAE" are non-pumping wells. Hydrographs for the "ERO" wells are contained in Appendix A of this report, along with a tabulation of the basalt formations and members to which the wells are open (for wells known to be open wholly or partially to the Wanapum Basalt). Hydrographs for the "AAE" wells are presented and discussed below.

Plates 4, 5, and 6 show groundwater elevation data collected by the USGS in early 2006 as part of a synoptic water level measurement event conducted throughout GWMA. Each plate shows this information for wells where both the construction and the lithology are known. The plates present this information for wells completed in the Priest Rapids and/or Roza Members of the Wanapum Basalt (Plate 4); wells completed in the Roza and/or Frenchman Springs Members of the Wanapum Basalt (Plate 5); and wells completed in the Grande Ronde Basalt (Plate 6). Inspection of these plates reveals that it is difficult, if not infeasible, to prepare groundwater elevation contour maps using recent water level data because of the geologic setting, and the variety of well depths and well designs that exist in the eastern GWMA. Most production wells are uncased, meaning that they intercept water from multiple interflow zones in the CRBG. Because the wells have long open intervals, and because individual interflow zones are generally thin and not in direct natural connection with overlying and underlying zones, the water level in an uncased well is a composite of the different water levels in each interflow zone, and commonly is dominated by one or more of the deepest zones to which the well is open. Additionally, the prevalence of open boreholes in a localized area can create complex patterns of groundwater movement during the irrigation season, as well as during the seasons that the agricultural production wells are not operating. Also, the amount of historical water level decline can be variable from one location to another. Finally, water level data are unavailable for some of the water-bearing zones over large areas; for example, for wells open exclusively to the Priest Rapids and/or Roza Members, few such wells exist in Adams and southern Lincoln County (see Plate 4).

Because preparing groundwater elevation contour maps is a difficult and tenuous exercise, the Subsurface Geologic Mapping and Hydrogeologic Assessment project has instead examined groundwater elevation trends (hydrographs) and interpreted them in the context of 1) the geologic conceptual model of the CRBG and 2) geochemical and age-dating indicators that identify different water types spatially and account for artificial mixing via uncased wells. With regards to elevation trends, during the 1970s and early 1980s, Ecology and the USGS constructed a number of multi-level observation well clusters in and around GWMA to evaluate the state of the groundwater resource, and in particular the response of the basalt aquifers to groundwater development. Nested observation wells are particularly useful for understanding how the multi-level aquifer systems respond to regional-scale groundwater development, because these wells show just the response of the aquifer, unlike production wells which show this same response but also include additional drawdown due to losses in hydraulic head that occur as groundwater enters the well and is pumped to the surface. Ecology has measured groundwater levels for as long as 40 years in its network of nested observation wells. Figure 32 is a schematic representation of one of the multi-level well clusters, showing the design of a well cluster south of the Town of Odessa (well cluster AAE563). As shown in the figure, a multi-level observation well actually consists of a collection of several wells in a single borehole with each well extending to a different depth and open to a different interflow zone(s). Cement grout plugs are used to seal the space between each well to prevent leakage between the zones monitored in the borehole.

In a vertically compartmentalized groundwater flow system such as the CRBG, nested wells are a valuable tool for understanding the differences in 1) water level elevations and 2) seasonal and longer-term water level trends between water-bearing zones. These differences can be readily evaluated at a single cluster of nested wells (i.e., at one geographic location) because the water level measured in each individual well represents the water pressure in the interflow zone(s) open to that particular well. Specifically:

- Differences or similarities in groundwater elevation measurements collected at a given nested well cluster on a given day provide a direct reading of how well connected the basalt interflow zones are laterally and vertically.
- Regular measurements taken over a number of years provide a record of seasonal and long-term water level trends and, when compared with other nested well clusters, provide a direct indication of the relative influences of regional-scale and sub-regional pumping and recharge on groundwater levels in the interflow zones monitored by the nested wells.

Between the various wells in a nested well cluster, similarities or differences in water level elevations, and similarities or differences in their trends, together define the hydraulic relationship between interflow zones monitored by each well in the well cluster. If good vertical connection exists between interflow zones, the water levels in different interflow zones would be expected to be similar, and to react similarly over time. Conversely, differences in levels and/or trends indicate vertical separation between the monitored interflow zones.

Nested observation wells were installed by the USGS and Ecology at a location near the City of George in Grant County (well AAE554) and at the following six locations in eastern GWMA:

- AAE552 (Cyril Hart) in southern Adams County
- AAE562 (Davenport) just southwest of the City of Davenport
- AAE559 (Dreger) in the channeled scablands of central Lincoln County
- AAE558 (Almira) in west-central Lincoln County
- AAE563 (Odessa) along Highway 21 south of the Town of Odessa
- AAE564 (Basalt Explorer) in the southwest Lincoln County, south of Crab Creek

Plate 3 shows the locations of these wells and the locations of production wells where groundwater elevation hydrographs are also available, showing groundwater elevation trends over various time periods. Water level trends at each of these nested observation wells within GWMA are discussed below, followed by a discussion of water level trend studies during the 1980s at the Hanford Site, which is located immediately southwest of GWMA in an inferred regional-scale groundwater discharge zone for CRBG groundwater. These discussions are then followed by a discussion of rainfall trends since 1950 (before irrigation-related groundwater development began in the eastern portion of GWMA).

Cyril Hart Nested Observation Well Cluster (Southern Adams County)

Figure 33 contains a schematic diagram of the construction of well cluster AAE552 (Cyril Hart), along with the groundwater elevation hydrographs for each individual observation well. The hydrographs show that the three zones monitored in the Wanapum Basalt have different groundwater elevations and different trends over time. Additionally, each of the three Wanapum Basalt wells shows distinctly different groundwater elevations than the two wells completed in the upper Grande Ronde Basalt (Sentinel Bluffs Member).

The two deepest wells have elevations and trends that are similar to each other. This may be attributable to 1) the long depth intervals monitored by each well (106 feet for E03 and 126 feet for the deeper E02 well); and 2) the limited thickness (15 feet) that separates the bottom of the open interval well for E03 from the top of the open interval for the underlying well (E02).

Most importantly, the hydrographs at the AAE552 well cluster provide substantial evidence of very limited hydraulic connection between the Wanapum Basalt and the

Grande Ronde Basalt at this location. The two Grande Ronde Basalt wells have groundwater elevations that are 1) between 250 and 300 feet lower than that of the upper two Wanapum Basalt wells, and 2) initially below the deepest Wanapum Basalt well. Additionally, the two Grande Ronde Basalt wells show an accelerating decline in groundwater elevations beginning in the late 1980s to early 1990s, and continuing to at least the year 2000, while the Wanapum Basalt wells generally do not follow this same trend. (One Wanapum Basalt well even shows a continued rise in water levels).

Davenport Nested Observation Well Cluster (Northeastern and East-Central Lincoln County)

Figure 34 contains a schematic diagram of the construction of well cluster AAE562 (Davenport), along with the groundwater elevation hydrographs for each individual well. The hydrographs show a pronounced separation of the groundwater elevations, by about 150 feet, between the upper six wells versus the two deepest wells. This difference in static water levels is consistent with the depth-variation in the specific capacity of the individual water-bearing zones, as measured during advancement of the open borehole, prior to well construction (Myers, 1972). The specific capacity is a measure of the potential water-bearing capability of the water-bearing zones to which the borehole or an individual well is open. The specific capacity equals the rate of flow into the borehole or well during pumping, divided by the amount of drawdown during pumping. The specific capacity in the open borehole was approximately 5 gallons per minute per foot of drawdown (gpm/ft) until the open borehole penetrated the deepest interflow zone, at which point the specific capacity increased by a factor of 15 (to 76.5 gpm/ft).

The water level and specific capacity data together indicate that the upper 6 zones are hydraulically separate from the two deepest zones penetrated by this nested well cluster. Additional evidence of this limited vertical interconnection is the somewhat different water level trends observed between these zones. In the two deepest wells, groundwater elevations declined steadily through the mid-1990s; abruptly increased for about three years (1995, 1996, and 1997); and have remained relatively steady since then. The shallowest wells show a shorter period of decline in groundwater elevations (from 1985 to 1994), and a rise that begins about 1 to 2 years earlier than in the deepest wells. While all the wells show similar trends after 1995, the approximate 150-foot difference in groundwater elevations did not change throughout the period of record.

The similar water level trends after 1995, together with the lack of a sustained water level decline in deep wells, are consistent with anecdotal knowledge that groundwater pumping demands are much lower than in areas further to the west. Given the low to modest nature of pumping in this area, the similar water level trends suggest that the Davenport observation well is near a source of groundwater recharge. Because the shallow piezometers have much different (higher) groundwater elevations than the deep piezometers throughout the period of record, seasonal and long-term trends in pumping alone do not explain the close similarity of the shallow and deep trends. Instead, a common source of groundwater recharge – probably related to precipitation – is the likely cause of the similar trends in shallow and deep groundwater levels in this area. As discussed below, other areas, located further from such recharge sources (particularly near Odessa and Lind) show very different water-level trends in shallow and deep zones due to the significant pumping from deep zones.

Possible sources of groundwater recharge near Davenport are 1) infiltration along the highlands lying between this well and the Spokane River; and 2) infiltration where the CRBG laps up against steptoes that are present to the east. While some subsurface inflow is thought to possibly occur into GWMA from the east, this likely occurs further south (primarily in Adams County) where the steptoes are absent. Because steptoes are present along the eastern boundary of Lincoln County, subsurface inflow from the east is likely not as significant a source of groundwater recharge to this portion of GWMA as it is in areas further to the south.

Dreger Nested Observation Well Cluster (North-Central Lincoln County, Northern Channeled Scablands)

Figure 35 contains a schematic diagram of the construction of well cluster AAE559 (Dreger), along with the groundwater elevation hydrographs for each individual well. This well cluster is located in north-central Lincoln County, in the Sinking Creek watershed, due south of the Town of Creston (Plate 3).

The groundwater elevations in the two Grande Ronde Basalt observation wells are 400 to 500 feet deeper than the groundwater elevations in the Wanapum Basalt observation wells, indicating that there is little, if any, direct hydraulic communication between these zones at the location of the well cluster. Specific capacity data are not available for the open borehole. However, before the individual wells (piezometers) were installed, water was observed to be entering the open borehole at depths of 300 feet (which is now monitored by piezometer J06) and 800 feet (which is not monitored by a piezometer). Additionally, a thief zone (an interflow zone that can drain water out of an open borehole) was observed at a depth of 1,080 feet which is below the deepest piezometer at this observation well cluster. This thief zone was sealed off prior to piezometer installation (Olson, 1984).

The water level data and the observations of downhole flow during drilling together indicate that the various water-bearing zones at this location are hydraulically distinct and have little natural vertical connection. Additional evidence of this limited vertical interconnection is the somewhat different water level trends observed between the two deepest and three shallowest wells in this nested well cluster. Well J06 shows significant seasonal variability, whereas the other wells do not show such a strong variation. Groundwater elevations in each individual well show long-term stability during the periods that data are available, though a very small decrease in the water level may have been occurring in the Grande Ronde Basalt (wells J03 and J04) at the time of the most recent measurement (May 1993). The overall stability of groundwater levels in each zone indicates that any groundwater pumping that might be occurring in the vicinity of this well cluster has not historically exceeded the rate of recharge to the various basalt water-bearing zones in this area. This is not surprising, given the close proximity of this area to the granitic hills that lie just to the north and likely shed runoff that can infiltrate to the various basalt interflow zones where they lap up against the hills.

Almira Nested Observation Well Cluster (West-Central Lincoln County)

Figure 36 contains a schematic diagram of the construction of well cluster AAE558 (Almira), along with the groundwater elevation hydrographs for each individual well. This well cluster is located in west-central Lincoln County, in the Wilson Creek watershed, just north of the Odessa Subarea and near the Grant County Line (Plate 3).

Groundwater elevations in the Grande Ronde Basalt were initially about 175 feet below those in the Wanapum Basalt. This difference in groundwater elevations has increased over time, to nearly 250 feet, as water levels have declined in the Grande Ronde Basalt. In 2007, groundwater elevations in the Grande Ronde Basalt wells were about 70 feet lower than the levels recorded during the first five to six years after these observation wells were installed (in 1971). Groundwater levels have remained comparatively stable in the Wanapum Basalt well and have shown less seasonal and year-to-year fluctuation than in the Grande Ronde Basalt wells.

Specific capacity data are available only for the deepest third of the open borehole (depths 546 and 750 feet, which showed specific capacities of 92 to 96 gpm/ft). However, the well construction report noted that the geophysical log showed evidence of slightly downward flow in the open borehole (Walters, 1972), which is consistent with the large difference in groundwater elevations (about 175 feet) that have been observed between water-bearing zones in the Wanapum Basalt versus the Grande Ronde Basalt.

The Almira well cluster lies just north of an inferred buried geologic structure which, if present, may be limiting the amount of drawdown occurring in the Grande Ronde Basalt in this area, particularly in comparison with the amount of groundwater level decline that has been observed to the south in the Odessa Subarea.

Odessa and Basalt Explorer Nested Observation Well Clusters (Odessa Area)

Figures 37 and 38 contain schematic well construction diagrams and groundwater elevation hydrographs for well clusters AAE563 (Odessa) and AAE564 (Basalt Explorer), respectively. These wells show the following:

- Groundwater elevations in the shallowest Wanapum Basalt well at the Odessa well cluster are relatively stable and have increased slightly since monitoring began in 1971.

- At the Odessa well cluster, the wells constructed across the Wanapum Basalt / Grande Ronde Basalt contact show somewhat deeper water levels, and greater fluctuations, than in the shallowest Wanapum Basalt well. However, groundwater elevations have returned to the levels seen in 1971 after declining slightly in the intervening years.
- At the Odessa well cluster, the deepest well (E06), which is constructed exclusively in the Grande Ronde Basalt, shows markedly different (in this case, lower) groundwater elevations than the shallower wells. This observation is consistent with marked differences in specific capacity data for these zones. Specifically, the open borehole showed a specific capacity of 22 gpm/ft once the open borehole was advanced to total depth, but less than 1 gpm/ft when the hole was above the zone where well E06 was later constructed. The geophysical log also noted that 120 gpm flowed into the well from the five uppermost zones (which are now monitored by wells E01 through E04).
- At both well clusters, the wells completed exclusively in the Grande Ronde Basalt show distinct declines in groundwater elevations, unlike the relatively stable trend observed in the Wanapum Basalt at the Odessa well cluster. By 2005, at the Odessa well cluster, the Grande Ronde Basalt groundwater elevations were 175 feet lower than measured in 1971. A similar decline has been seen in the Grande Ronde Basalt at the middle well in the Basalt Explorer well cluster (M03), and the deepest well (M04) has shown 100 feet of decline, most of which has occurred since the year 2000.

At the Odessa and Basalt Explorer wells, the vertical differences in groundwater elevations and the groundwater elevation trends observed during the past 35 to 40 years corroborate the observations of local residents and the measurement of declining water level trends during previous studies in the Odessa-Lind area (Garrett, 1968; Luzier et al., 1968; Luzier and Burt, 1974; Cline, 1984; Hansen et al., 1994; Vaccaro, 1999; Bauer and Hansen, 2000). Specifically, the long-term water level record shows that the historical problem of declining groundwater yields and lowering of groundwater levels in this area continues to this day. This is particularly evident from the measured increase in the rate of decline in the deepest penetrated basalt zone at the Basalt Explorer observation well, which shows the effects of the continued shift in pumping to ever deeper aquifers in the Odessa Subarea.

Hanford Site

Observations at the Hanford Site in Benton County during the 3-year period 1984 through 1986 show the compartmentalization of water-bearing zones in the CRBG, in terms of both differing time-trends and differences in the elevation of the piezometric surface (USDOE, 1988). Figure 39 shows the time trends in three separate boreholes containing six nested observations wells – three in Wanapum Basalt interflow zones (the Basalt of Rosalia, Priest Rapids Member; and the Basalt of Sentinel Gap and Basalt of Gingko, Frenchman Springs Member) and three in Grande Ronde Basalt interflow zones (the Rocky Coulee and Cohassett flow tops and the Umtanum Member). The hydrographs shown in the figure display the presence of an upward vertical hydraulic gradient through the entire section, as indicated by the progressive increase in groundwater elevations from the shallowest piezometer to successively deeper piezometers. Two of the three boreholes (DC-20C and DC-22C) show that this difference is slight between the three uppermost piezometers, but that this group of piezometers has notably lower groundwater elevations than those of the three deepest piezometers. Additionally, in all three boreholes (DC-19C, DC-20C, and DC-22C), during 1985 and 1986 the three shallowest piezometers in a given borehole show very different responses in timing to various anthropogenic events (drilling, pumping) and natural events (distant seismic events) than are observed in the three deepest piezometers. These two observations together indicate that the interflow zones monitored by the three shallowest piezometers have limited hydraulic connection to the zones monitored by the three deepest piezometers.

Figures 40 and 41 show the water level trends that were observed in distinct CRBG interflow zones during drilling of open boreholes at the Hanford Site. Figure 40 shows the trends in two boreholes – borehole DC-14, which is along the Columbia River in the northern portion of the Hanford Site, where the river turns from flowing northeasterly to beginning its southward course towards the City of Richland; and borehole DB-15, which is located in the interior of the Hanford Site. Figure 41 shows the trends in three boreholes located just east of borehole DB-15, within the controlled study area in the interior of the Hanford Site. These two figures together show the following:

- Borehole DC-14 along the Columbia River shows a notable increase in groundwater elevation with depth through the Saddle Mountain Basalt, an overall decrease in groundwater elevation with depth in the Wanapum Basalt, and the general continuation of lower groundwater elevations with depth in the Grande Ronde Basalt. Together, these data indicate the presence of a generally downward hydraulic gradient in the Wanapum Basalt and the Grande Ronde Basalt, with distinct changes in the magnitude and direction of the vertical gradient across specific basalt members within these two formations and also relative to the overlying Saddle Mountains Basalt.
- Borehole DB-15, in the Hanford Site interior, shows a downward gradient through the Saddle Mountains Basalt; an upward gradient across the Saddle Mountains Basalt / Wanapum Basalt geologic contact (which is suggestive of more highly confined conditions in the upper Wanapum Basalt); and an overall downward gradient in the Wanapum Basalt, though an upward gradient is present within a discrete middle portion of the Wanapum Basalt.
- Boreholes DC-19, DC-20, and DC-22 in the Hanford Site interior show a downward gradient through the Saddle Mountains Basalt, a slight downward or slight upward gradient within the Wanapum Basalt and Grande Ronde Basalt. The three boreholes each show vertical hydraulic gradients that are seemingly directed to the Wanapum Basalt from both the overlying Saddle Mountain Basalt and the underlying Grande Ronde Basalt.

These data together indicate that limited potential exists for the movement of significant volumes of groundwater vertically through the CRBG at and south of the Columbia River. Vertical hydraulic gradients are downwards near the Columbia River in the northern portion of the Hanford Site, and the vertical gradients are very low further to the south, in the Hanford Site interior, which is located closer to the more southern reaches of the Columbia River where other researchers (for example, Hansen et al., 1994; Vaccaro, 1999; Bauer and Hansen, 2000) have inferred the presence of a CRBG regional groundwater discharge zone to the Columbia River.

Trends in Rainfall and Streamflow

Bauer and Vaccaro (1990) estimated that deep percolation (groundwater recharge) rates in eastern GWMA are less than 2 inches and could be as low as 0.13 inches under undeveloped conditions. Bauer and Hansen (2000) estimated that recharge on non-irrigated lands is zero in low-elevation portions of the Columbia Plateau that receive less than 8 inches of precipitation annually. The low amounts of recharge estimated from these studies are consistent with the observation that since groundwater development for irrigation began in the 1960s, declines in rainfall amounts have not occurred in eastern GWMA. Figures 42, 43, and 44 show the year-to-year differences in rainfall compared with the historical average at three precipitation gaging stations with long-term records (Wilbur, Odessa, and Ritzville, respectively). These figures show frequent occurrence of above-normal rainfall conditions, including in most years during the following time periods: 1956 through 1961, 1978 through 1984, and 1994 through 2000. Most of the groundwater recharge that has occurred since 1950 likely has occurred during these time periods and during the single years of above-normal rainfall that occurred sporadically during other time periods. Given the arid to semi-arid climate, and given the findings by Bauer and Vaccaro (1990) and Bauer and Hansen (2000), it is likely that little, if any, recharge occurs during years of near-normal or below-normal rainfall.

Because of the fine-grained soils that lie at ground surface in most upland areas, recharge occurs predominantly in the coulees and the channeled scablands, where these fine-grained soils are thin or largely absent. As a result, the groundwater recharge that occurs in the interior of GWMA (away from its margins) occurs as infiltration of precipitation runoff and streamflow. Figure 45 shows a hydrograph of the spring-season (March through July) flows in Crab Creek at Irby, along with the spring-time precipitation as recorded at the Wilbur, Odessa, and Ritzville rain gages. The figure also shows the evapotranspiration demand (as measured in an open pan lysimeter at monitoring stations near Lind and Othello), which averages between 30 and 35 inches during the spring season. In most years, little runoff occurs during the winter season because the ground is frozen. Consequently, the Crab Creek hydrograph for the spring season is an indicator of the relative amounts of recharge that occur over many years, in that it shows the streamflow that occurs as a result of watershed yield after accounting for evapotranspiration losses. The streamflow, and thus the watershed yield, arise from 1) real-time precipitation runoff and 2) to a varying extent from one year to the next, the melting of accumulated snowpack.

Figure 45 shows that spring-season rainfall since 1950 has ranged from as little as 1 inch to nearly 10 inches, and Crab Creek flows have ranged from nearly zero to almost 400 cfs. Figure 45 also shows frequent oscillation in the amount of spring-season rainfall since 1950. While the figure shows that the annual fluctuations in spring-season Crab Creek flows generally follows the fluctuations in spring-season rainfall, the figure also shows an apparent downward trend in the Crab Creek spring-season flows. The fact that the downward trend in the Crab Creek flow is accompanied by a lack of such a precipitation trend indicates that streamflow losses from Crab Creek upstream of the Irby stream gage have increased over time. This increased loss of streamflow is likely in the form of increased groundwater recharge that is caused by the lowering of the regional water table in the shallow alluvial and basalt zones in the floor of the Crab Creek coulee, upstream of the Irby stream gage. As discussed elsewhere in this report, such a lowering of the shallow water table has been seen elsewhere (such as in the Sinking Creek watershed [Wildrick, 1991]) and is coincident in time with the regional increase in the amount of groundwater pumping and the associated increase in the number of deep uncased (open-borehole) production wells that artificially allow groundwater drainage to occur from shallow to deep water-bearing zones. Decreases in rainfall since the onset of groundwater development have not occurred and, therefore, cannot be the cause of the historical declines in groundwater elevations.

The trends shown in Figure 45 also explain the presence of water in the coulee lake systems prior to groundwater development. Prior to the installation of water supply wells, and in particular because of the absence of uncased wells penetrating both the shallow (Wanapum Basalt) and deep (Grande Ronde Basalt) aquifers, the pre-development hydrology consisted of a shallow basalt groundwater system that was “full”, in that groundwater levels were likely at or near ground surface in the coulees. Precipitation runoff in the coulees could not appreciably infiltrate into the shallow groundwater system and therefore remained as surface runoff, creating the lake system and the abundant flows of other well-known features such as Delzer Falls. From a groundwater perspective, this pre-development hydrology can be thought of as a condition of “rejected groundwater recharge”, in that streamflow in the coulee floors (i.e., precipitation runoff) could not appreciably infiltrate into the shallow basalt system because of its high water table elevation. Once groundwater levels began to decline in the shallow basalt system (because of pumping and well construction practices), the subsequent lowering of the water table in the shallow basalt system created space to accommodate the infiltration of surface flows into the sediments and shallow basalt on the coulee floors.

Implications of Declining Trends in Groundwater Levels

Our interpretations of the data from the nested well clusters have several important implications for the eastern portion of GWMA, and in particular in the Odessa Subarea. First, the data show that natural recharge to the aquifers hosted by the Grande Ronde Basalt is minimal, and where recharge does occur, it occurs very slowly. Recharge to the aquifers in the Grande Ronde Basalt is minimal because of the lack of vertical connection between shallow and deep aquifer zones, and the lack of both potential recharge locations and recharge water. Specific reasons that recharge to the aquifer zones in the Grande Ronde Basalt is minimal include:

- There are few places where the Grande Ronde Basalt interflow zones can receive recharge because of their general lack of surface exposure to water bodies or precipitation. Additionally, the amount of exposure to potential recharge sources diminishes with depth in the Grande Ronde Basalt.
- The Grande Ronde Basalt interflow zones that are exposed at or near ground surface are relatively thin and do not provide much area for precipitation or surface water to infiltrate.
- Precipitation and winter/spring runoff are small in magnitude compared to pumping.
- Natural leakage from shallower basalt interflow zones to deeper zones is miniscule.

The recent local-scale mapping activities conducted for the Subsurface Geologic Mapping and Hydrogeologic Assessment project (GWMA, 2009a, 2009b) has found that there are few exposures of the Grande Ronde Basalt that could be receiving significant amounts of groundwater recharge. Specifically:

- The updated mapping work shows that the portion of the Snake River pooled behind Lower Monumental Dam is in contact with the Sentinel Bluffs Member of the Grande Ronde Basalt. Additionally, a well drilled in 2008 just south of Connell and approximately 16 miles west-southwest of Lower Monumental Dam (in T12N, R21E, Section 13, SW ¼) showed a static water level elevation of approximately 460 feet, which is about 80 to 85 feet below the typical elevation of the pool behind the dam. Based on this elevation relationship and the west-southwest direction of dip of the top of the Grande Ronde Basalt, it is likely that this portion of the Snake River is a recharge boundary for the upper one or two members of the Grande Ronde Basalt in the southern-most portions of GWMA (in Franklin County).
- Elsewhere, the few exposures of the Grande Ronde Basalt that exist are present 1) on highlands where precipitation averages no more than about 15 inches per year, and 2) in lowlands on the periphery of GWMA, such as Long Lake and the Grand Coulee lake system, where the basalt members dip towards the lakes, rather than away from the lakes, and therefore cannot act to convey water to the interior of GWMA.

These findings are consistent with earlier studies. In particular, Tolan et al. (1989) and Reidel et al. (1989b) prepared maps that show that only the uppermost member of the Grande Ronde Basalt (the Sentinel Bluffs Member) and possibly one or two of the five deeper Grande Ronde Basalt members (the Umtanum and Wapshilla Ridge Members) are present at and beyond the northern and eastern margins of GWMA (see Figure 46). These observations result in a significant finding that with the exception of Franklin County, the

Grande Ronde Basalt aquifers elsewhere in GWMA are not connected to perennial surface water bodies (rivers, streams, or lakes) anywhere in or near GWMA, and therefore are not recharged by the surface water bodies that are in or near GWMA.

The groundwater level record from the nested wells within eastern GWMA (the Odessa Subarea) also indicates that the existing groundwater supplies in the deeper Grande Ronde Basalt flows are not reliable or sustainable in the long-term at current usage rates. Therefore, continuing to drill deeper into progressively deeper aquifers in the Grande Ronde Basalt is only a temporary solution for declining water levels and pumping rates. These implications derive not only from the study of GWMA geology and water level trends, but also from geochemical studies that evaluate the ages and characteristic signatures of groundwater at various locations and depths, as discussed below.

GEOCHEMICAL AND AGE-DATING INDICATORS

Variations in the chemical and isotopic composition of groundwater in CRBG aquifers provide spatial information on 1) the recharge sources, at present and during the past; 2) a time-integrated record of water-rock interactions; and 3) groundwater residence times. In particular, different recharge sources (ancient glacial melt water, irrigation waters, and recharge from present-day surface waters such as lakes, rivers, and canals) can be identified using geochemical tracers and groundwater dating methods. A general understanding of the geochemical processes responsible for the hydrochemical evolution of groundwaters within the CRBG aquifer system is required to place the observed water quality and isotopic data in perspective. A brief summary of the current understanding of the geochemical characteristics of CRBG groundwater is presented first, followed by a discussion of specific isotopic and chemical tracers relevant to recharge and groundwater age considerations. A detailed report on the findings of a geochemical evaluation conducted under the Subsurface Geologic Mapping and Hydrogeologic Assessment project is contained in a companion report (GWMA, 2009c).

Hydrochemical Evolution in CRBG Aquifers

The chemical composition of groundwaters in the CRBG aquifer system depends on 1) the source and chemical composition of the recharge water, 2) the nature and dissolution rates of the mineral phases in the rock formations through which the water flows, and 3) the residence time of water in the aquifer system. A number of studies have examined the geochemical controls on groundwater composition and chemical evolution within the CRBG aquifers (Deutsch et al., 1982; Hearn et al., 1985, 1990; Steinkampf et al., 1985; Early et al., 1986; USDOE, 1988; Steinkampf, 1989; Steinkampf and Hearn, 1996; Reidel et al., 2002).

The chemical evolution of groundwater in CRBG aquifers is influenced by two major processes: (1) dissolution of basalt by carbonic acid and (2) silicate hydrolysis. The chemical evolution path begins with the initial reaction of oxygenated, weakly acidic,

CO_2-charged meteoric waters with the basaltic rocks in the outcrop/recharge areas along ridges or regional outcrops. In recharge areas where a significant soil zone is present, additional CO_2 can be generated by microbial oxidation of soil organic matter, increasing the reactivity of the recharging water. CRBG flows consist primarily of plagioclase feldspar (labradorite), pyroxene (augite), and iron oxides (titanomagnetite), with minor amounts of apatite, olivine, and metal sulfides set in a glassy to cryptocrystalline matrix. Secondary minerals include nontronitic (Fe-rich) smectite, silica polymorphs, clinoptilolite, and iron oxyhydroxides (Ames and McGarrah, 1980; Benson and Teague, 1982; Hearn et al., 1985).

Infiltration of precipitation and other surface waters initially results in dilute calcium-magnesium-bicarbonate (Ca-Mg-HCO_3) type water. As groundwater moves along regional flow paths, toward the center of the basin, progressive silicate hydrolysis and dissolution results in an increase in silica, plus an increase in pH from around 8 to 10, and leaching of fluoride and chloride from the basalt matrix. Precipitation and ion-exchange reactions further modify the water by removing calcium and magnesium in exchange for sodium (Na), resulting in Na-HCO_3 type water. Long groundwater residence times during which secondary minerals (iron-rich smectite clays, zeolites, calcite, and silica) precipitate also result in removal of calcium, magnesium, potassium, iron, carbonate, and silica from basalt groundwaters. This results in sodium-chloride (Na-Cl) dominated water in the deepest parts of the CRBG aquifer system sampled in the central basin (Reidel et al., 2002).

These highly chemically evolved (deeper and older) groundwaters often contain elevated fluoride concentrations (up to several tens of milligrams per liter [mg/L]) in the Grande Ronde Basalt aquifers of the central Columbia Basin (Pasco Basin). Local anomalies of elevated sulfate and dissolved methane are also superimposed on the general evolutionary sequence described above. For example, on the eastern side of the Pasco Basin, deep Grande Ronde Basalt aquifers are high in dissolved sulfate but devoid of dissolved methane. On the western side of the basin, high dissolved methane occurs with low dissolved sulfate (Johnson et al., 1993). Localized areas of methane, with a stable carbon and hydrogen isotope signatures indicating a thermogenic source, occur near the Cold Creek fault in the northwestern part of the Pasco Basin. Lower methane concentrations appear to be of biogenic origin (Johnson et al., 1993).

Stable Isotopes, Age Tracers, and Groundwater Recharge Mechanisms

As part of recent investigations in the GWMA, selected irrigation, municipal and private supply wells, as well as surface water bodies representing potential recharge sources, were sampled and analyzed for a suite of geochemical and isotopic parameters, including major and trace element concentrations, stable isotopes, dissolved gases, and age tracers (radiocarbon, tritium, chlorofluorocarbons [CFCs]). The sampling work was designed to allow evaluation of the origins and hydrochemical evolution of the groundwater and, in particular, to evaluate recharge mechanisms and timescales in the deeper basalt aquifer system. In particular, tritium and CFCs allows for identifying and quantifying recent recharge components (a few decades to a few years old), while radiocarbon is useful for identifying groundwater that is hundreds to tens of thousands of years old. By combining data for age tracers with different characteristic timescales, it is possible to estimate the time elapsed since the water entered the subsurface and also to identify mixtures of older and younger groundwater in production wells. This information has been used in conjunction with the geologic model and water level trend data discussed earlier in this report to identify connections to current potential sources of recharge in the aquifer system.

As shown in Figure 47 and 48, relatively young groundwater recharge ages (i.e. less than 50 years) are generally found for shallow wells open to unconfined sediment aquifers, indicating direct connections to present day recharge sources (canals, seasonally water-filled coulees, creeks and lakes). In samples from some deeper CRBG municipal supply wells that are open over large vertical intervals, age tracers indicate the produced groundwater is a mixture of old (thousands of years) and young water entering from different flow zones with different connections to present day recharge. However, as shown in Figure 49, wells that are cased through shallow zones and obtain water exclusively from deep zones will show apparent ages that are much older.

These data, in combination with static water level trends, provide insights on the sustainability of current groundwater use on a local and regional scale. The findings of the geochemical studies are consistent with interpretations about groundwater occurrence, movement, and declining water level trends, as derived from the subsurface geologic mapping and interpretation activities (GWMA, 2009a, 2009b) and the available long-term water level record. Examples of this consistency are as follows:

- Just west of the East Low Canal, near Moses Lake, the City of Moses Lake Well 18 is completed in the Wanapum Basalt (Lower Roza Member and Frenchman Springs Member) and has historically shown stable static water levels. The water from this well is less than 50 years old as indicated by radiocarbon, tritium and CFC data, which implies a direct connection to the nearby East Low Canal through the Roza Member and Frenchman Springs Member interflow zones. This is consistent with the mapped subsurface geology, in that the Roza Member is erosionally thinned in this area and provides a window into the Frenchman Springs Member in which Well 18 is constructed (see Figure 50).
- Nearby, another City of Moses Lake well (Well 17) is completed in the upper portion of the Grande Ronde Basalt. Overlying water-bearing zones in the Wanapum Basalt have been sealed off in this well. Accordingly, the apparent radiocarbon age for groundwater produced by this well is approximately 6,000 years, but contains detectable tritium, indicating a mixture of old and young water. The proportion of recharge from the young water component is estimated to be less than 20 percent and is too little to offset withdrawals (i.e. 80 percent of the water production is derived from storage, therefore water levels are declining). There are no geologic features indicating a direct connection to surface water; therefore, the young recharge component likely represents limited vertical leakage through the many uncased wells present in the vicinity of the City of Moses Lake.

- Likewise, in the Odessa Subarea approximately 20 miles east of Moses Lake, irrigation wells sealed into the deep members of the Grande Ronde Basalt have declining static water levels, apparent radiocarbon ages ranging from 10,000 to 20,000 years, and generally no detectable tritium or CFCs. In one example, illustrated in Figure 51, a recently drilled well completed in the Umtanum Member and Ortley Member of the Grande Ronde Basalt has an apparent radiocarbon age of 15,800 years and shows no geologic connection to any surface water recharge sources.

Radiocarbon and stable isotope data, and the absence of detectable tritium and CFCs, indicate that in the Odessa Subarea, groundwater produced from deep irrigation wells completed in the lower Grande Ronde Basalt is pre-Holocene in age (more than 10,000 years old). The ancestral origin of the groundwater in the Grande Ronde Basalt is consistent with the subsurface geologic mapping and with other prior studies, which together show the following:

- Studies (including Lindberg, 1989) of the cooling joints that are abundant in the basalt flow interiors have concluded that water can move through the joints soon after emplacement of the basalt, but the joints seal up over time as a result of this movement. Consequently, the deeper the basalt flow, the more likely it is that groundwater cannot move vertically through the flow, except possibly at limited rates along some regional-scale or local-scale structural features such as faults and folds. As a result, the deeper the flow, the more isolated it is from groundwater-bearing zones in shallower flows, particularly in the basin interior.
- The Grande Ronde Basalt members have little, if any, direct contact with surface water bodies (rivers, streams, lakes, canals) in and bordering GWMA, except possibly the portion of the Snake River immediately downstream of, and pooled behind, Lower Monumental Dam. Specifically:
    - Geologic mapping indicates that the Snake River is in contact with the Sentinel Bluffs Member and, possibly, the deeper Umtanum Member and Ortley Member, and therefore may be a recharge boundary for these Grande Ronde Basalt interflow zones in the southern-most portions of GWMA (in Franklin County).
    - In contrast, statistical analyses of Grande Ronde Basalt groundwater in GWMA indicates that very old waters are present not only within the interior of the Odessa Subarea (i.e., in western Adams County and southwestern Lincoln County), but also close to the margins of the Grande Ronde Basalt in eastern Adams County and northern Lincoln County. This is particularly evident from a spatial and statistical analysis (using the Principal Components Analysis [PCA] method) that was conducted on the ensemble of geochemical sample data for Grande Ronde Basalt groundwater. The PCA method identified a principal component (called PC1) that consisted of chemical evolution, or aging, of CRBG groundwater, reflecting the importance of how water-rock reactions dominate the observed geochemistry of these groundwater samples. On

Figure 52, the highest PC1 values, which correspond to the most chemically-evolved, and therefore oldest waters, are displayed in red (oldest) and orange (next oldest). As shown in the figure, such samples are seen in Marlin Hollow (east of Highway 21, about halfway between Odessa and Wilbur), in the City of Davenport, and at all six Grande Ronde wells located around Ritzville and Sprague. Additionally, many of these Grande Ronde Basalt groundwater samples were collected from wells that are open not only to the Grande Ronde Basalt, but also to the Wanapum Basalt. These observations suggest that the Grande Ronde and deep Wanapum groundwater zones near the eastern and northeastern limits of GWMA contain highly evolved groundwater that was recharged in the past by ancient water sources, rather than recently by young water sources.

The radiocarbon dating, subsurface geologic mapping, and cooling joint studies together provide significant evidence that with the exception of Franklin County, groundwater in the Grande Ronde Basalt members within GWMA probably has not received appreciable recharge for many centuries and essentially was a subsurface “reservoir” with little to no significant inflows or outflows prior to groundwater development. Because the Grande Ronde aquifer system probably has not seen significant natural recharge since at least the late Pleistocene, when conditions were wetter than present, it is highly likely that little replenishment of groundwater resources in the Grande Ronde Basalt has occurred in Adams, Grant, or Lincoln counties since the onset of groundwater development in this deep aquifer system.

Geochemical Indicators of Groundwater Discharge Mechanisms

Insights to the natural discharge mechanisms for CRBG groundwater, particularly groundwater in the Grande Ronde Basalt, can be obtained from studies conducted at the Hanford Site for the BWIP project. These studies (USDOE, 1988) are particularly useful because the Hanford Site lies both within, and immediately south and west of, the southwestern boundary of GWMA. Additionally, the Hanford Site and the adjoining reaches of the Columbia River are located at the structurally lowest point in the Columbia Basin, with the CRBG basalt flows beneath GWMA dipping towards this area from the north and east.

USDOE (1988) examined geochemical data for surface waters, springs, shallow groundwater (the Saddle Mountains Basalt), and deep groundwater (the Wanapum Basalt and Grande Ronde Basalt). The study concluded that the geochemical signatures show evidence of upwards groundwater leakage from the Grande Ronde Basalt to the Wanapum Basalt at the Hanford Site. The study concluded that the Wanapum Basalt is likely a mixing zone for groundwater from both the underlying Grande Ronde Basalt and the overlying Saddle Mountains Basalt. Additionally, the study found two zones of Grande Ronde water beneath the Hanford Site that were distinguished by high methane in one area (up to 1,200 mg/L) and high sulfate in another area (at concentrations exceeding 100 mg/L). The study concluded that these waters likely originate from sub-basalt

Tertiary sediments, as the geochemical signatures cannot be explained solely by considering the geochemical reactions that occur between basalt and groundwater. Based on this and other information, USDOE (1988; p 3.9-173) concluded that "the concept that significant, areally distributed, vertical groundwater flow through cooling and tectonic fractures is a general phenomenon in the central Columbia Plateau probably is incorrect based on hydrochemical data." The study report concluded that faults or fracture zones are more likely to be the primary conduits for vertical movement of groundwater.

While USDOE (1988) did not estimate the rates of groundwater exchange between the Grande Ronde Basalt and the overlying Wanapum Basalt, it is possible to estimate the general range of time frames over which such exchanges might occur in the Hanford Site area. USDOE (1988) reported that the magnitude of the upward vertical gradients in the Wanapum Basalt and Grande Ronde Basalt are approximately 10^{-3} feet per foot beneath the Hanford Site. Given the range of vertical hydraulic conductivity values estimated at the Hanford Site (1×10^{-9} to 3×10^{-3} feet per day [USDOE, 1988]), the equivalent depth (or volume per unit area) of water moving upwards from the Grande Ronde Basalt to the Wanapum Basalt is likely on the order of 1×10^{-12} to 3×10^{-6} feet of water each day in this general area. This in turn suggests that under the conditions observed at the Hanford Site, a hypothetical 1-foot high column of water would take between 1,000 years and 3 billion years to migrate vertically out of a basalt interflow zone in the Grande Ronde Basalt. This calculation indicates that any upwards movement of groundwater from the Grande Ronde Basalt to the overlying Wanapum Basalt near the Columbia River probably occurs extremely slowly. This finding in turn is consistent with the understanding that limited recharge is occurring regionally to the Grande Ronde Basalt, except possibly along the Snake River in eastern Franklin County.

PRINCIPAL OBSERVATIONS AND CONCLUSIONS

Long-term water level records for CRBG wells in GWMA indicate that groundwater levels in shallow and deep CRBG water-bearing zones have declined markedly in Adams County and much of Lincoln County since the onset of groundwater development for irrigation purposes in the 1960s. The data indicate that groundwater levels in this part of GWMA are continuing to decline as time goes on, particularly in the deepest water-bearing zones that have been tapped for groundwater development (in the upper and lower Grande Ronde Basalt).

The data and interpretations provided by past and present geologic studies, hydrologic evaluations, groundwater level analyses, and water quality (geochemical, age-dating and isotopic) studies, collectively provide a consistent understanding of the geologic framework of the Columbia Plateau and the behavior of the many CRBG aquifers that comprise the local basalt groundwater resource inside GWMA. The groundwater recharge and flow system in the CRBG aquifers underlying the GWMA is characterized by a series of separate, water-bearing layers found in interflow zones at the tops and bottoms of individual basalt flows. These interflow zone layers, or aquifers, are separated by the dense, solid, unfractured basalt rock that forms the bulk of the basalt section in the Columbia Basin. The aquifers in the interflow zones can receive recharge where they are at and near the ground surface, in direct hydrologic connection with surface water and high precipitation areas. An interflow zone can also receive recharge if its outer margin is buried, in which case the lateral "pinching out" of the interflow zone allows upgradient groundwater in adjoining interflow zones to subsequently recharge the pinched-out zone at its margin. Groundwater in the interflow zones moves more-or-less parallel to stratification along the tops and bottoms of the individual dense basalt flows. The water table elevation in a given interflow zone is dictated by the vertical positions (elevations) of the interflow zone and the elevation of the recharge area for the interflow zone. The horizontal hydraulic gradient is dictated by the slope (dip) of the top of the underlying dense basalt flow. In the central portion of the study area (away from its margins), vertical movement of groundwater through the dense basalt flow interiors is extremely small in magnitude, occurring primarily in coulees and artificially through wells that are constructed as uncased boreholes open to multiple interflow zones.

In the Columbia Basin, the CRBG groundwater system is compartmentalized not only vertically, but also laterally. Folds and faults commonly act to restrict lateral groundwater movement and can almost act as barriers to lateral groundwater flow, especially in the interior of the basin. An example of this is a monoclinal flexure zone that was first inferred by Luzier and Burt (1974) and has now been identified by the Subsurface Geologic Mapping and Aquifer Assessment Project (see Plate 2). This monoclinal flexure zone coincides with the occurrence of significant groundwater declines (east of the flexure) with areas where lesser declines have occurred to the west. Other examples of features that can restrict lateral groundwater movement include a suspected dike system along Cow Creek in eastern Adams County and a dike system that has been mapped near the City of Cheney, just east of GWMA.

Generally speaking, the Wanapum Basalt and the Grande Ronde Basalt have some important differences in their water-bearing capability, the age of their waters, their ability to receive recharge from surface water sources, and thereby their ability to sustain groundwater pumping on a long-term basis. Specifically:

1. In eastern GWMA, the Wanapum Basalt has notably lower water-yielding capability, and therefore a lower apparent permeability, than the Grande Ronde Basalt. This is indicated by the large number of production well deepenings in the area, as well as by data from specific capacity tests conducted in the State observation well network. Water level data from the State observation well network also show that the initial declines in Wanapum Basalt groundwater levels in eastern GWMA have largely stabilized during the past 3 or more decades, whereas groundwater levels in the Grande Ronde Basalt are continuing to decline markedly in this same area.
2. From the perspective of water supply development and sustainability, the Wanapum Basalt and the Grande Ronde Basalt have virtually no interconnection in the interior of GWMA, other than through uncased boreholes. At the State observation wells, trends in water levels over time are distinctly different in the Wanapum Basalt members than in the Grande Ronde Basalt. Water levels in the

Wanapum Basalt have generally shown only minor fluctuations from year to year since the early 1970s, with little if any long-term changes occurring as groundwater pumping has shifted into the Grande Ronde Basalt during the past few decades. Compared with the Wanapum Basalt, the Grande Ronde Basalt shows much deeper water levels with distinct declining trends in recent years. If the Grande Ronde Basalt members were highly interconnected with the various members of the Wanapum Basalt, then the trends and water levels would be similar. Yet this is not the case, which means that the Wanapum Basalt is not significantly recharging the Grande Ronde Basalt, except where uncased boreholes create artificial cross-connections. This finding is consistent with data from the Hanford Site (USDOE, 1988), which is located in an inferred regional discharge zone for Wanapum Basalt and Grande Ronde Basalt groundwater. The Hanford Site data suggest that it would take between 1,000 and 3 billion years for a hypothetical 1-foot water column to migrate upwards out of the Grande Ronde Basalt, given the typical values for the vertical hydraulic gradient and vertical hydraulic conductivity of the basalt flow interiors. The data at Hanford and in GWMA are consistent in that they provide substantial evidence that natural vertical connection between the Wanapum Basalt and the Grande Ronde Basalt is minimal in the inferred regional groundwater discharge area at and near Hanford and also in the interior of the Columbia Basin.

3. Natural interconnection may exist at the outer margins of the Wanapum Basalt, where in some locations the underlying Grande Ronde Basalt may extend a limited distance outward from the margin of the Wanapum Basalt, closer to potential recharge sources. However, any such areas where a natural interconnection exists are far from the areas where the largest water level declines have occurred (in the Odessa Subarea). Additionally, the subsurface geologic mapping conducted under this study has demonstrated that the Wanapum Basalt and Grande Ronde Basalt aquifers are not recharged by the Columbia and Spokane Rivers. Furthermore, statistical analyses of the geochemical data for the Grande Ronde Basalt indicate that the water types are as highly evolved near the eastern margin of GWMA as in the interior of the Odessa Subarea, which suggests that any recharge to the Grande Ronde Basalt from the east and north is extremely limited in magnitude.

4. The Wanapum Basalt tends to have younger groundwater than the Grande Ronde Basalt. Groundwater in Wanapum Basalt members is recharged by 1) streamflows in coulees, primarily in eastern GWMA where the Wanapum Basalt is exposed in the coulee floors, and 2) and by canal systems that penetrate into the Wanapum Basalt in certain areas in the central and western portions of GWMA (for example, near Moses Lake and Royal City). The geologic, water level, and age-dating studies together indicate that modern artificial recharge is occurring to the Wanapum Basalt via artificial and natural pathways. Because of the significant exposures of shallow (Wanapum) basalt in the coulee floors of northern and eastern GWMA, additional artificial recharge in the coulee floors would likely increase groundwater elevations in the Wanapum Basalt.

5. As first discussed by Luzier and Burt (1974), uncased wells are a significant cause of historical groundwater levels declines in the Wanapum Basalt members, because the non-pumping water levels in these members are much higher than groundwater levels in the underlying Grande Ronde Basalt, which is the target of many irrigation and other production wells in GWMA. As a result, drainage of groundwater from the shallow zones via uncased boreholes is a passive process, occurring whether or not the well is actively pumping from its deep target water-bearing zone in the Grande Ronde Basalt.
6. Variations in rainfall do not explain the historical declines in groundwater levels and, where observed (i.e., Sinking Creek and Crab Creek), the historically observed declines in streamflows. The past 40 to 50 years of groundwater development have not been accompanied by predominantly drier-than-normal conditions.
7. Groundwater in the Grande Ronde Basalt, both in areas of significant declines and other areas, is very old and may be receiving little natural recharge under present conditions, except possibly in Franklin County where the Grande Ronde Basalt appears to be in connection with the Snake River. In the Odessa Subarea, radiocarbon and stable isotope data, and the absence of detectable tritium and CFCs, indicate that groundwater produced from deep irrigation wells completed in lower Grande Ronde Basalt members is pre-Holocene (more than 10,000 years old), indicating that it recharged the Grande Ronde Basalt prior to the late-Pleistocene Missoula Floods. Studies of the cooling joints that are present in the basalt flow interiors have concluded that water can move through these joints soon after emplacement of the basalt, but that the joints seal up over time as a result of this movement. Consequently, it is possible that many centuries, or thousands of years, have passed since appreciable recharge occurred to the Grande Ronde Basalt. This means that prior to groundwater development, the water-bearing zones in the Grande Ronde Basalt essentially constituted a subsurface "reservoir" with little to no significant inflows or outflows (i.e., ambient predevelopment groundwater recharge and groundwater discharge rates were extremely small in magnitude). With the onset of groundwater development, the water level data indicate that significant discharges of groundwater by pumping activities have not been balanced by groundwater recharge, particularly in the Odessa Subarea. This observation, the radiocarbon dating, and the cooling joint studies together indicate that the post-development groundwater budget in Adams, Grant, and Lincoln counties can be described as "discharge via pumping is approximately equal to the change in groundwater storage, with little or no subsequent recharge of the aquifer system".
8. Deepening wells is only a temporary solution to mitigating declining groundwater levels and well yields. In past years, the increase in the number of wells being deepened into the Grande Ronde Basalt likely caused an increase in the volume of water draining out of the Wanapum Basalt in some areas. Additionally, the increase in pumping from the Grande Ronde Basalt, is tapping ancient sources of water that receive little if any recharge near groundwater pumping centers or even at the margins of GWMA.

9. Items 1 through 8, taken together, indicate that while the existing groundwater supplies in the Grande Ronde Basalt may remain viable for continued use in the near future, these supplies are not reliable or sustainable in the long-term under current water management programs, particularly in the portions of Adams County and southern Lincoln County that lie east of the flexure zone and west of the Cow Creek drainage. While the long-term outlook for Grande Ronde Basalt groundwater supplies in this portion of GWMA is not promising, increasing the groundwater levels in the Wanapum Basalt via artificial recharge may be possible in this same area because of the prevalence of Wanapum Basalt exposures in coulee floors and the northern channeled scablands of northern Lincoln County.

These findings are based on the data and interpretations provided by past and present studies of the geologic characteristics, groundwater level trends, and groundwater ages inside GWMA. The confidence in these findings has been substantially increased by the recent completion of subsurface geologic mapping in northern Lincoln County, and also by the consistency of these findings with many of the previous hydrogeologic studies conducted in the Columbia Basin. The findings in this report thus constitute a hydrogeologic conceptual model for the CRBG aquifer system, which provides a working framework for future monitoring and management of the regional groundwater resource, including the formulation, analysis, and implementation of resources management strategies.

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FIGURES 1 THROUGH 52

FOR THE REPORT TITLED

GROUNDWATER LEVEL DECLINES IN THE COLUMBIA RIVER BASALT GROUP AND THEIR RELATIONSHIP TO MECHANISMS FOR GROUNDWATER RECHARGE: A CONCEPTUAL GROUNDWATER SYSTEM MODEL FOR THE COLUMBIA BASIN GROUND WATER MANAGEMENT AREA OF ADAMS, FRANKLIN, GRANT, AND LINCOLN COUNTIES, WASHINGTON

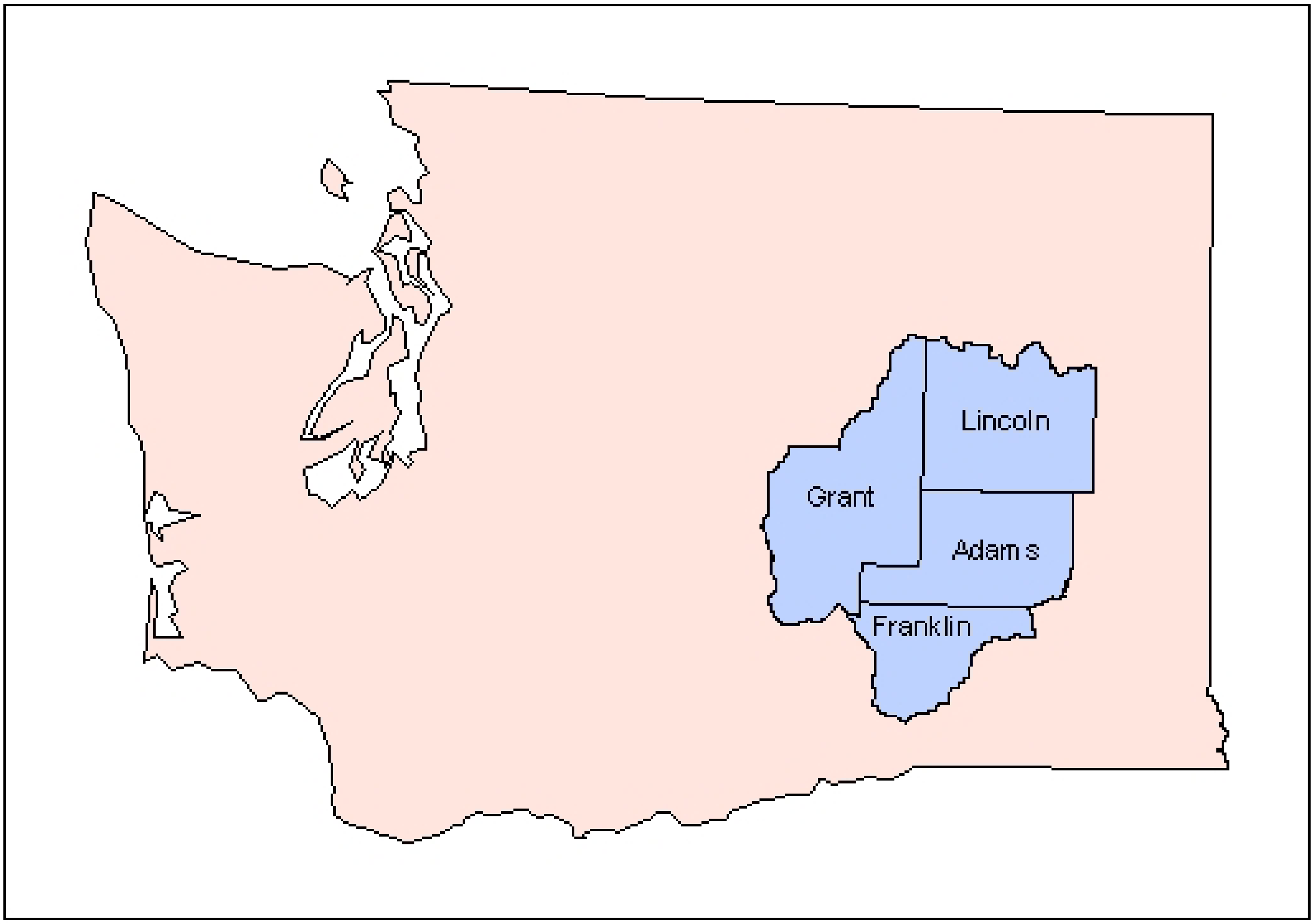


Figure 1. Location of Columbia Basin Ground Water Management Area,
(Adams, Franklin, Grant, and Lincoln Counties, Washington)

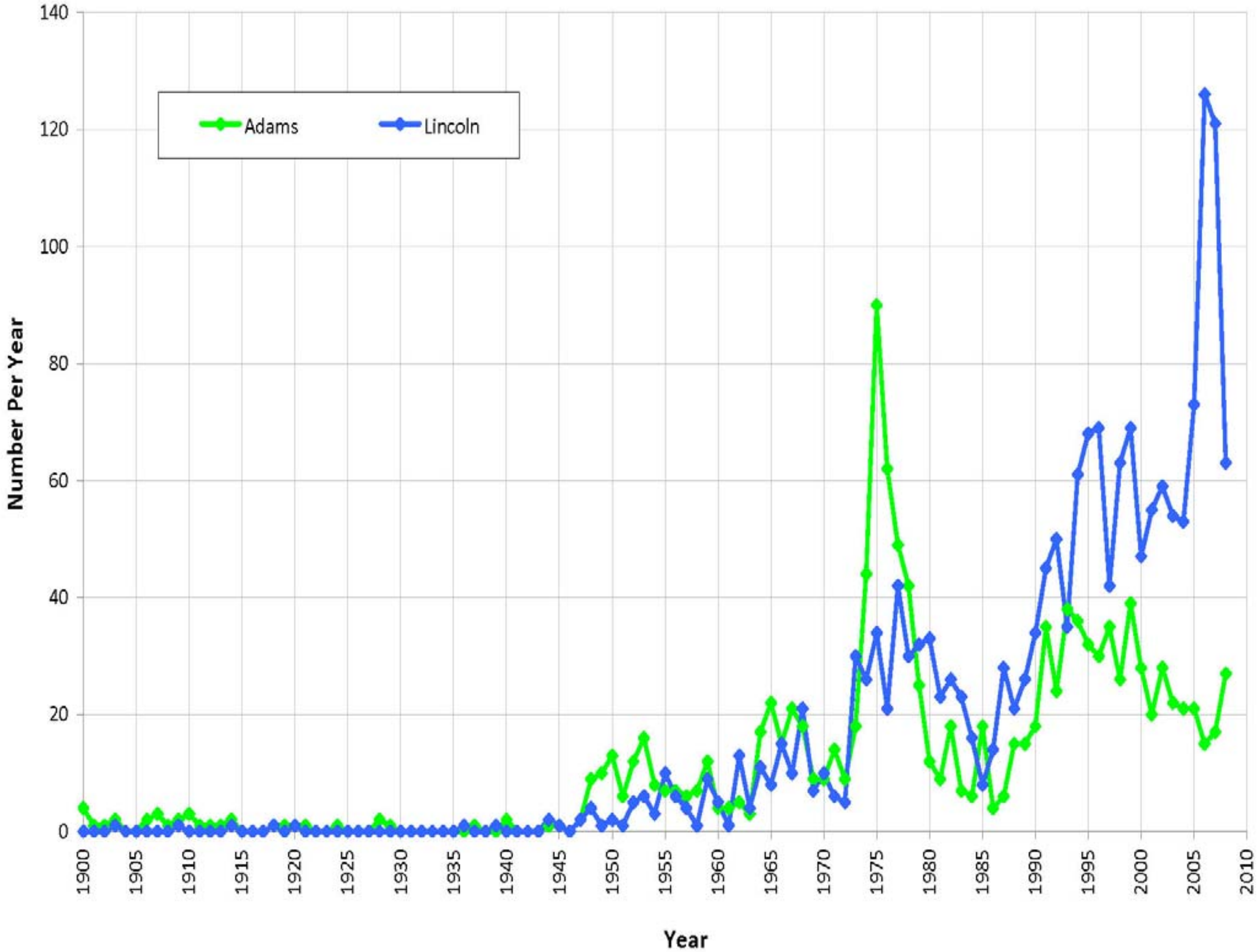


Figure 2. Number of water wells drilled or deepened per year in Adams and Lincoln County. Source: Washington Department of Ecology.

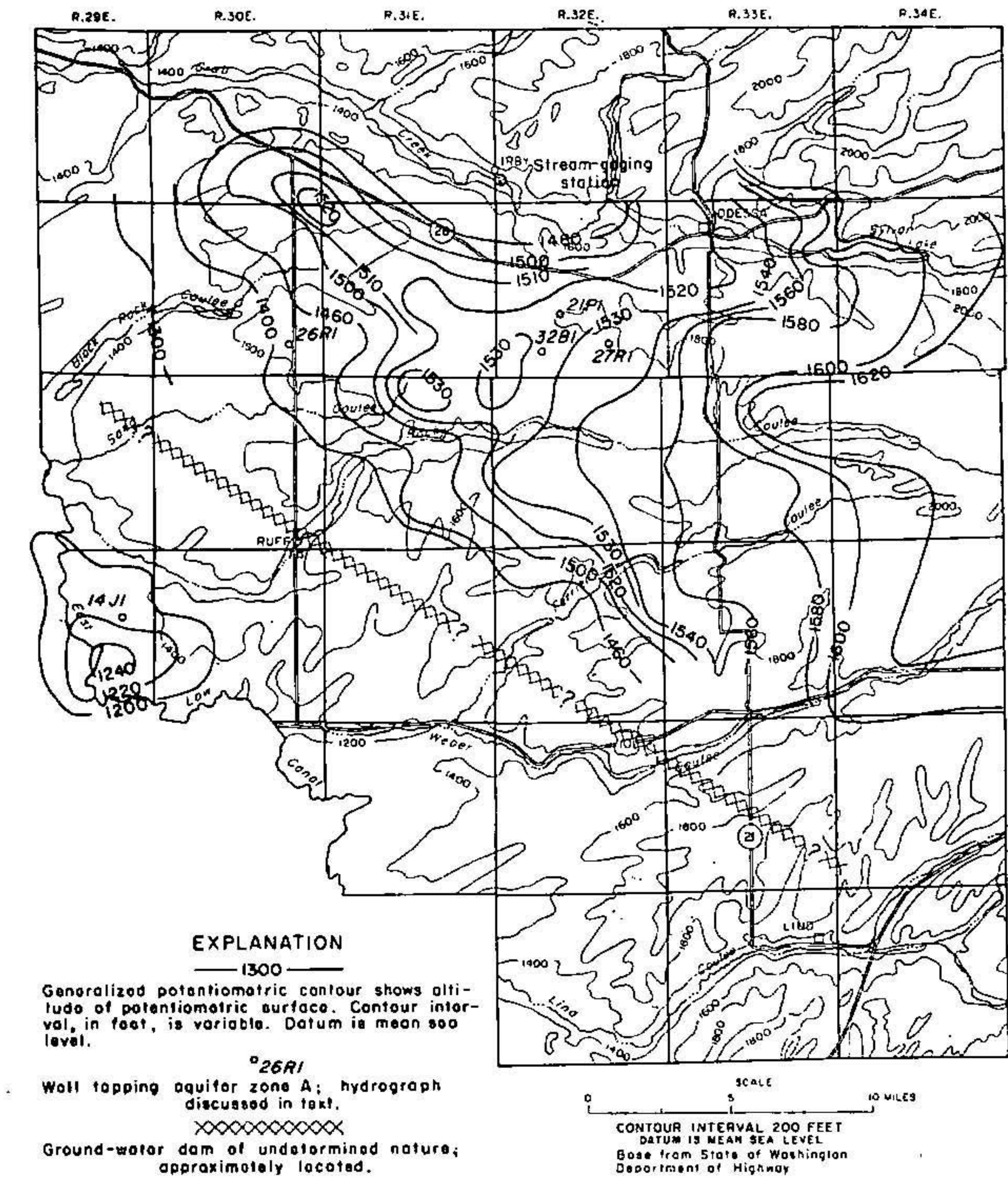


Figure 3. Contours of equal groundwater elevations (potentiometric surface) in the Odessa area, Spring 1967, for the “upper aquifer zone” in the CRBG, as described by Luzier and Burt (1974). The hatched line is the “groundwater dam” whose presence they inferred from the groundwater elevation contours.

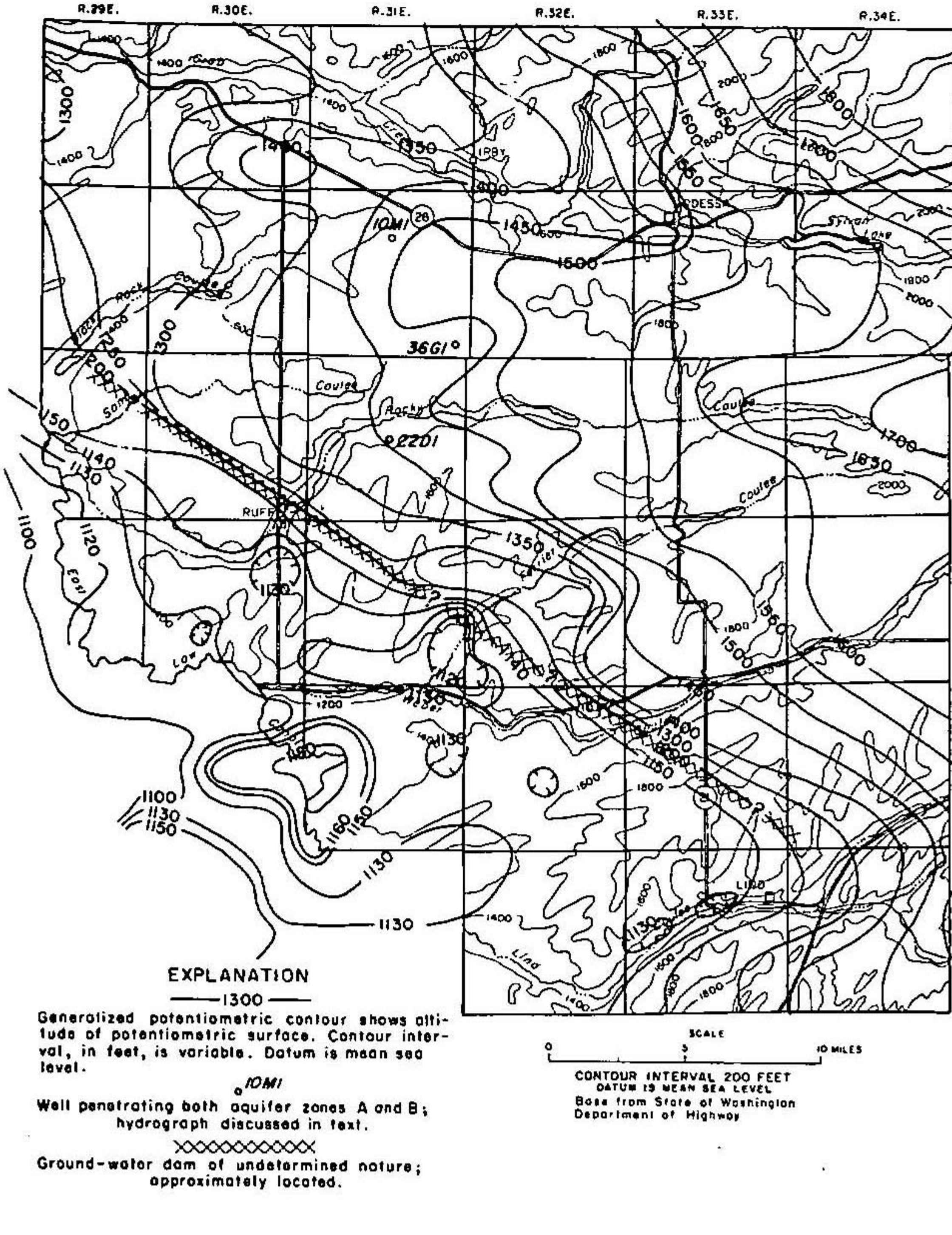


Figure 4. Contours of equal groundwater elevations (potentiometric surface) in the Odessa area, Spring 1967, for the “lower aquifer zone” in the CRBG, as described by Luzier and Burt (1974). The hatched line is the “groundwater dam” whose presence they inferred from the groundwater elevation contours.

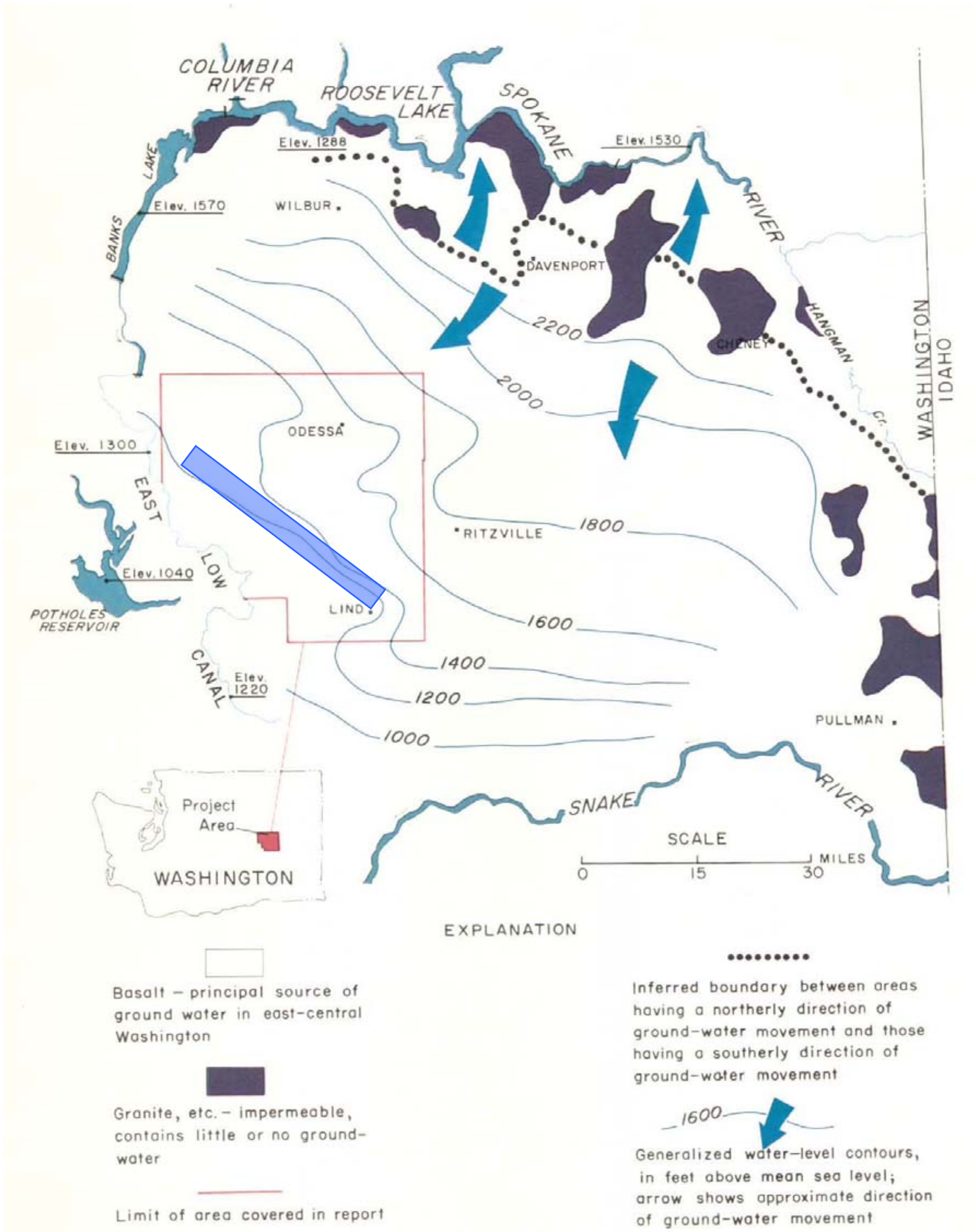


Figure 5. Generalized groundwater elevation contours and groundwater flow directions for the CRBG during the mid 1960s, in and upgradient of the Odessa-Lind area, as mapped by Luzier and others (1968). The blue-shaded area is the approximate location of the "groundwater dam" whose presence Luzier and Burt (1974) later inferred from groundwater elevation contours constructed for Spring 1967.

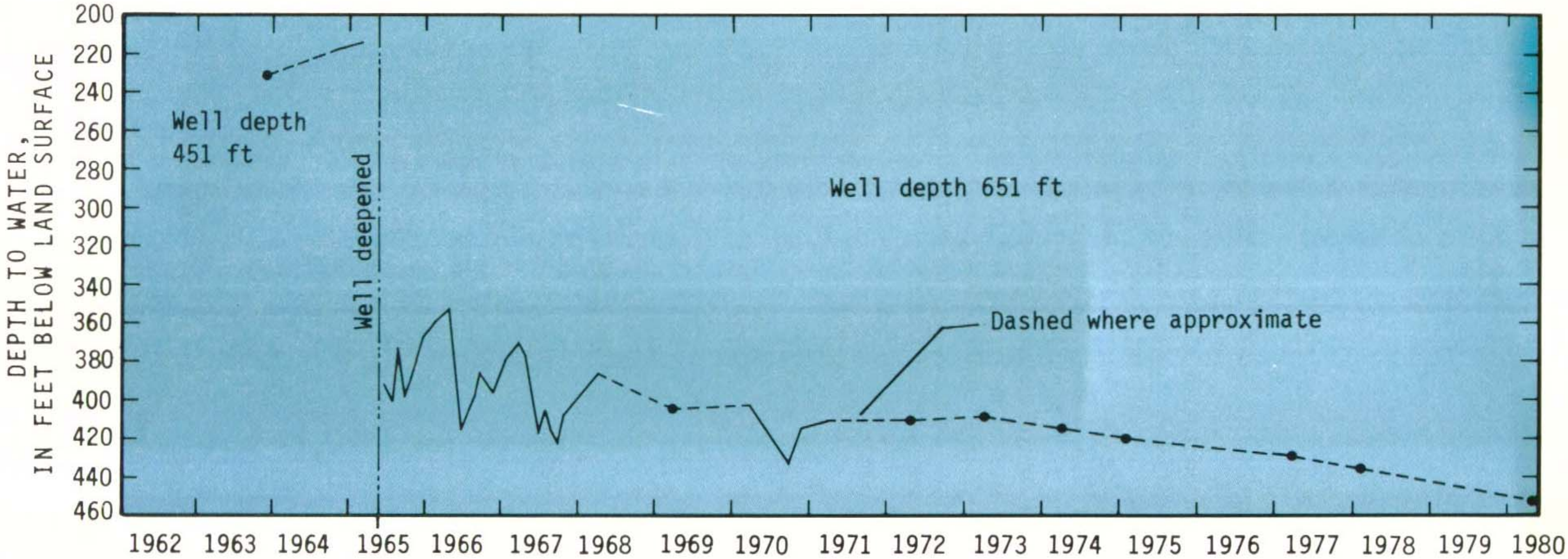


Figure 6. Groundwater elevation changes in a production well (T21N, R30N, 3E1) before and after well deepening occurred in early 1965. From Cline (1984).

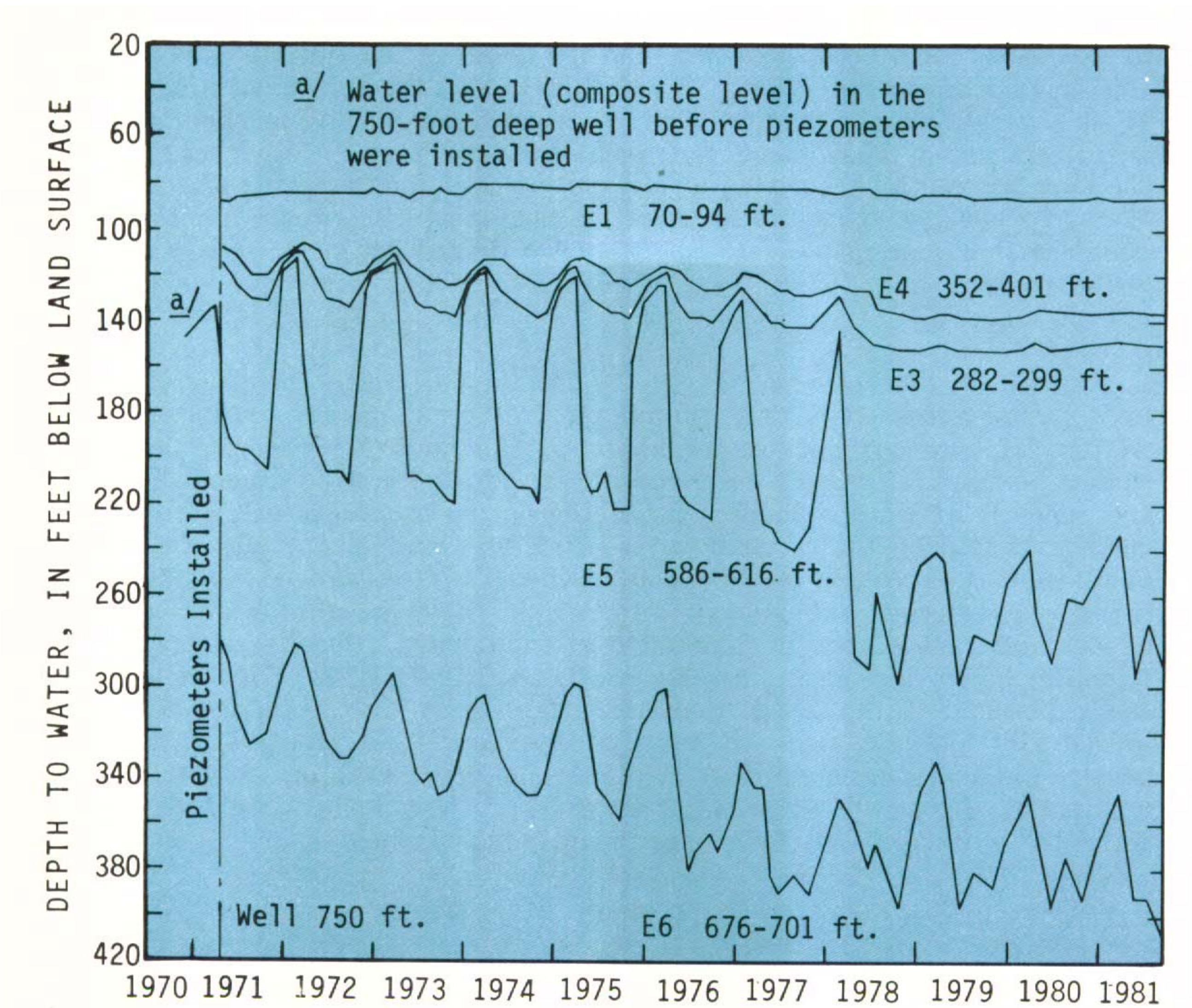


Figure 7. Groundwater elevation changes following piezometer installation in the Odessa test observation well (T20N, R33E, 16E1-E6). The water level in the open borehole prior to piezometer installation in early 1971 is indicated by the "a/" notation in the figure. From Cline (1984).

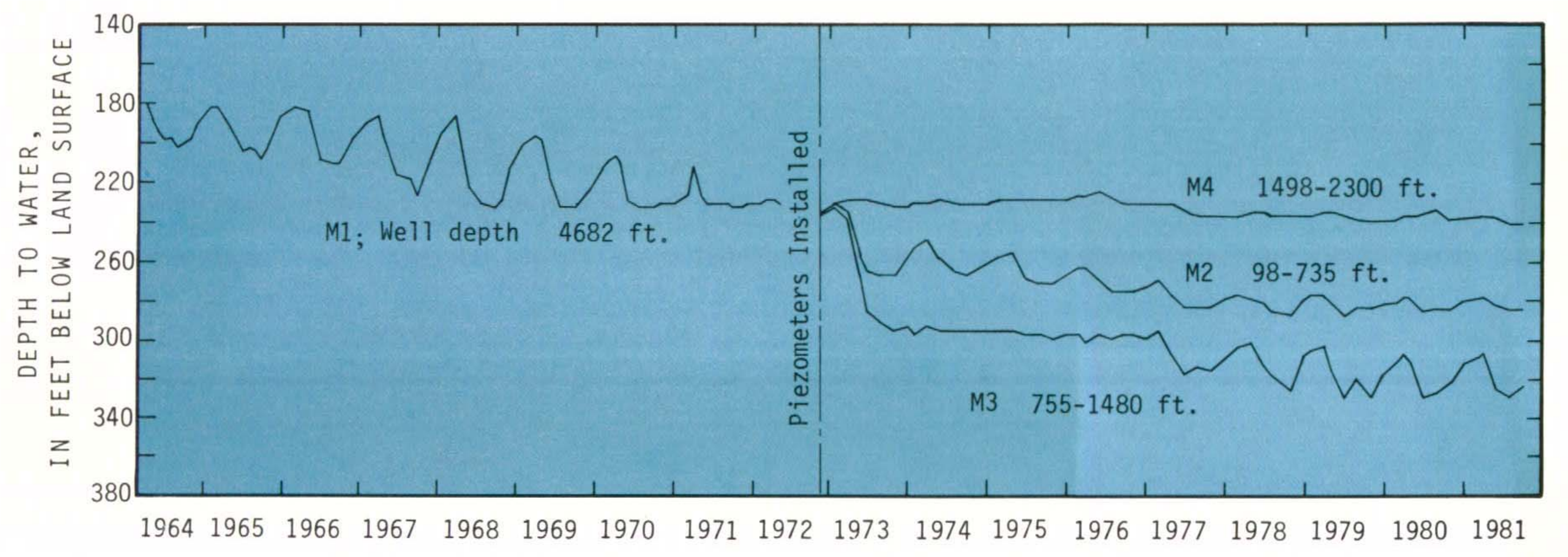


Figure 8. Groundwater elevation changes in the Basalt Explorer test observation well. Data from the open borehole (T21N, R31N, 10M01) are shown prior to 1973, and data beginning in 1973 are from three piezometers (T21N, R31N, 10M02-M04). The range of numbers displayed next to the name of a piezometer indicates the depth interval that the particular piezometer is open to. Piezometer M02 is the shallowest piezometer, and piezometer M04 is the deepest. From Cline (1984).

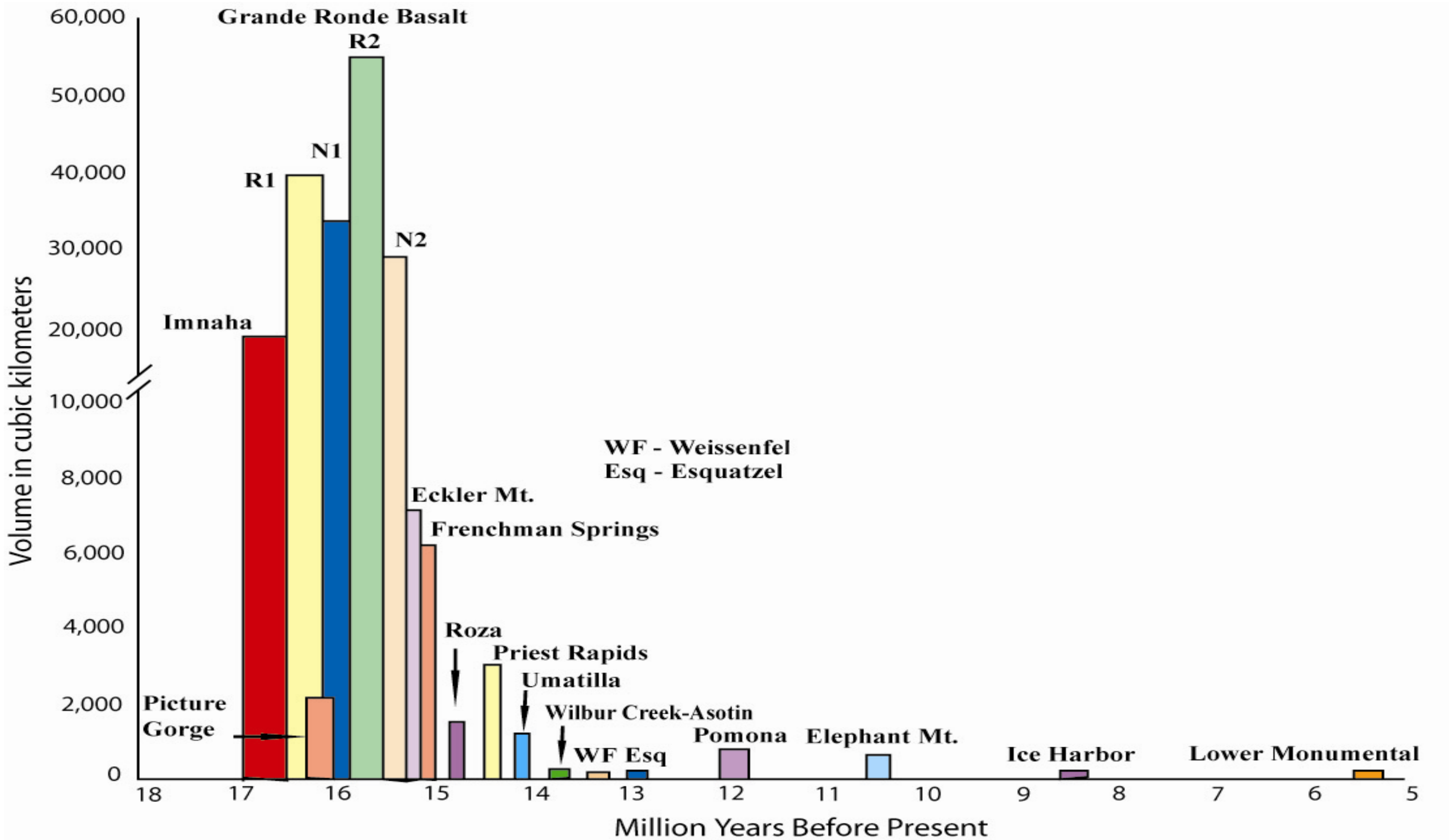


Figure 9. Plot showing the emplacement history for the CRBG units based on volume estimates from Tolan and others (1989). Estimated volume of lava emplaced is indicated by the top end of the bars. Base of the bar represents the potential duration of eruptive activity estimated from available isotopic dates. Note the change in scale for volume. Modified from Tolan and others (1989).

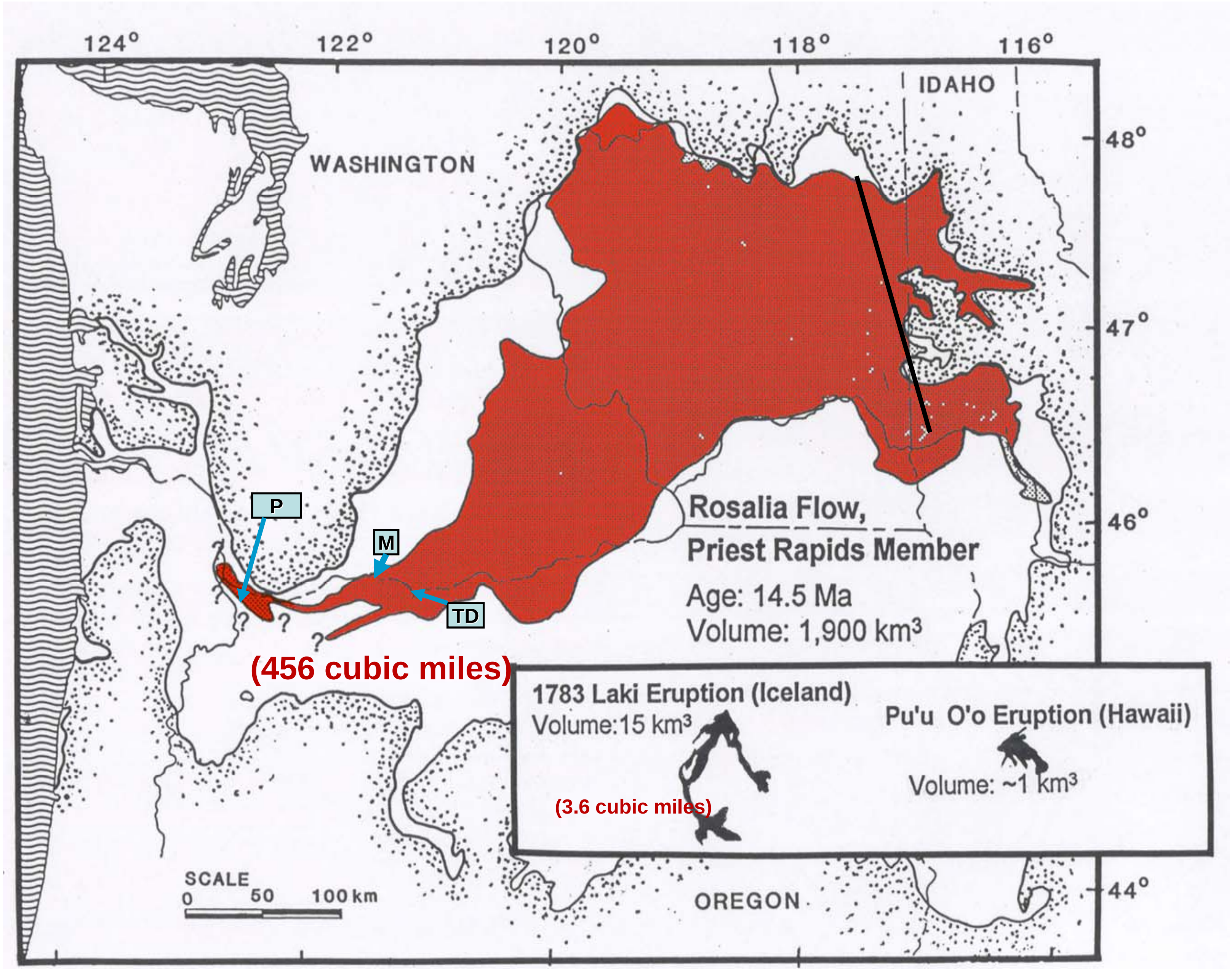
Figure 10. Size of Columbia River Basalt Group Flows

Although CRBG eruptive activity spanned an 11 million year period, most (>96 volume %) of the CRBG flows were emplaced over a 2.5 million year period from 17 to 14.5 million years ago.

Most CRBG flows were of extraordinary size, commonly exceeding 120 to 240 cubic miles in volume, traveled many hundreds of miles from their linear vent systems, and covered many thousands of square miles. These gigantic CRBG flows are hundreds to thousands of times larger than any lava flow erupted during recorded human history, as a same-scale comparison between a CRBG flow, the Laki (Skaftar Fires) flow field (largest basalt eruption in recorded human history), and the ongoing Pu'u O'o eruption on the Big Island of Hawaii shows. CRBG flows represent the largest individual lava flows know on the earth.

Field evidence also indicates that these gigantic CRBG flows were very rapidly emplaced – on the order of a few weeks to less than six months.

P = Portland, OR
M = Mosier, OR
TD = The Dalles, OR

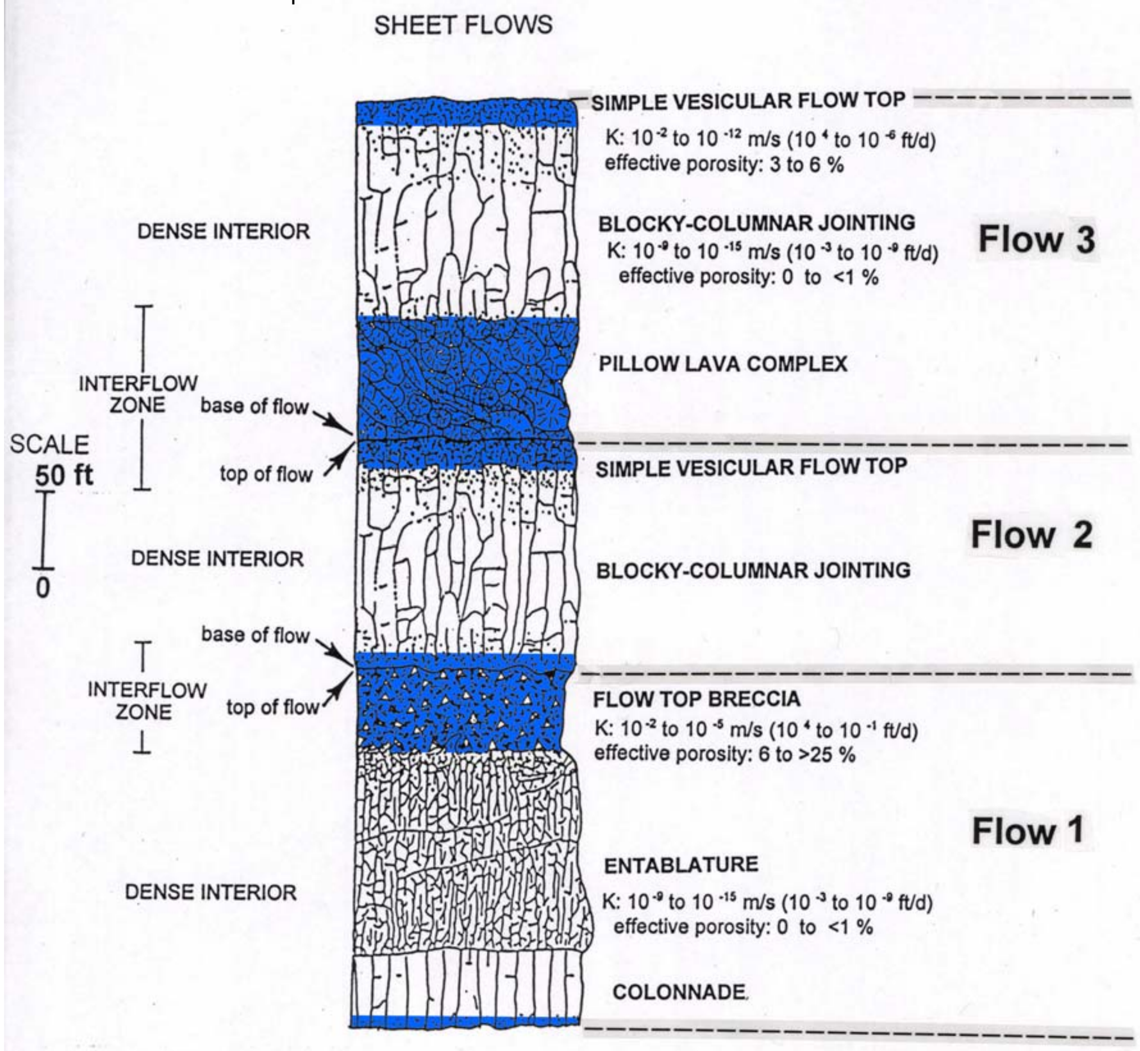


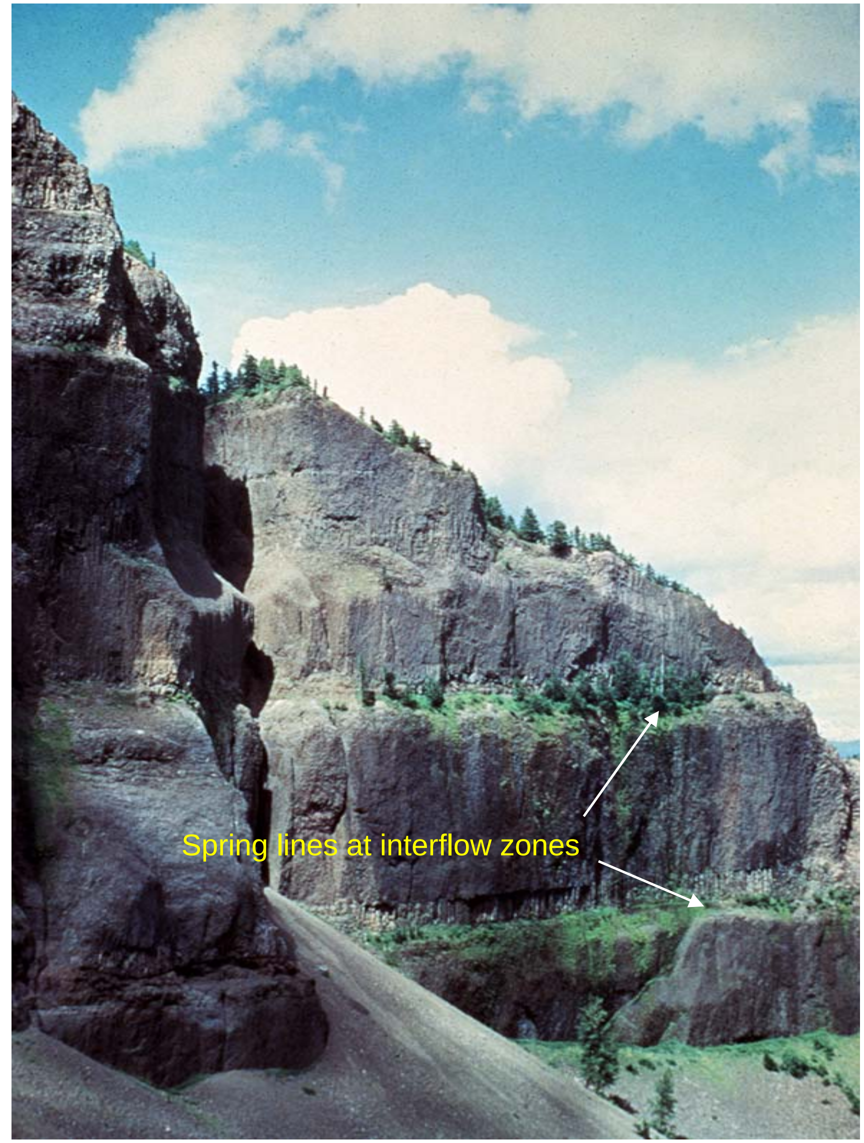
Series		Group		Formation	Member	Isotopic Age (m.y.)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Yakima Basalt Subgroup	Saddle Mountains Basalt	**Lower Monumental Member**	6	N
					Ice Harbor Member	8.5	
					Basalt of Goose Island		N
					Basalt of Martindale		R
					Basalt of Basin City		N
					Buford Member		R
					Elephant Mountain Member	10.5	N, T
	Middle				**Pomona Member**	12	R
					Esquatzel Member		N
					Weissenfels Member		
					Basalt of Slippery Creek		N
					Basalt of Tenmile Creek		N
					Basalt of Lewiston Orchards		N
					Basalt of Cloverland		N
					Asotin Member	13	
					Basalt of Huntzinger		N
					Wilbur Creek Member		
					Basalt of Lapwai		N
					Basalt of Wahluke		N
					Umatilla Member		
					Basalt of Sillusi		N
					Basalt of Umatilla		N
				Wanapum Basalt	**Priest Rapids Member**	14.5	
					Basalt of Lolo		R
					Basalt of Rosalia		R
					Roza Member		T, R
					Shumaker Creek Member		N
					Frenchman Springs Member		
					Basalt of Lyons Ferry		N
					Basalt of Sentinel Gap		N
					Basalt of Sand Hollow	15.3	N
					Basalt of Silver Falls		N, E
					Basalt of Ginkgo	15.6	E
					Basalt of Palouse Falls		E
					Eckler Mountain Member		
					Basalt of Dodge		N
					Basalt of Robinette Mountain		N
					Vantage Horizon		
				Grande Ronde Basalt	**Sentinel Bluffs Member**	15.6	N_2
					Slack Canyon member		
					Fields Springs member		
					Winter Water member		
				Prineville Basalt	**Umtanum member**		
					Ortley member		
	Lower				**Armstrong Canyon member**		
					Meyer Ridge member		R_2
					Grouse Creek member		
					Wapshilla Ridge member		
				Picture Gorge Basalt	**Mt. Horrible member**		
					China Creek member		N_1
					Downy Gulch member		
					Center Creek member		R_1
					Rogersburg member		
					Teepee Butte Member		
					Buckhorn Springs member	16.5	
				Imnaha Basalt			R_1
							T
							N_0
						17.5	R_0

Figure 11. Stratigraphic nomenclature of the CRBG. From Tolan and others (1989) and Reidel and others (1989b).

Figure 12. CRBG intraflow structures & their relevance to groundwater occurrence

CRBG intraflow zones typically host groundwater (aquifers) while the dense interiors of the flows are usually confining layers (aquitards). In their undisturbed state, the layered CRBG can consist of a series of confined aquifers.





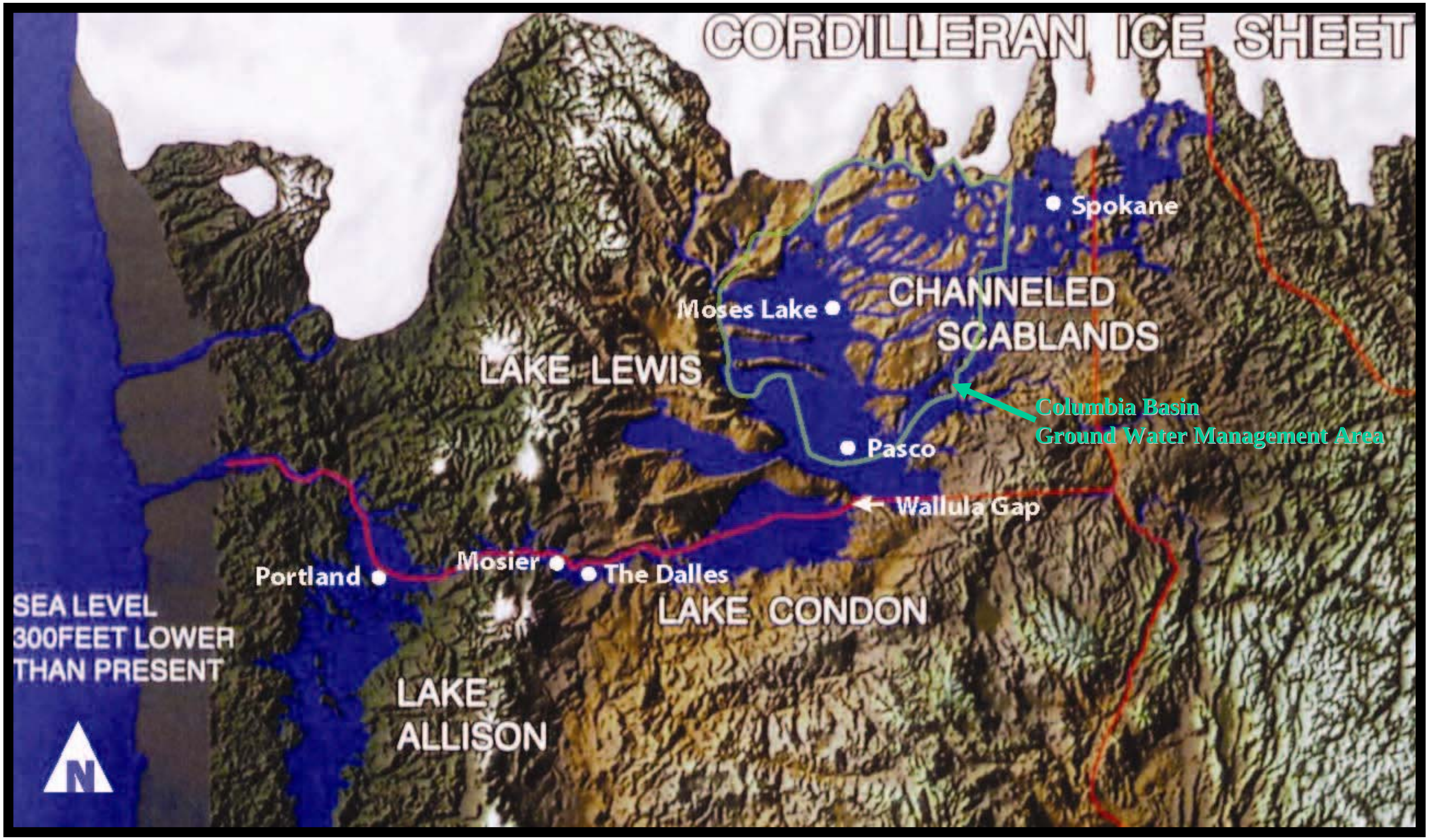


Figure 13. Map showing the extent of Cataclysmic Floods.

Figure 14. Geometry of CRBG lava flows

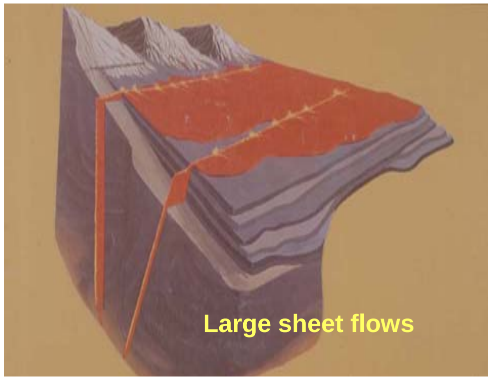
Sheet vs. Compound Flows. Rate/volume of lava erupted, lava composition/temperature, vent geometry, topography, and environmental conditions all play significant roles in controlling the overall geometry of individual basalt lava flows or flow fields. There are two basic types of flow geometries – compound flows and sheet flows.

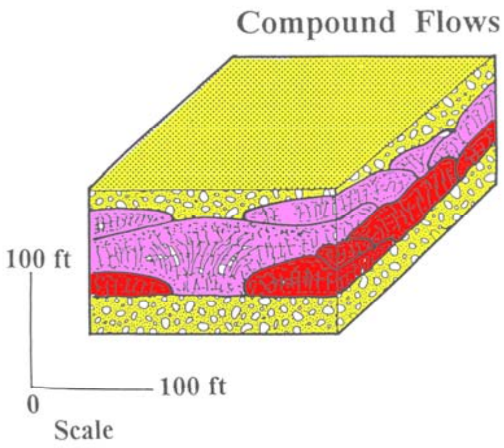
A compound flow develops when the lava flow advances away from its vent in a series of distinct and separate lobes (flows) of flowing lava. Each lobe is subsequently covered by later lava lobes as the emplacement of lava continues. This results in the accumulation of elongated bodies of basalt with numerous, local, discontinuous, and relatively thin layers of basalt lava. In comparison, a sheet flow results when lava is erupted at a high rate and is able to advance away from the vent as a single, uniform, moving sheet of lava. This type of flow consists of a relatively extensive, single layer or "sheet" of lava. Each successive sheet flow will create a similar layer, with the flow boundaries being delineated by distinct vesicular flow tops and flow bottoms.

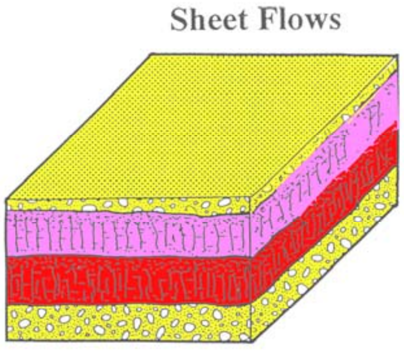
Individual, large volume CRBG flows (especially Grande Ronde and Wanapum Basalts) display characteristics consistent with sheet flows. CRBG flows typically only exhibit the complex features associated with compound flows at their flow margins.

Typical Basalt Eruptions

CRBG Eruptions







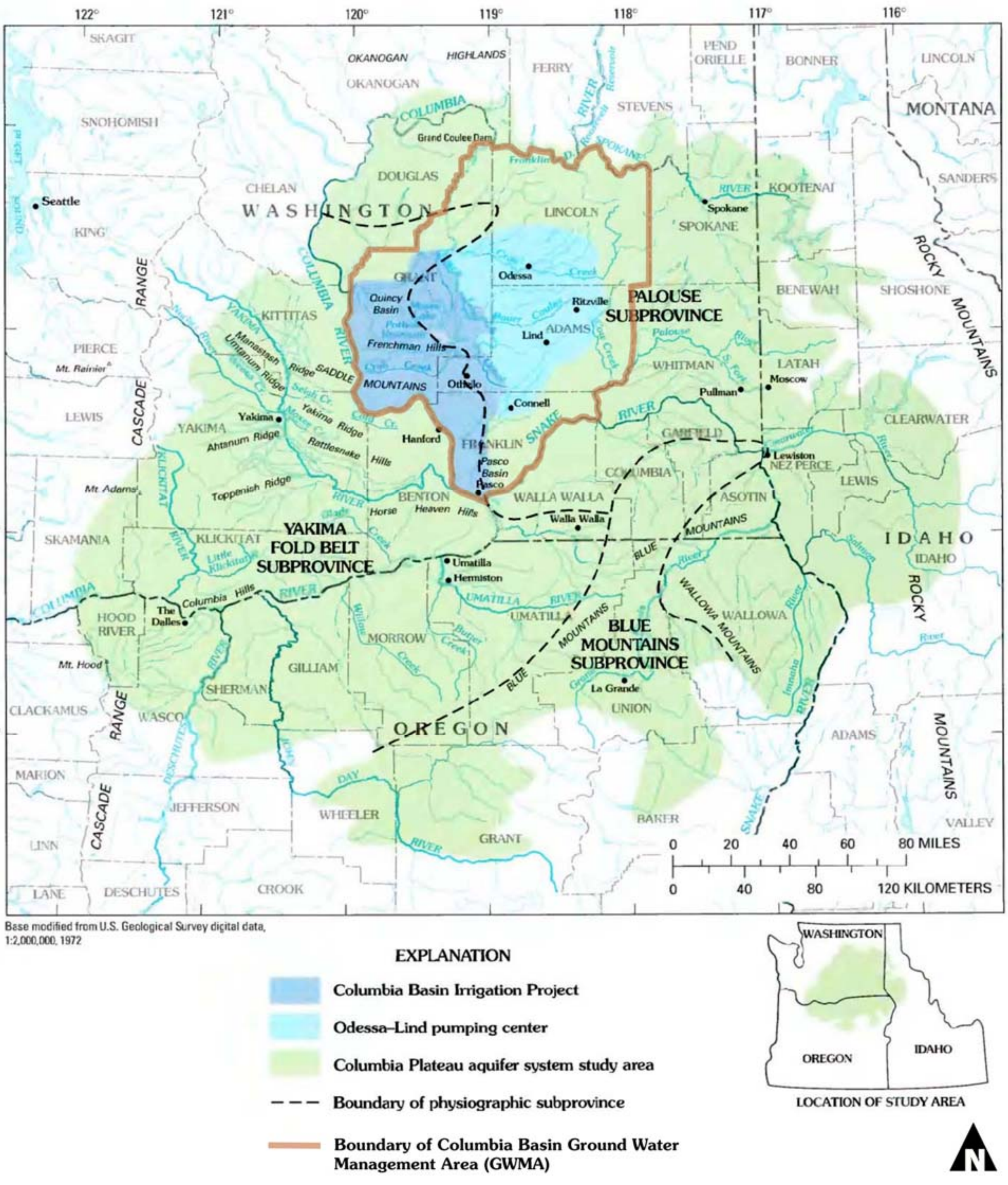


Figure 15. Location of Columbia Plateau physiographic subprovince boundaries and major physiographic features. After Vaccaro (1999).

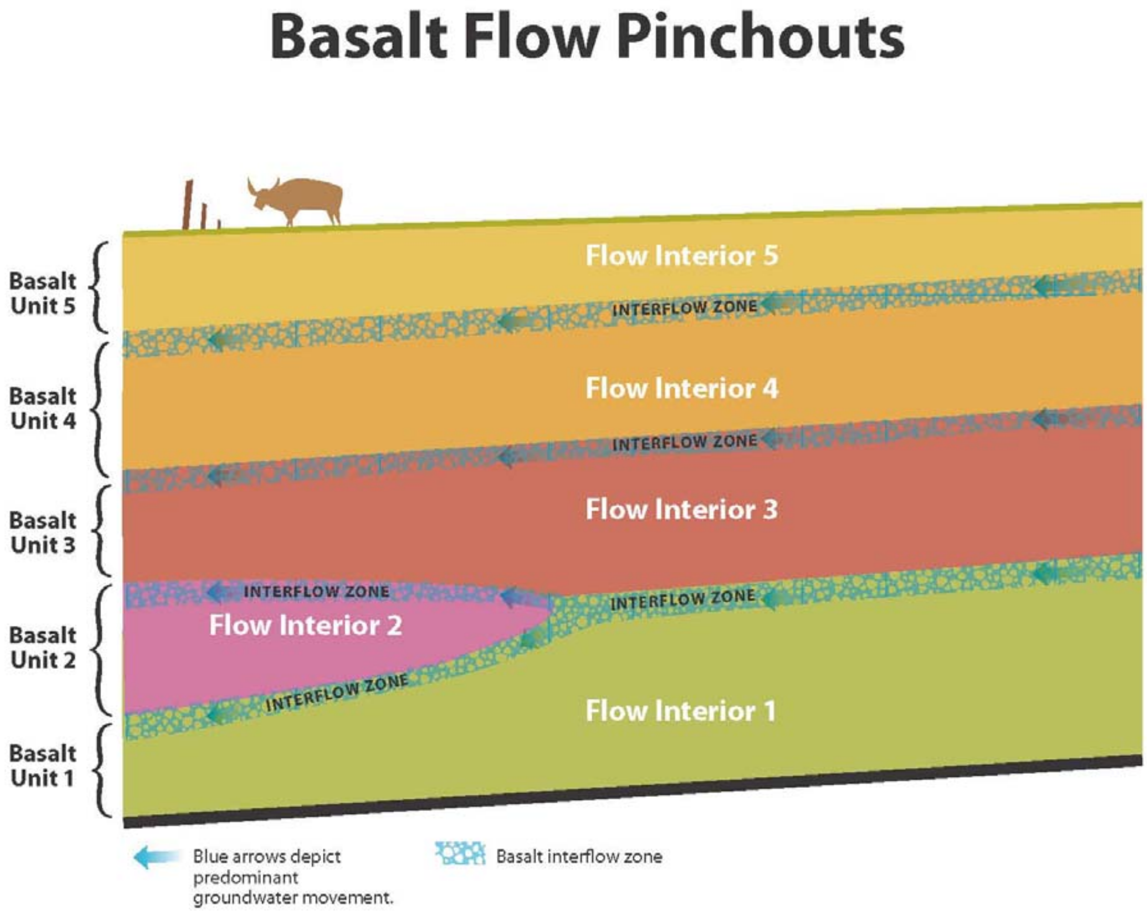


Figure 16. Influence of basalt flow pinchouts on groundwater movement.

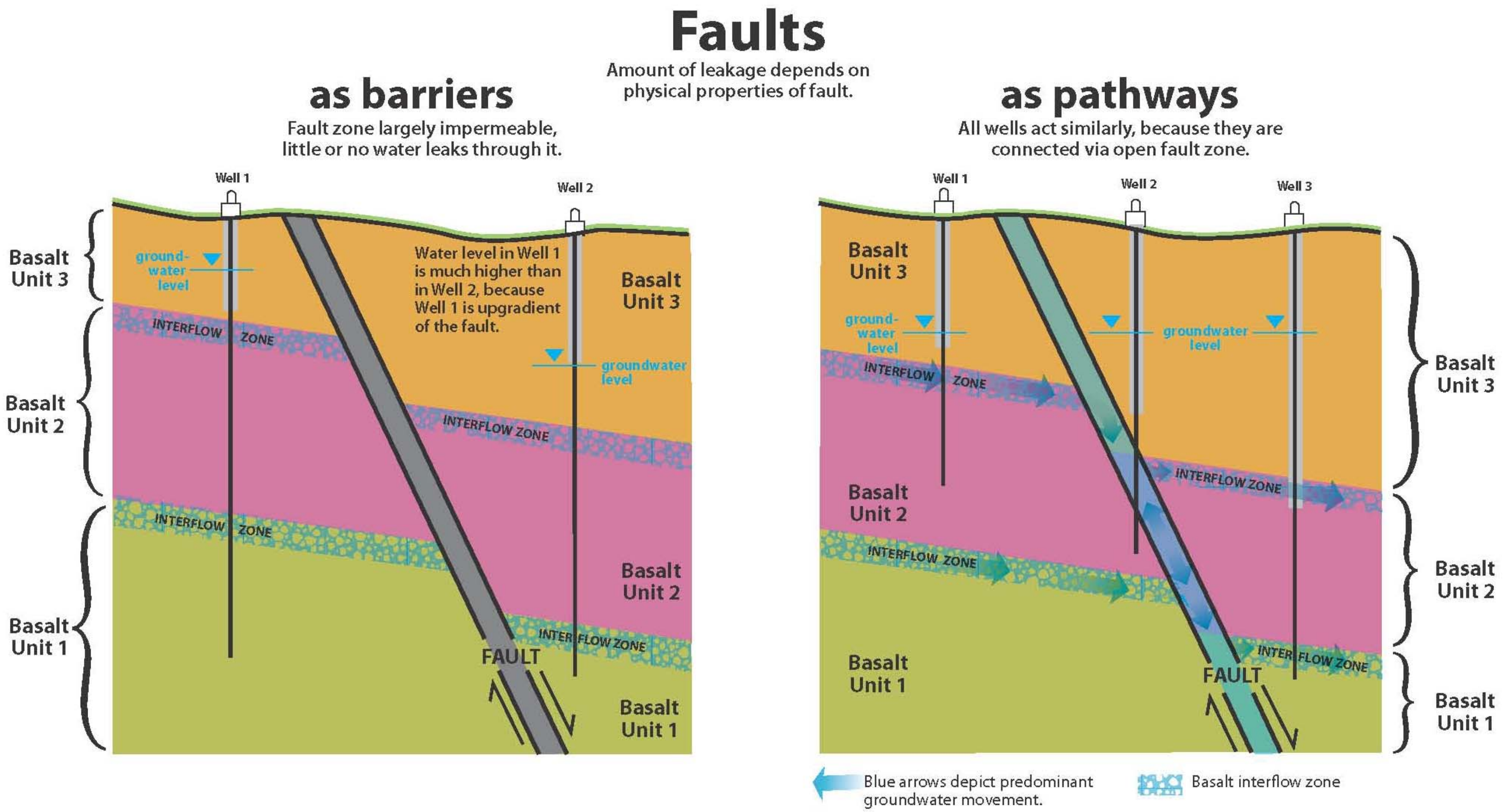


Figure 17. Influence of faults on groundwater movement.

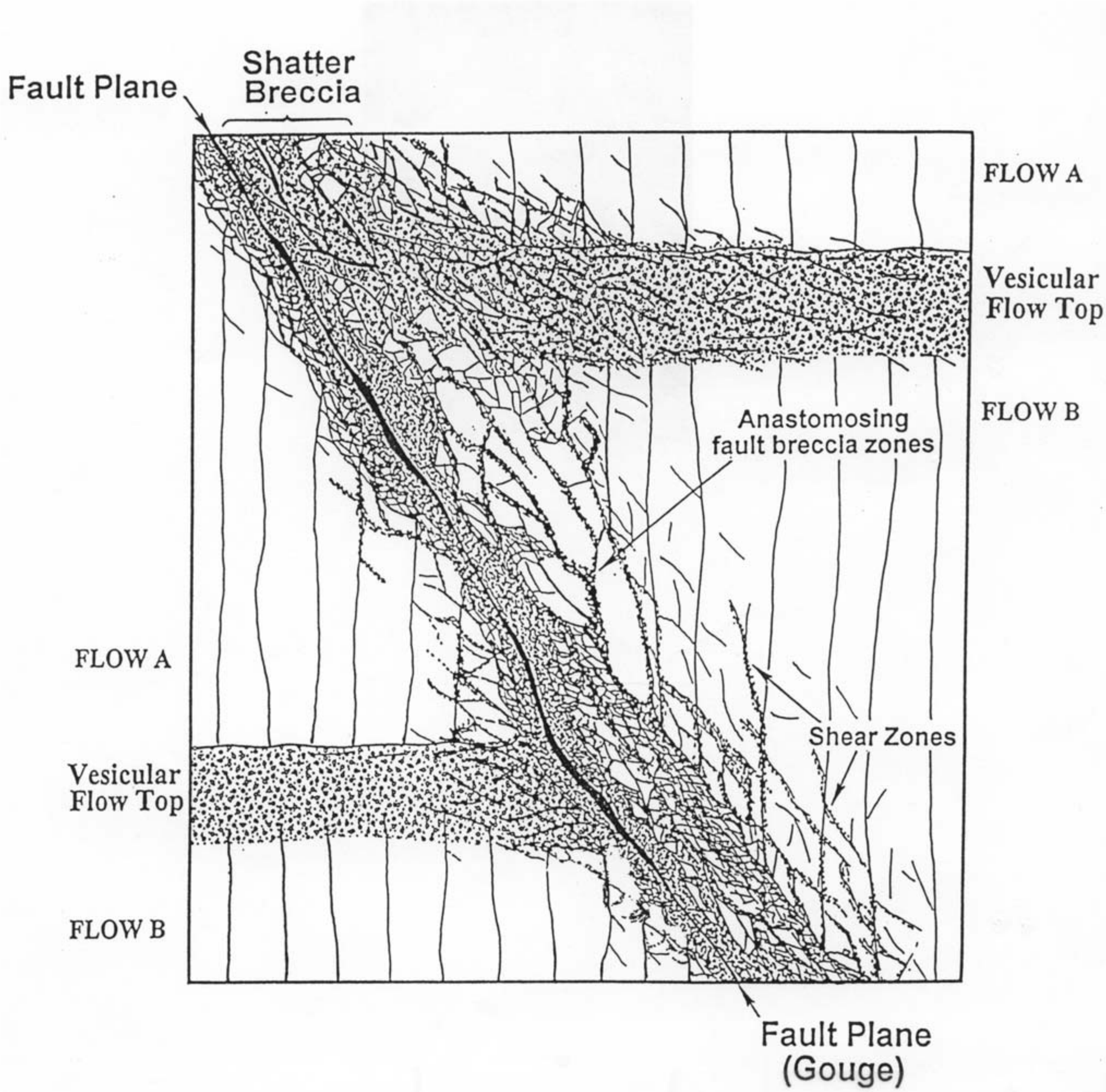


Figure 18. Diagram depicting common features found within fault zones that transect CRBG flows.

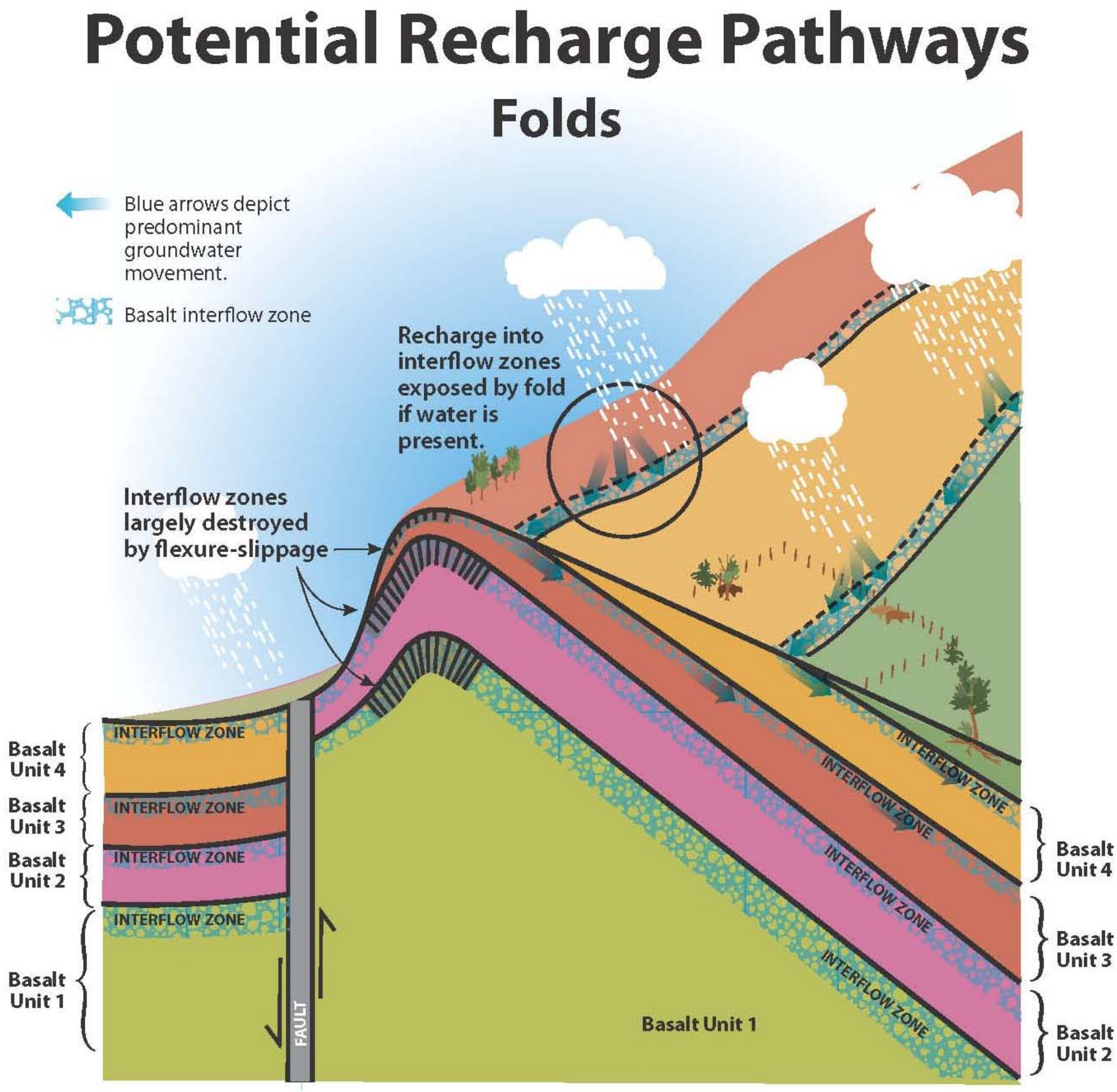


Figure 19. Influence of folds on groundwater movement. Folds can control the CRBG aquifer system, usually forming barriers to ground water flow, and subdividing the aquifer system into groundwater sub-basins. Groundwater systems on either side of these folds typically do not display significant hydrologic connection.

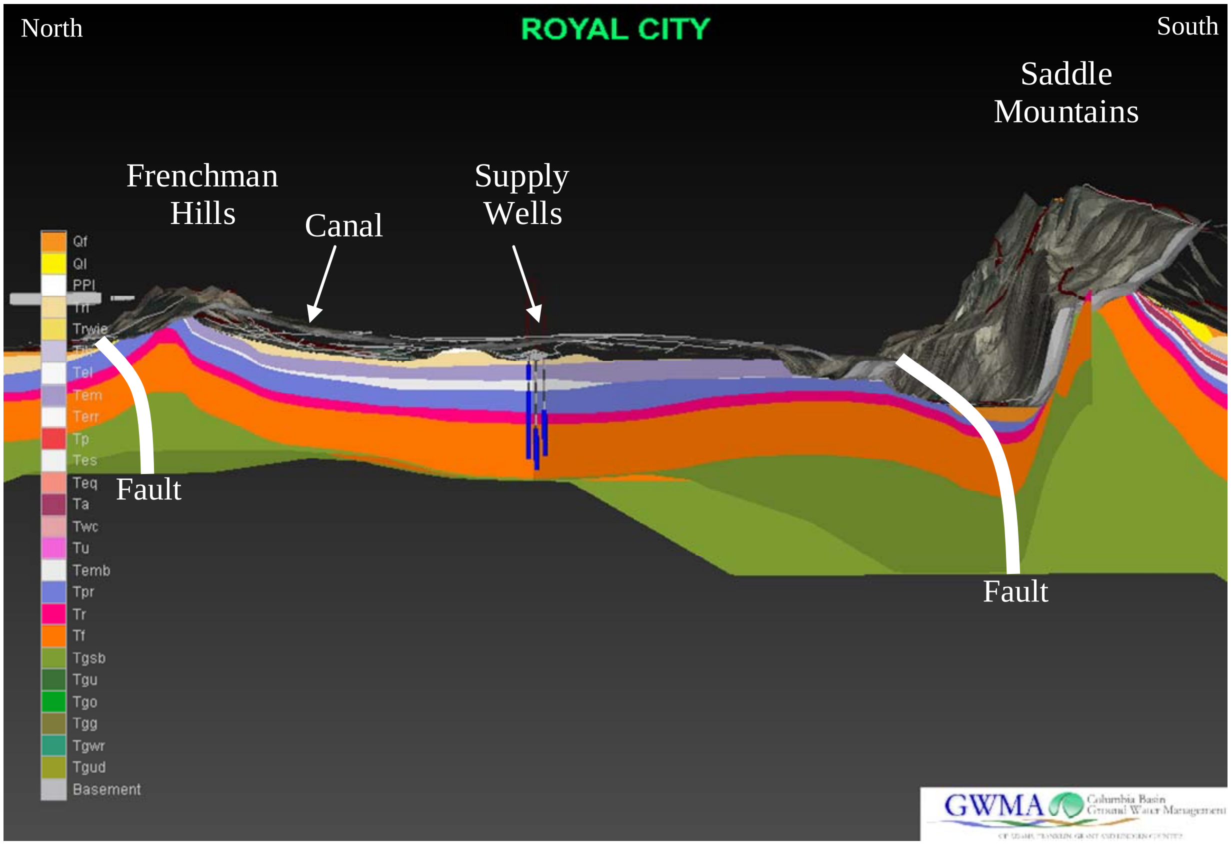


Figure 20. North-south cross-section, looking to the east, showing the anticlinal folds of the Frenchman Hills and Saddle Mountains, and the location of the Royal City municipal supply wells in the valley between these two regional structures. The Frenchman Canal lies between the Frenchman Hills and the Royal City supply wells, which produce a mixture of young water derived from leaky canals and old water derived from natural recharge in the Frenchman Hills.

Limited Groundwater Movement Across Monoclinal Flexure Zones

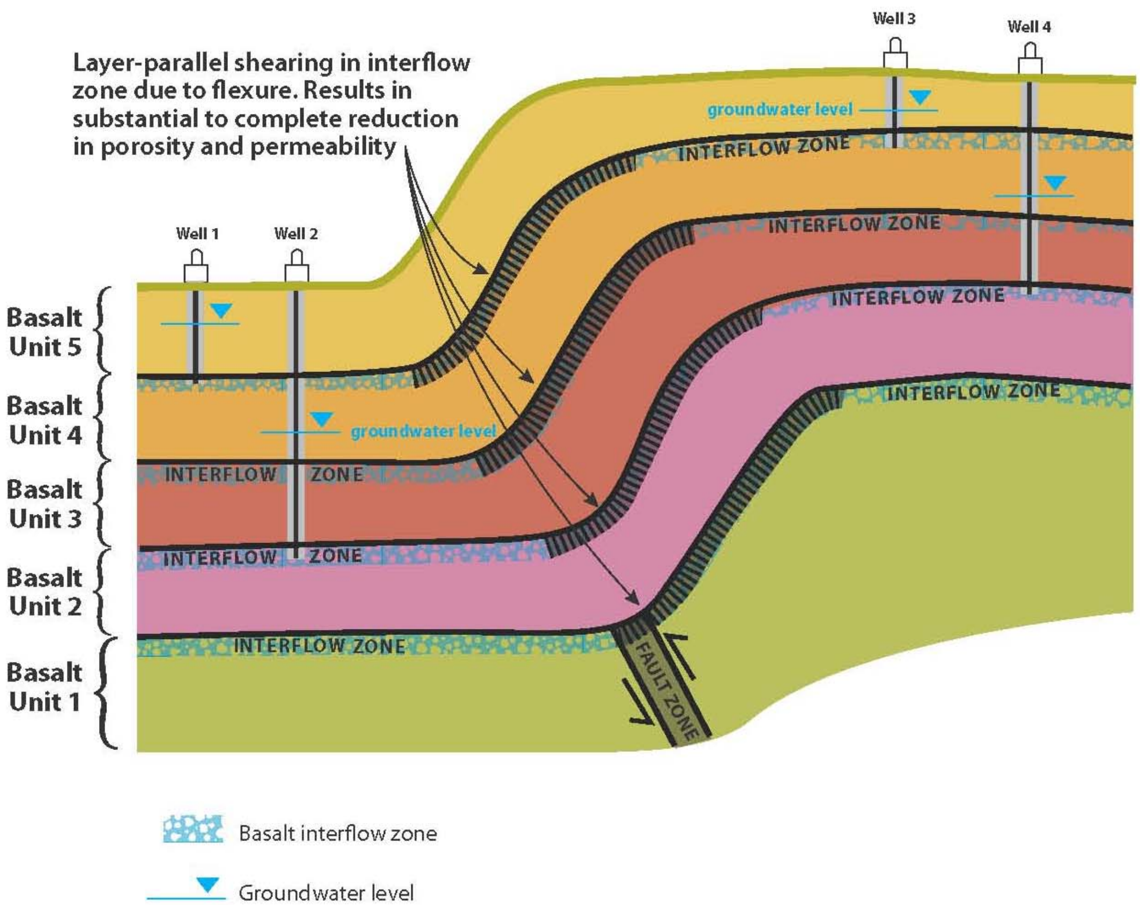


Figure 21. Influence of a monoclinal flexure zone on groundwater movement. During its formation, the flexure zone, which is commonly associated with a reverse fault, experiences compressional forces that shear the layers, which reduces the porosity and permeability of the interflow zones. Groundwater elevations in a given interflow zone therefore are much higher upgradient of the flexure zone than downgradient of the flexure zone. This difference exists in part because of the elevation difference across the flexure zone, but also because the reduced permeability in the axis of the flexure zone causes the flexure zone to act as a partial, or nearly complete, hydraulic barrier to groundwater movement.

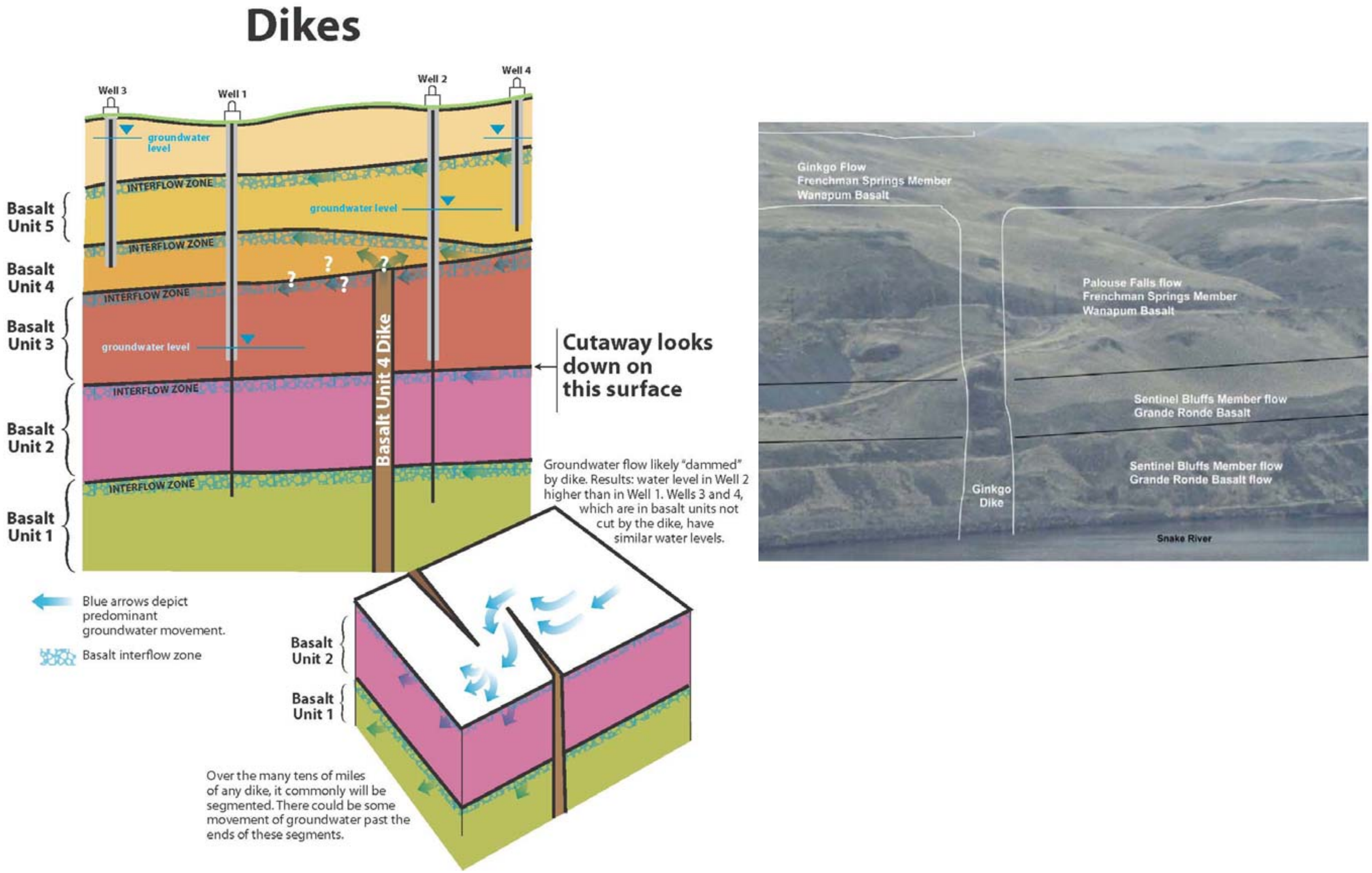


Figure 22. Feeder dikes, from which a Columbia River basalt lava flow erupted approximately 15.5 million years ago, form long, nearly vertical subsurface features which probably form boundaries to groundwater flow.

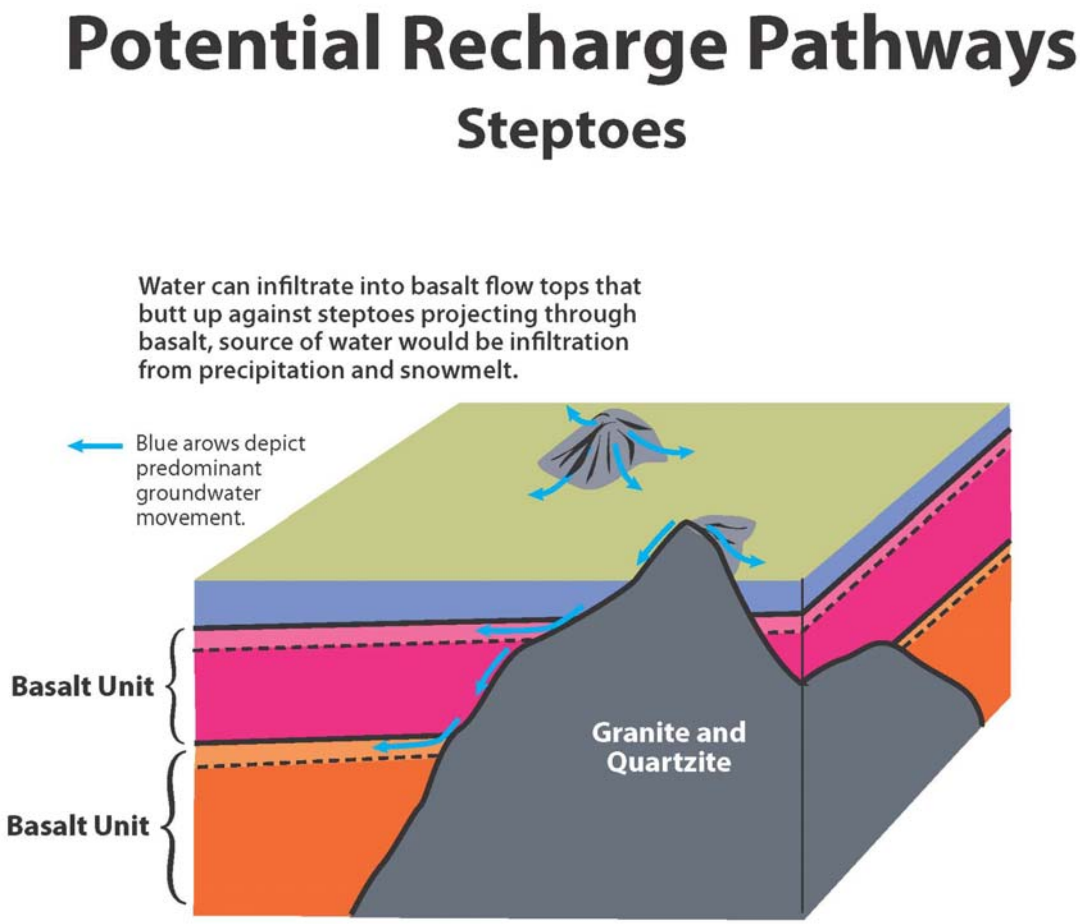


Figure 23. Influence of steptoes on groundwater movement.

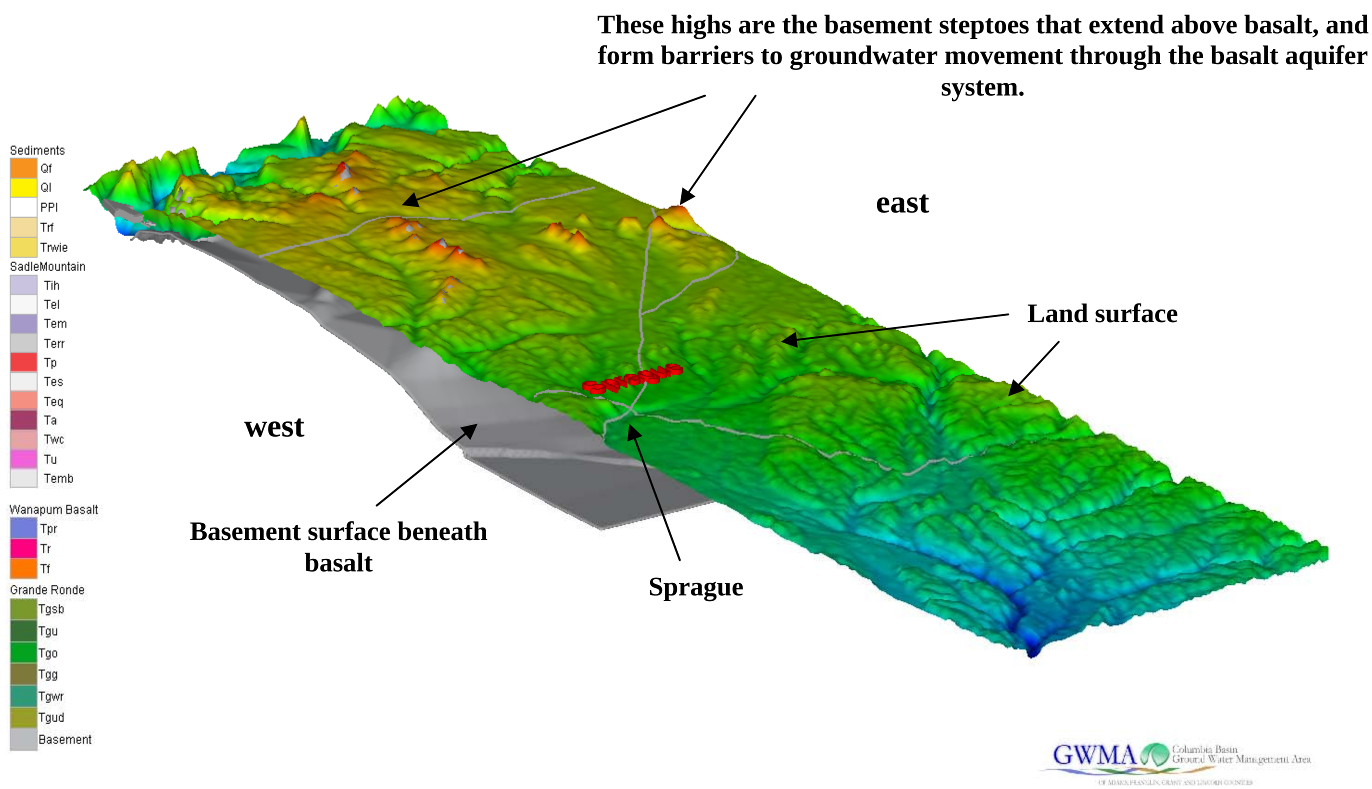


Figure 24. View looking to the northeast, showing ground surface topography, and the granitic basement surface that lies beneath the CRBG. The steptoes are the hills north of Sprague that are the surface expression of the buried granitic structure. The steptoes form basement highlands, which in the northern portion of this area block groundwater movement into GWMA from the east, out of Spokane County. Further south, the granitic structure is much deeper, which may allow groundwater to move into this portion of GWMA from the east, out of Whitman County.

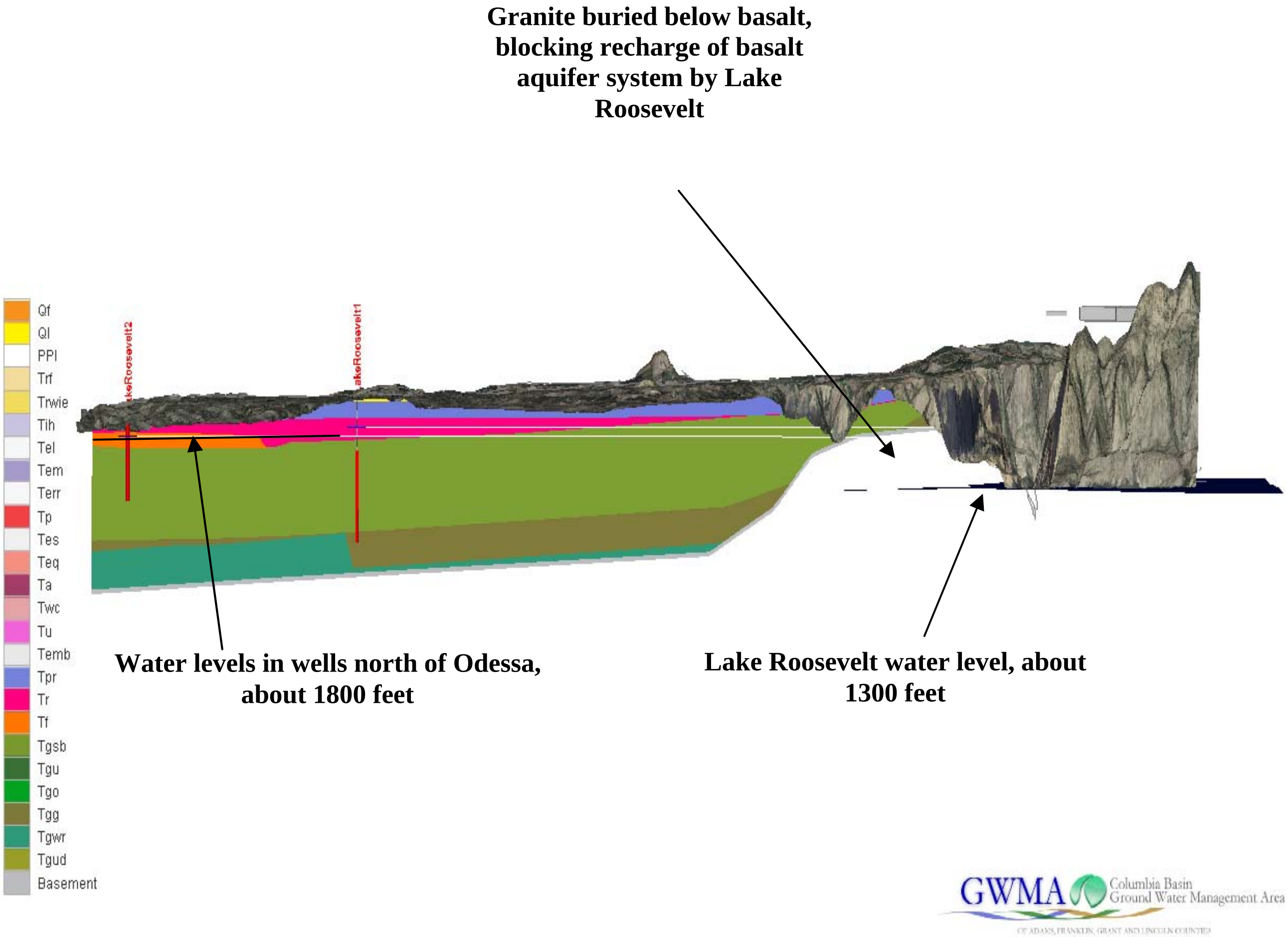


Figure 25. North-south cross-section, looking west, showing CRBG members (colors), buried granitic structure (white and gray), and the Lake Roosevelt pool (black)

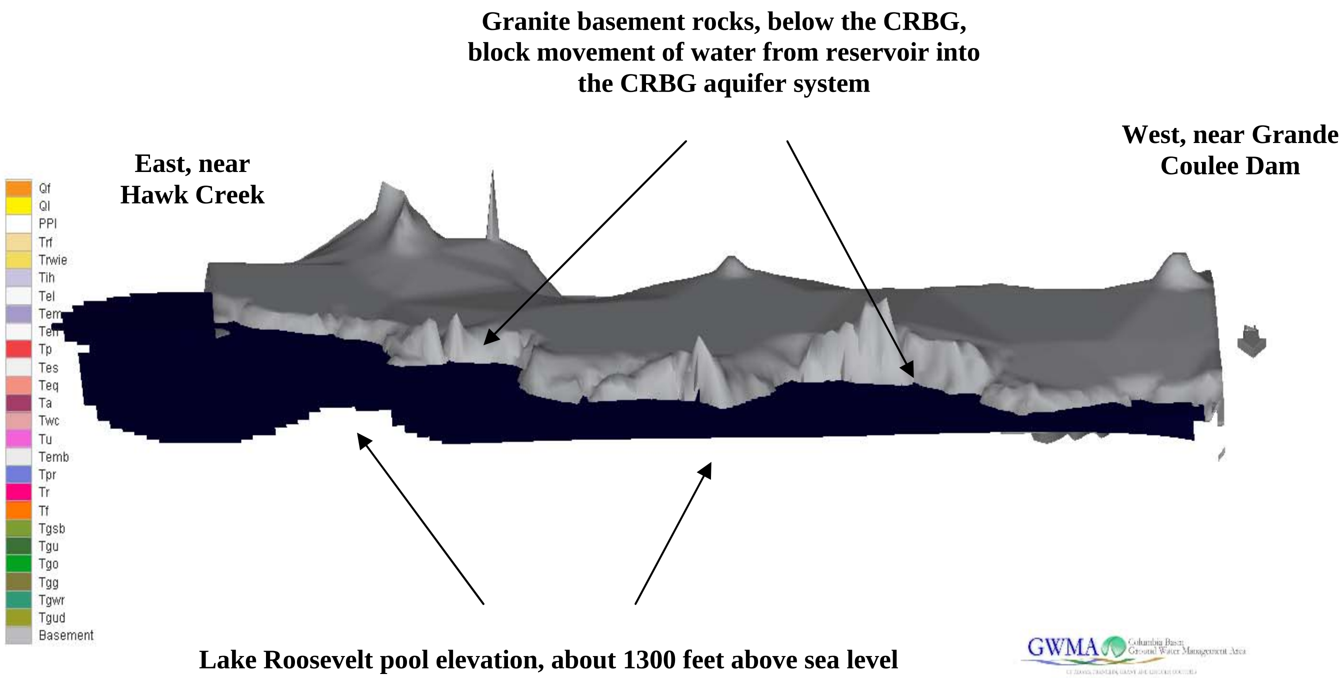


Figure 26. East-west cross-section, looking to the south, showing the granitic structure's outcrops (gray) along the south shore of Lake Roosevelt (black). The presence of this structure prevents Lake Roosevelt from recharging the CRBG aquifer system which lies to the south. A possible exception to this is at Hawk Creek. However, groundwater elevation data indicate that the CRBG near Hawk Creek has groundwater levels that are lower than in GWMA, which indicates that any Lake Roosevelt water entering the CRBG near Hawk Creek is not migrating into GWMA.

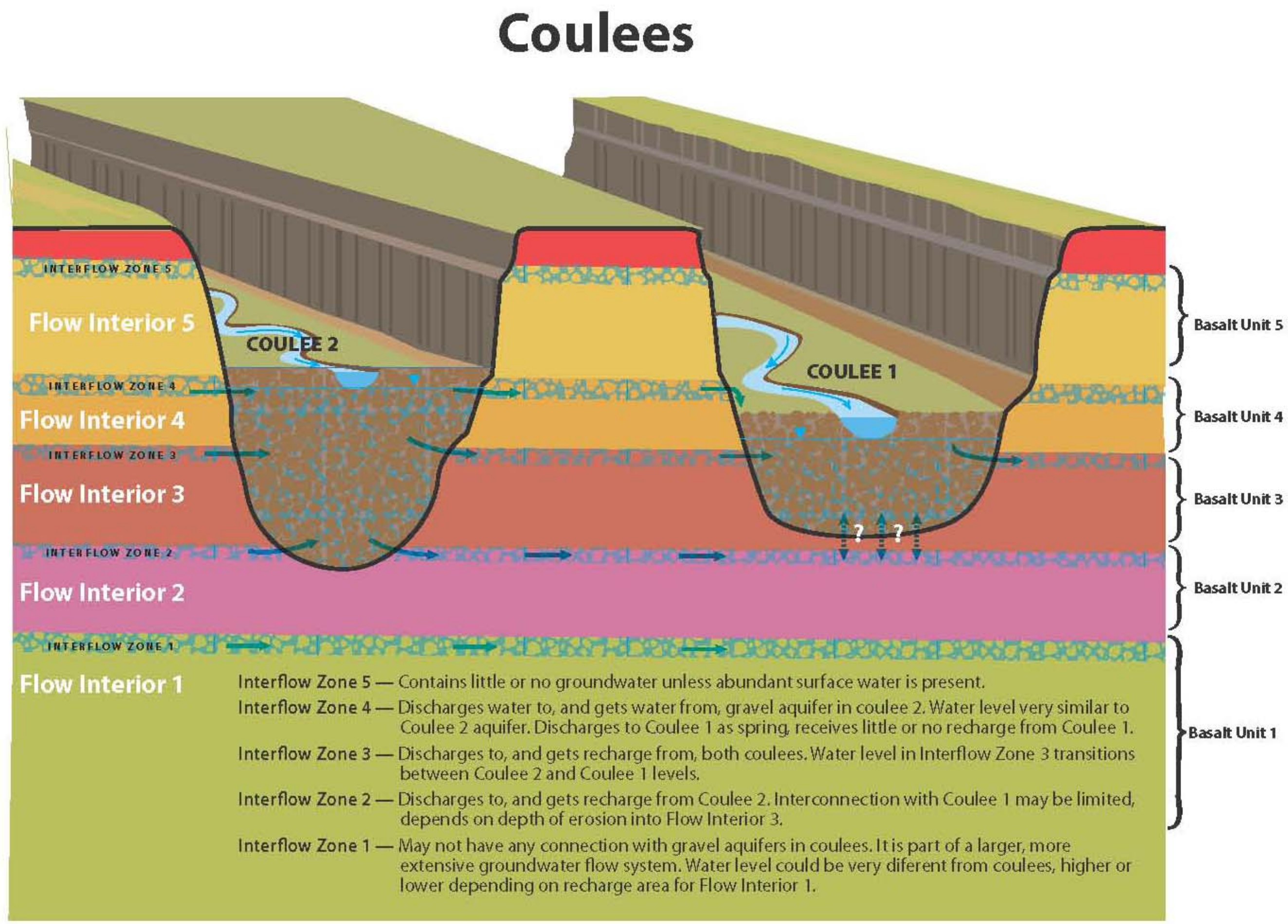


Figure 27. Influence of coulees on groundwater movement.

Figure 28. Natural spring on bench above Canniwai Creek coulee. This natural spring has been present at this location for many years. It appears to be developed in an interflow zone which receives recharge from the east (direction view is looking).

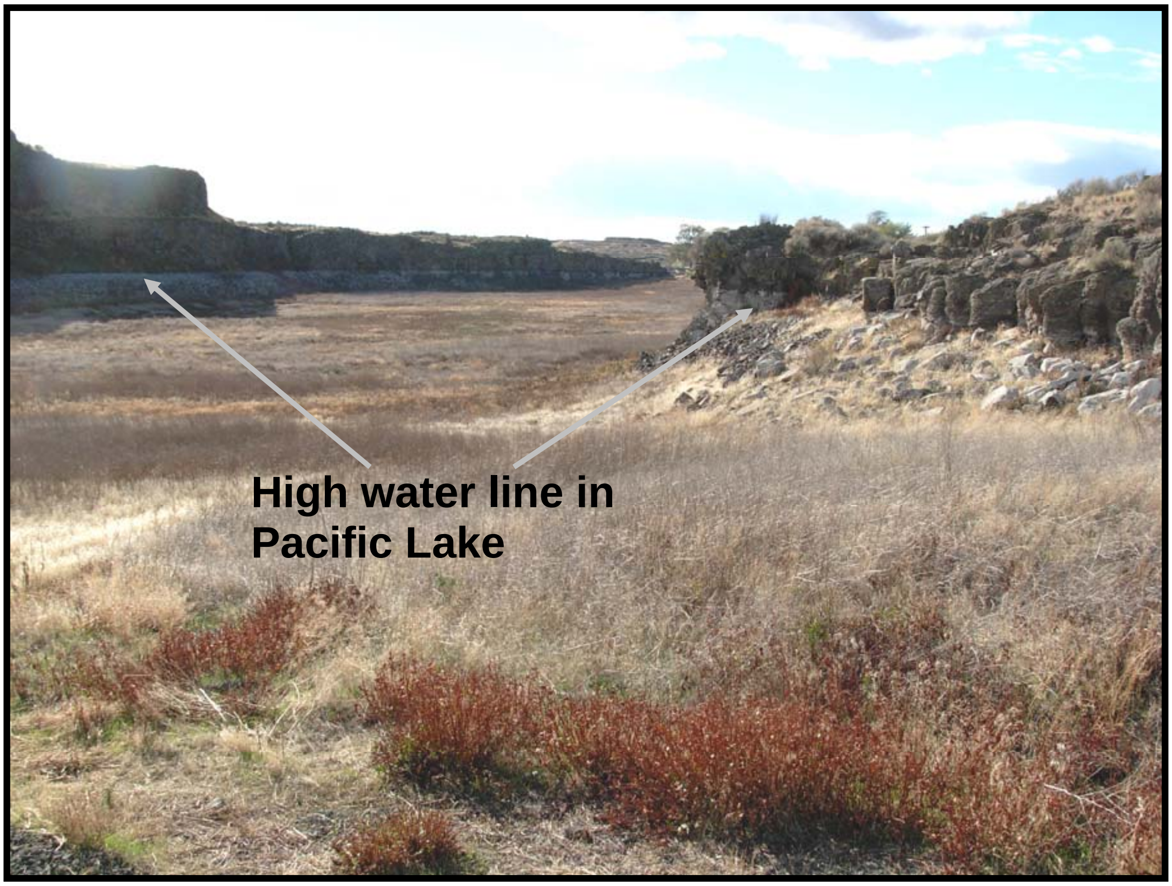


Figure 29. View of Pacific Lake, part of the Lake Creek system, which is currently dry. The lake occupied a Pleistocene Cataclysmic Flood coulee cut into the Roza Member of the Wanapum Basalt. Eyewitness reports indicate Pacific Creek is predominantly filled by surface run-off coming down Lake Creek from the north. A few small springs located in the lake also may contribute some water to the lake when the springs are active.

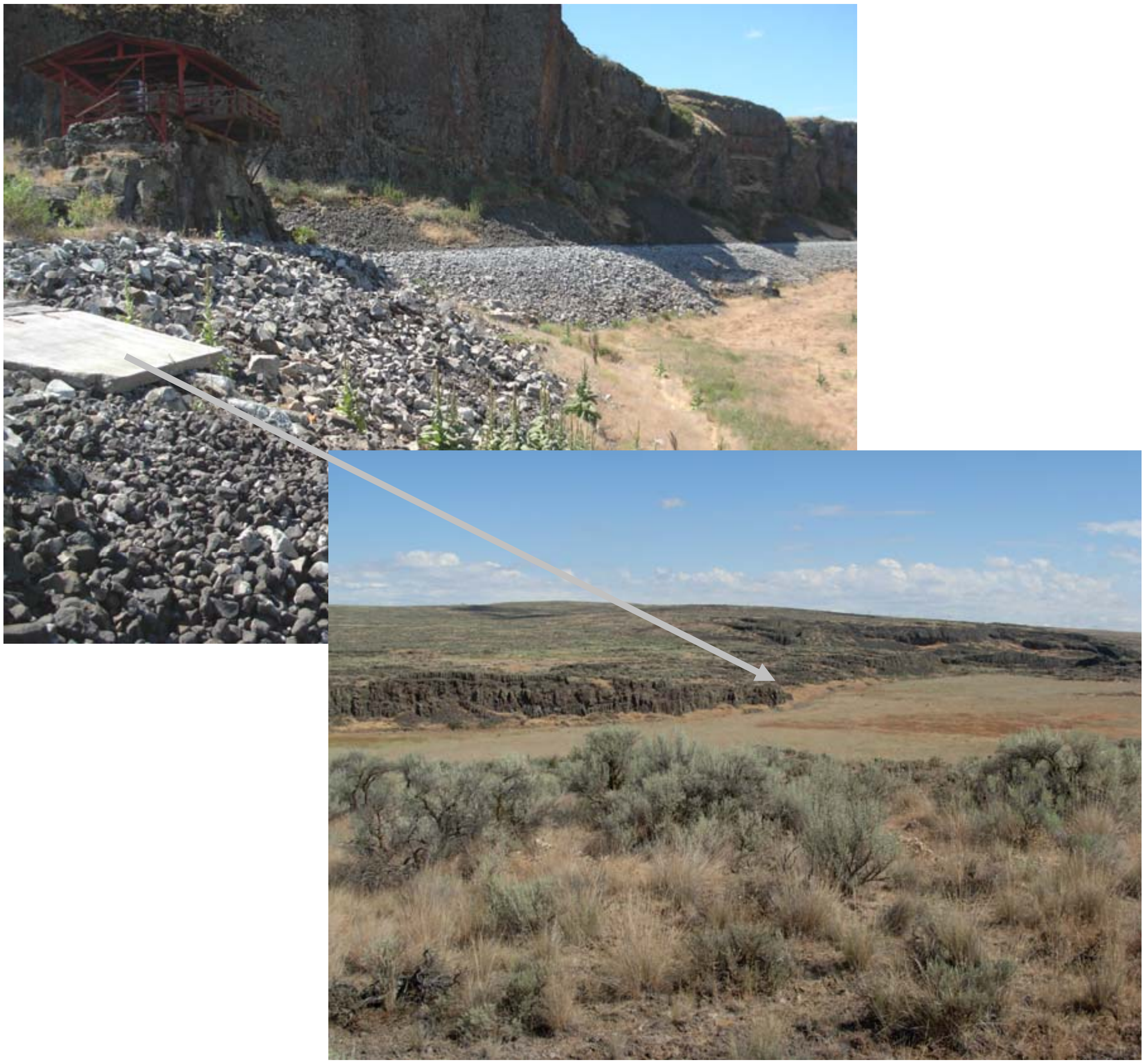


Figure 30. Two views into Pacific Lake. The upper view shows the high water line, and the now dry private boat launch. The lower view looks into Pacific Lake from the north. The arrow points to the location of the private boat launch.

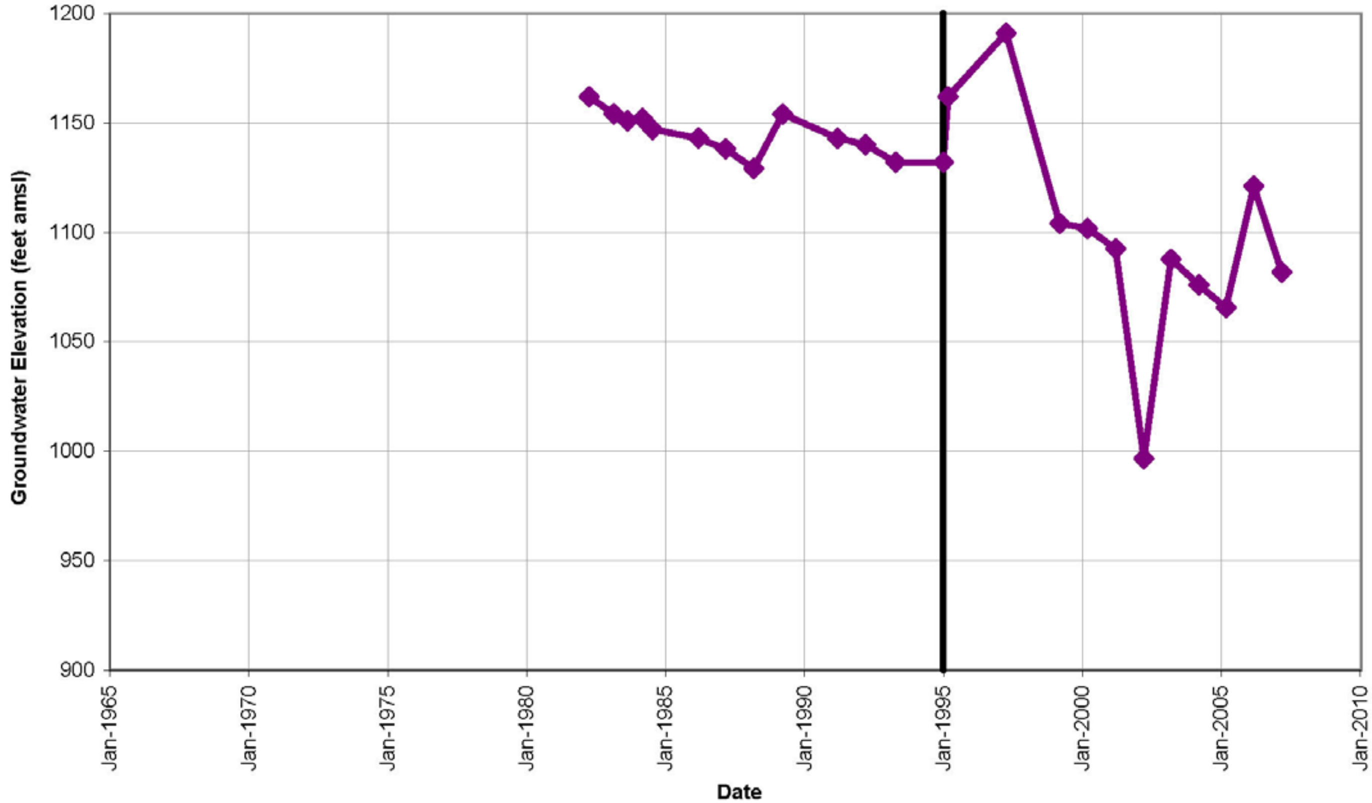


Figure 31. Groundwater elevation hydrograph for agricultural production well ERO212. This well is located west of the Town of Odessa. The well was 800 feet deep until January 1995, when it was deepened to a depth of 1,100 feet. After deepening, the well is open to both the Wanapum Basalt and the upper Grande Ronde basalt.

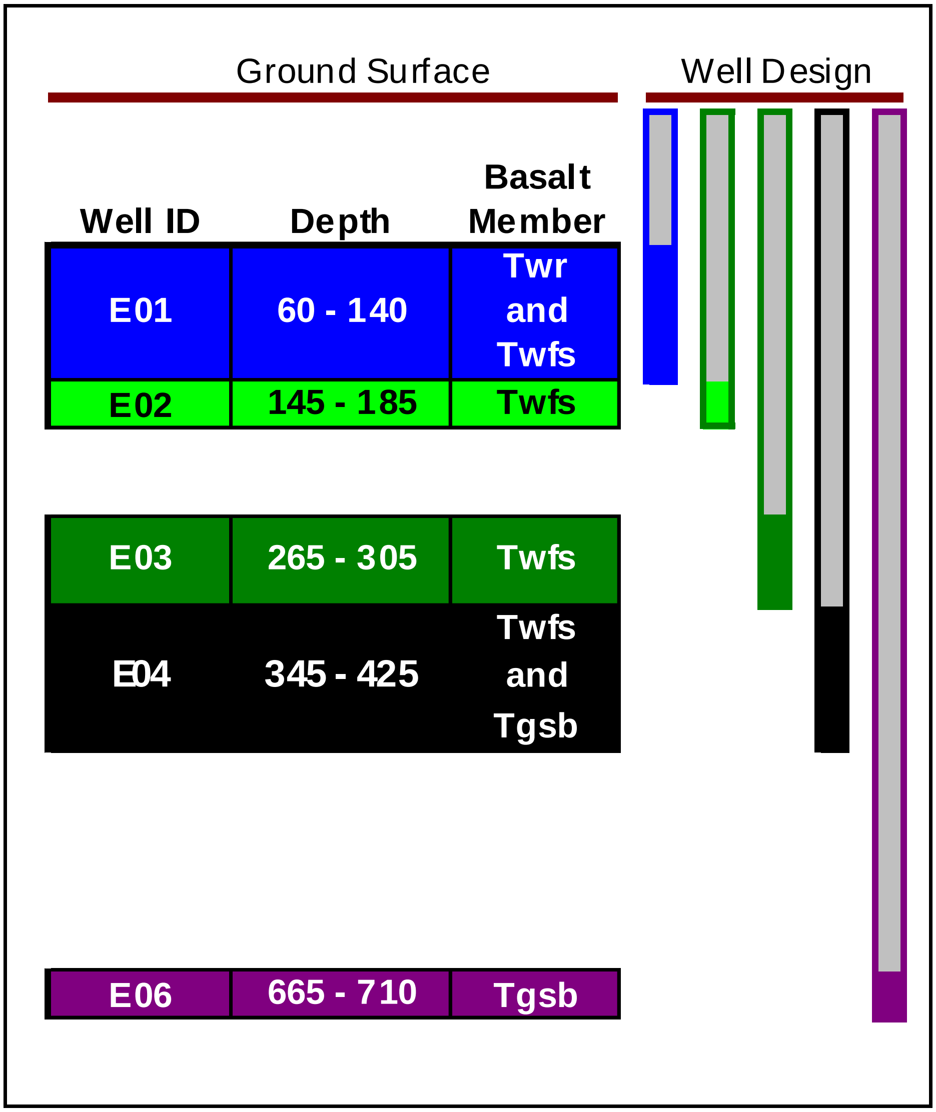


Figure 32. This diagram shows the design of a multi-level well cluster (AAE563) located in north-central Adams County (south of the Town of Odessa). A multi-level observation well actually consists of a collection of several wells in a single borehole. Each individual well extends to a different depth and is open to a different interflow zone(s). For a given well, the open interval is the solid color shown on the diagram, and the gray interval represents overlying zones that are sealed off for that particular well. Cement grout plugs are used to seal the space between each well to prevent leakage between the zones monitored in the borehole. Wells E01, E02, and E03 are open to different depth zones in the Wanapum Basalt. Well E04 is open to the lowermost member of the Wanapum Basalt (Frenchman Springs) and the Sentinel Bluffs Member of the upper Grande Ronde Basalt. Well E06 is open to the Sentinel Bluffs Member.

Twr = Roza Member of the Wanapum Basalt
Twfs = Frenchman Springs Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt

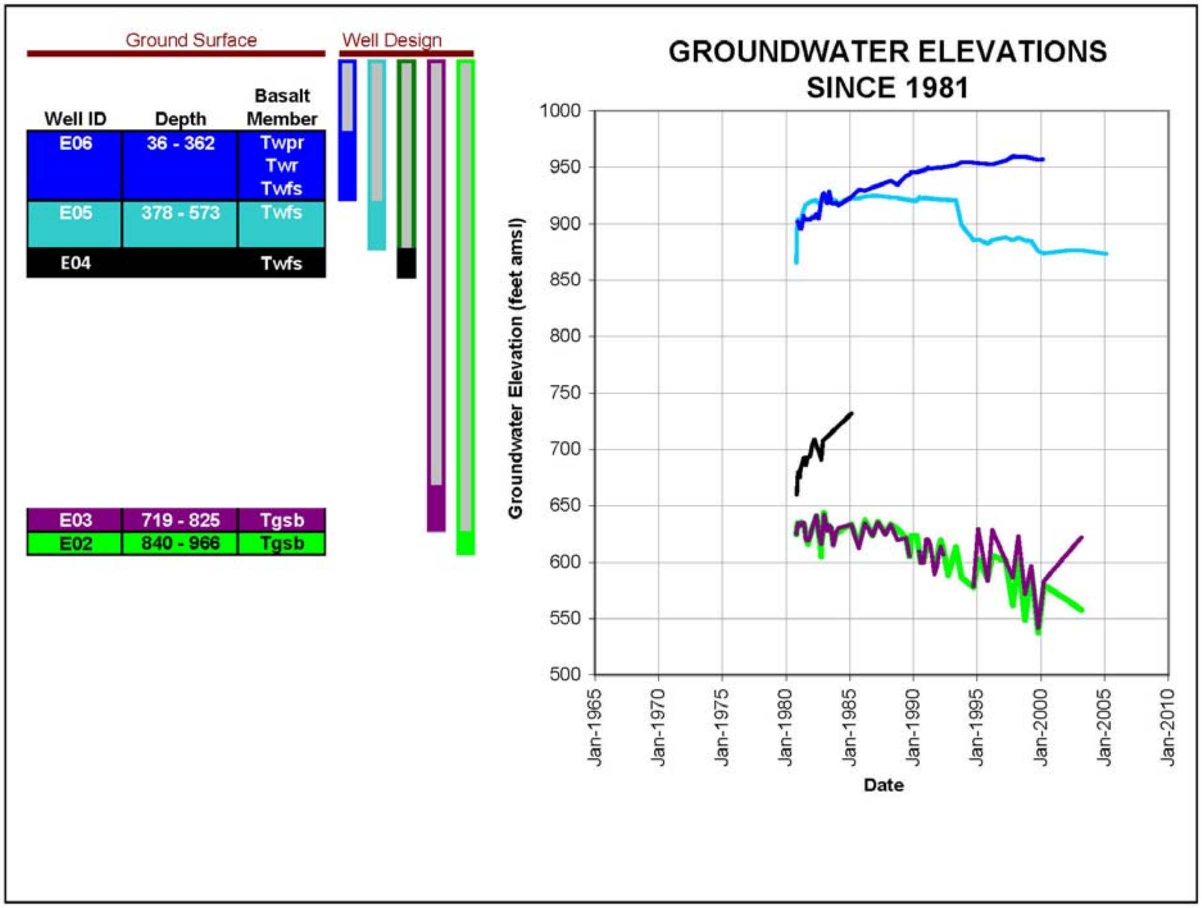


Figure 33. Well construction and groundwater elevation hydrographs for well cluster AAE552 (Cyril Hart), located in southern Adams County. Wells E02 and E03 are open to different depth zones in the Sentinel Bluffs Member of the upper Grande Ronde Basalt. Wells E04, E05, and E06 are each open to different portions of the Wanapum Basalt. The colors of the hydrographs correspond to the colors shown on the schematic well construction diagrams.

Twpr = Priest Rapids Member of the Wanapum Basalt
Twr = Roza Member of the Wanapum Basalt
Twfs = Frenchman Springs Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt

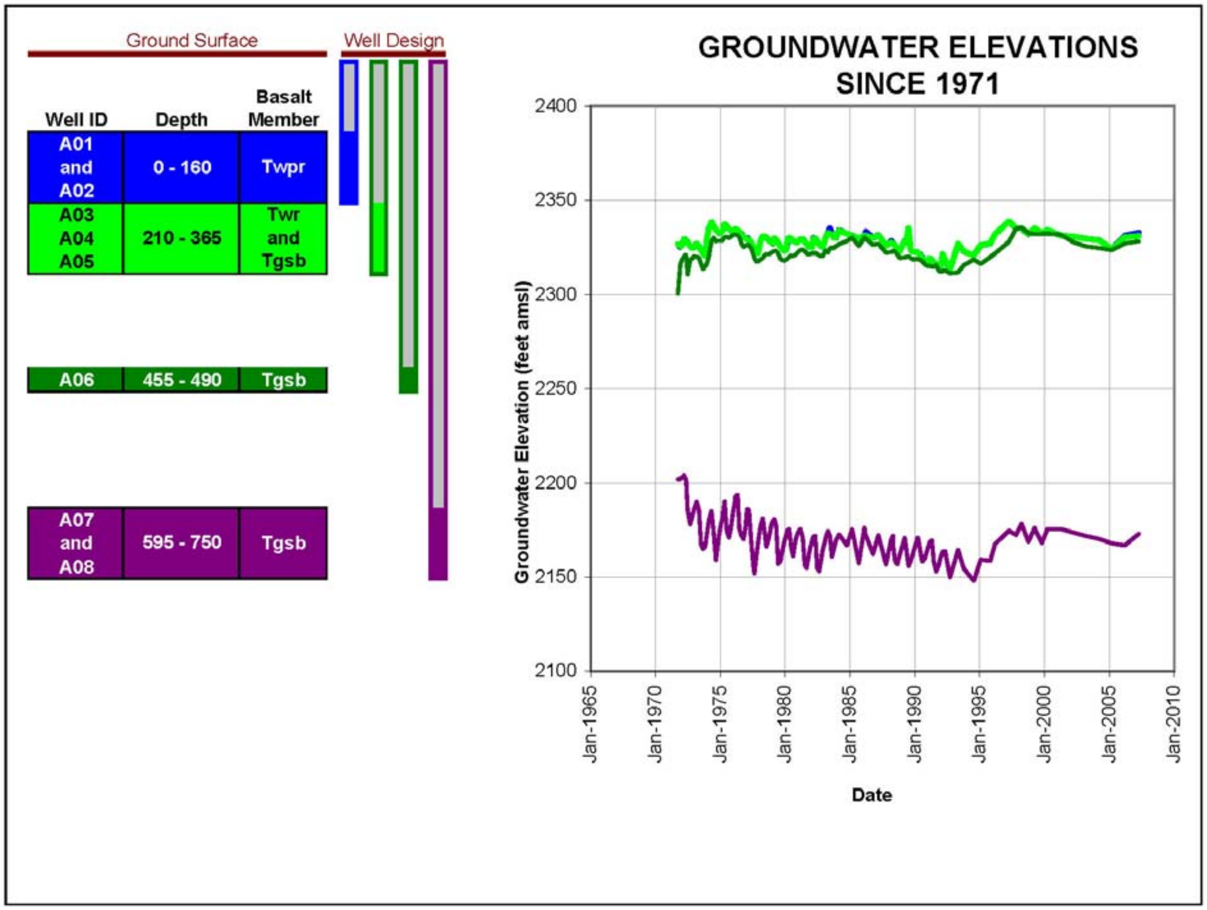


Figure 34. Well construction and groundwater elevation hydrographs for well cluster AAE562 (Davenport), located in northeastern Lincoln County. Wells A01 and A02 are open to different depth zones in the Wanapum Basalt. Wells A03, A04, and A05 are all screened in both the Wanapum Basalt and the uppermost (Sentinel Bluffs) member of the Grande Ronde Basalt. Wells A06, A07, and A08 are each open to different portions of the Grande Ronde Basalt. The colors of the hydrographs correspond to the colors shown on the schematic well construction diagrams.

Twpr = Priest Rapids Member of the Wanapum Basalt
Twr = Roza Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt

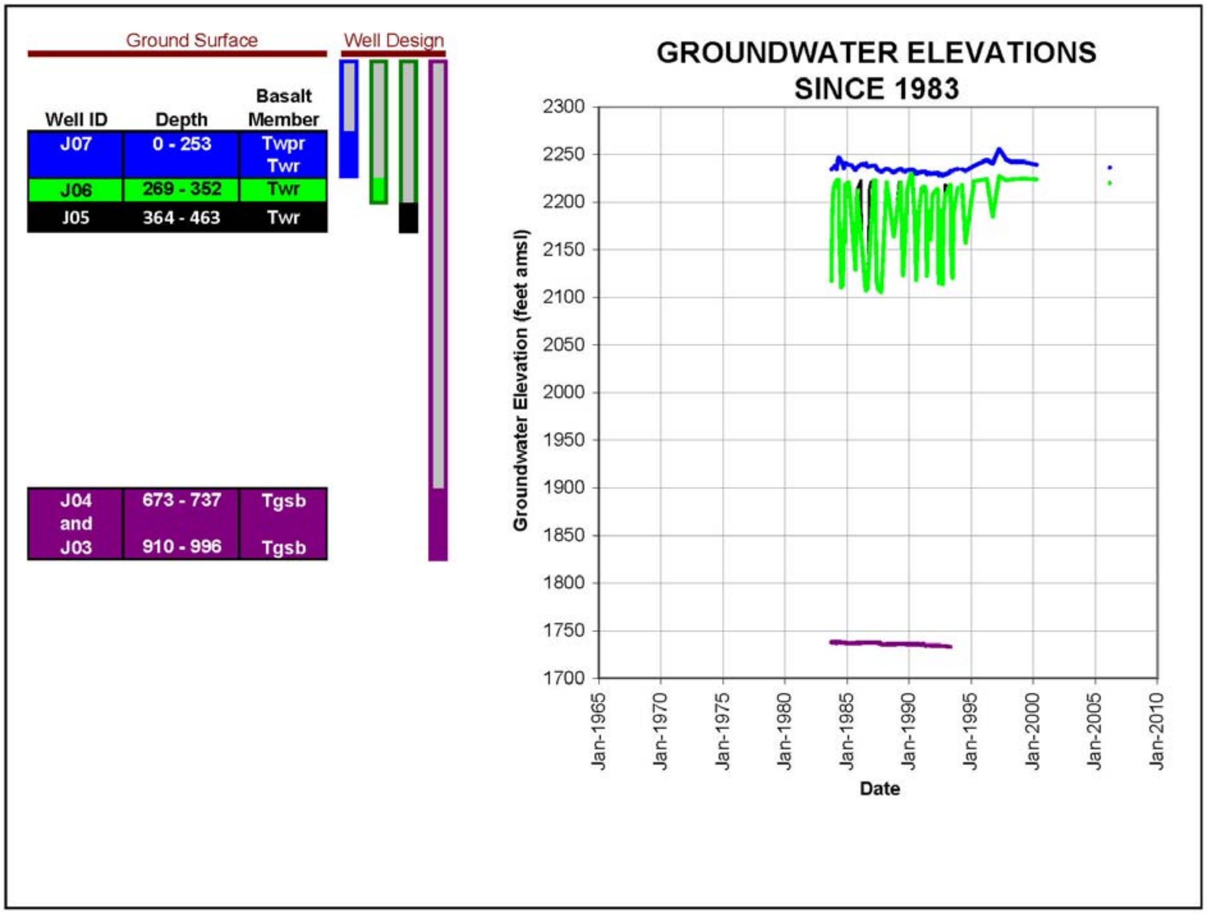


Figure 35. Well construction and groundwater elevation hydrographs for well cluster AAE559 (Dreger), located in the channeled scablands of north-central Lincoln County. Wells J05, J06, and J07 are open to different depth zones in the Wanapum Basalt. Wells J03 and J04 are both screened in the uppermost (Sentinel Bluffs) member of the Grande Ronde Basalt. The colors of the hydrographs correspond to the colors shown on the schematic well construction diagrams.

Twpr = Priest Rapids Member of the Wanapum Basalt
Twr = Roza Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt

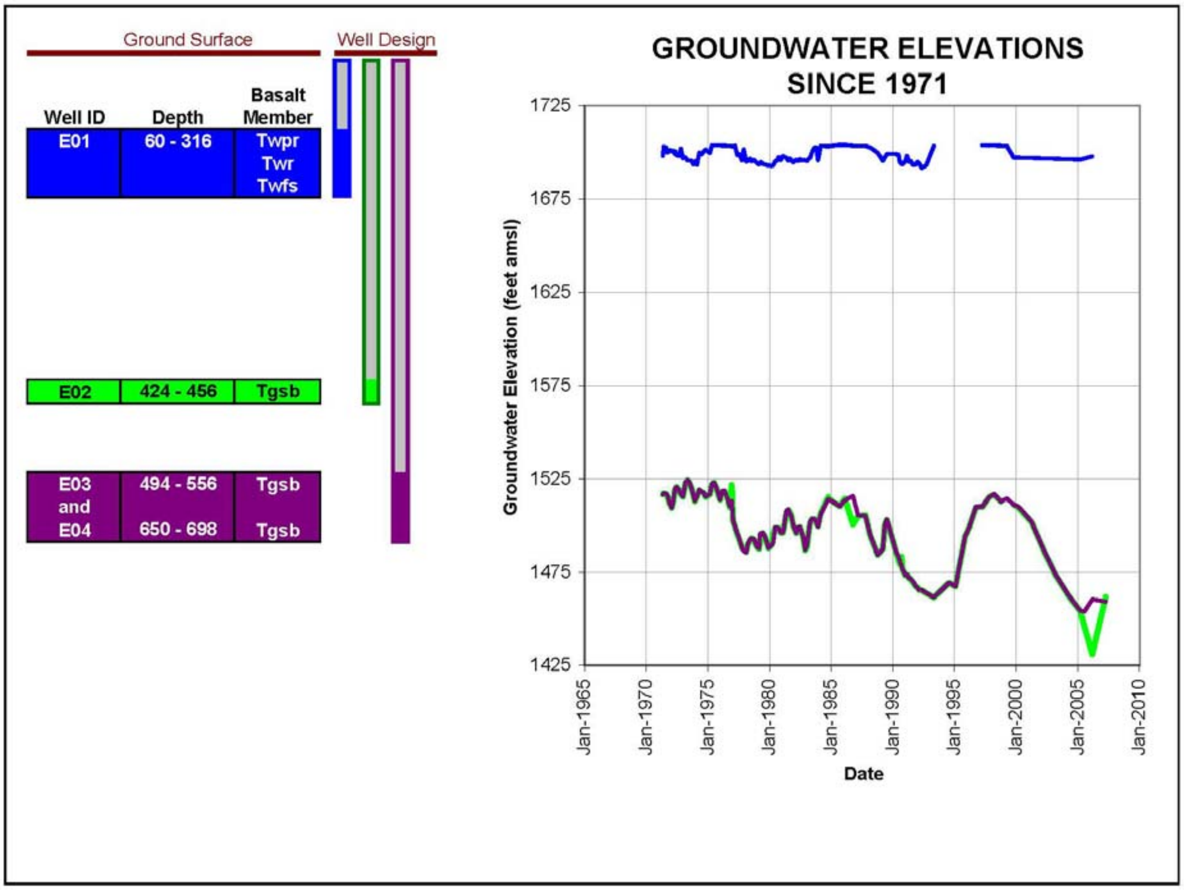


Figure 36. Well construction and groundwater elevation hydrographs for well cluster AAE558 (Almira), located in west-central Lincoln County. Wells E02, E03, and E04 are open to different depth zones in the Sentinel Bluffs Member of the upper Grande Ronde Basalt. Well E01 is open to the Wanapum Basalt. The colors of the hydrographs correspond to the colors shown on the schematic well construction diagrams.

Twpr = Priest Rapids Member of the Wanapum Basalt
Twr = Roza Member of the Wanapum Basalt
Twfs = Frenchman Springs Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt

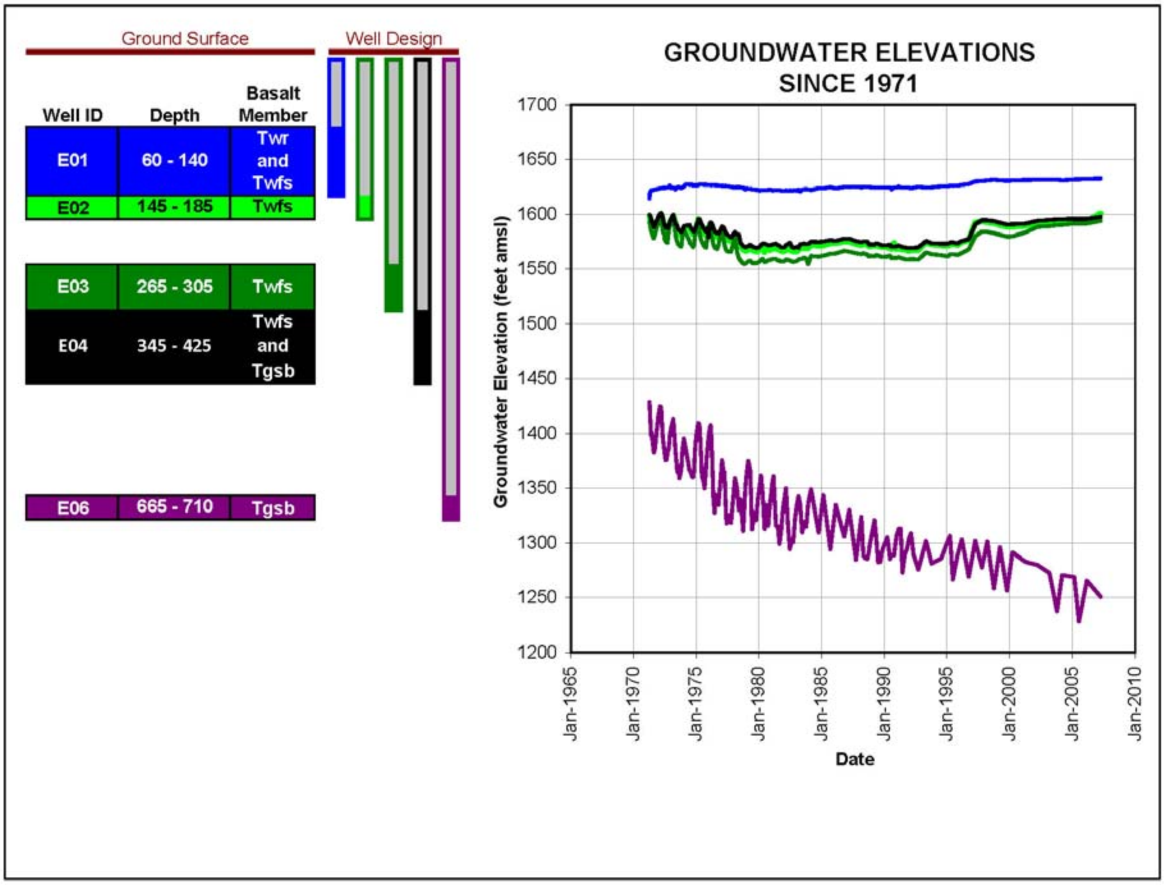


Figure 37. Well construction and groundwater elevation hydrographs for well cluster AAE563 (Odessa), located in north-central Adams County. Wells E01, E02, and E03 are open to different depth zones in the Wanapum Basalt. Well E04 is open to the lowermost member of the Wanapum Basalt (Frenchman Springs) and the Sentinel Bluffs Member of the upper Grande Ronde Basalt. Well E06 is open to the Sentinel Bluffs Member. The colors of the hydrographs correspond to the colors shown on the schematic well construction diagrams.

Twpr = Priest Rapids Member of the Wanapum Basalt
Twr = Roza Member of the Wanapum Basalt
Twfs = Frenchman Springs Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt

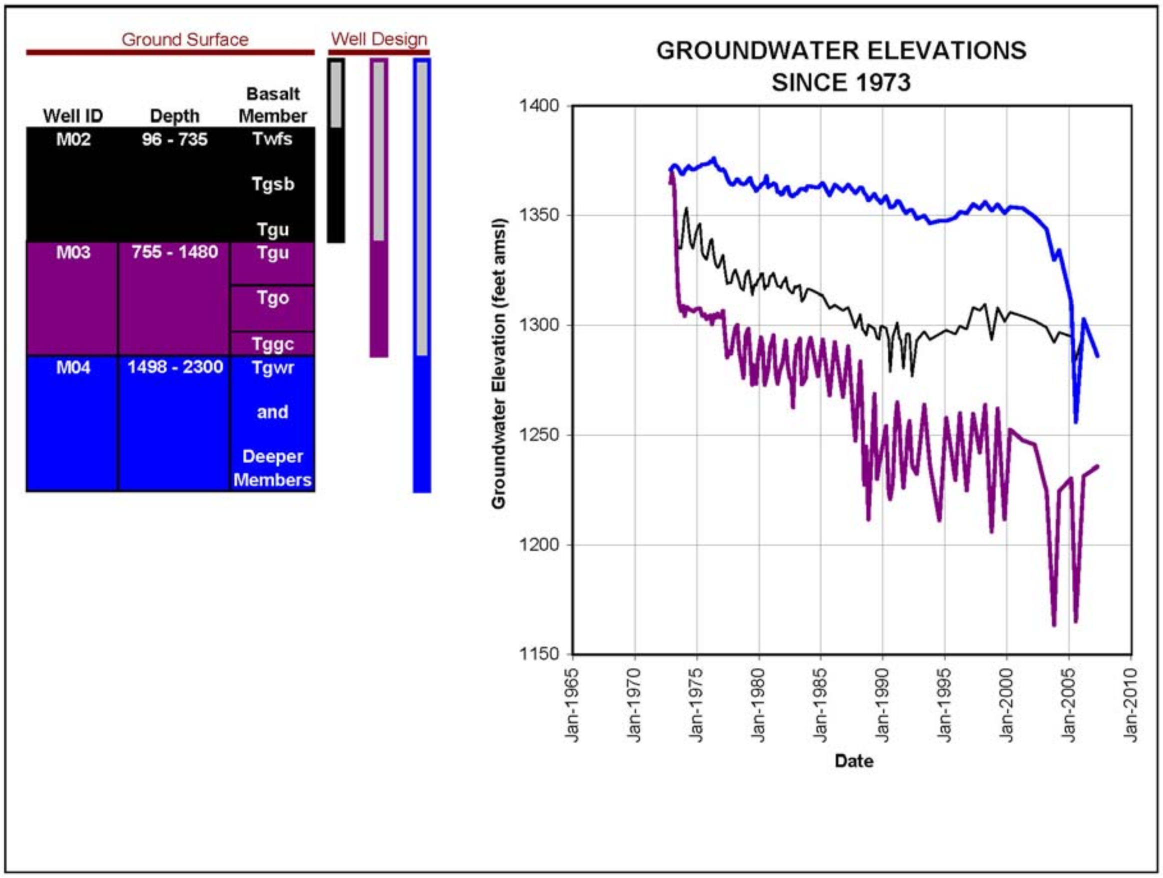


Figure 38. Well construction and groundwater elevation hydrographs for well cluster AAE564 (Basalt Explorer), located in the southwest corner of Lincoln County. The individual wells in this cluster are much deeper than in any of the other state observation wells inside GWMA, penetrating primarily the upper and lower Grande Ronde Basalt. The colors of the hydrographs correspond to the colors shown on the schematic well construction diagrams.

Twfs = Frenchman Springs Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt
Tgu = Umtanum Member of the Grande Ronde Basalt
Tgo = Ortley Member of the Grande Ronde Basalt
Tggc = Grouse Creek Member of the Grande Ronde Basalt
Tgwr = Wapshilla Ridge Member of the Grande Ronde Basalt

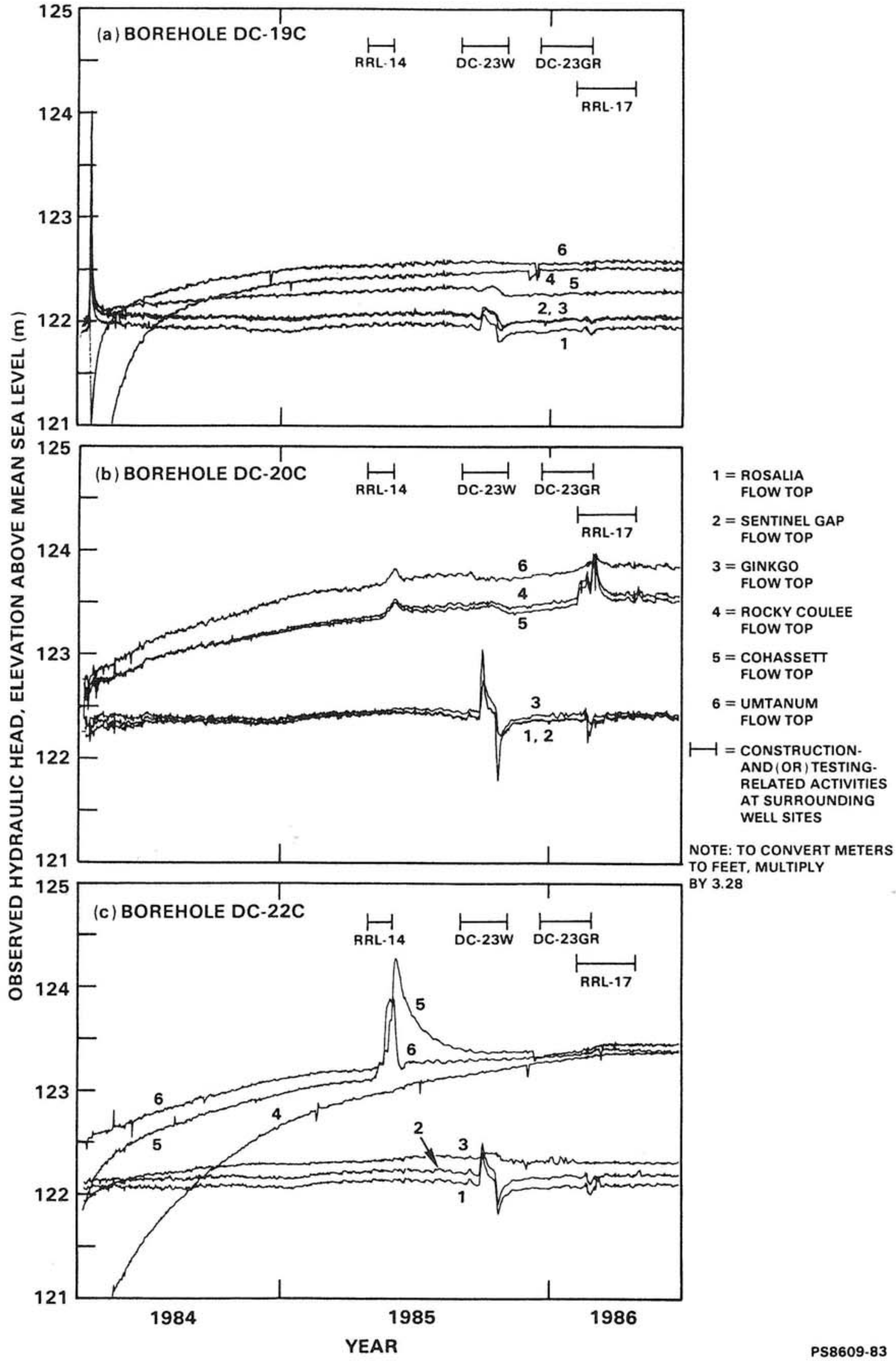


Figure 39. Groundwater elevation (piezometric surface) hydrographs for CRBG interflow distributions in the Wanapum Basalt and the Grande Ronde Basalt within the controlled study area on the Hanford Site. From USDOE (1988).

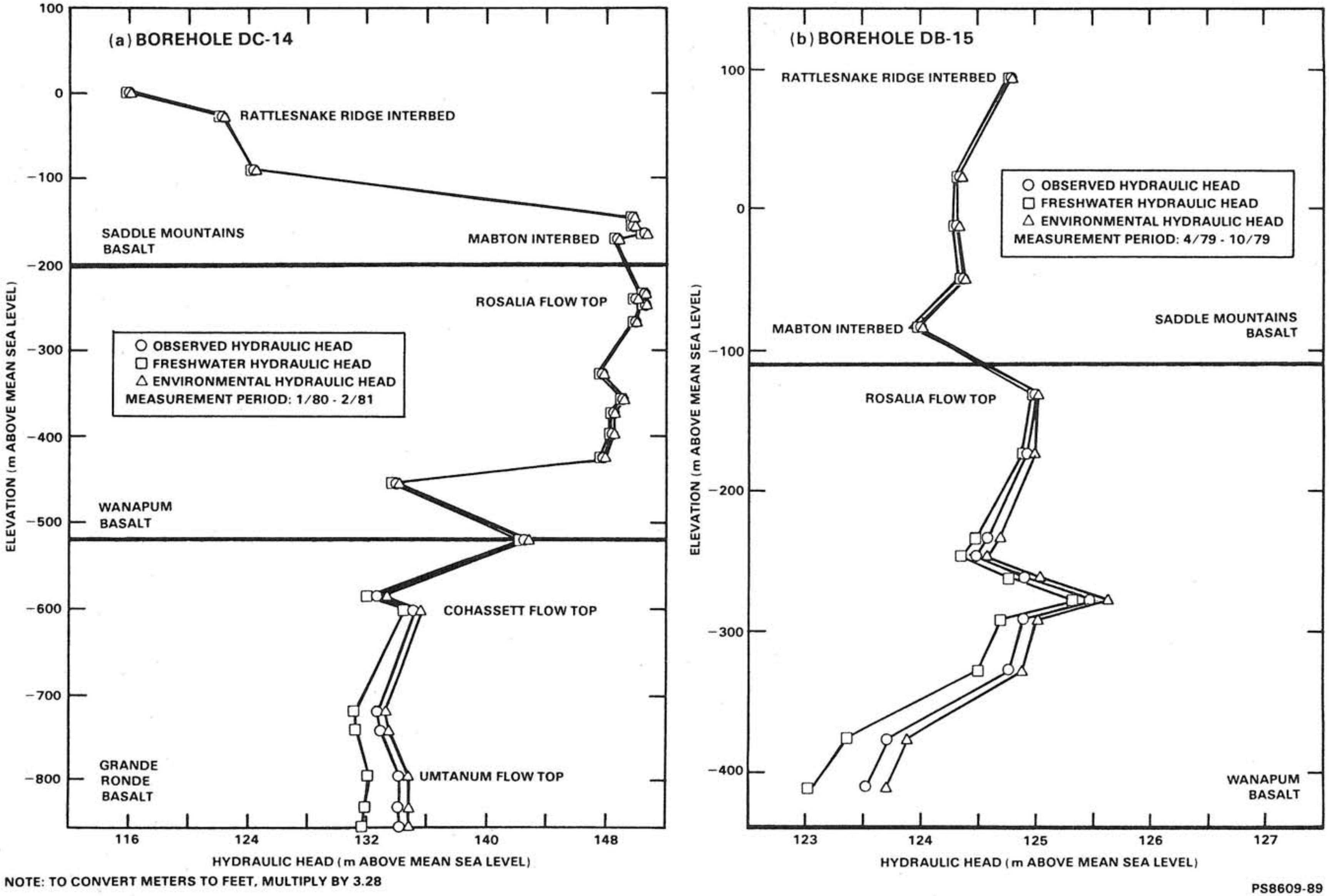


Figure 40. Vertical hydraulic head (piezometric surface) distributions with depth within the CRBG in two boreholes on the Hanford Site. From USDOE (1988).

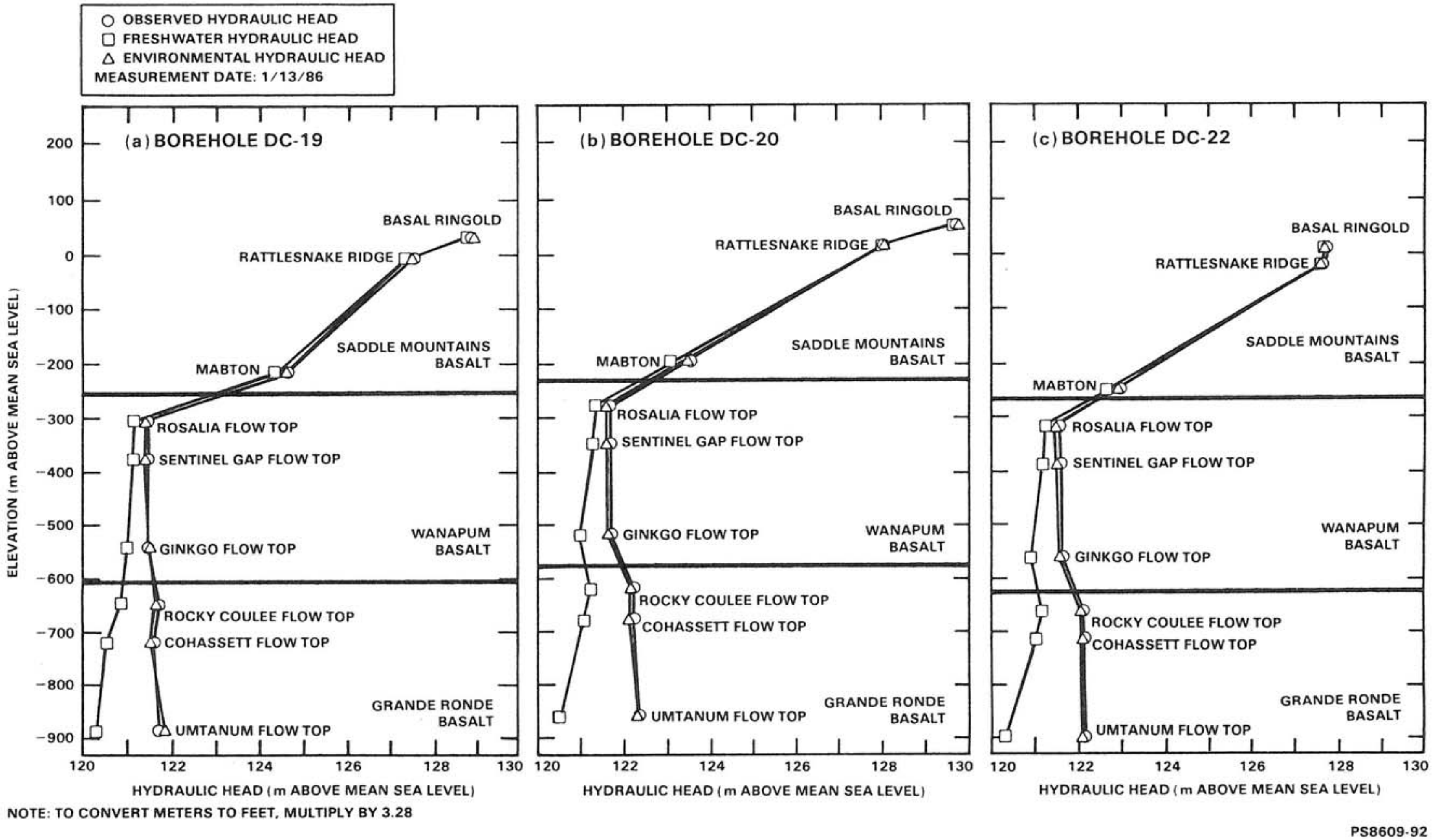


Figure 41. Vertical hydraulic head (piezometric surface) distributions with depth within the CRBG in three boreholes within the controlled study area on the Hanford Site. From USDOE (1988).

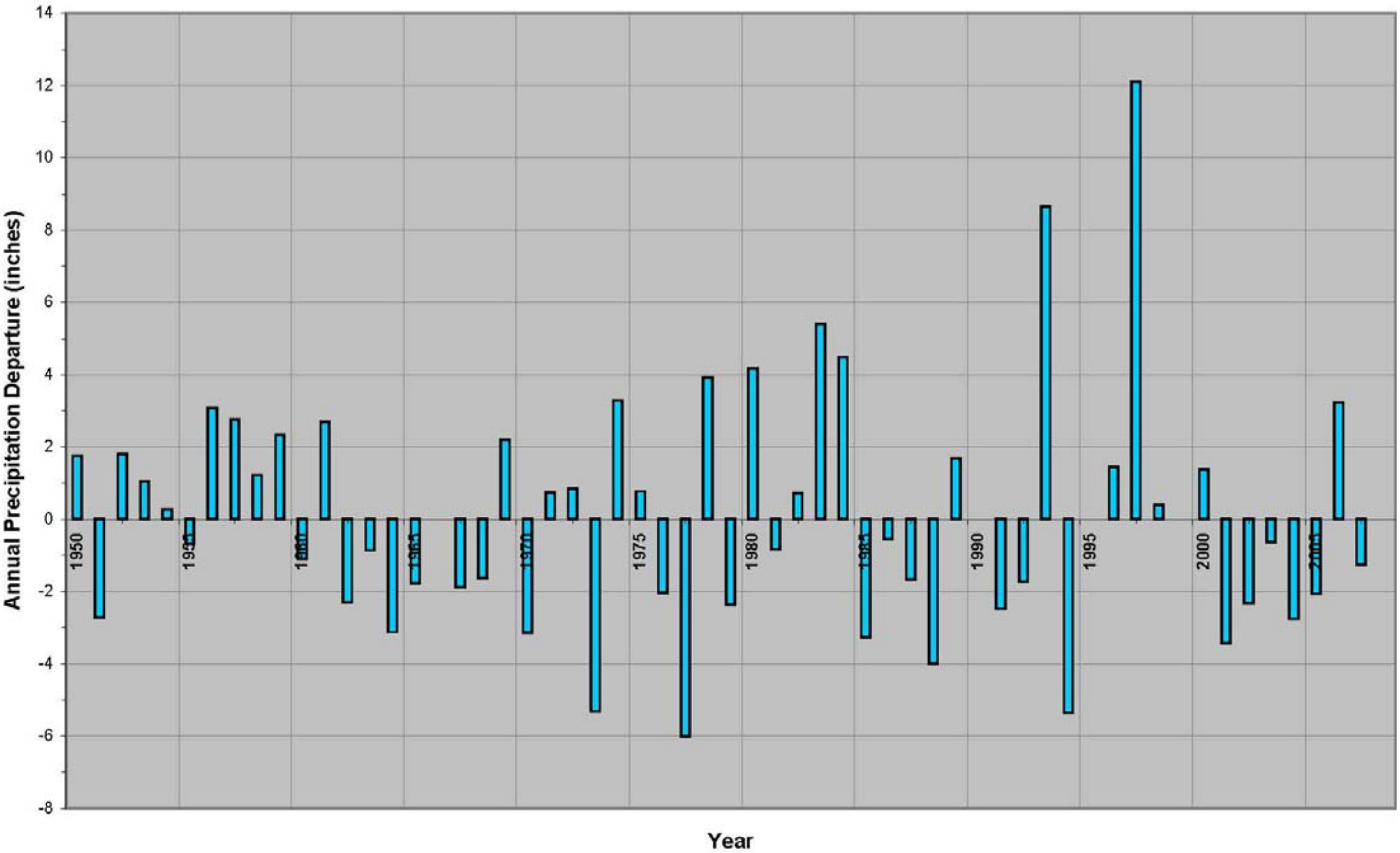


Figure 42. Annual departure from long-term average precipitation, Wilbur rain gage. The official average annual rainfall at the Wilbur rain gage is 12.47 inches. The annual departure values shown on the plot are for each water year. A given water year begins on October 1 of the prior year and ends on September 30 of the given water year.

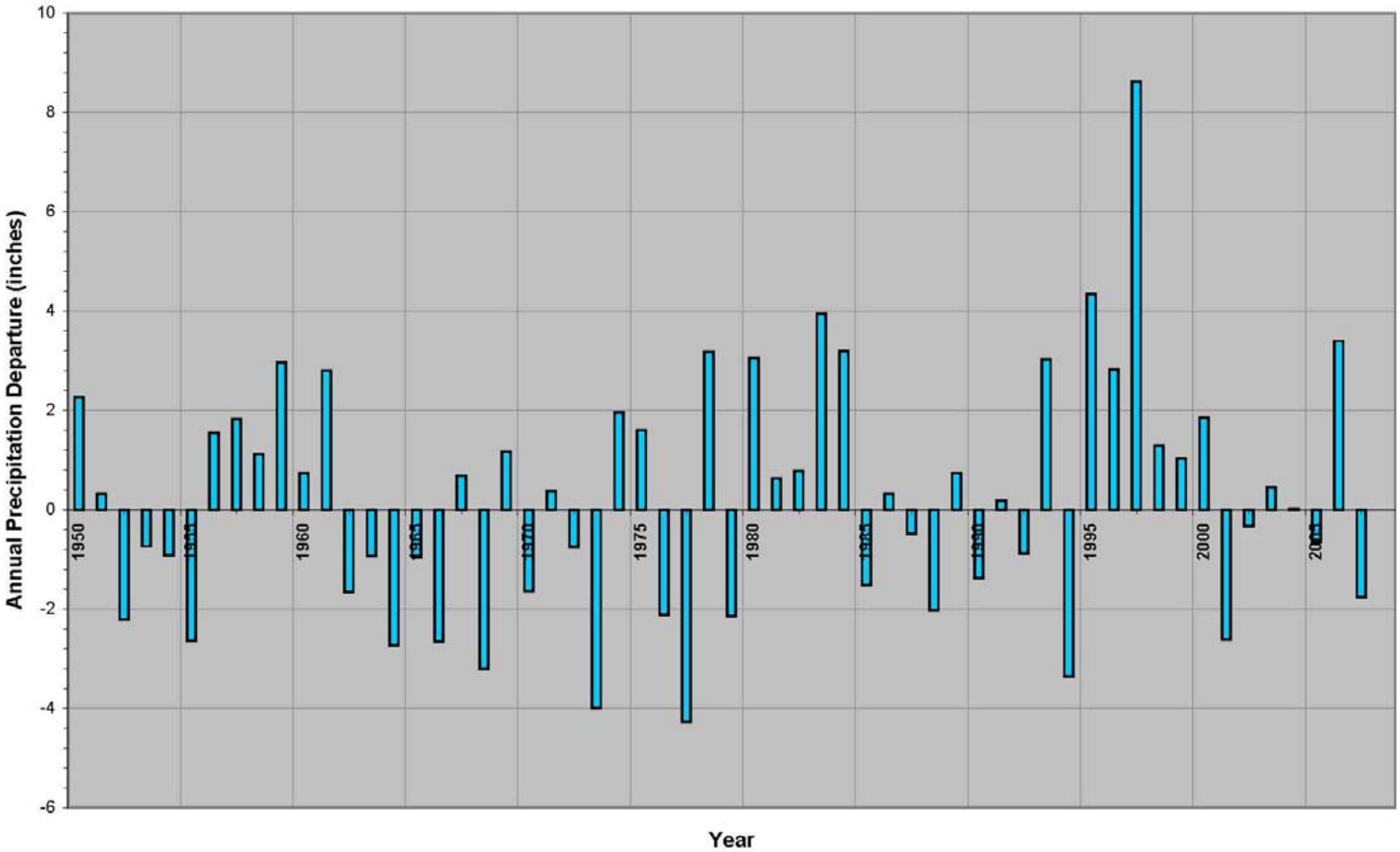


Figure 43. Annual departure from long-term average precipitation, Odessa rain gage. The official average annual rainfall at the Odessa rain gage is 10.12 inches. The annual departure values shown on the plot are for each water year. A given water year begins on October 1 of the prior year and ends on September 30 of the given water year.

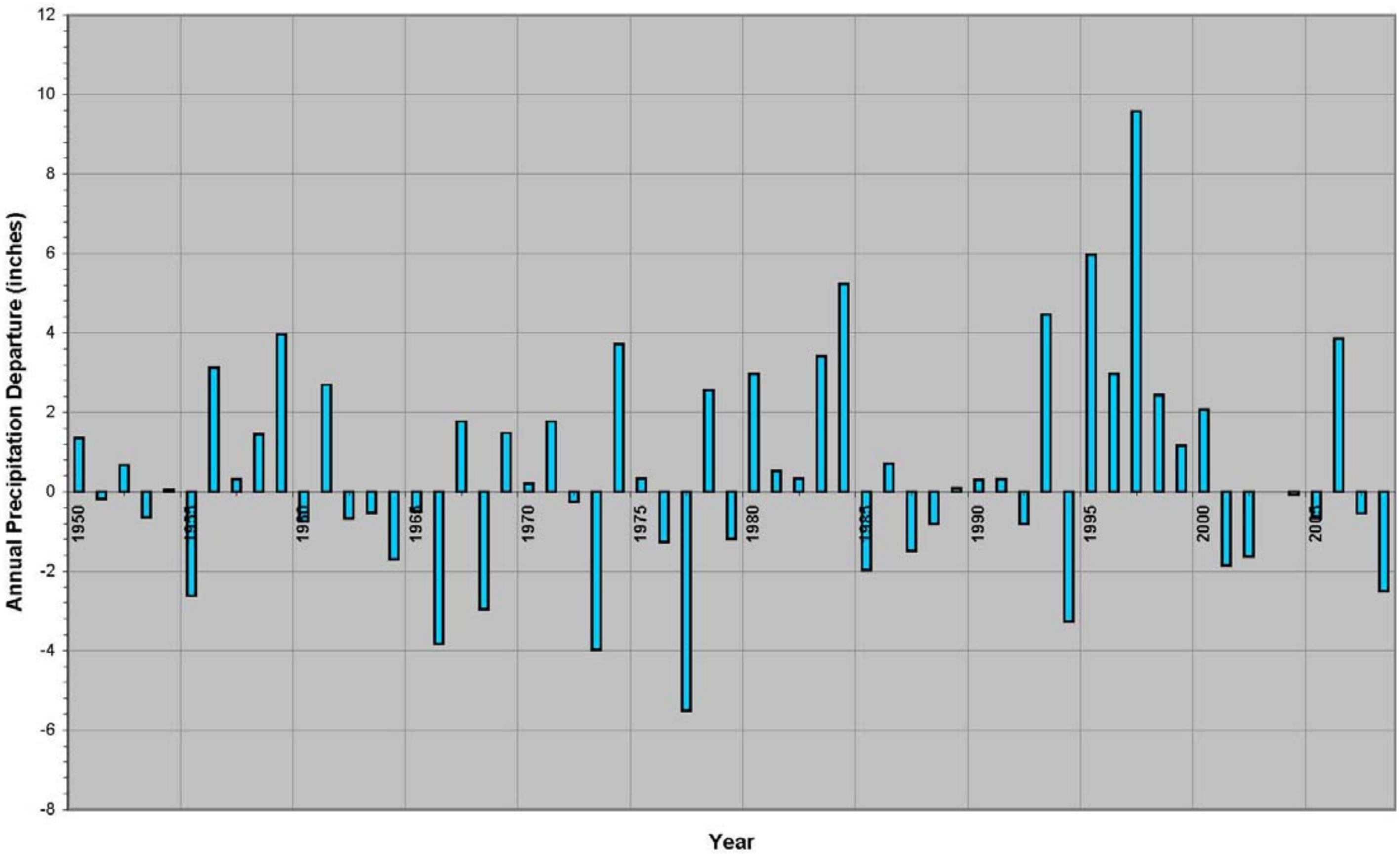


Figure 44. Annual departure from long-term average precipitation, Ritzville rain gage. The official average annual rainfall at the Ritzville rain gage is 11.30 inches. The annual departure values shown on the plot are for each water year. A given water year begins on October 1 of the prior year and ends on September 30 of the given water year.

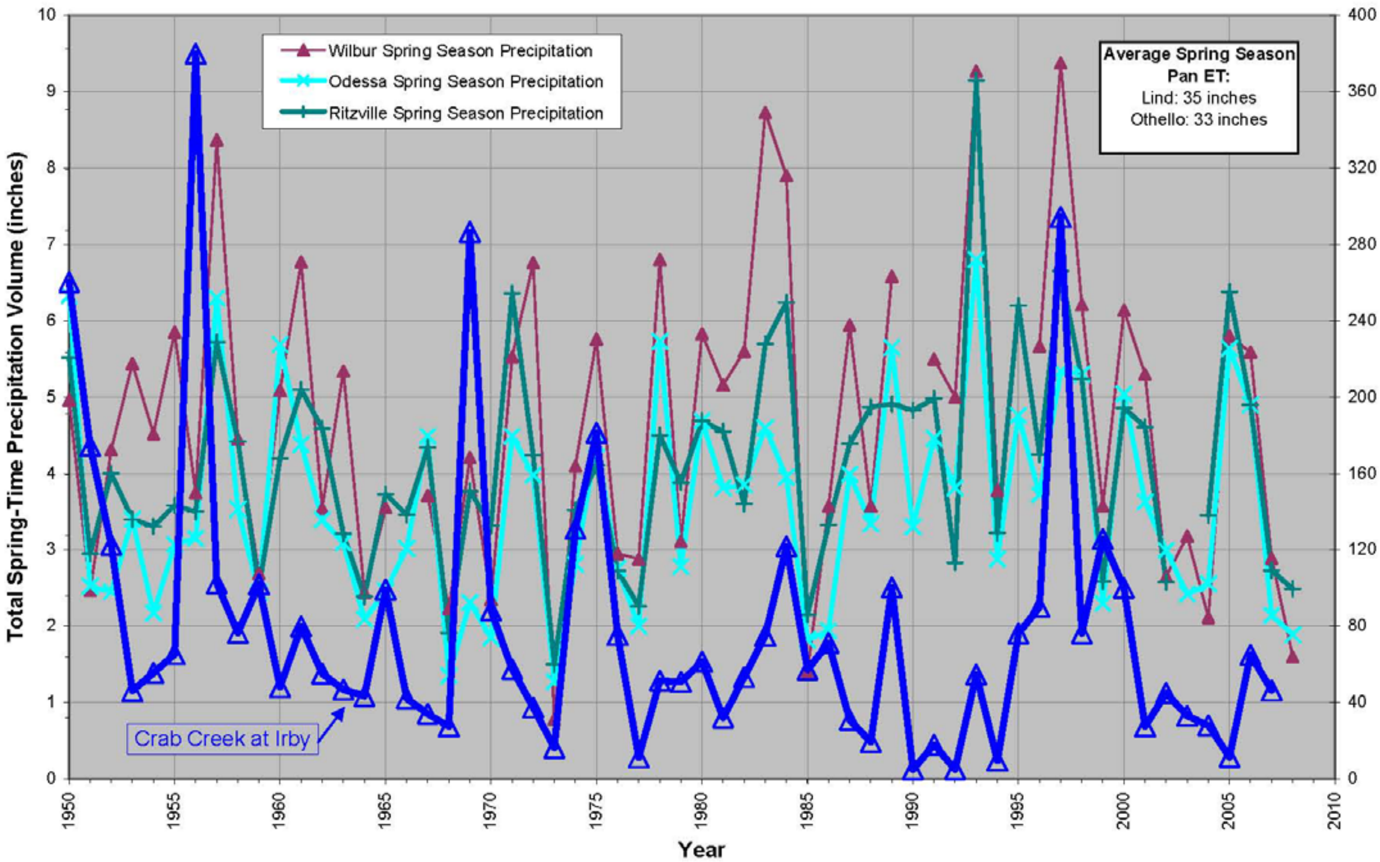


Figure 45. Spring-season (March through July) volumes of Crab Creek flow at the Irby stream gage and precipitation at the Wilbur, Odessa, and Ritzville rain gages, 1950 through 2008.

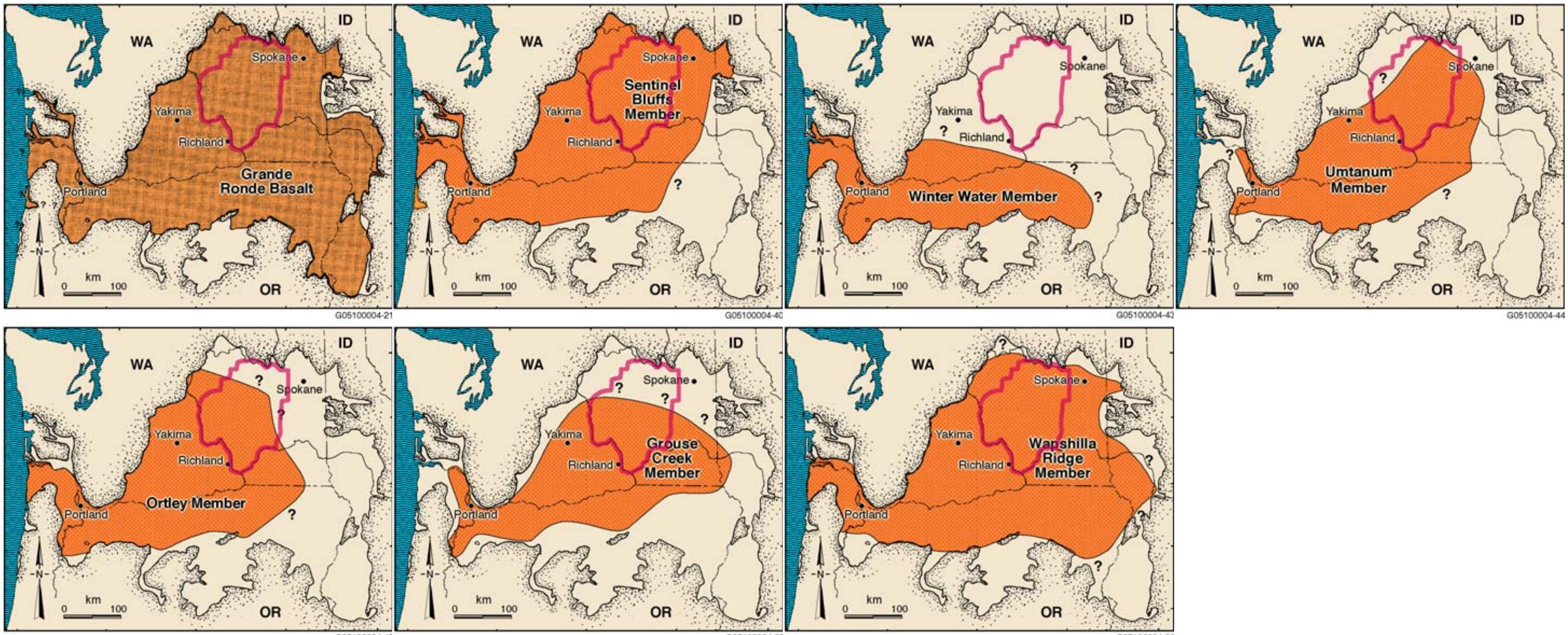


Figure 46. Maps showing the areal extent of the individual basalt members in the Grande Ronde Basalt. Modified from Tolan and others (1989) and Reidel and others (1989b) to show the outline of the Columbia Basin Ground Water Management Area (GWMA) in red.

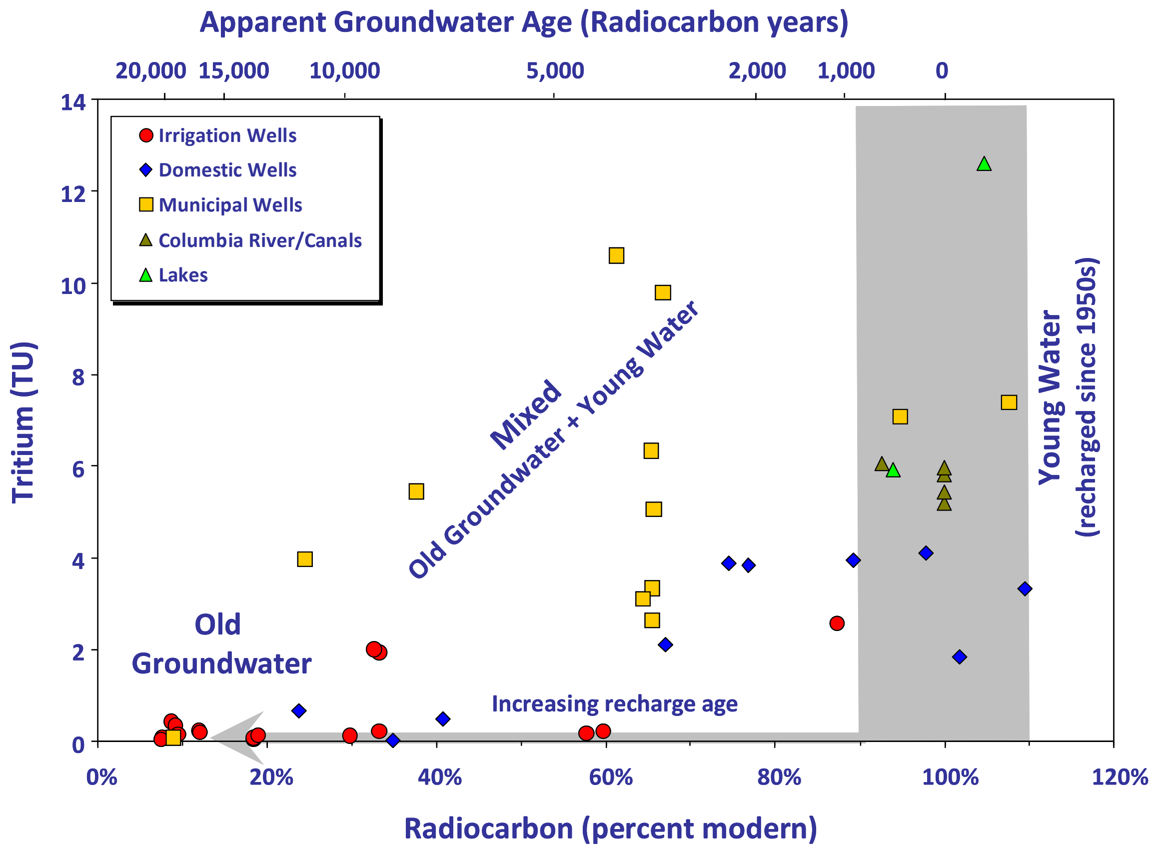


Figure 47. Radiocarbon and tritium contents in selected CRBG wells and local surface waters.

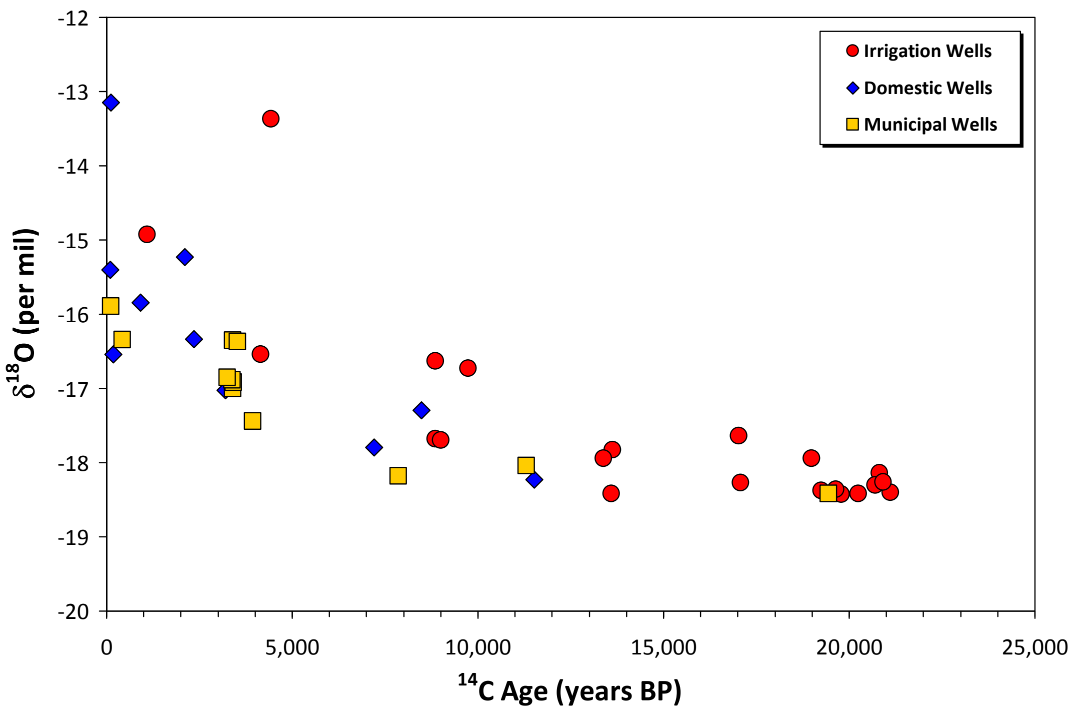


Figure 48. Stable oxygen isotope ratios of groundwater as a function of age. Samples with ages greater than 10,000 years (Pleistocene) are uniformly isotopically depleted relative to younger waters.

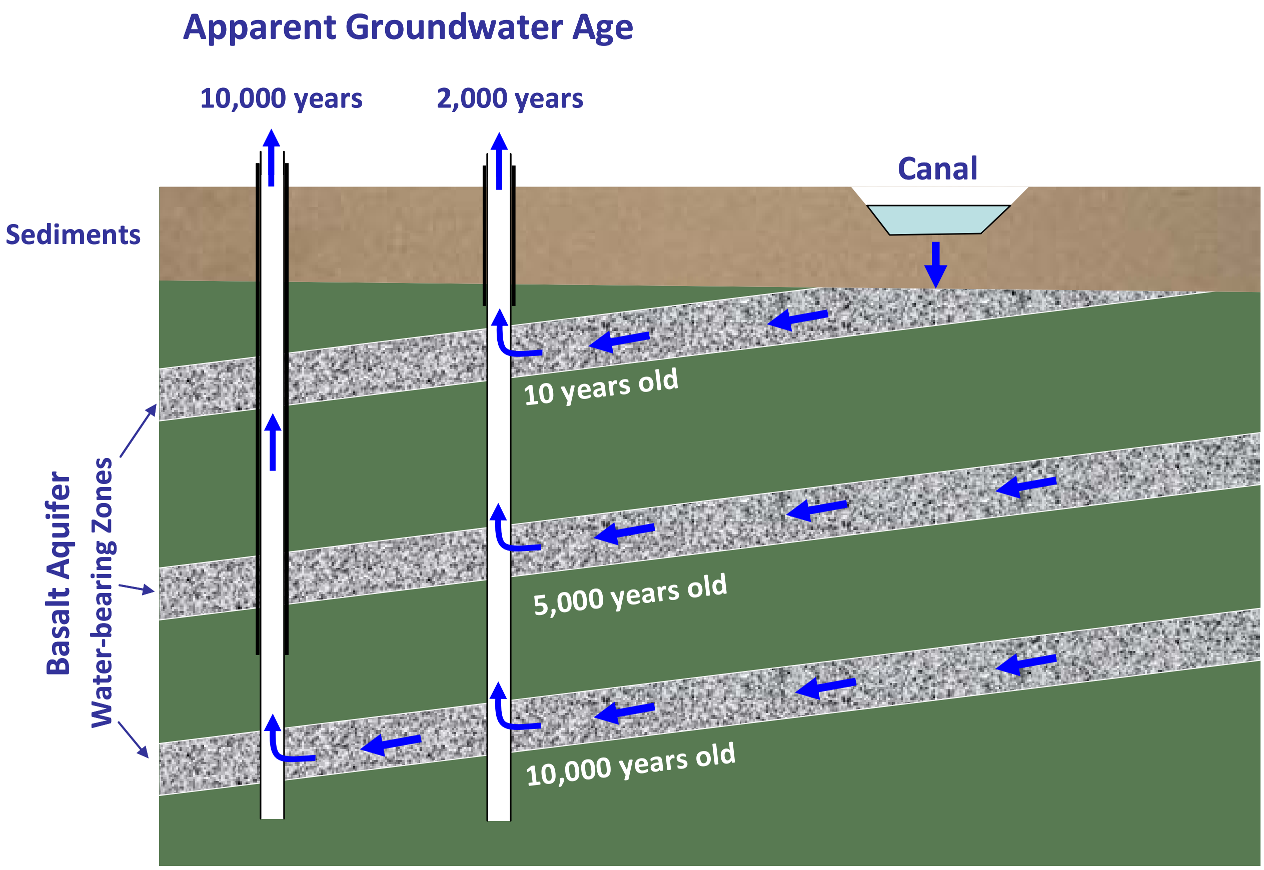


Figure 49. Schematic cross-section showing a canal that serves as a modern source of recharge to groundwater. The canal is located upgradient (up-dip) of two water supply wells that have different construction. The well on the left is cased through all but the deepest water-bearing zone and shows a comparatively old age (10,000 years). The well to the right is open to shallow, intermediate, and deep zones and shows a younger apparent age that indicates how the open borehole mixes groundwater from each zone to which the well is open.

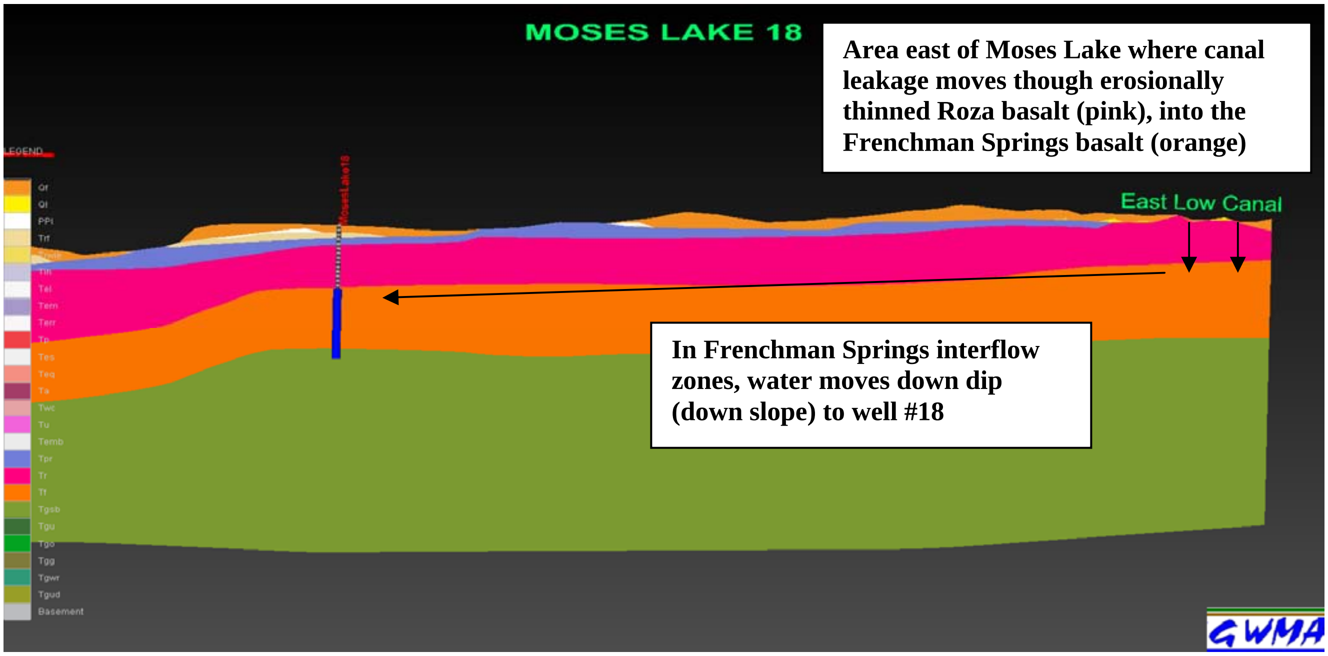


Figure 50. West-east cross-section, looking to the north, showing the East Low Canal to the east and to the west the City of Moses Lake well 18, which lies downgradient (down-dip) of the canal.

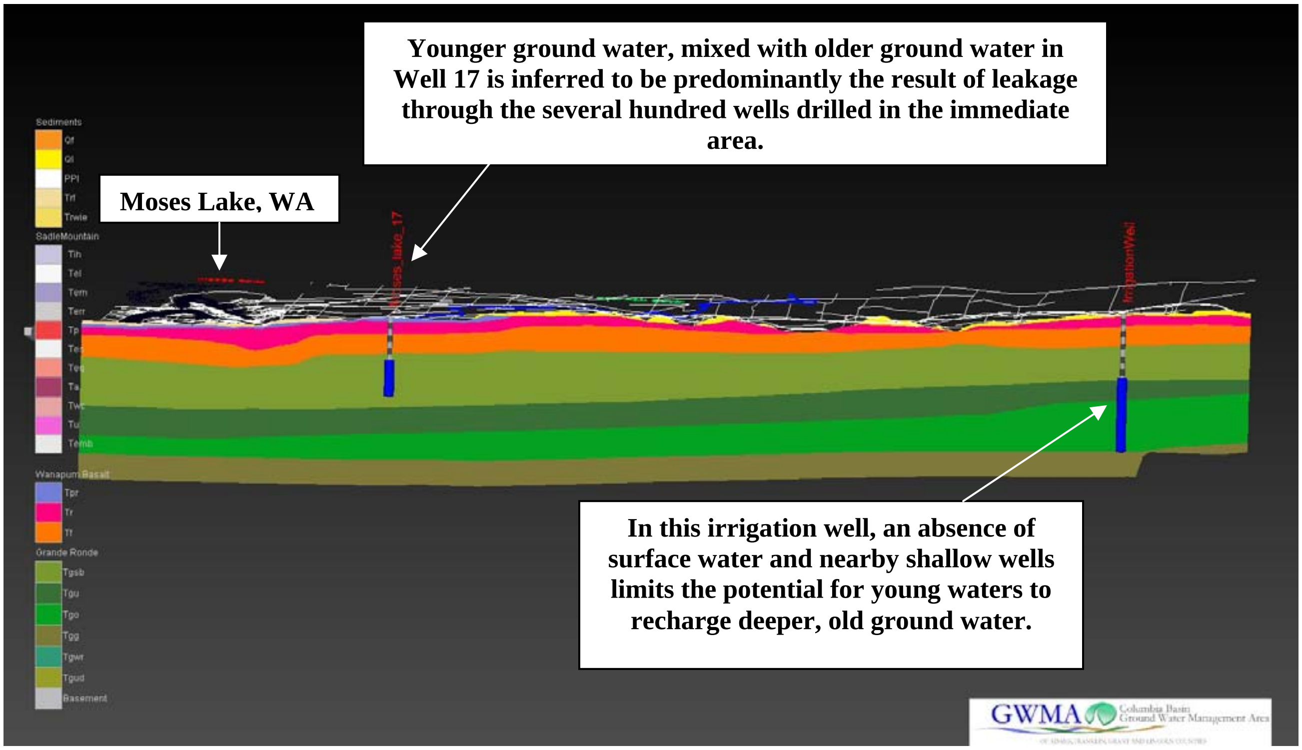


Figure 51. West-east cross-section, looking to the north, showing the City of Moses Lake to the west and Grande Ronde basalt wells located further east.

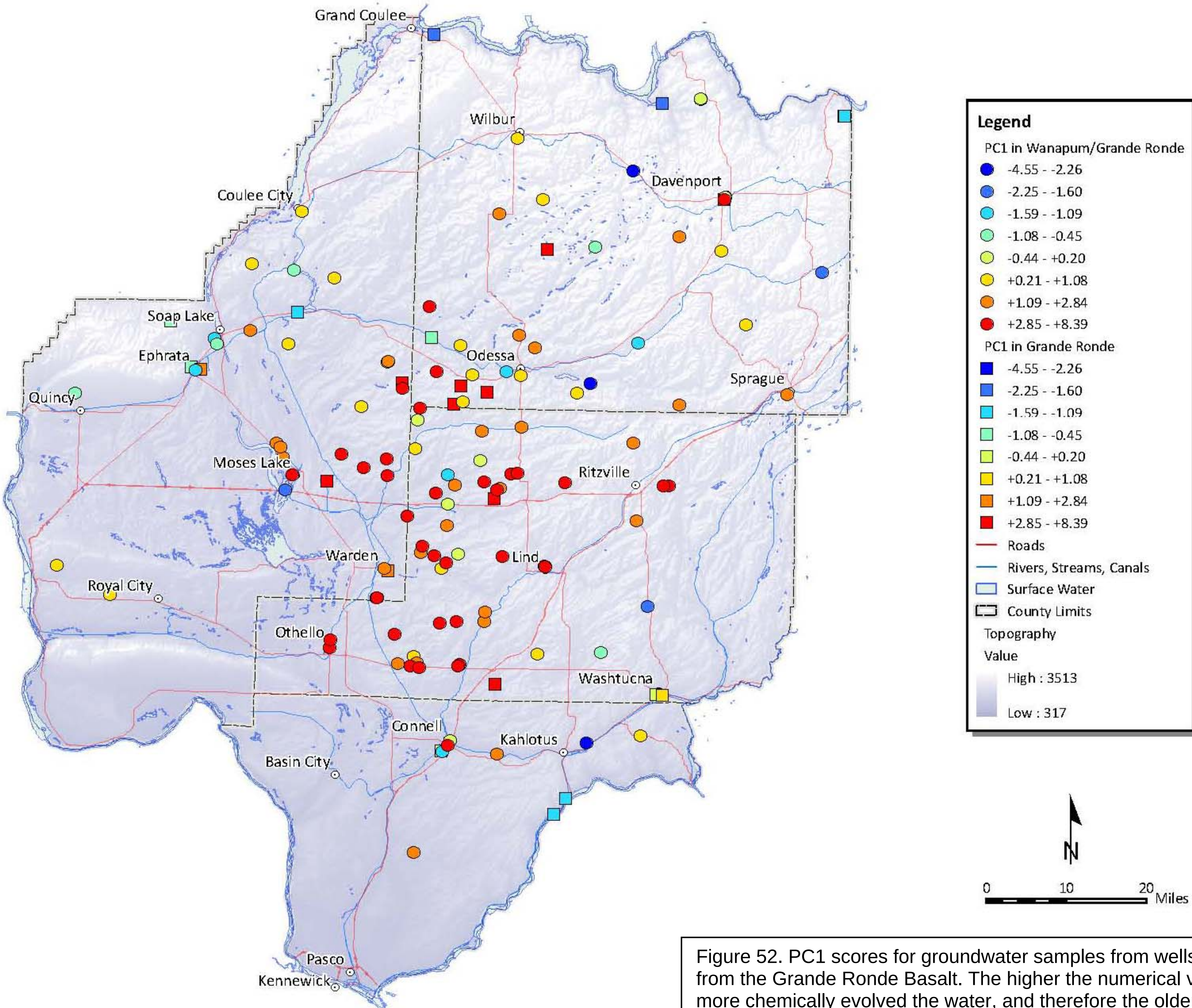


Figure 52. PC1 scores for groundwater samples from wells producing from the Grande Ronde Basalt. The higher the numerical value, the more chemically evolved the water, and therefore the older the water.

APPENDIX A

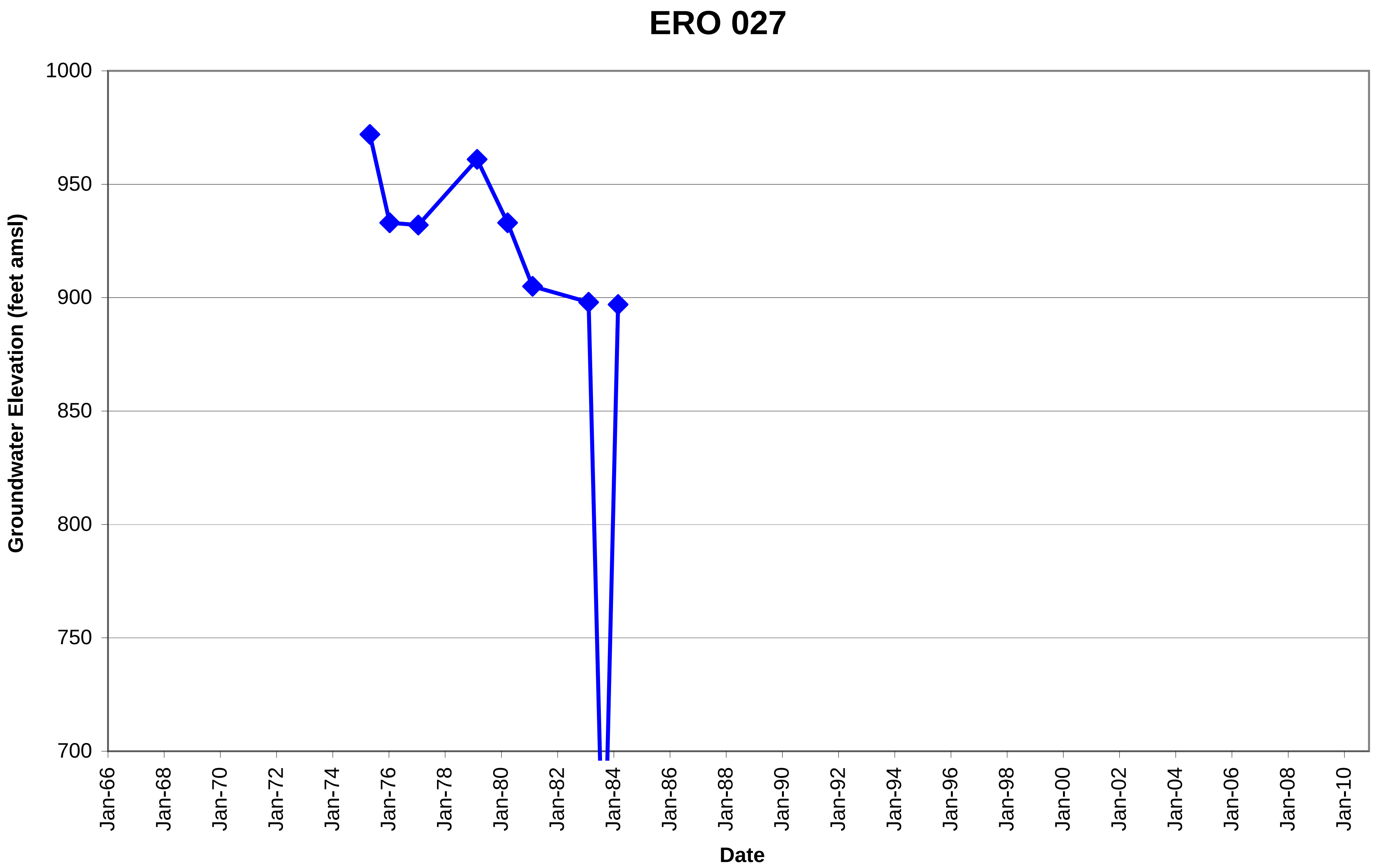
GROUNDWATER ELEVATION HYDROGRAPHS
FOR PRODUCTION WELLS LOCATED IN THE
COLUMBIA BASIN GROUND WATER MANAGEMENT AREA OF
ADAMS, FRANKLIN, GRANT, AND LINCOLN COUNTIES

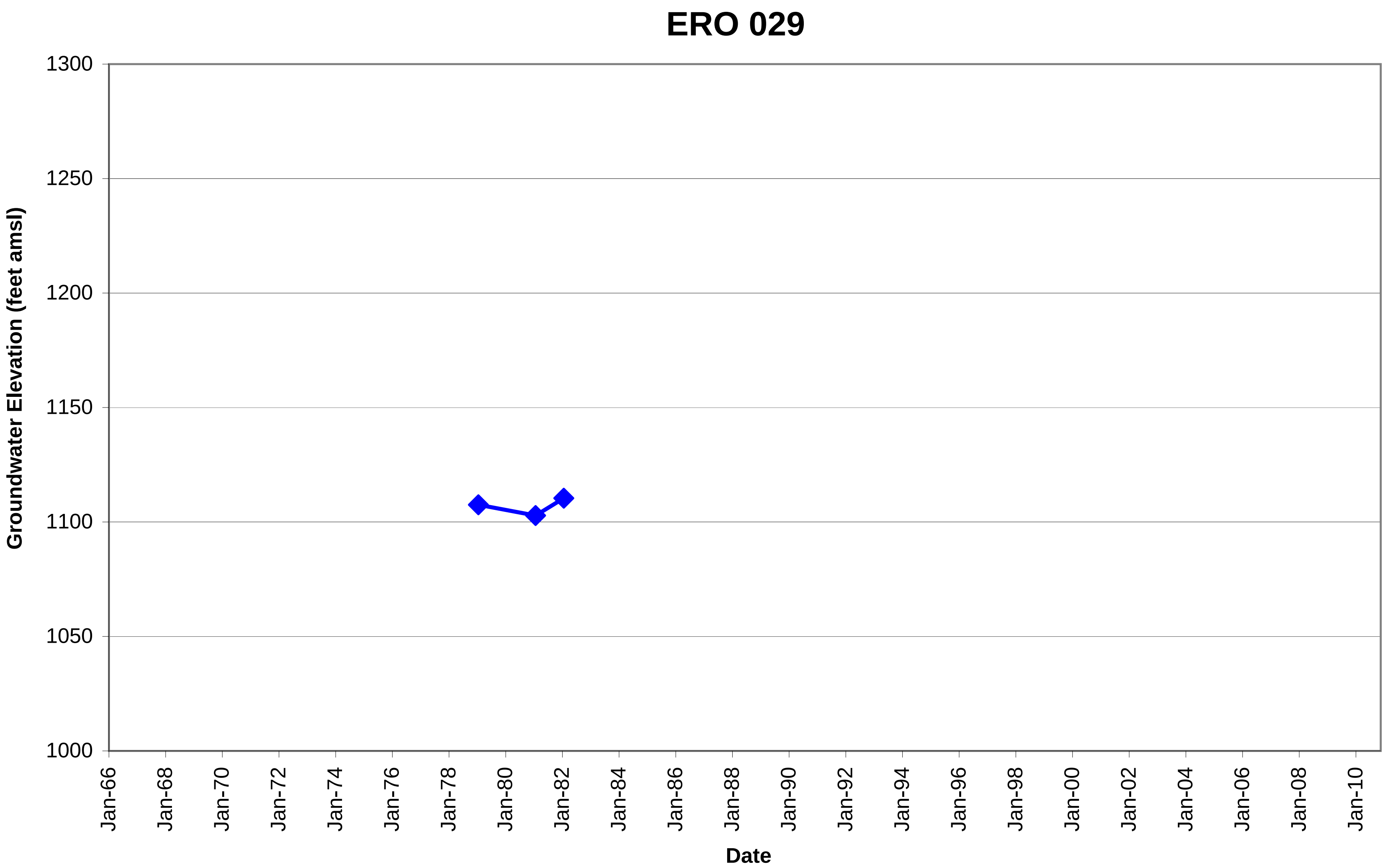
Wells Screened Wholly or Partially in the Wanapum Basalt and Showing Declining Groundwater Levels Over Time

Columbia Basin Ground Water Management Area

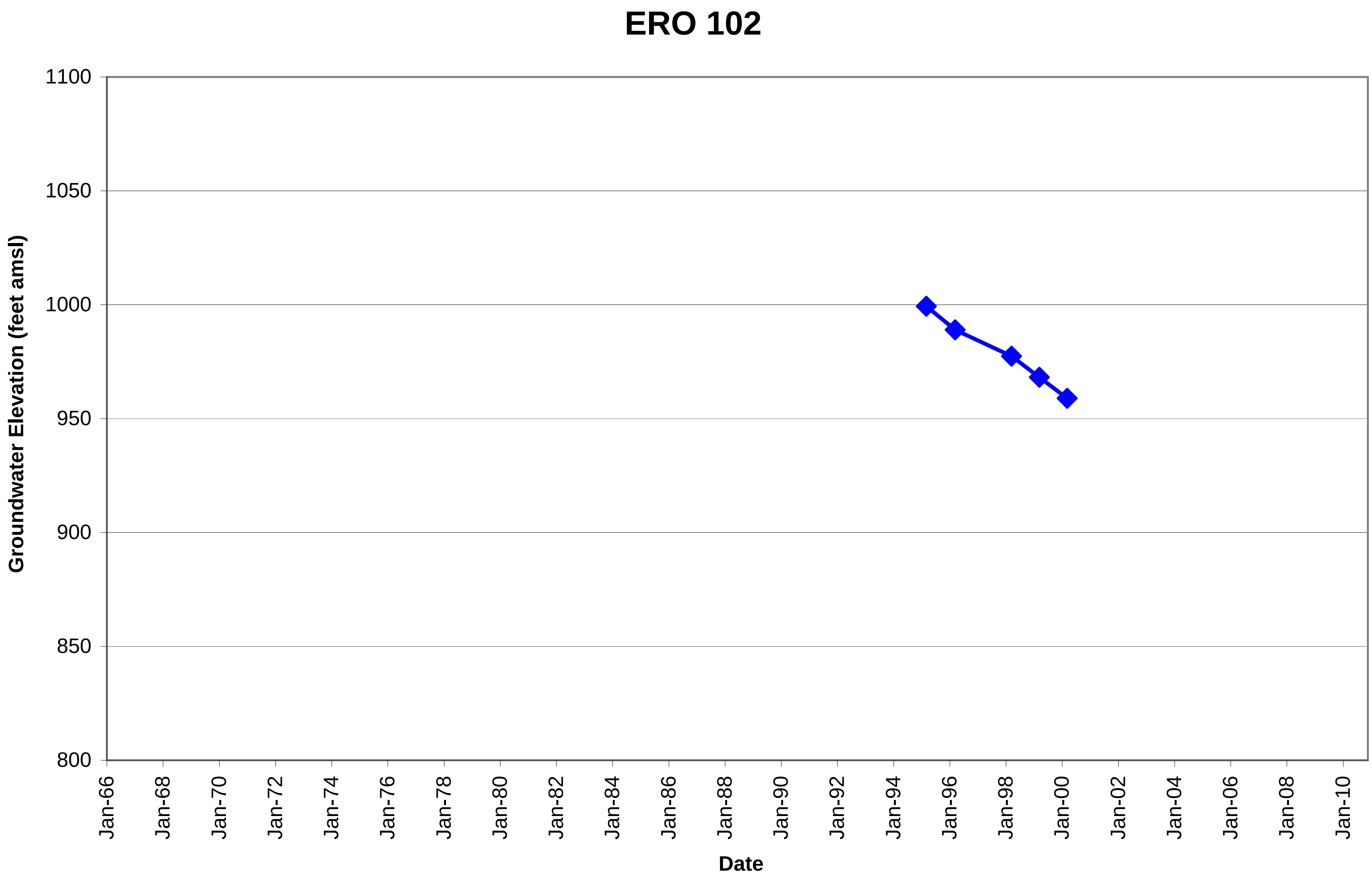
Well ID	Top Open Interval (feet amsl)	Bottom Open Interval (feet amsl)	Top Wanapum Basalt (feet amsl)	Top Grande Ronde Basalt (feet amsl)	Total Open Interval (feet)	Wanapum (feet)	Wanapum %	Grande Ronde (feet)	Grande Ronde %	CRBG Members that Well is Open To
ero175: North Shannon #2	1658.00	933.00	1600	1135	725.00	465	64%	201.55	28%	Twr, Twfs, Tgsb
ero178: North Shannon #3	1600.00	-565.00	1614	1169	2165.00	445	21%	1734.24	80%	Twr, Twfs, Tgsb, Tgu, Tgo, Tggc, Tgwr
ero027: Johnson Section 19	1175.00	112.00	1140	437	1063.00	703	66%	324.72	31%	Twpr, Twr, Twfs, Tgsb
Schiebel Well North	1773.00	1123.00	1713	1368	650.00	345	53%	245.18	38%	Twr, Twfs, Tgsb
ero126	1185.21	984.21	1177	855	201.00	193	96%	NONE		Twfs
ero139: T-16N #5	1279.00	70.00	1295	824	1209.00	455	38%	753.52	62%	Twr, Twfs, Tgsb, Tgu
ero212: Frick #1	1547.00	533.00	1567	1059	1014.00	488	48%	525.58	52%	Twr, Twfs, Tgsb, Tgu
ero424: McP I#1	1768.00	697.00	1793	1508	1071.00	260	24%	810.71	76%	Twpr, Twr, Twfs, Tgsb
ero432: McPherson DN	1697.00	986.00	2039	1700	711.00	NONE		714.00	100%	Tgsb
ero453: Quirk House Well	2198.00	1304.00	2150	1736	894.00	414	46%	432.29	48%	Twpr, Twr, Tgsb
ero464: Schmeirer Peck	2074.00	1067.00	2074	1650	1007.00	424	42%	583.00	58%	Twpr, Twr, Twfs, Tgsb
ero466: Mcph-Schr	2050.00	1303.00	2000	1631	747.00	369	49%	327.69	44%	Twpr, Twr, Twfs, Tgsb
ero483	1092.10	187.10	900	27	905.00	873	96%	NONE		Twpr, Twr, Twfs

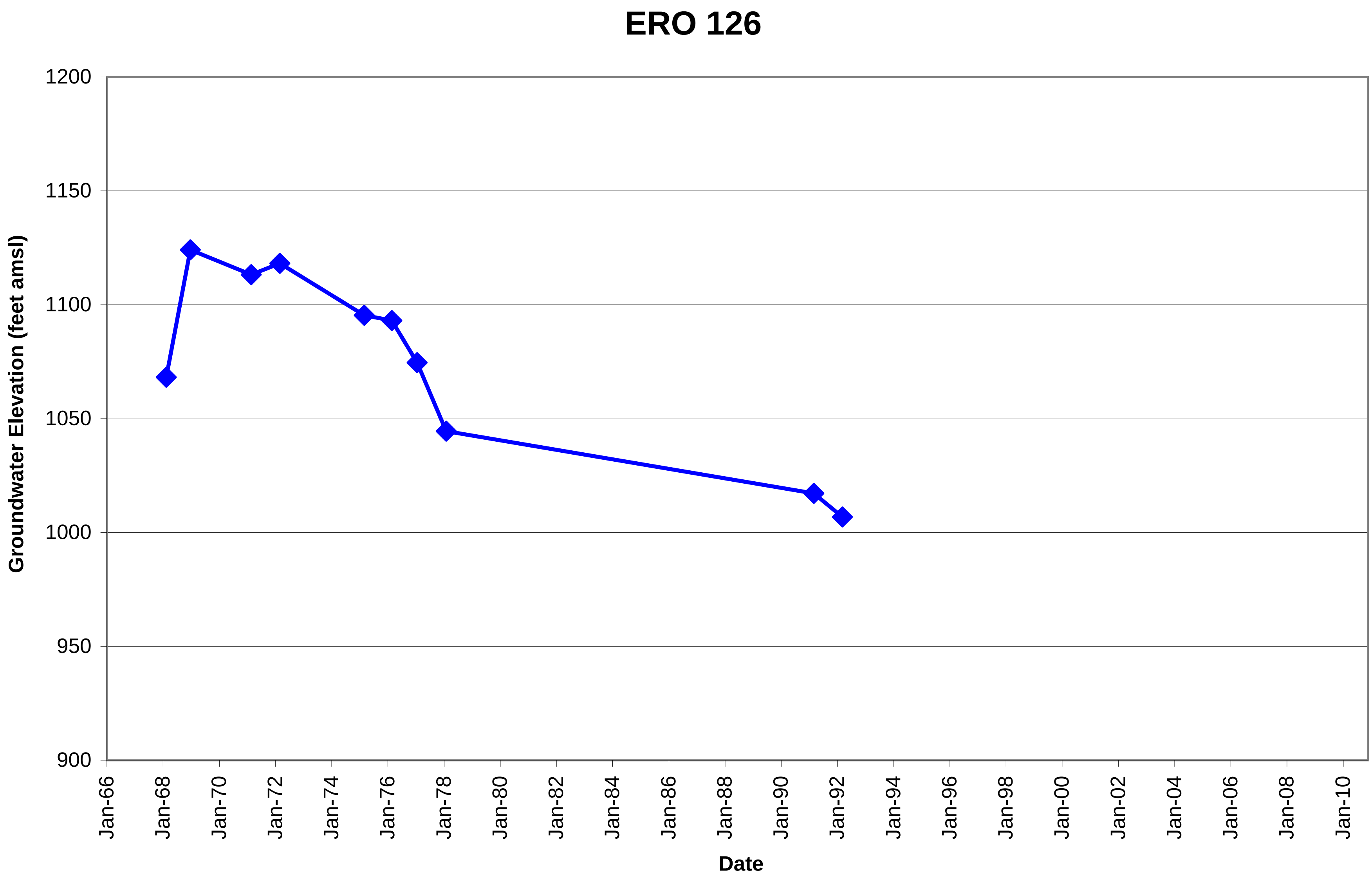
Twpr = Priest Rapids Member of the Wanapum Basalt
Twr = Roza Member of the Wanapum Basalt
Twfs = Frenchman Springs Member of the Wanapum Basalt
Tgsb = Sentinel Bluffs Member of the Grande Ronde Basalt
Tgu = Umtanum Member of the Grande Ronde Basalt
Tgo = Ortley Member of the Grande Ronde Basalt
Tgcc = Grouse Creek Member of the Grande Ronde Basalt
Tgwr = Washilla Ridge Member of the Grande Ronde Basalt

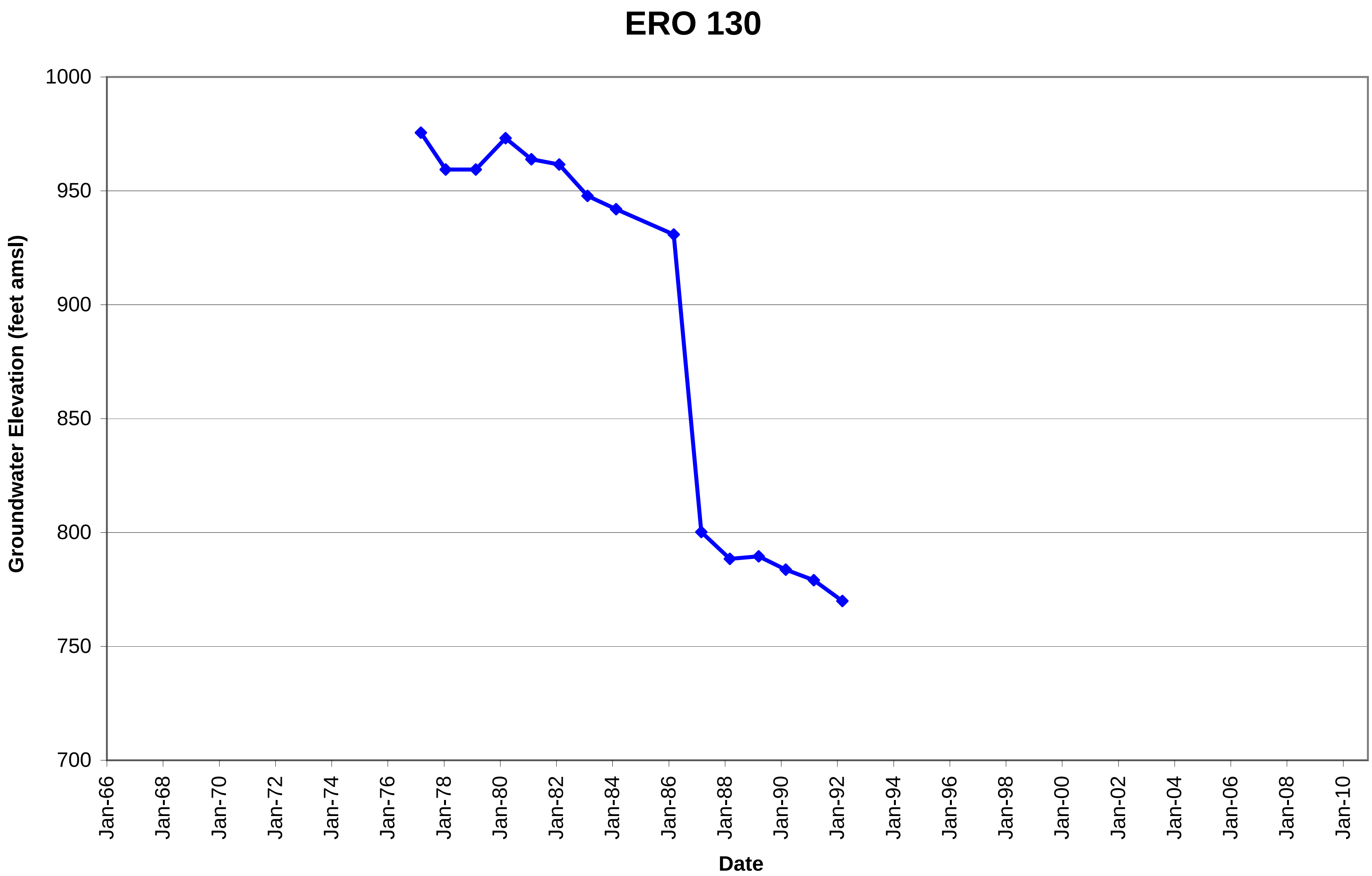

ERO 027
Groundwater Elevation (feet amsl)
1000
950
900
850
800
750
700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

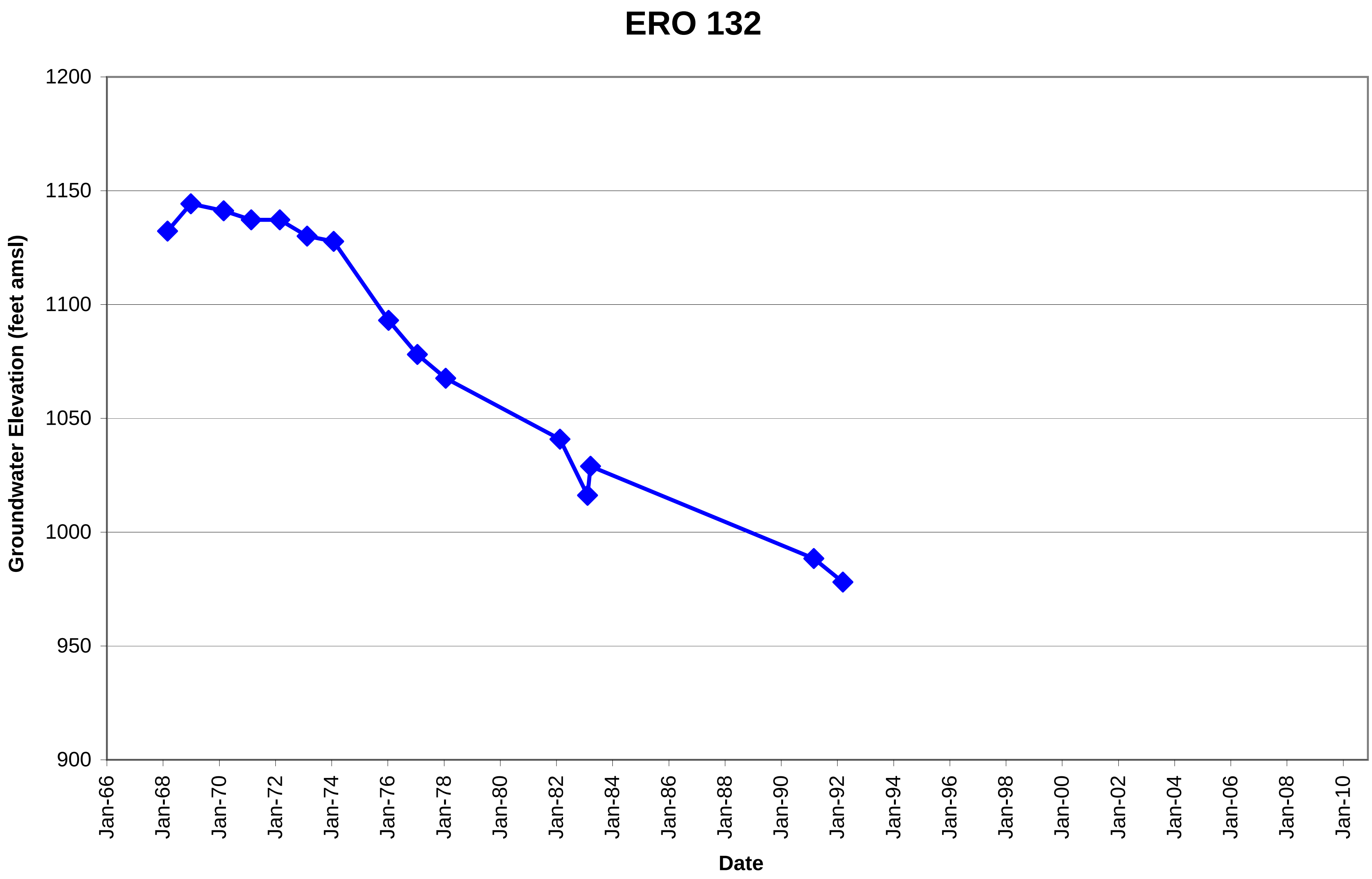


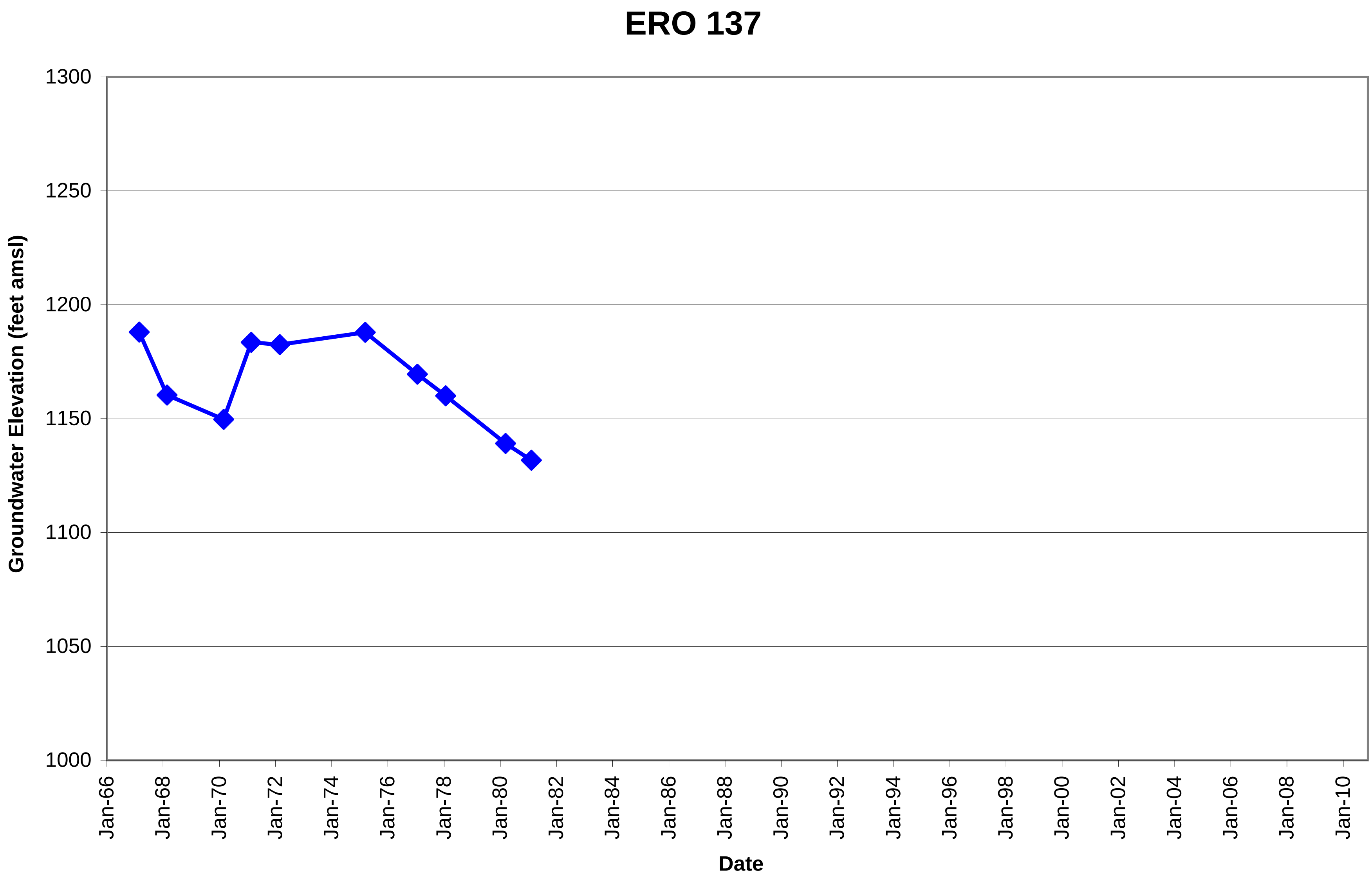
ERO 029
Groundwater Elevation (feet amsl)
1300
1250
1200
1150
1100
1050
1000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 102
Groundwater Elevation (feet amsl)
1100
1050
1000
950
900
850
800
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

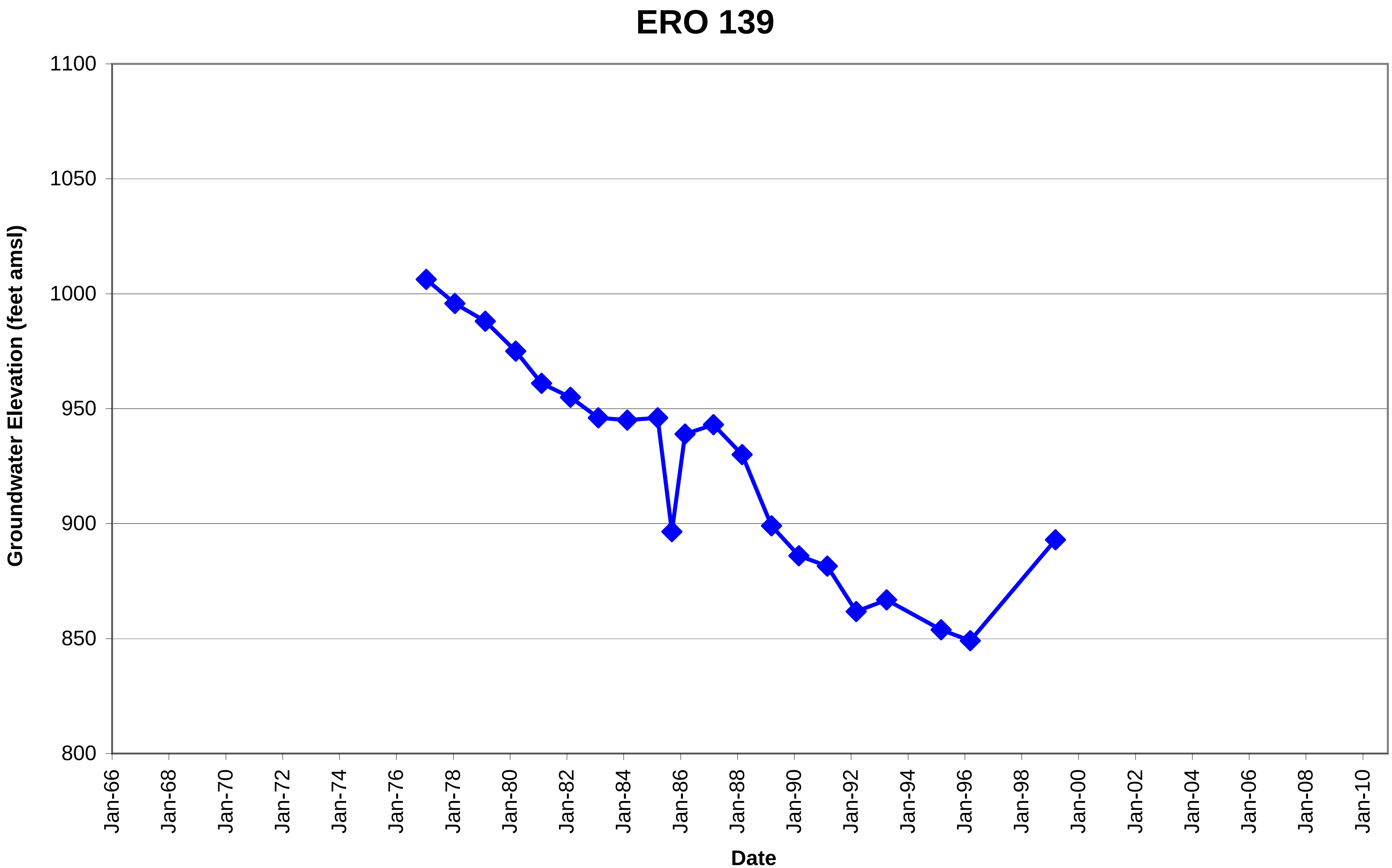

ERO 126
Groundwater Elevation (feet amsl)
1200
1150
1100
1050
1000
950
900
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

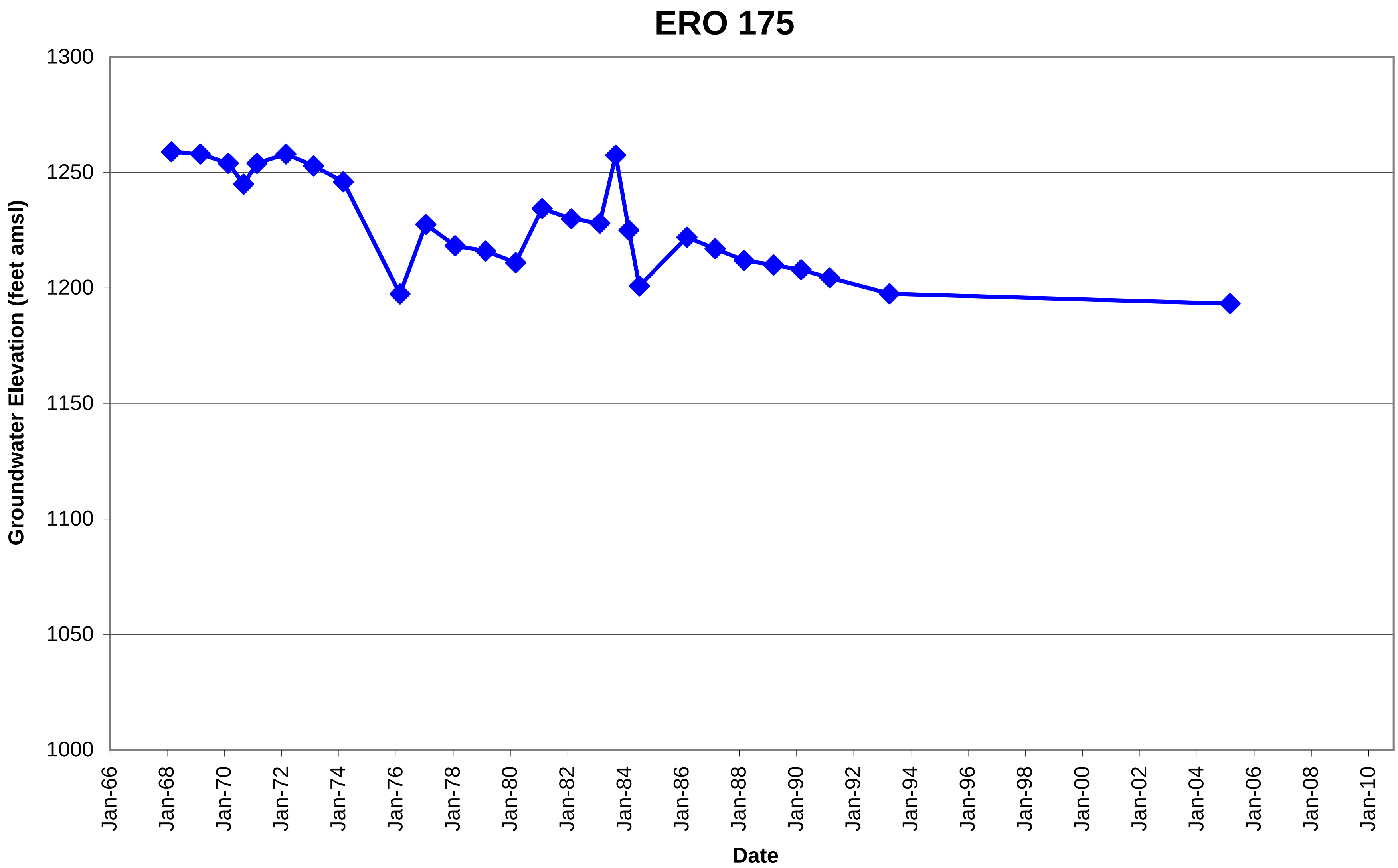

ERO 130
Groundwater Elevation (feet amsl)
1000
950
900
850
800
750
700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 132
Groundwater Elevation (feet amsl)
1200
1150
1100
1050
1000
950
900
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

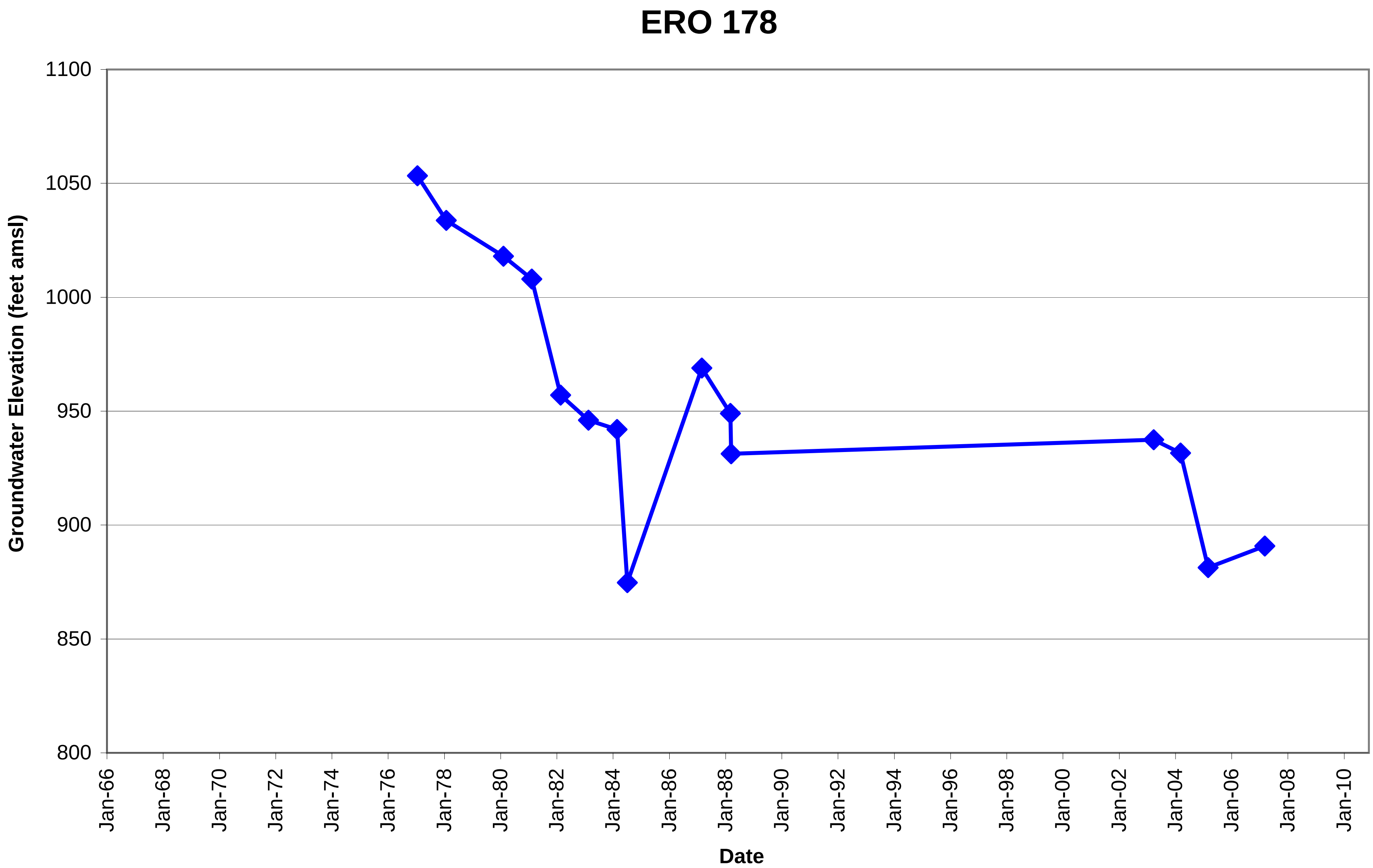


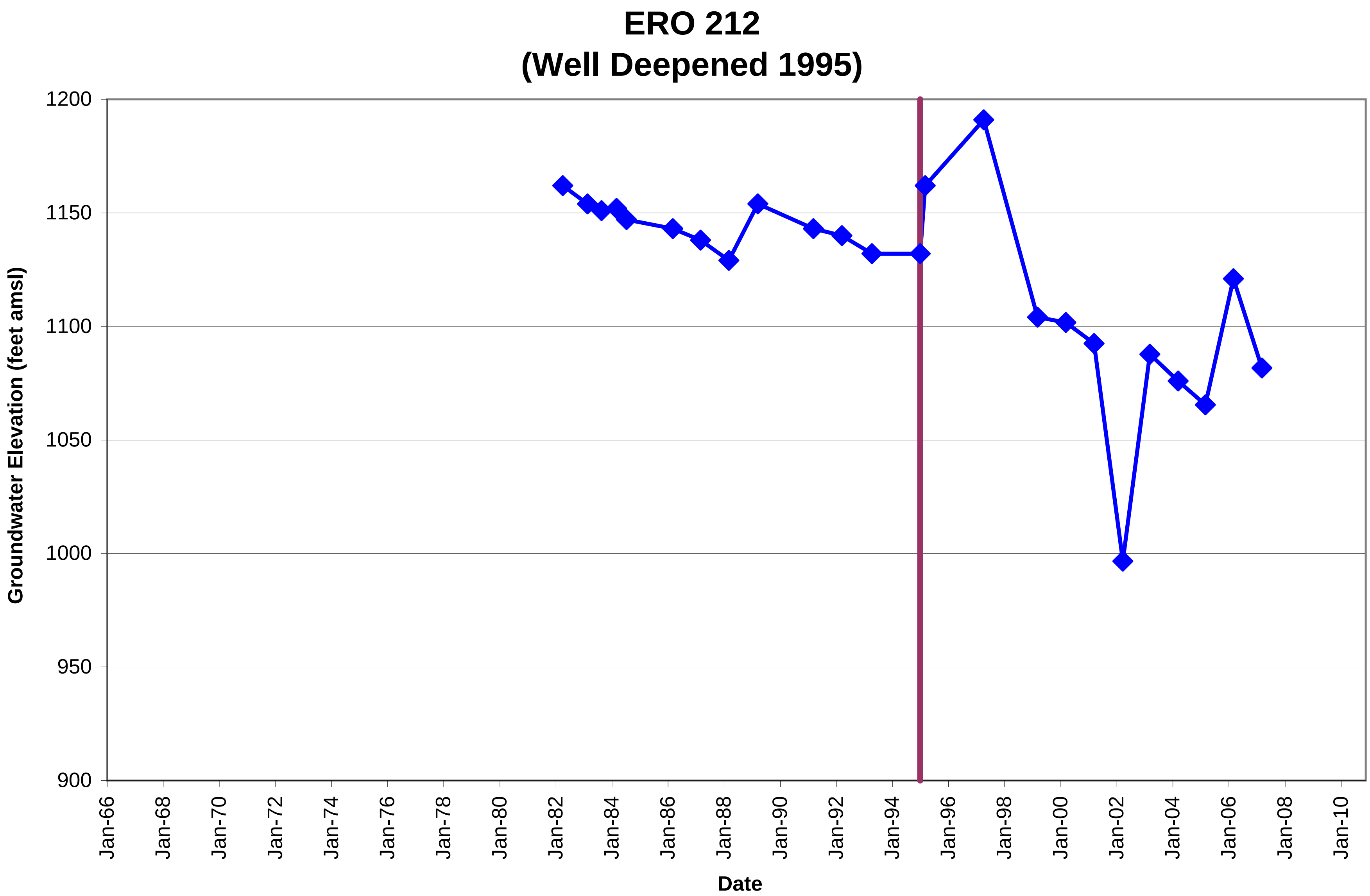
ERO 137
Groundwater Elevation (feet amsl)
1300
1250
1200
1150
1100
1050
1000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

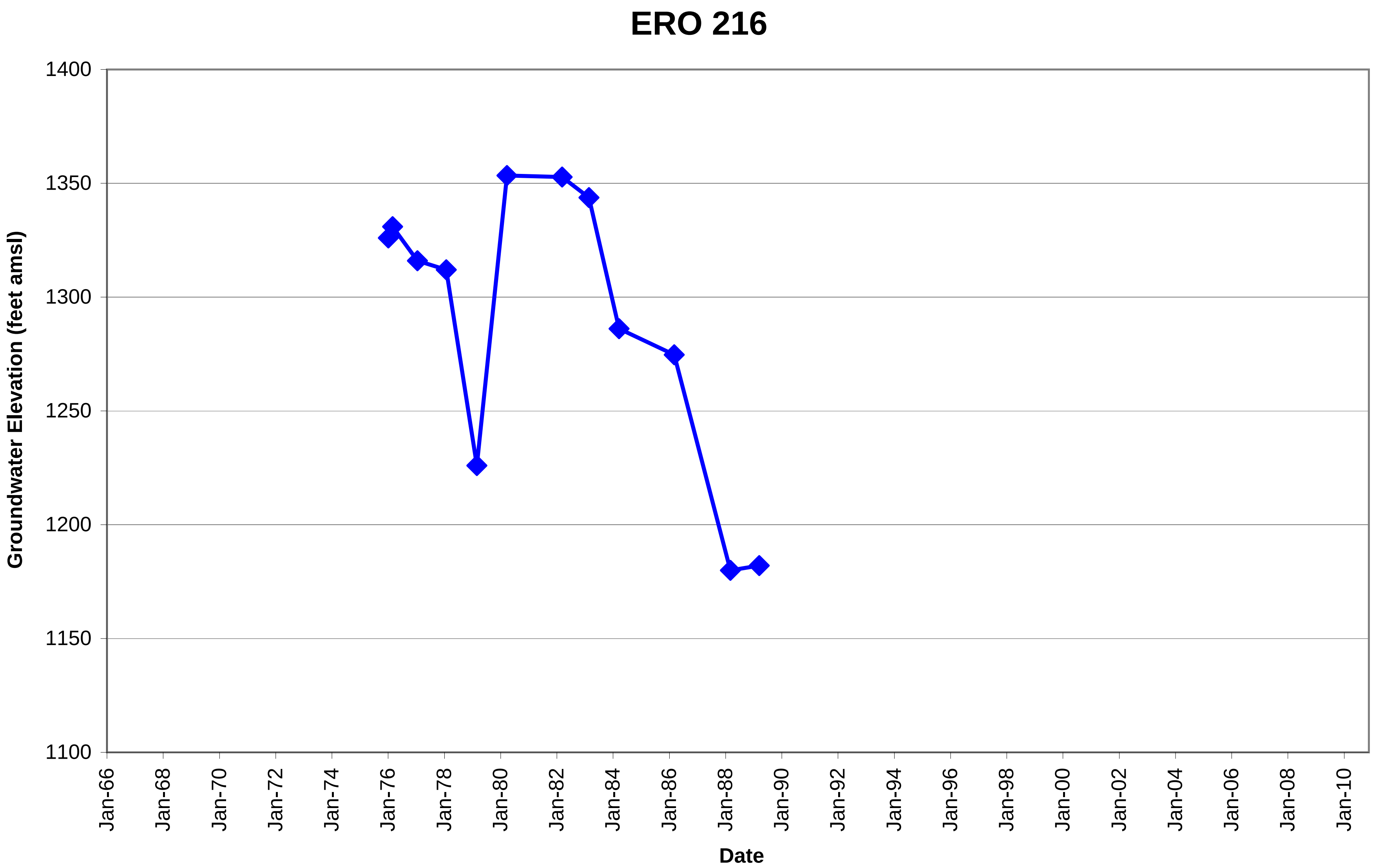

ERO 139
Groundwater Elevation (feet amsl)
1100
1050
1000
950
900
850
800
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date



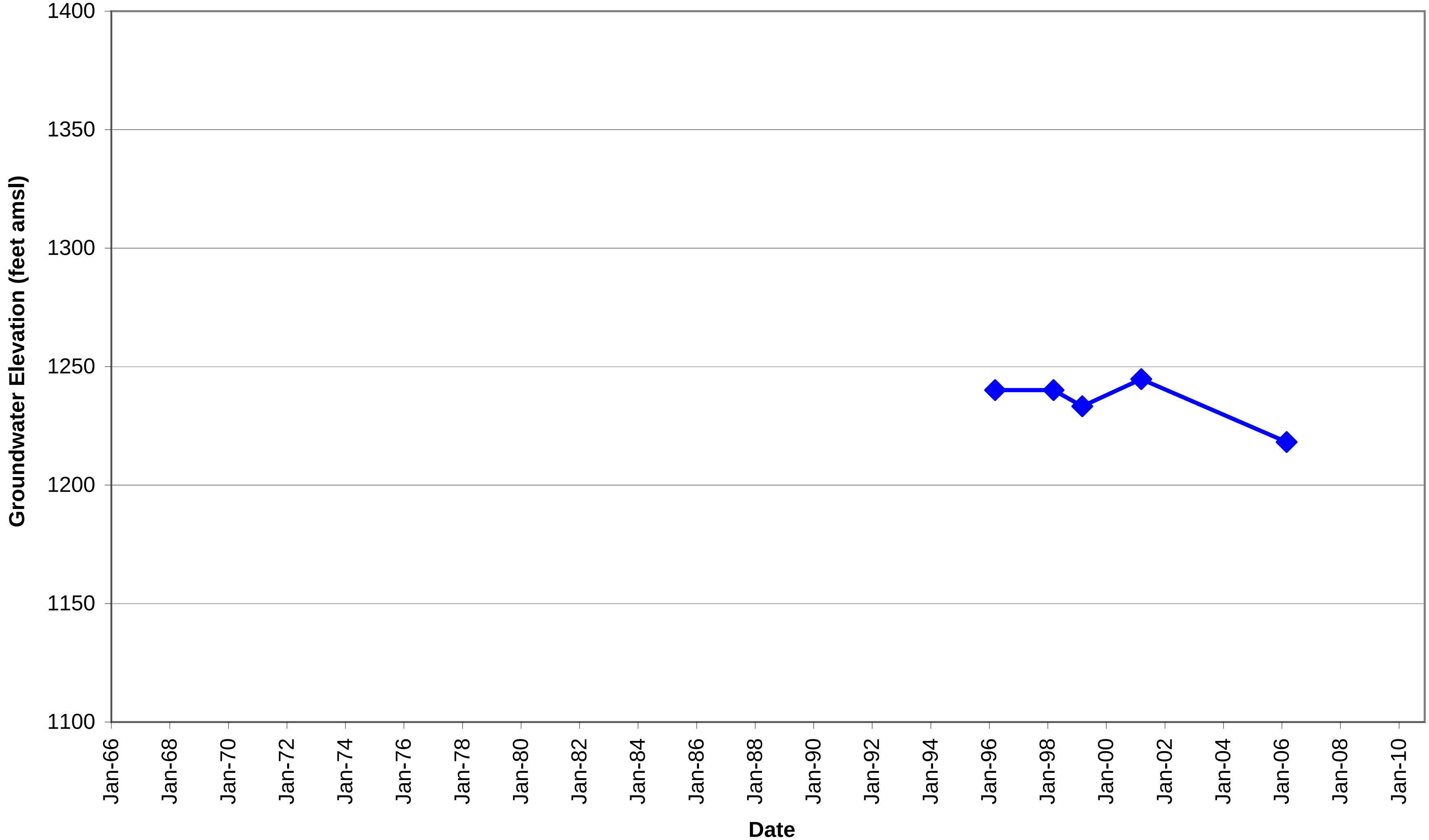
ERO 175
Groundwater Elevation (feet amsl)
1300
1250
1200
1150
1100
1050
1000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 178
Groundwater Elevation (feet amsl)
1100
1050
1000
950
900
850
800
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

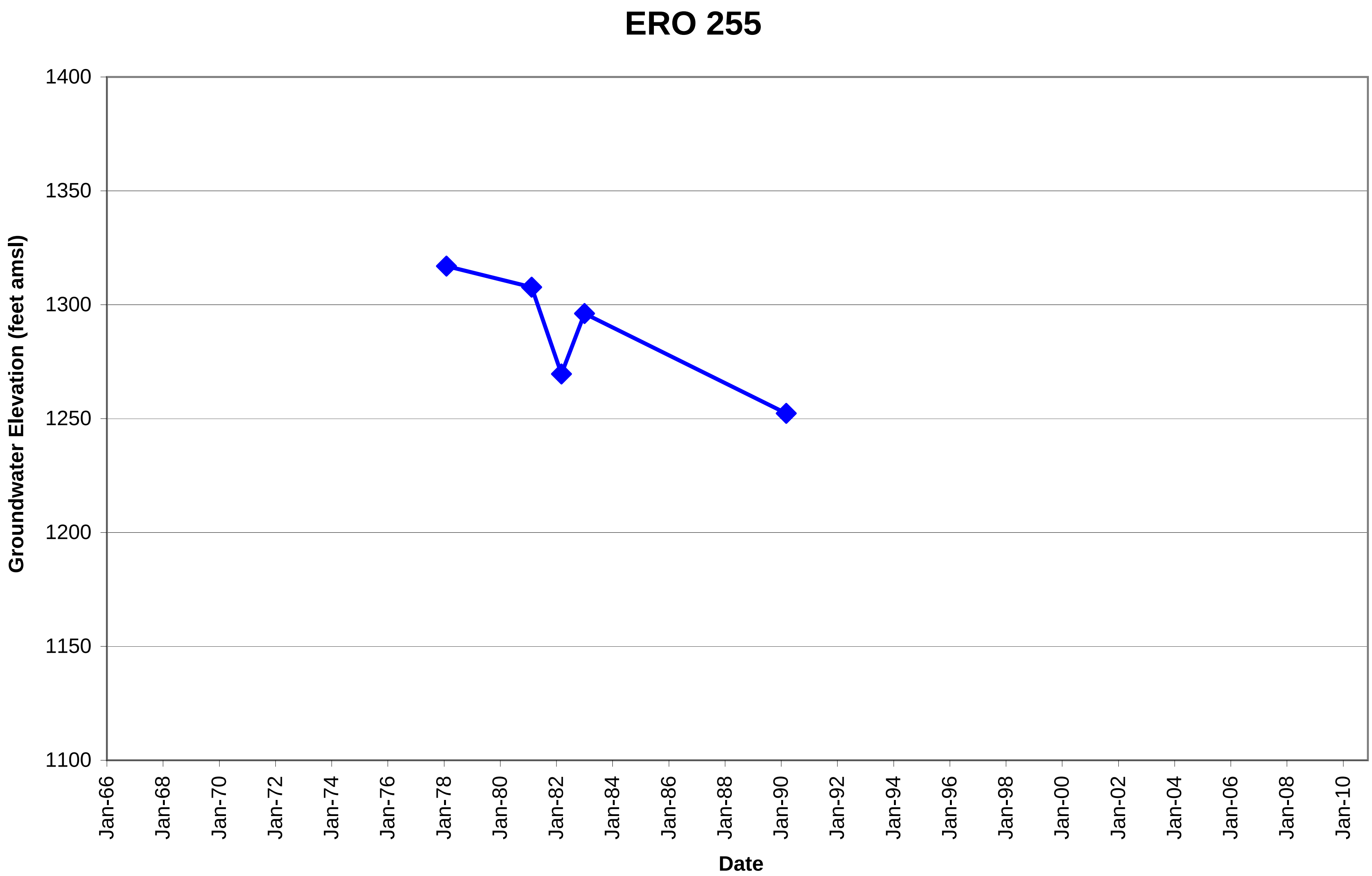

ERO 212
(Well Deepened 1995)
Groundwater Elevation (feet amsl)
1200
1150
1100
1050
1000
950
900
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

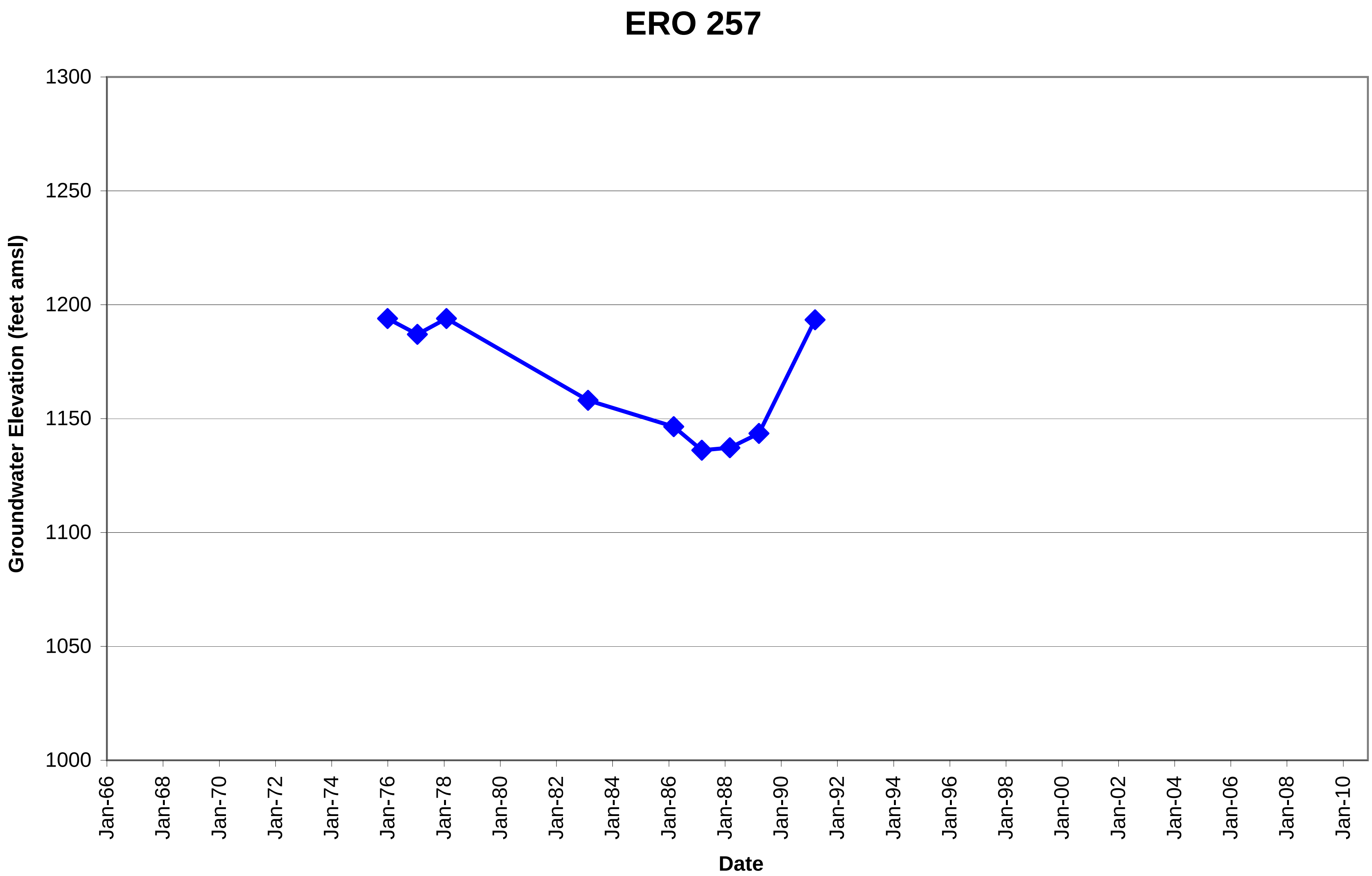

ERO 216
Groundwater Elevation (feet amsl)
1400
1350
1300
1250
1200
1150
1100
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

ERO 219

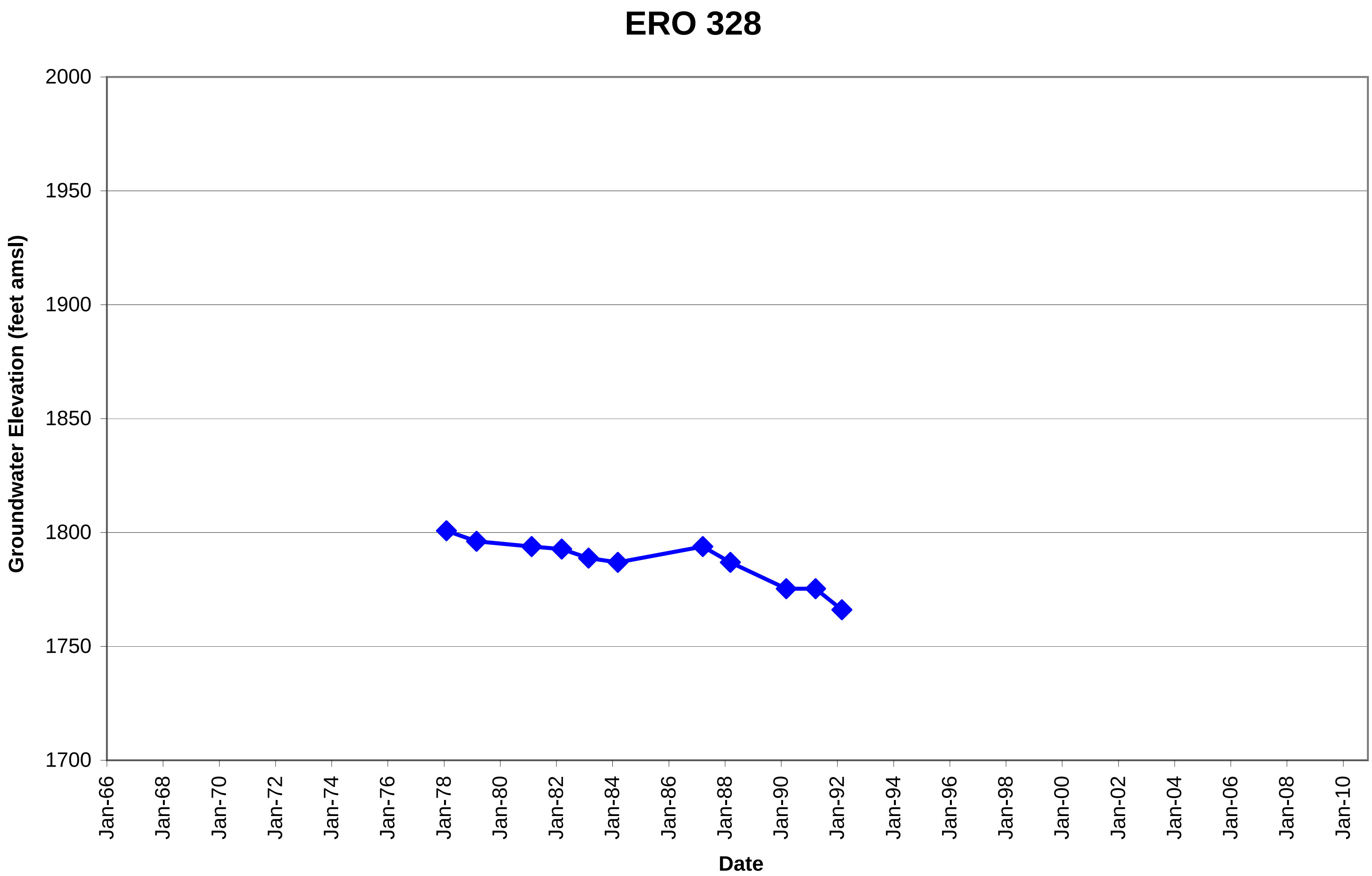


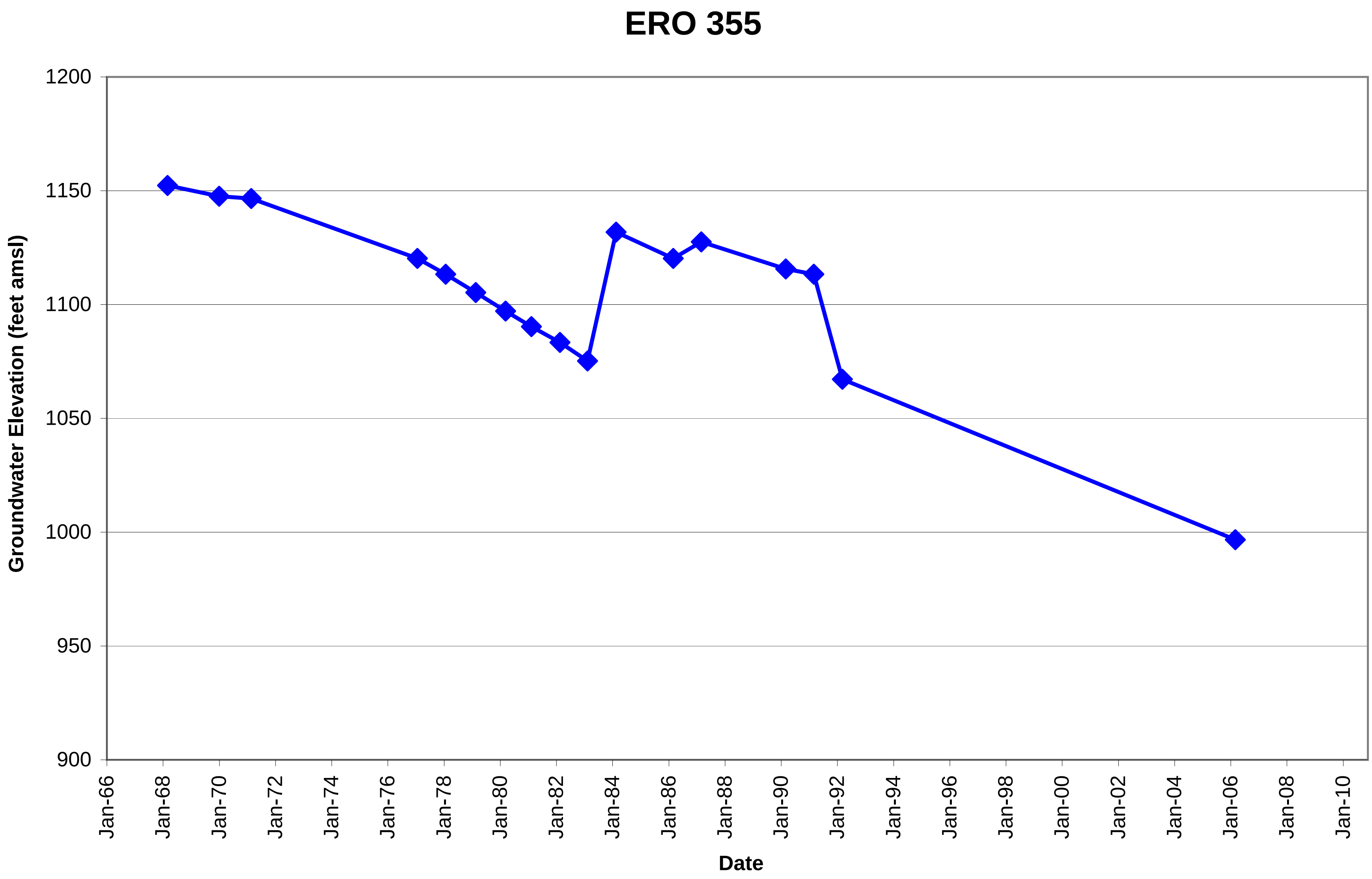
Groundwater Elevation (feet amsl)
1400
1350
1300
1250
1200
1150
1100
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

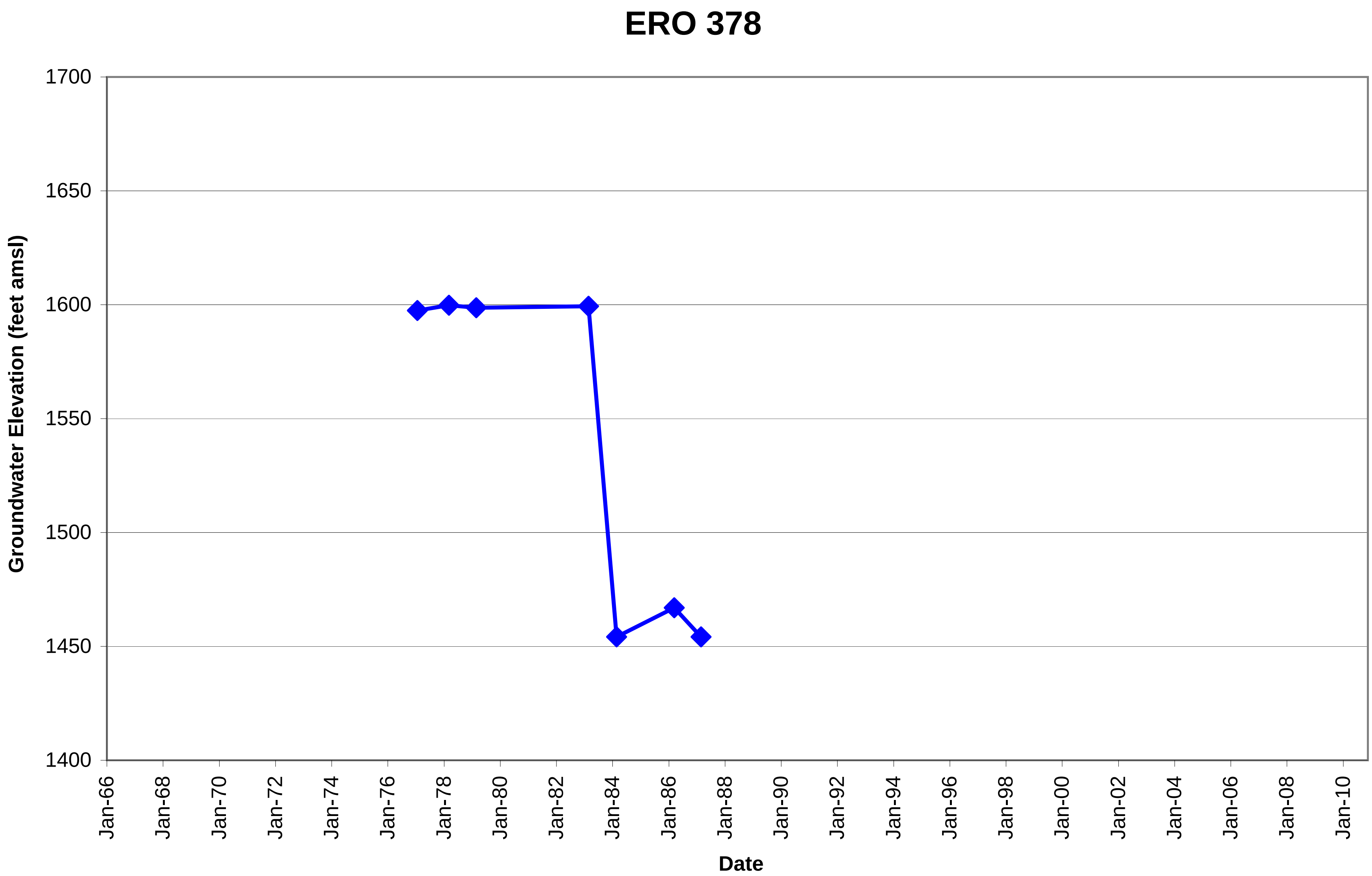

ERO 255
Groundwater Elevation (feet amsl)
1400
1350
1300
1250
1200
1150
1100
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

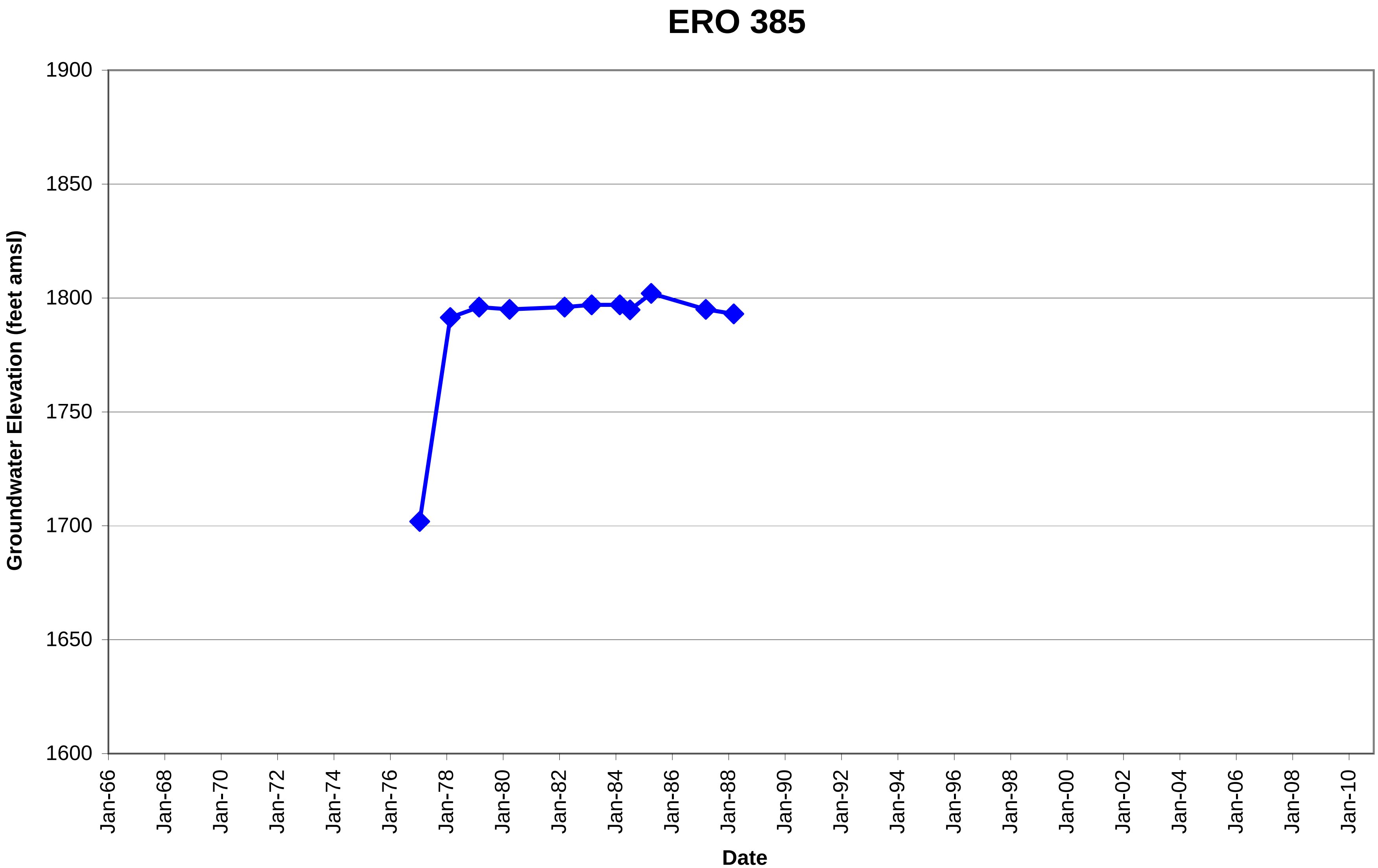


ERO 257
Groundwater Elevation (feet amsl)
1300
1250
1200
1150
1100
1050
1000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

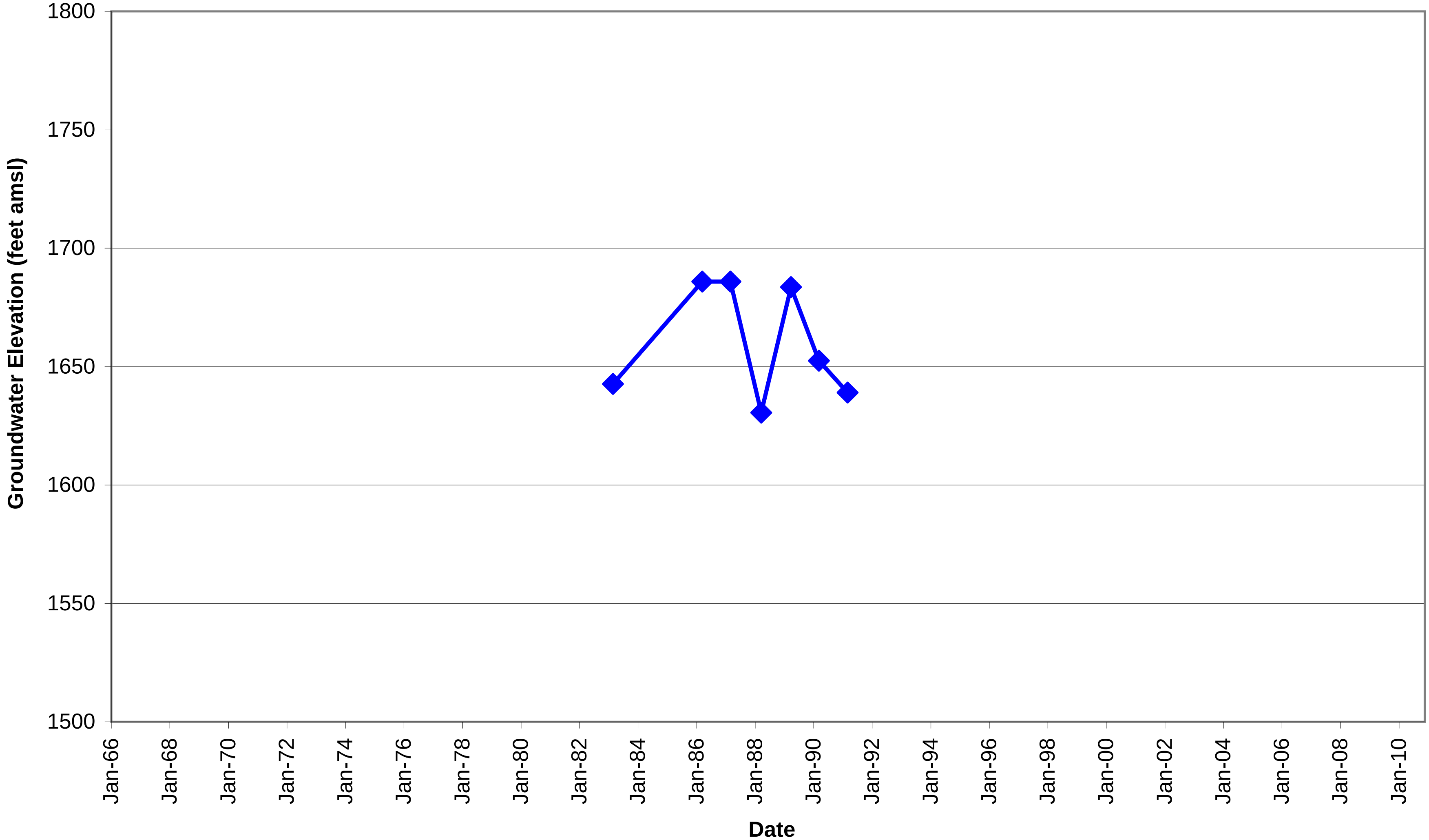

ERO 328
Groundwater Elevation (feet amsl)
2000
1950
1900
1850
1800
1750
1700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 355
Groundwater Elevation (feet amsl)
1200
1150
1100
1050
1000
950
900
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

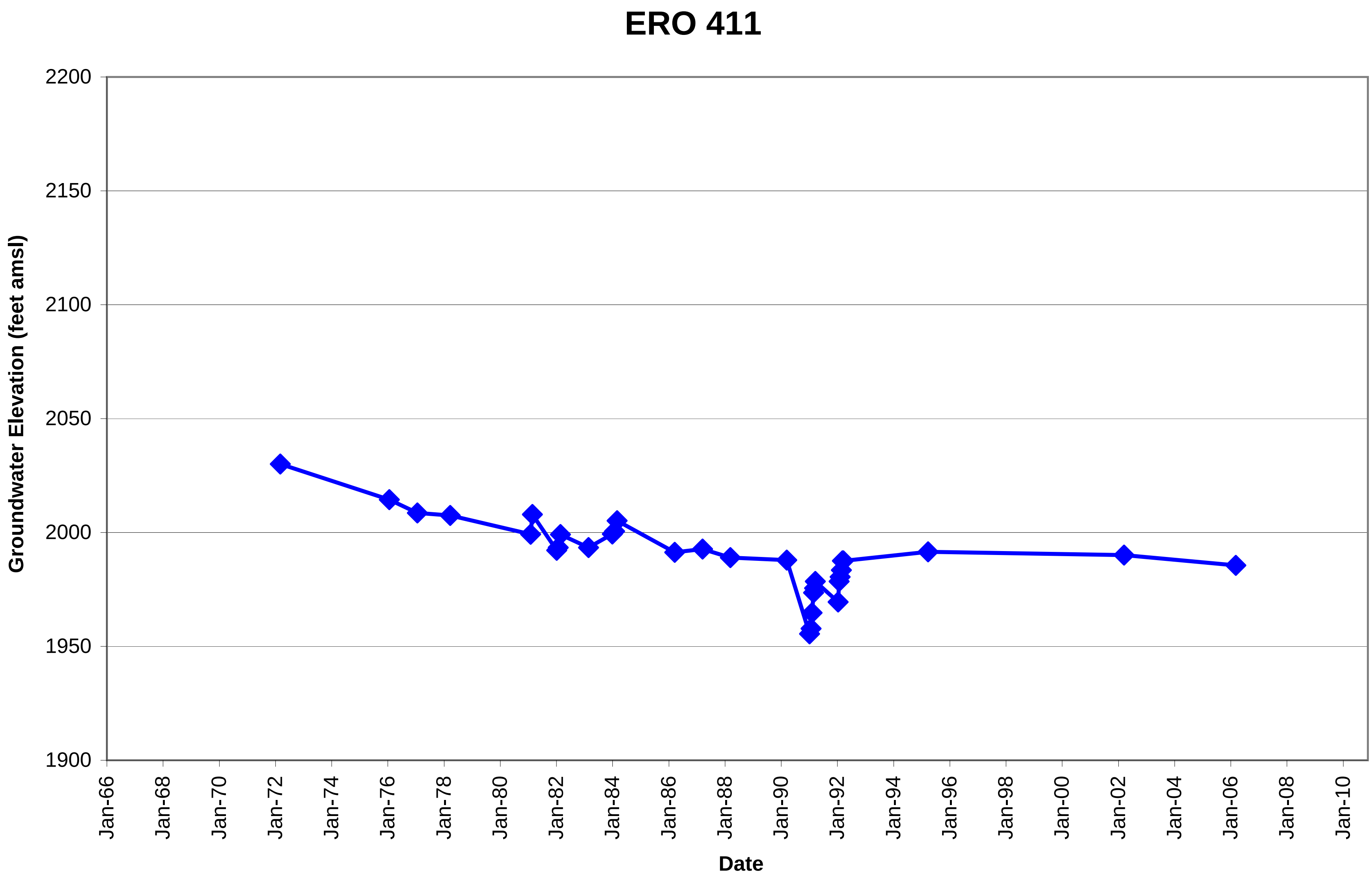

ERO 378
Groundwater Elevation (feet amsl)
1700
1650
1600
1550
1500
1450
1400
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 385
Groundwater Elevation (feet amsl)
1900
1850
1800
1750
1700
1650
1600
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

ERO 387



1800
1750
1700
1650
1600
1550
1500
Groundwater Elevation (feet amsl)
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 411
Groundwater Elevation (feet amsl)
2200
2150
2100
2050
2000
1950
1900
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
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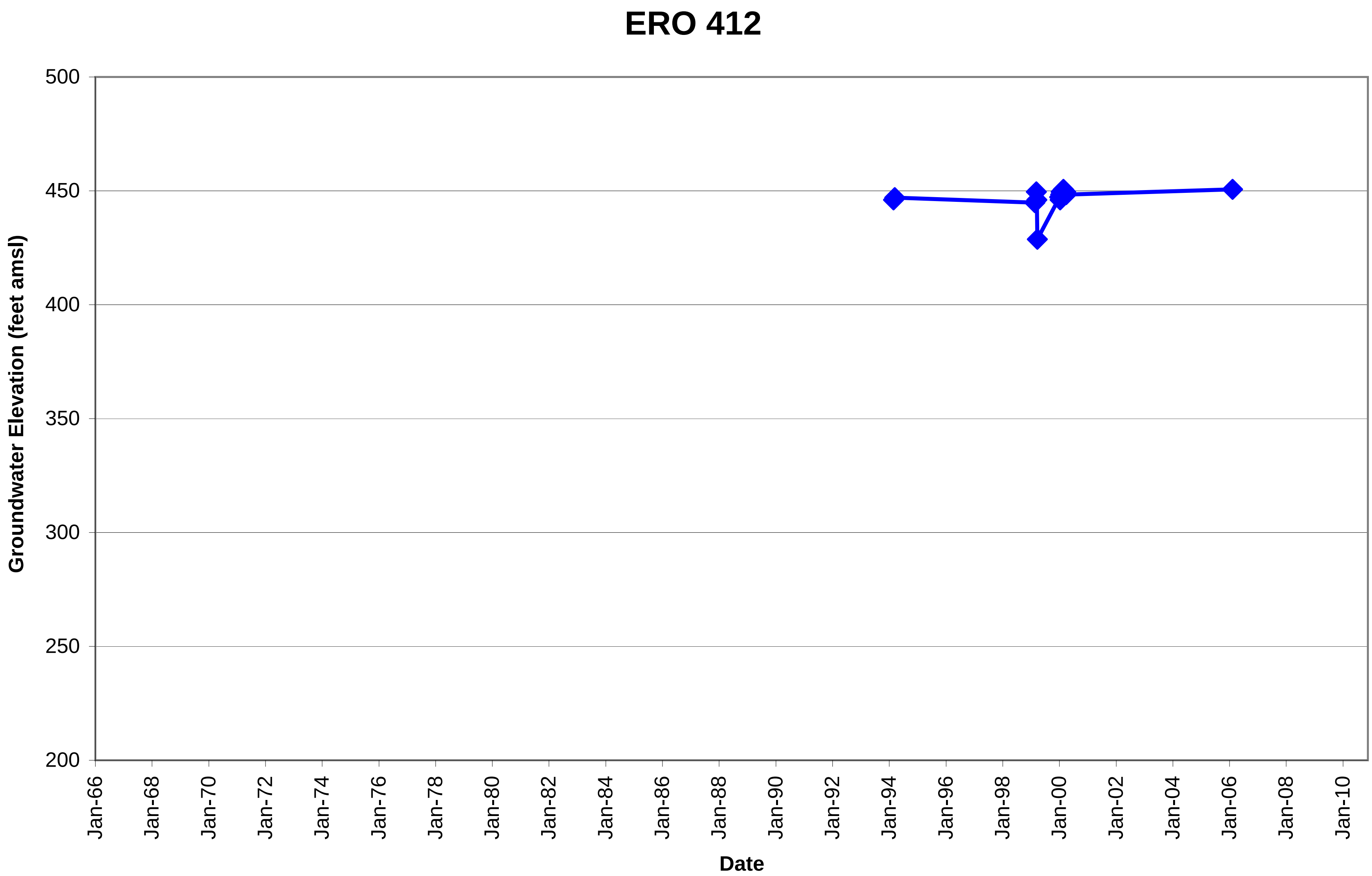
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 412
Groundwater Elevation (feet amsl)
500
450
400
350
300
250
200
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
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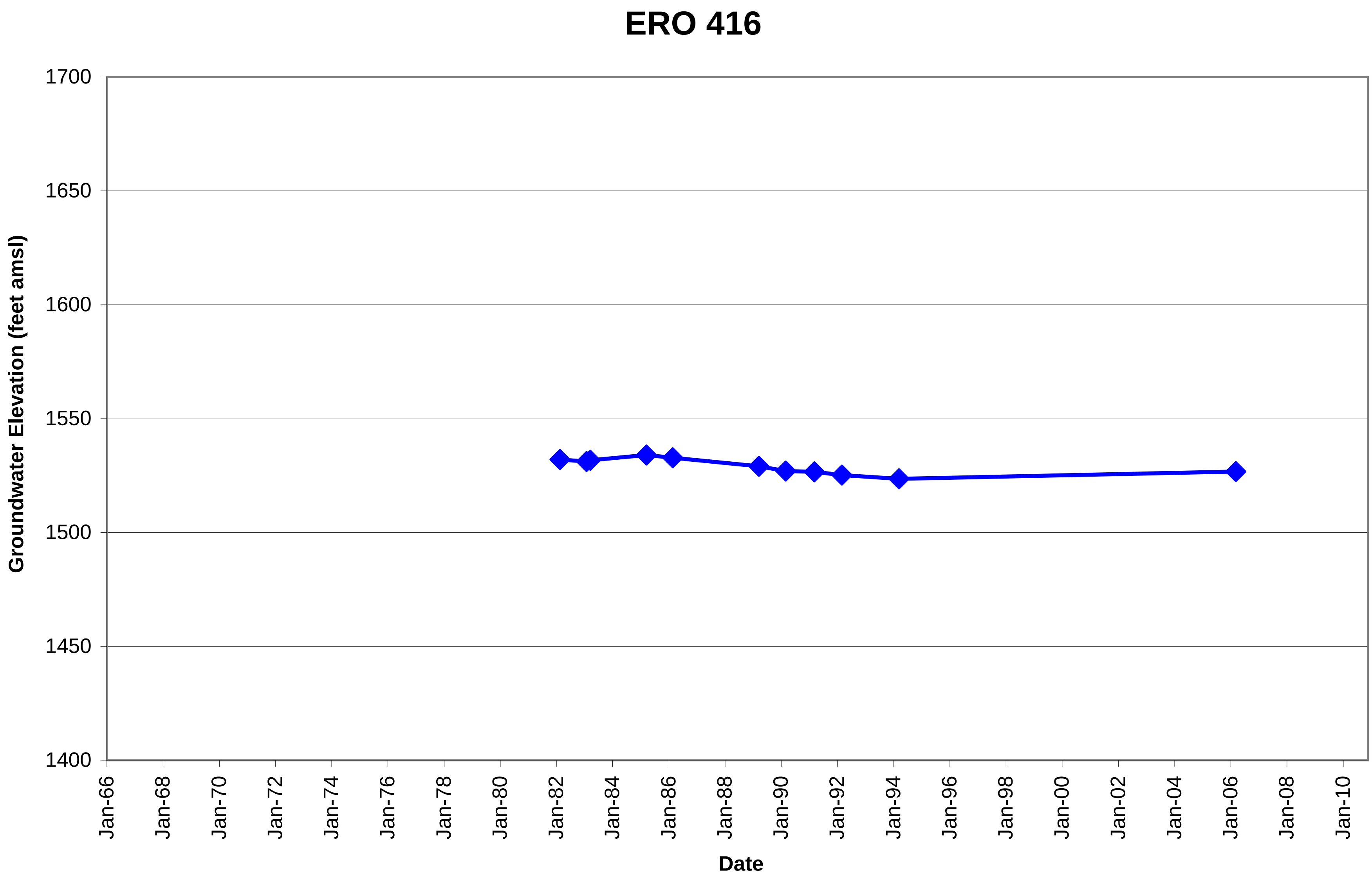
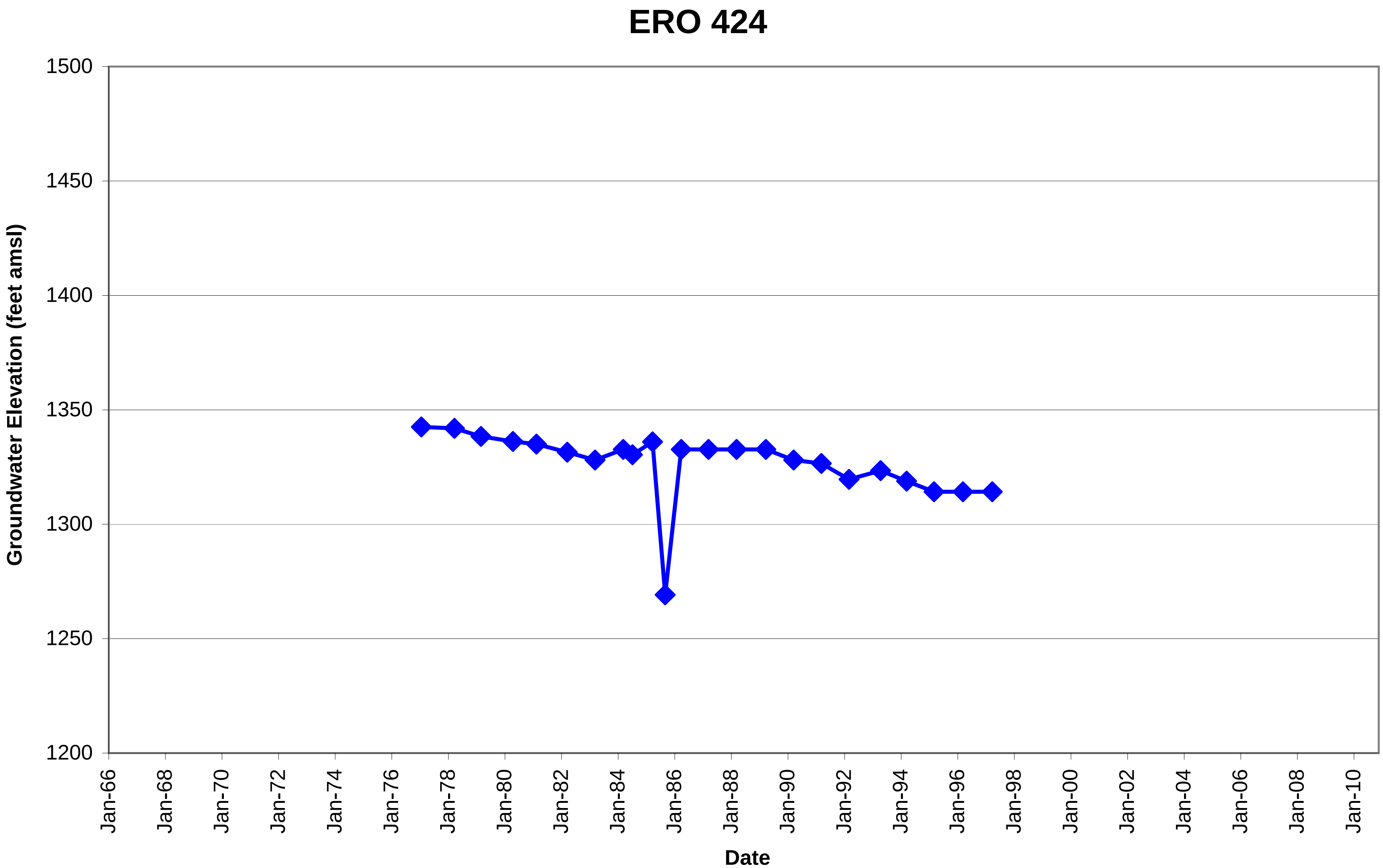
Jan-06
Jan-08
Jan-10
Date

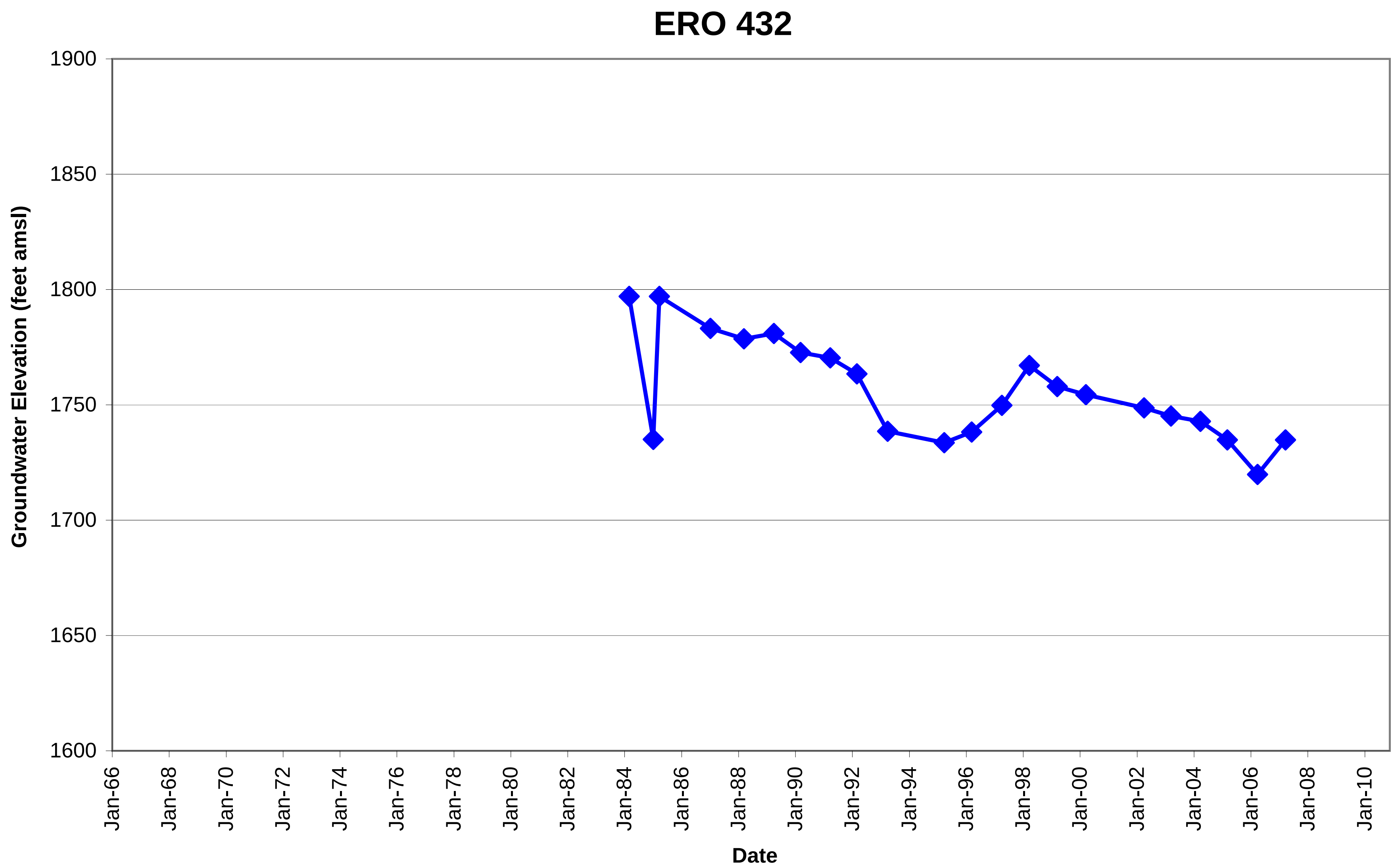


ERO 416
Groundwater Elevation (feet amsl)
1700
1650
1600
1550
1500
1450
1400
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

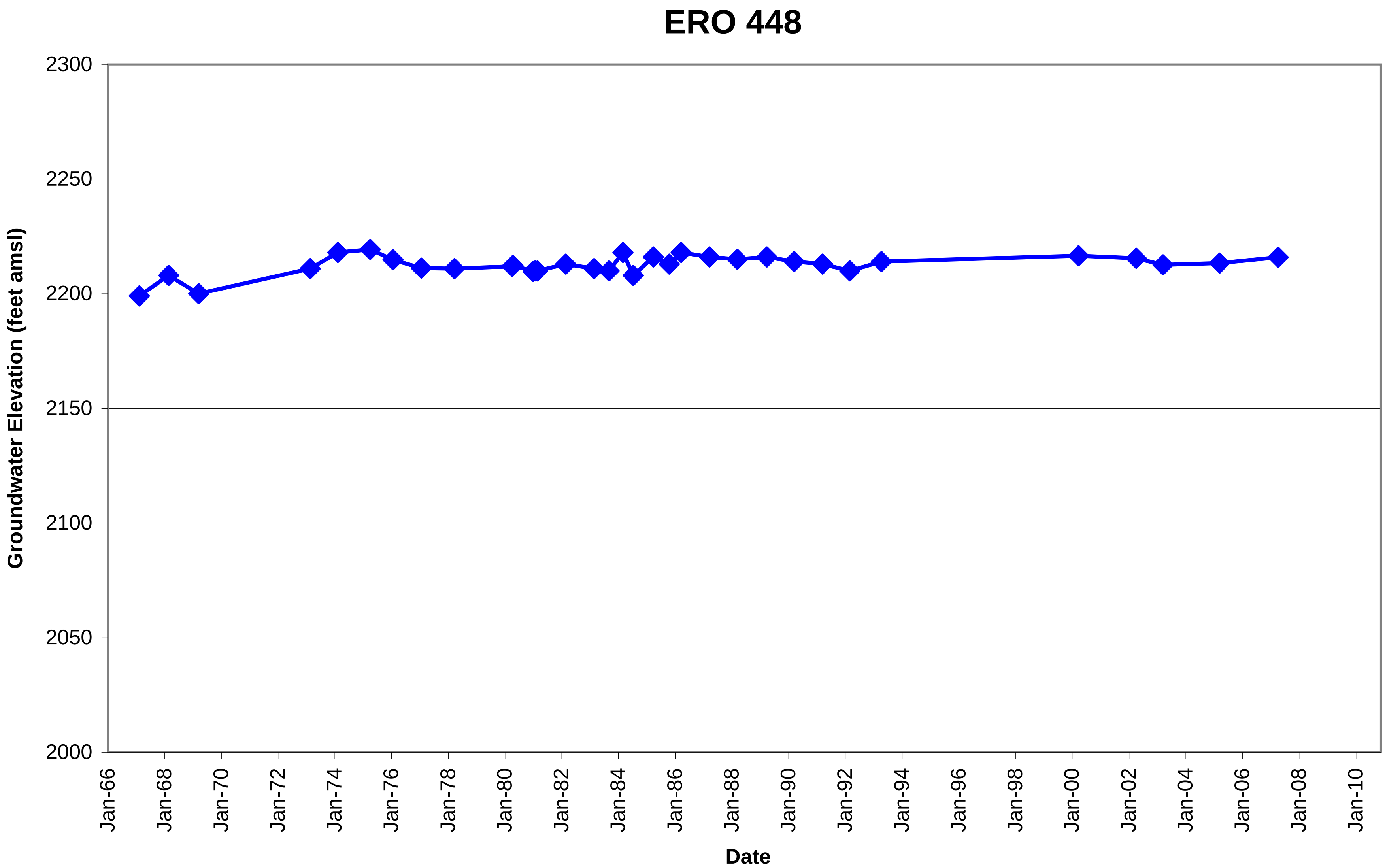
ERO 424

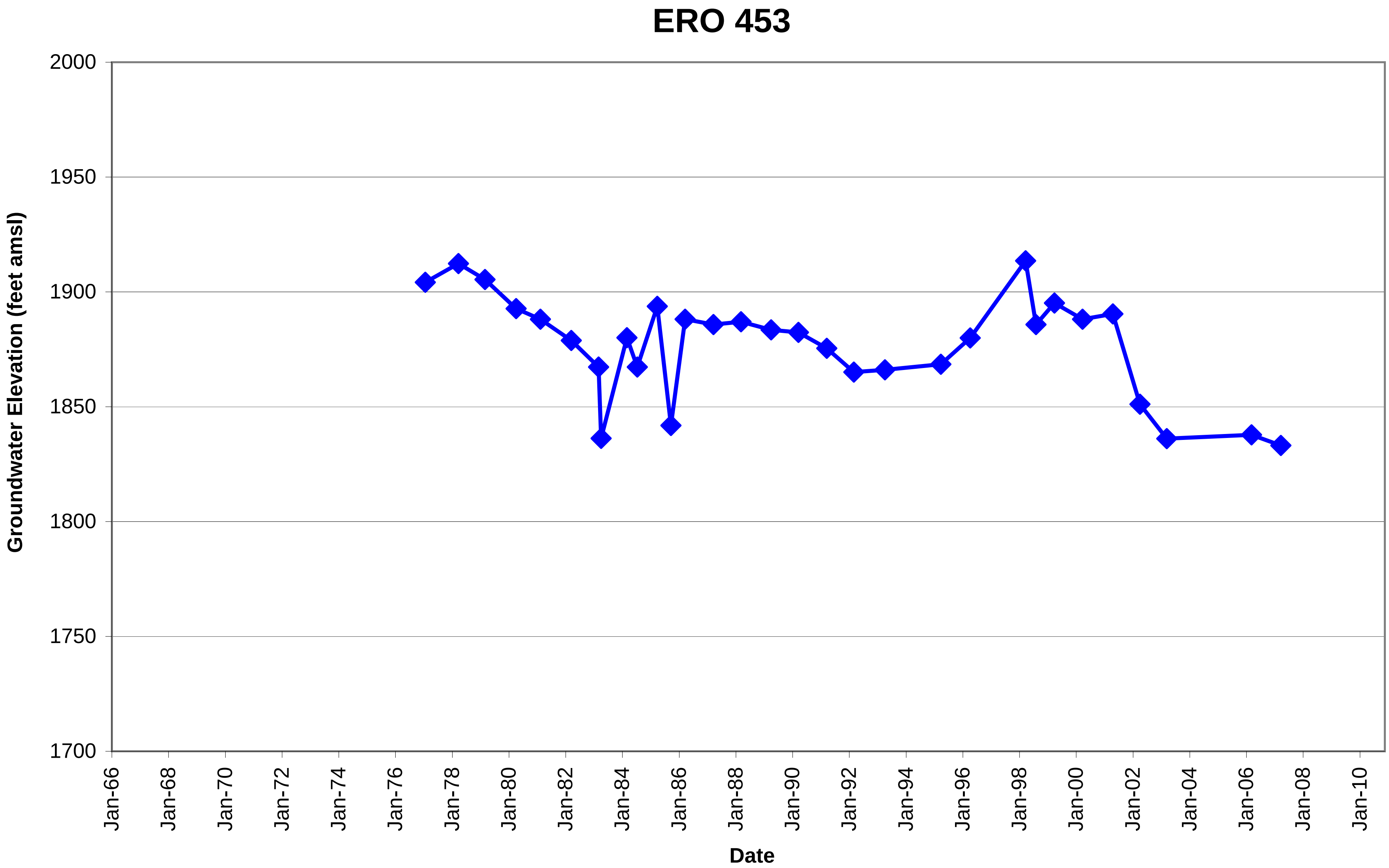


ERO 424
Groundwater Elevation (feet amsl)
1500
1450
1400
1350
1300
1250
1200
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date



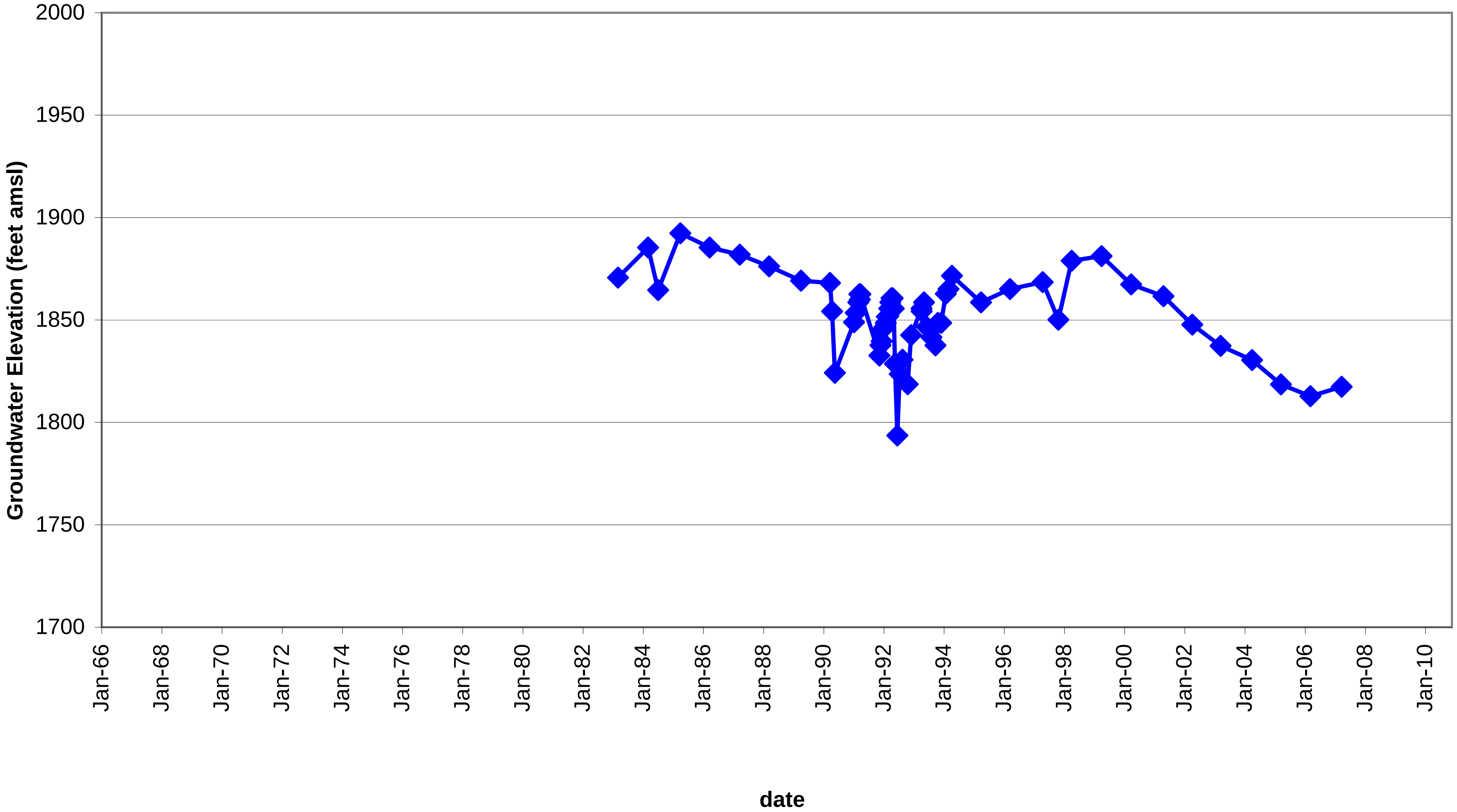
ERO 432
Groundwater Elevation (feet amsl)
1900
1850
1800
1750
1700
1650
1600
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 448
Groundwater Elevation (feet amsl)
2300
2250
2200
2150
2100
2050
2000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date



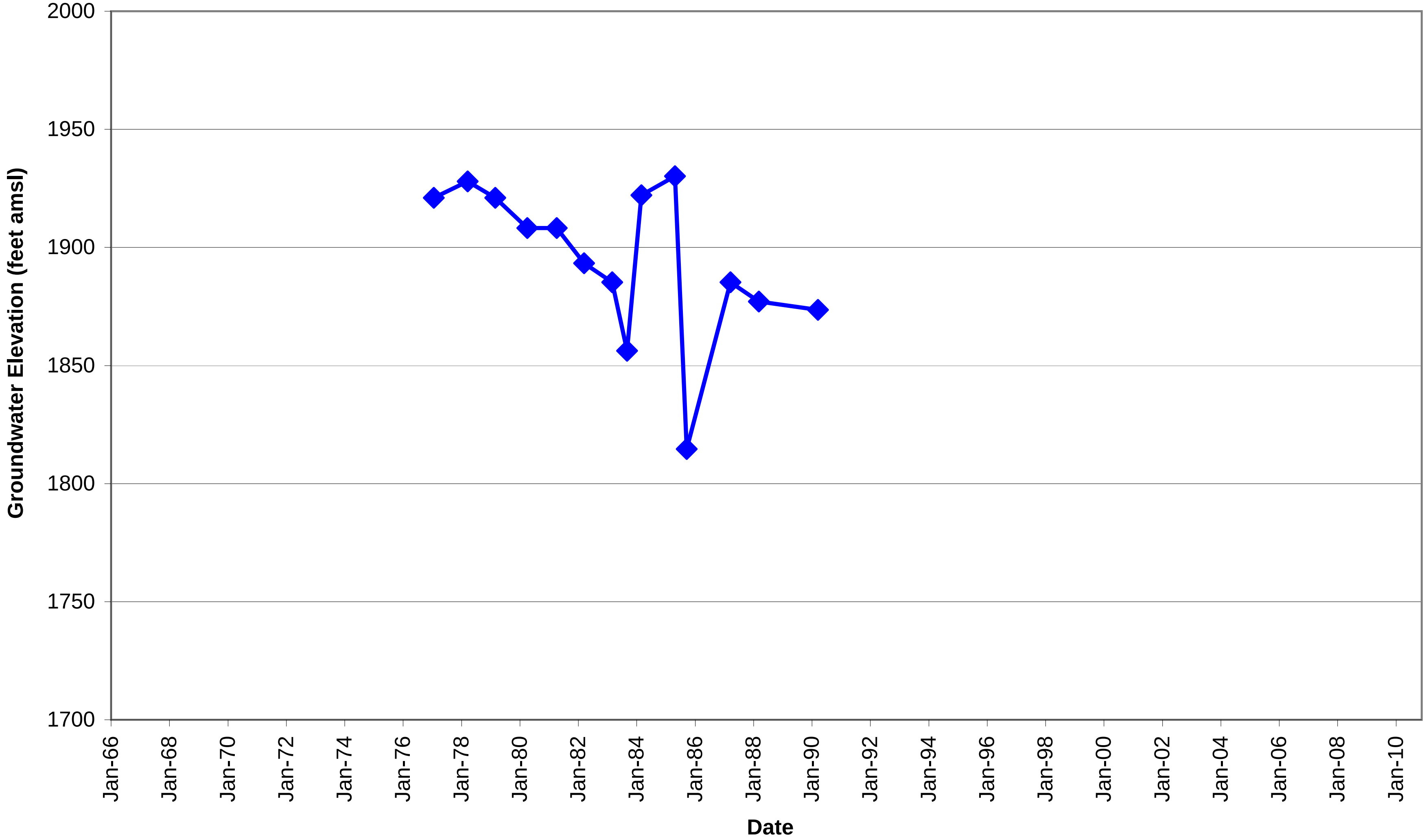
ERO 453
Groundwater Elevation (feet amsl)
2000
1950
1900
1850
1800
1750
1700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

ERO 454

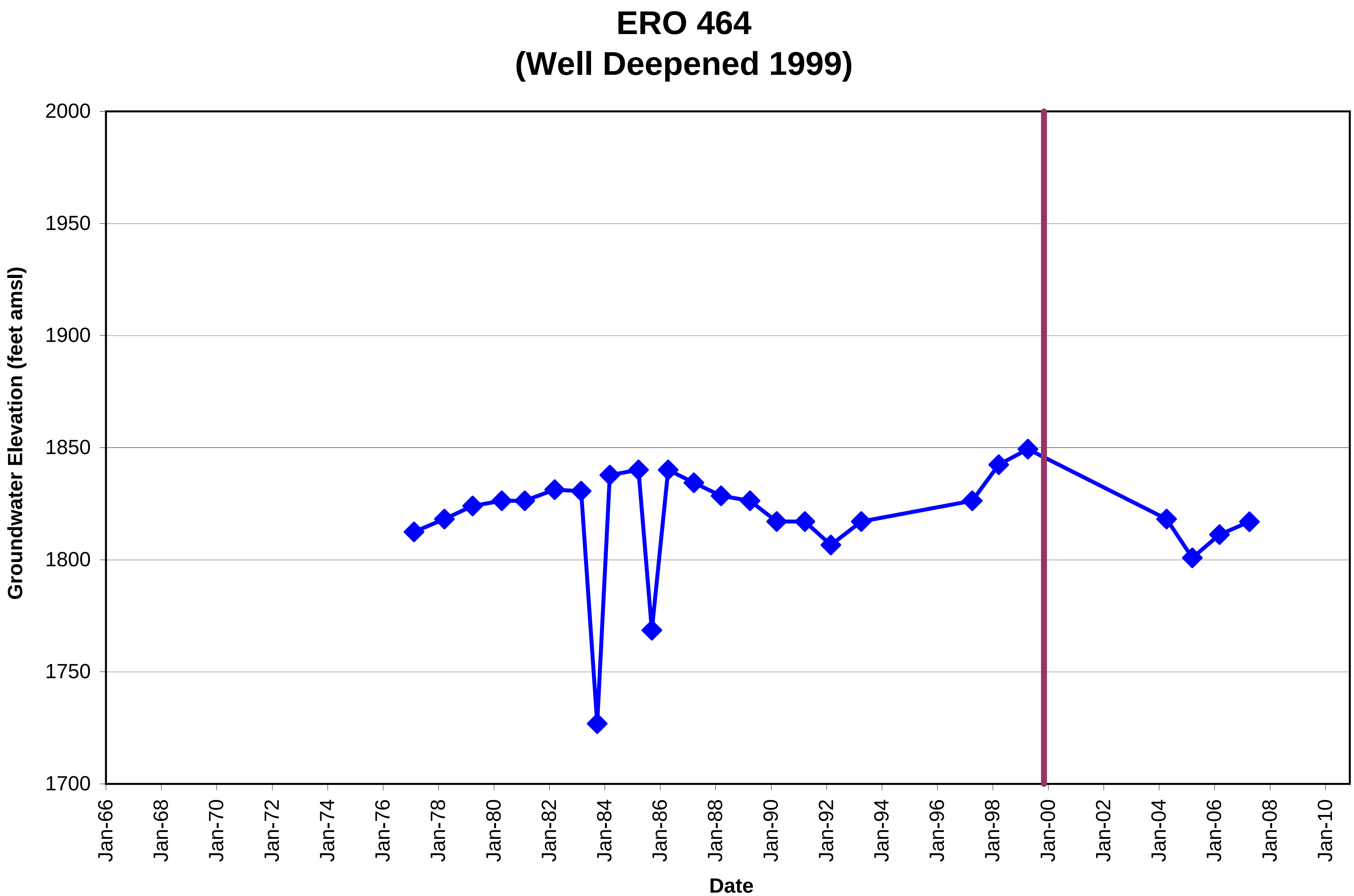


ERO 454
Groundwater Elevation (feet amsl)
2000
1950
1900
1850
1800
1750
1700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
date

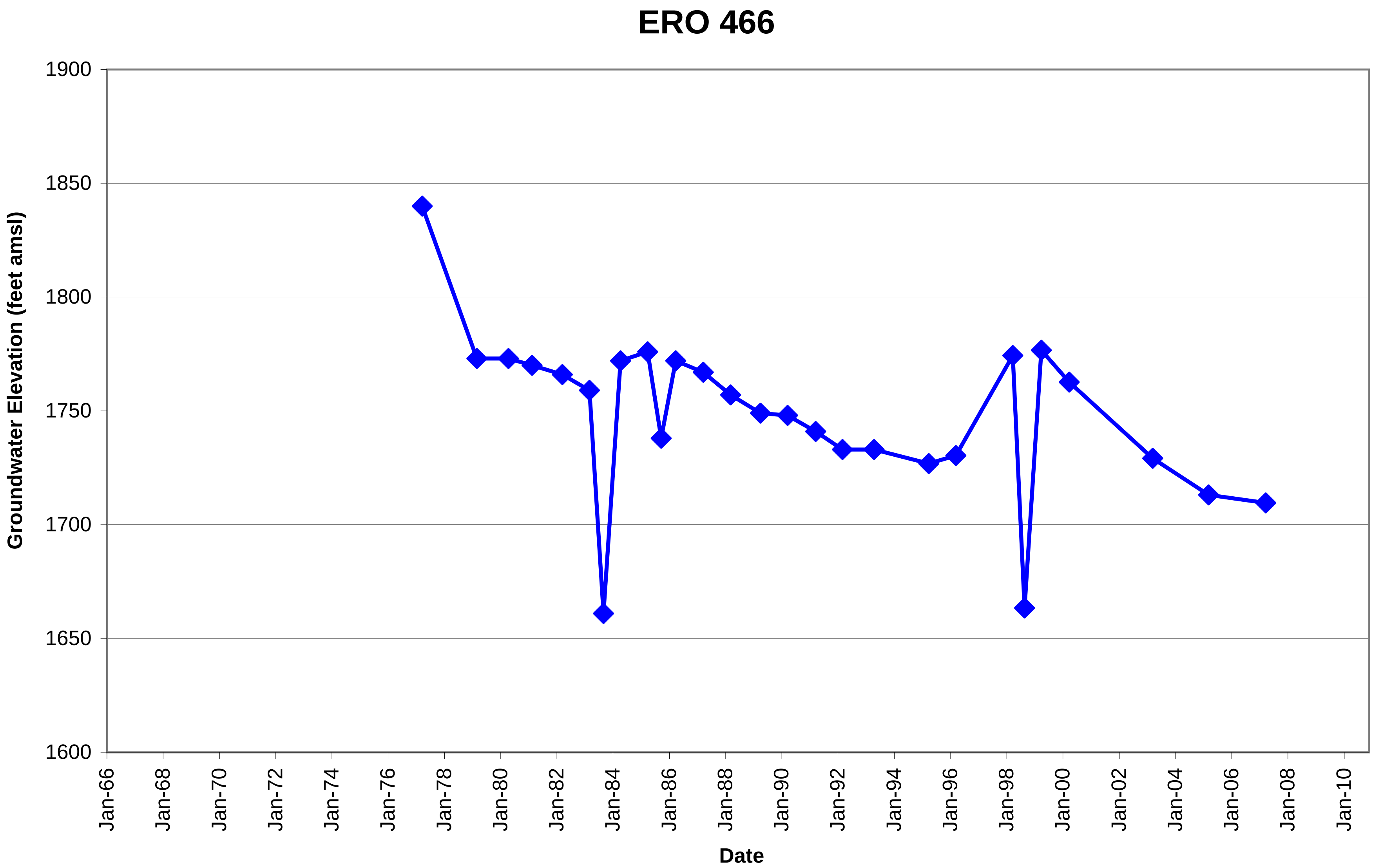
ERO 457

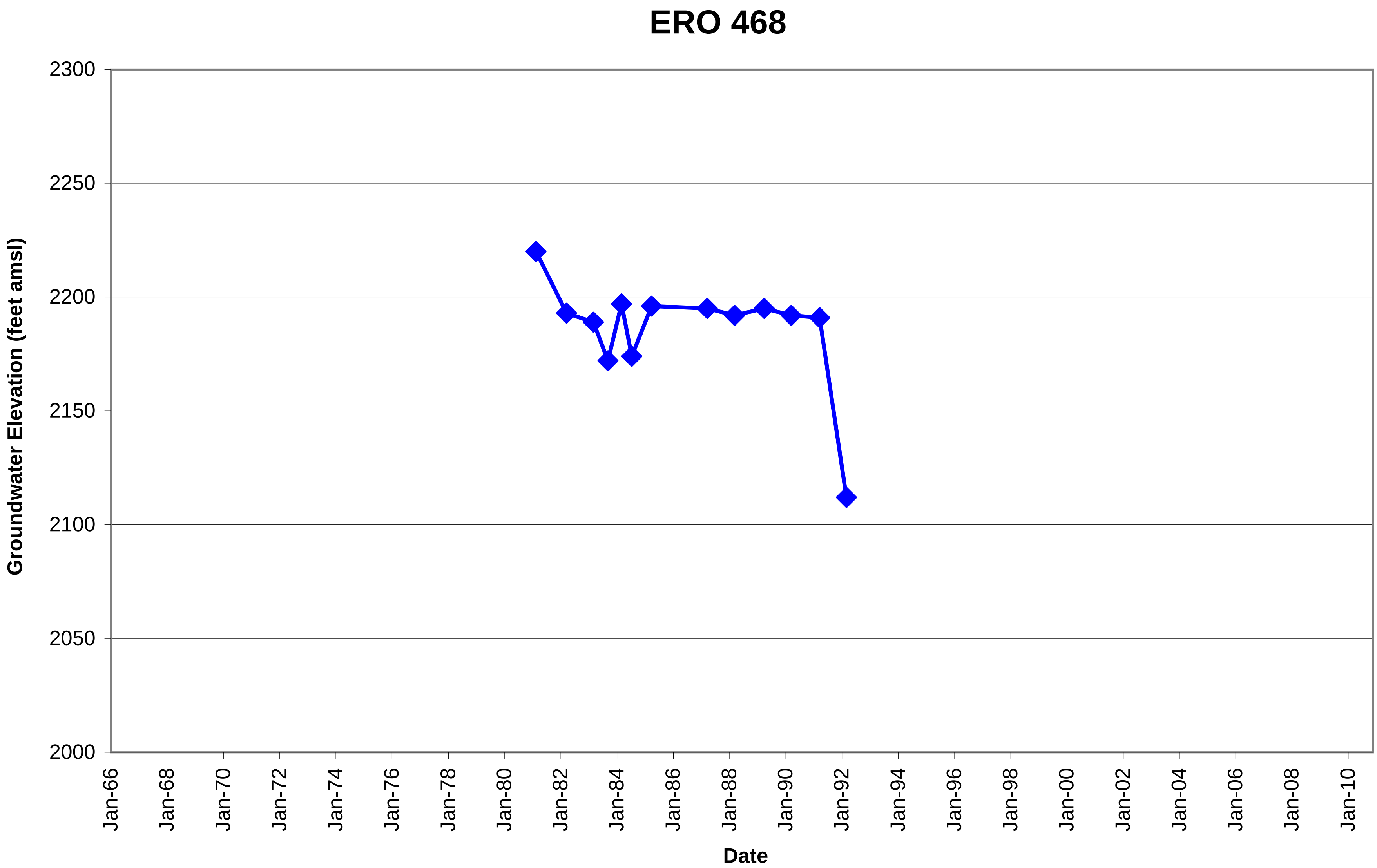


Groundwater Elevation (feet amsl)
2000
1950
1900
1850
1800
1750
1700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

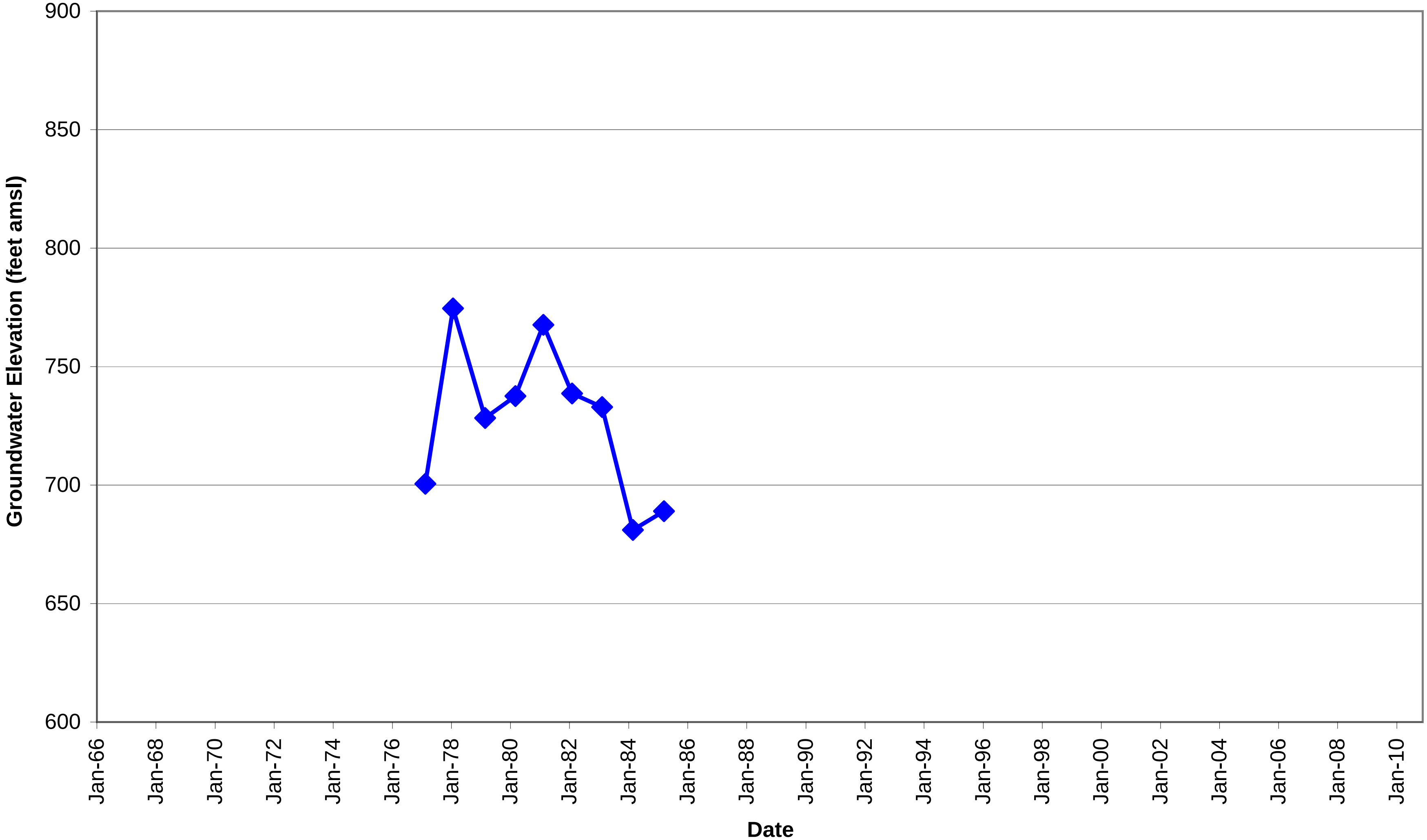


ERO 464
(Well Deepened 1999)
Groundwater Elevation (feet amsl)
2000
1950
1900
1850
1800
1750
1700
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

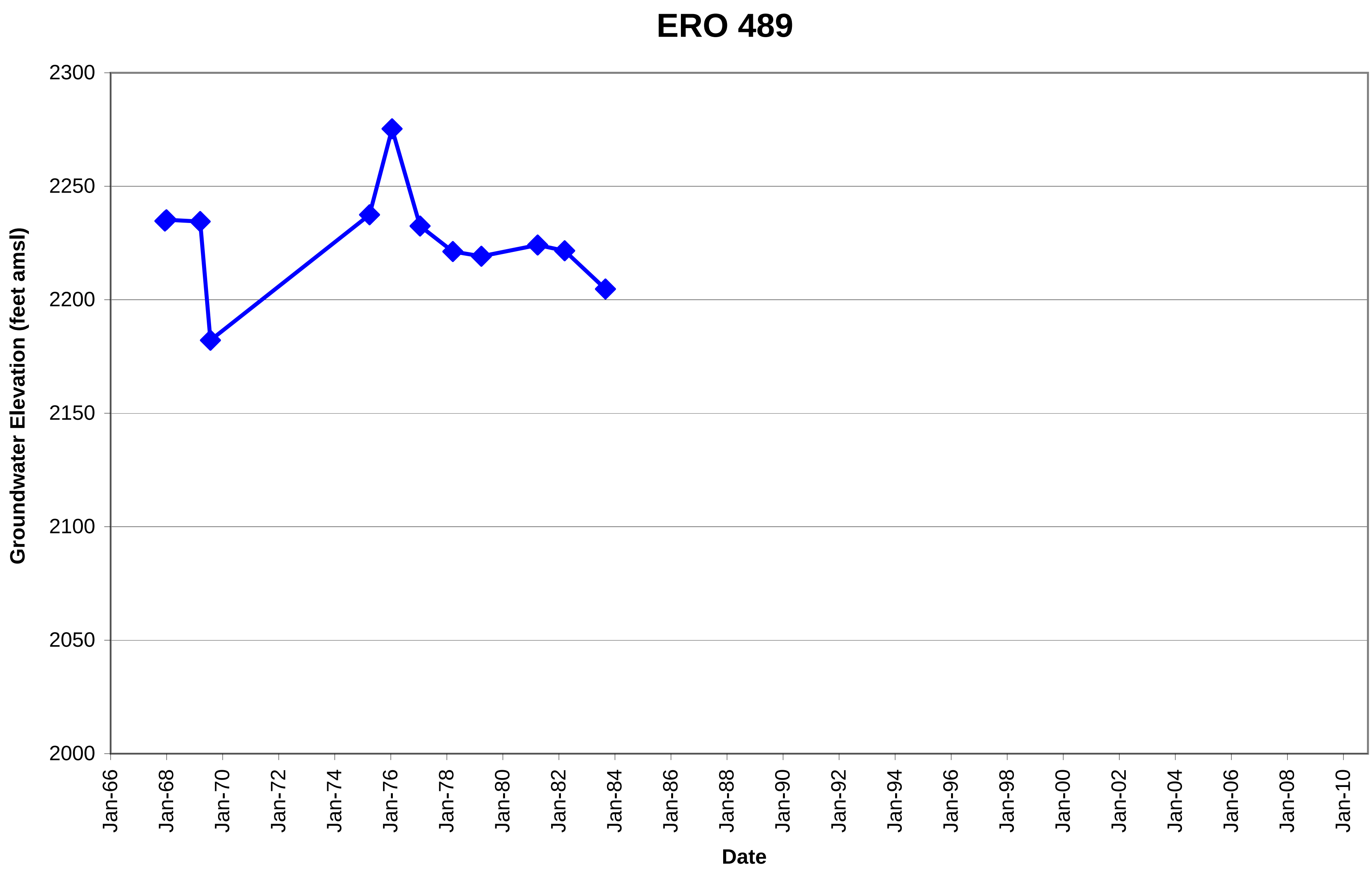

ERO 466
Groundwater Elevation (feet amsl)
1900
1850
1800
1750
1700
1650
1600
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 468
Groundwater Elevation (feet amsl)
2300
2250
2200
2150
2100
2050
2000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

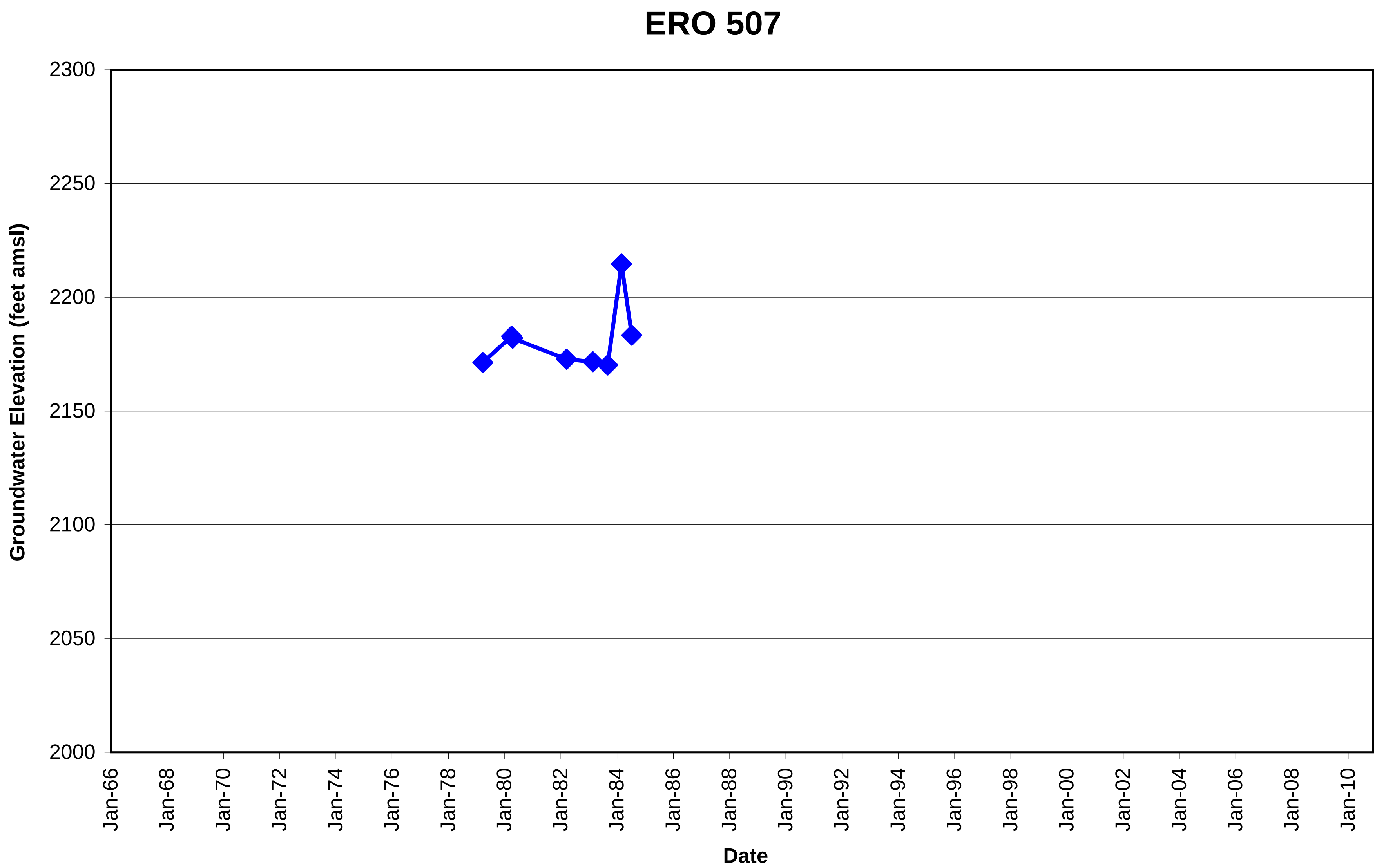
ERO 483

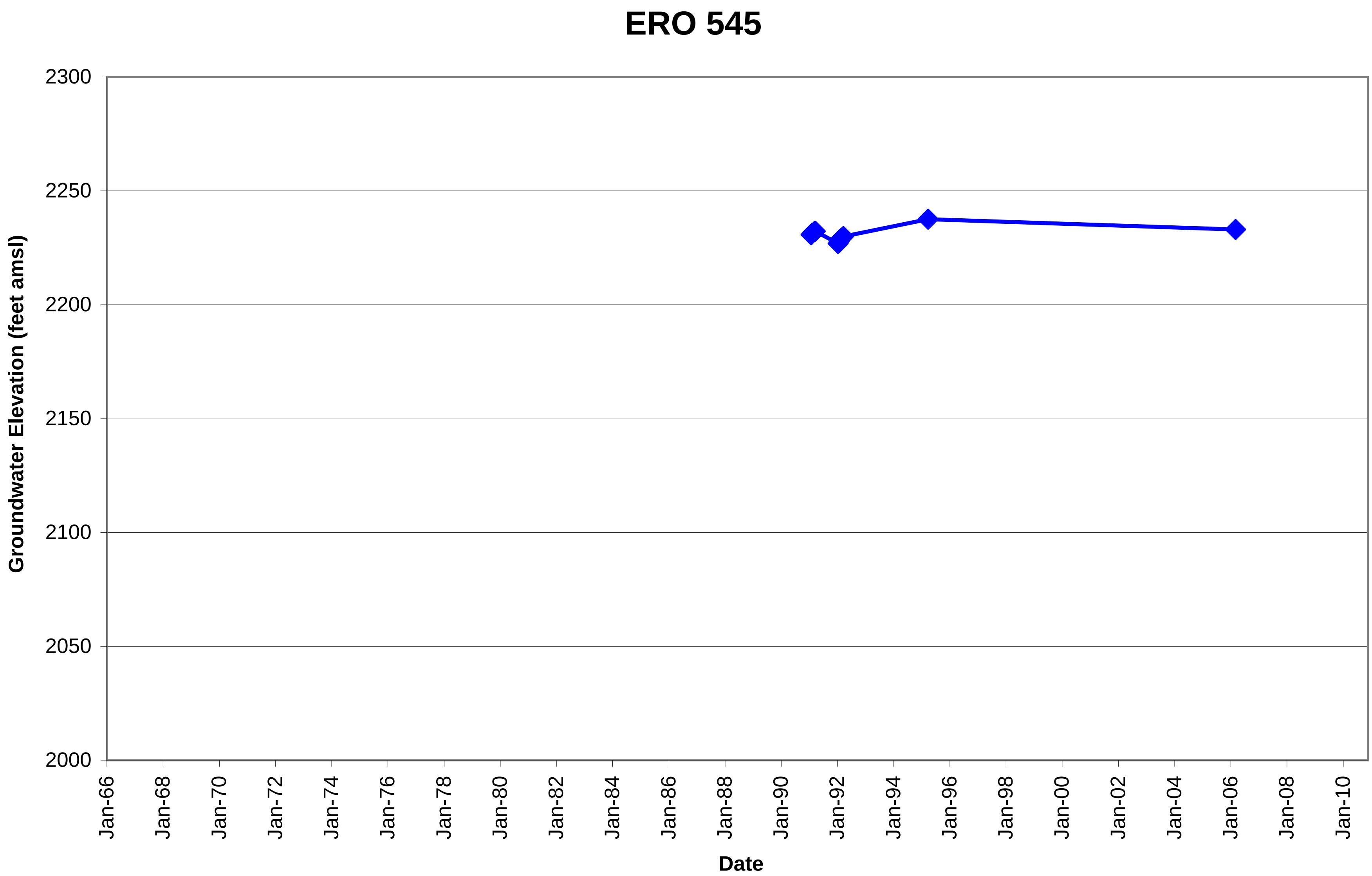


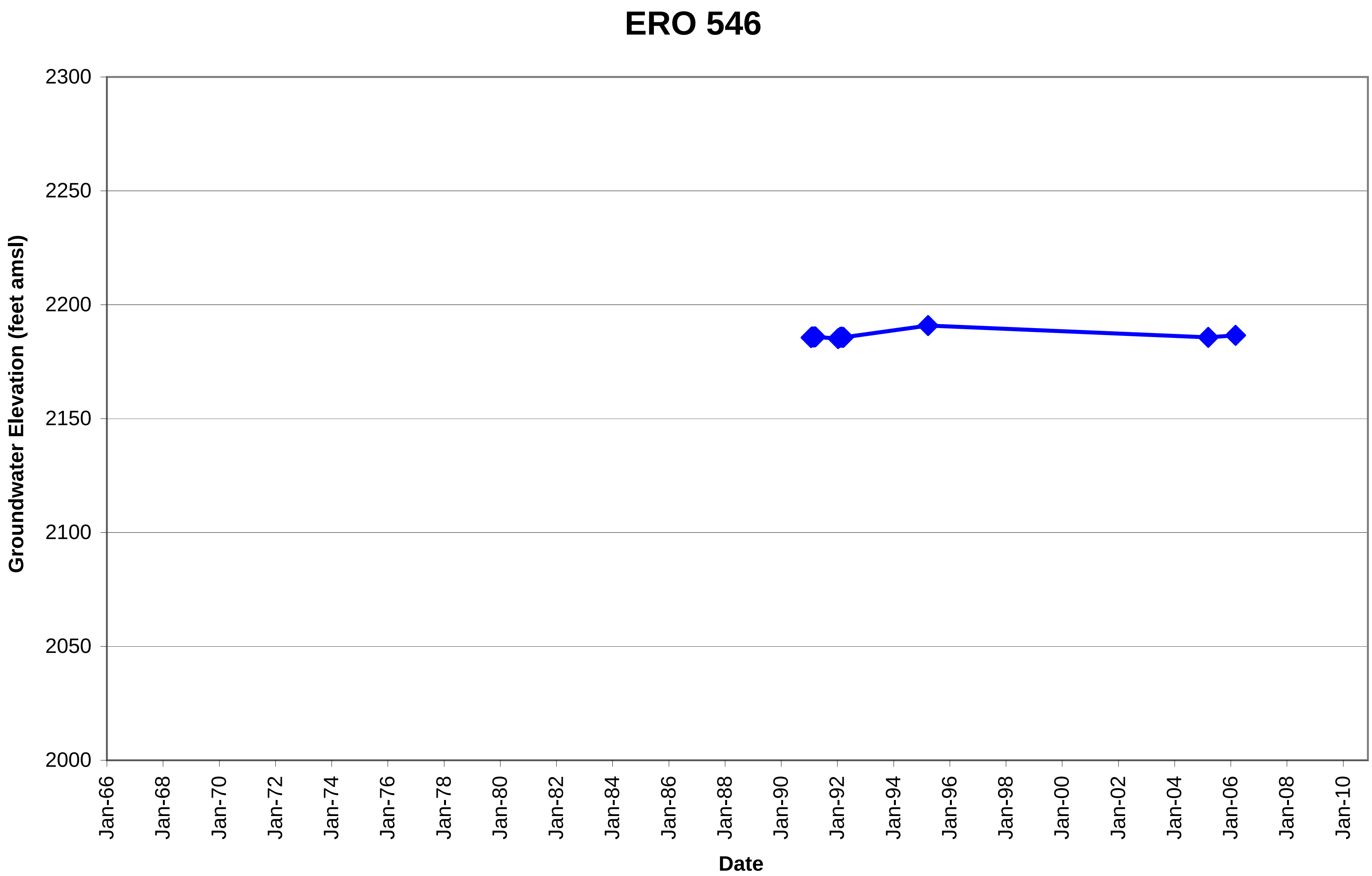
Groundwater Elevation (feet amsl)
900
850
800
750
700
650
600
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date



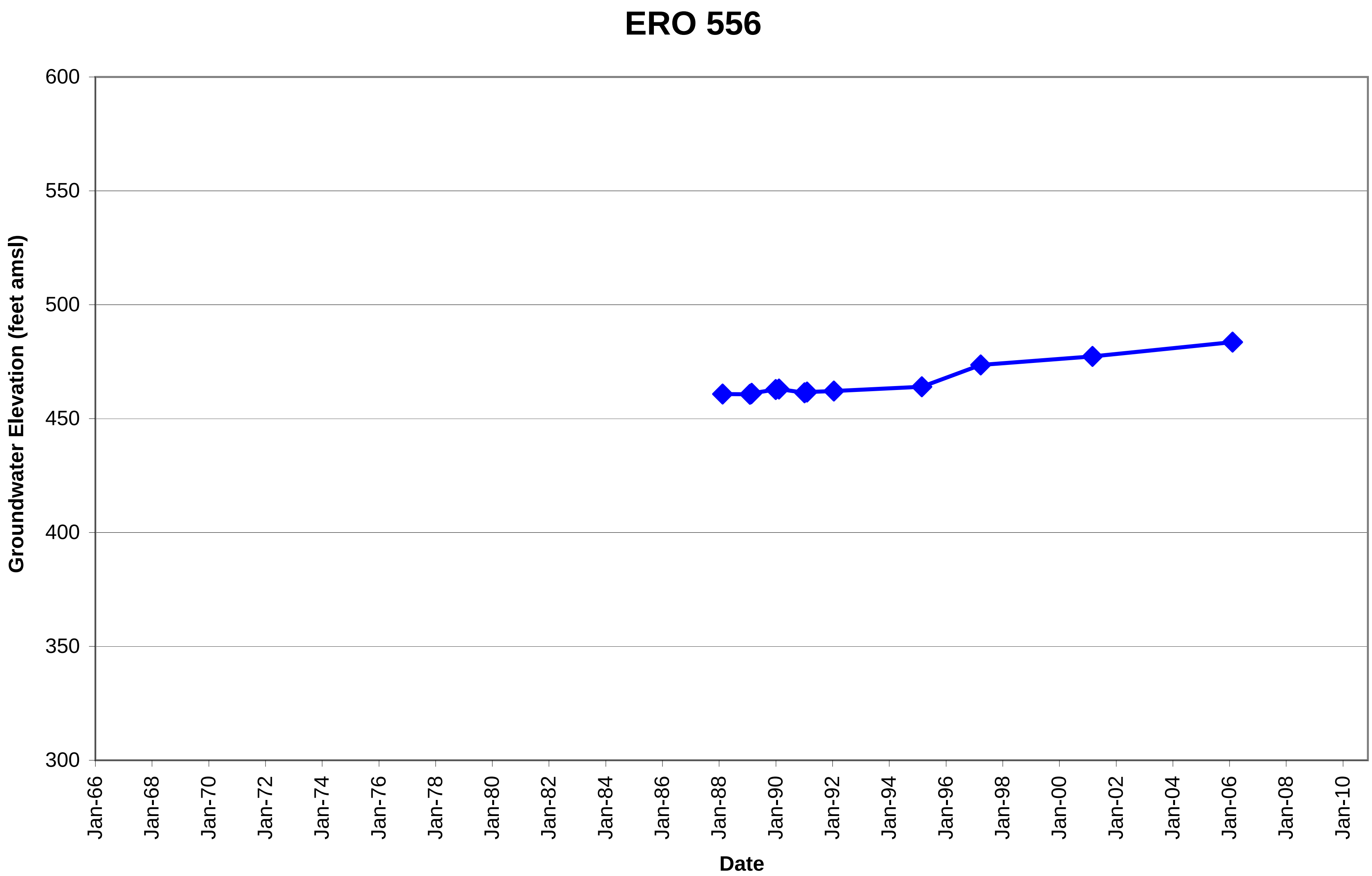
ERO 489
Groundwater Elevation (feet amsl)
2300
2250
2200
2150
2100
2050
2000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

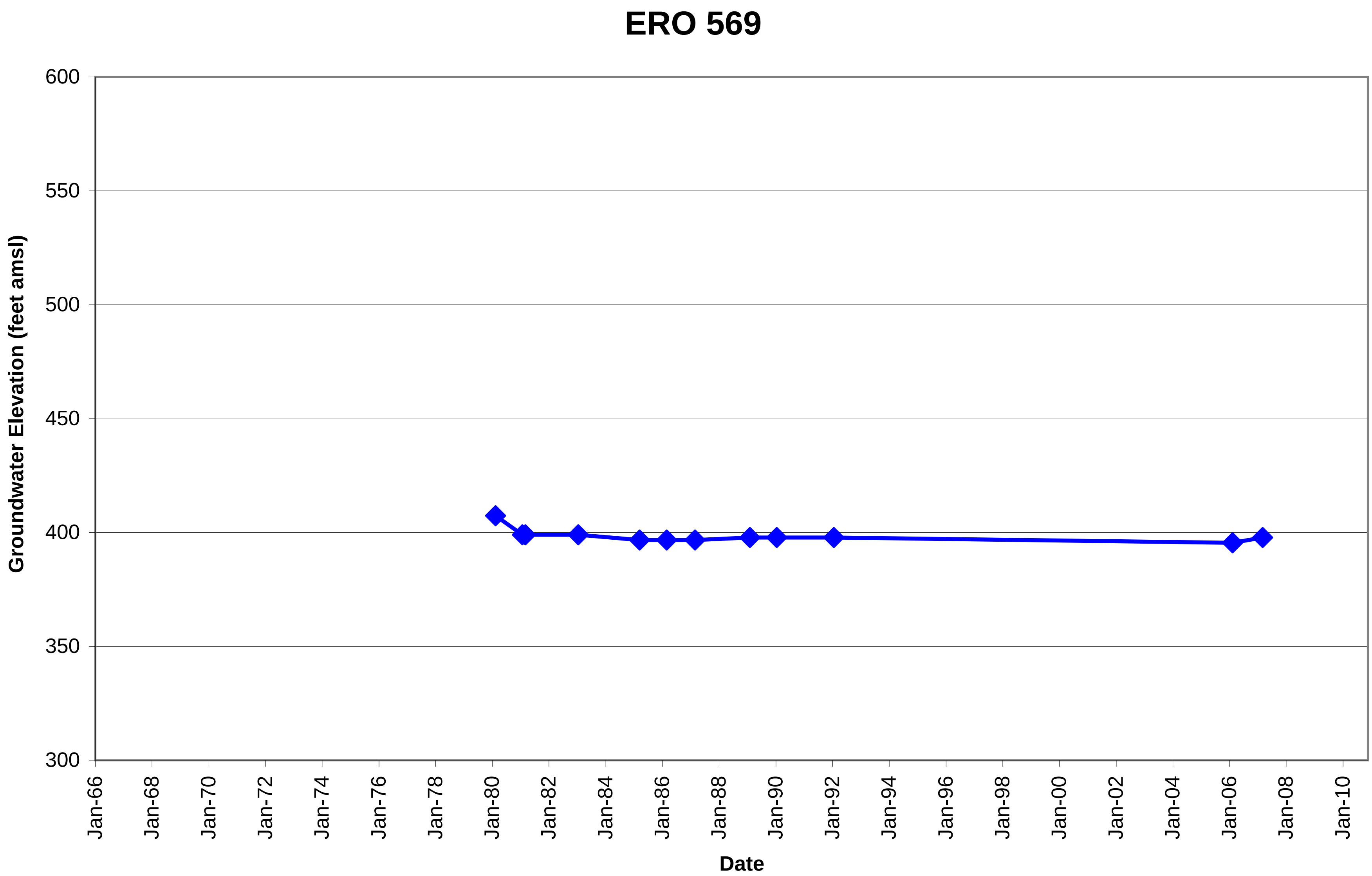

ERO 507
Groundwater Elevation (feet amsl)
2300
2250
2200
2150
2100
2050
2000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 545
Groundwater Elevation (feet amsl)
2300
2250
2200
2150
2100
2050
2000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date

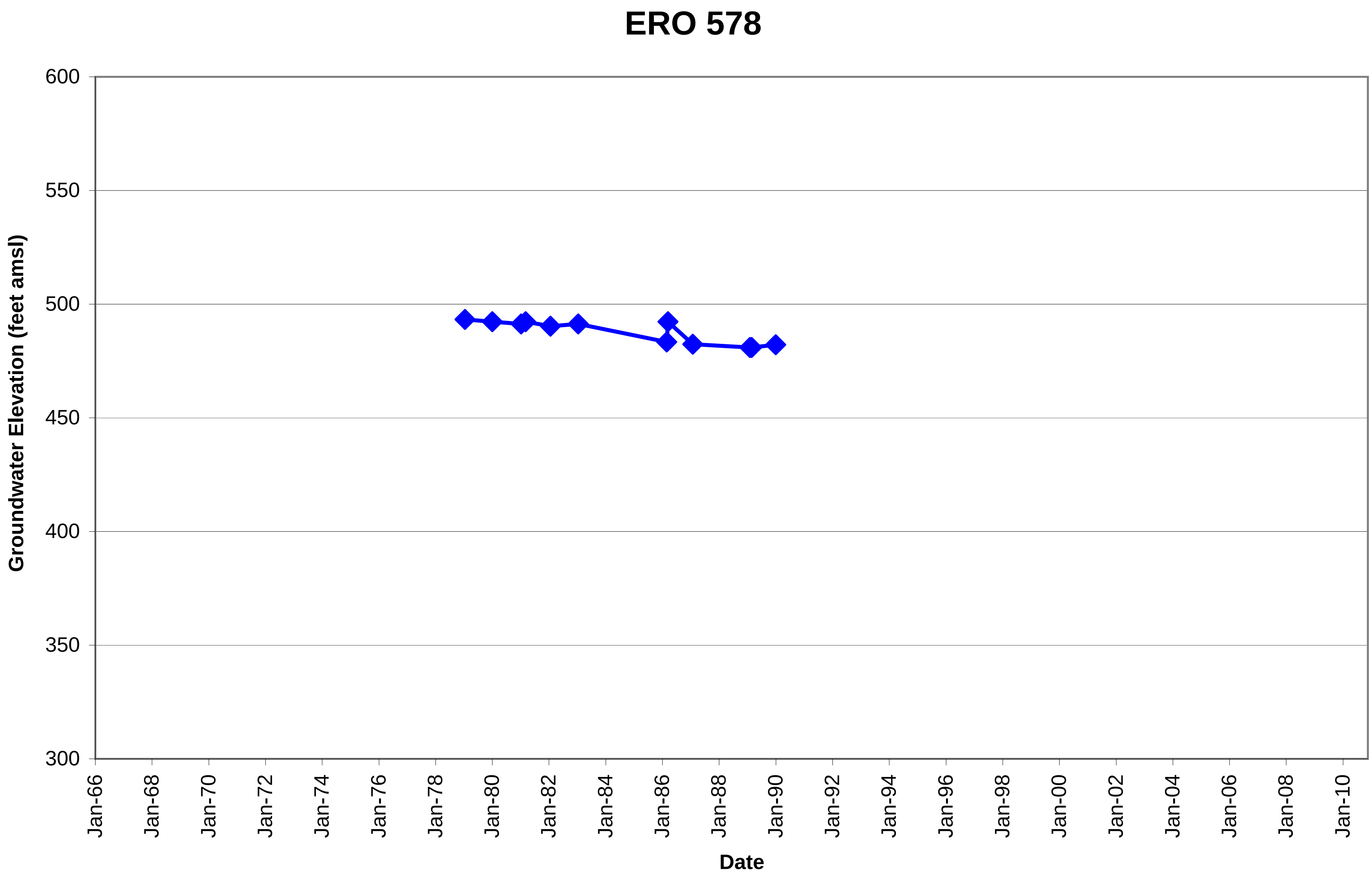


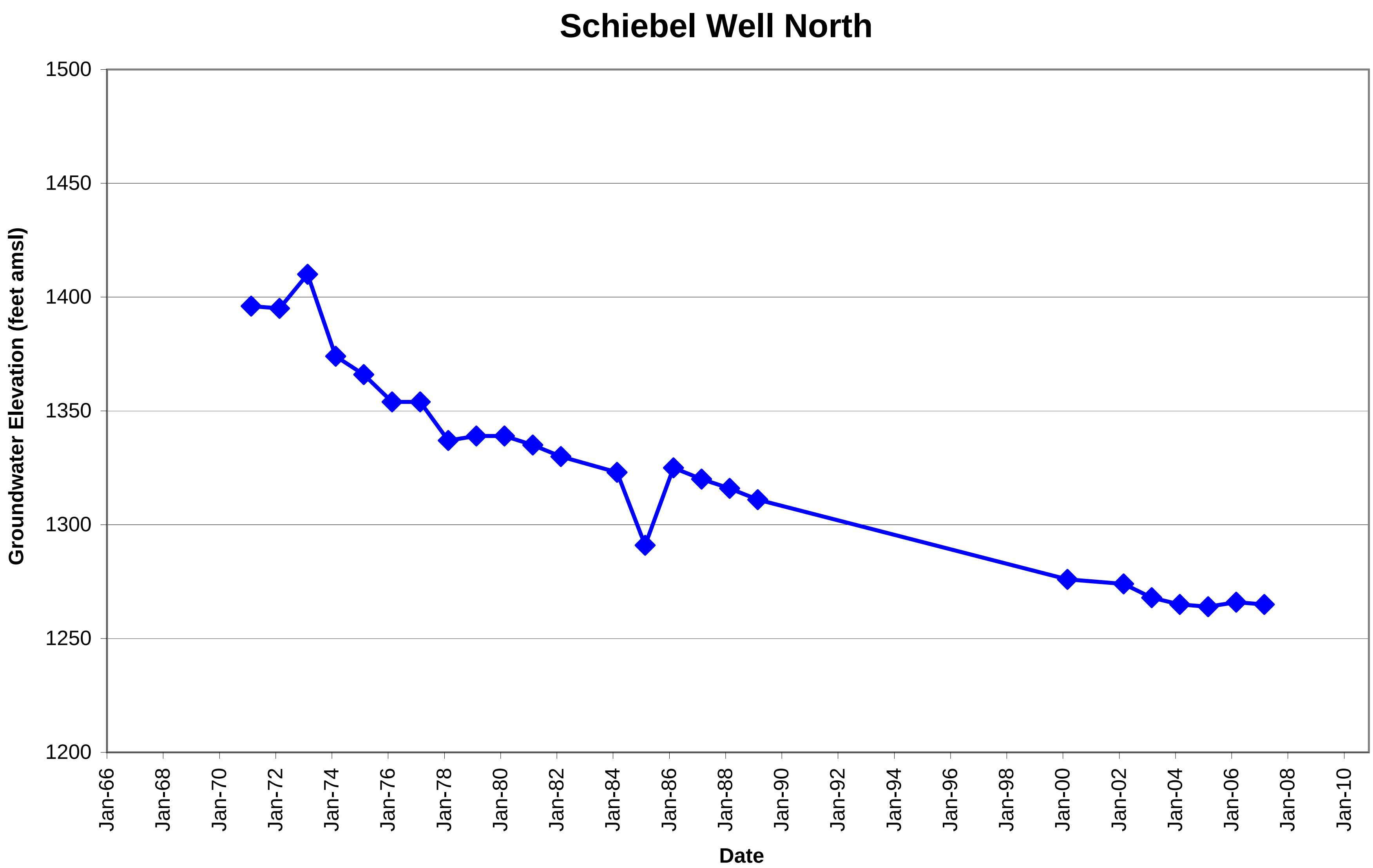
ERO 546
Groundwater Elevation (feet amsl)
2300
2250
2200
2150
2100
2050
2000
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 556
Groundwater Elevation (feet amsl)
600
550
500
450
400
350
300
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date



ERO 569
Groundwater Elevation (feet amsl)
600
550
500
450
400
350
300
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


ERO 578
Groundwater Elevation (feet amsl)
600
550
500
450
400
350
300
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date


Schiebel Well North
Groundwater Elevation (feet amsl)
1500
1450
1400
1350
1300
1250
1200
Jan-66
Jan-68
Jan-70
Jan-72
Jan-74
Jan-76
Jan-78
Jan-80
Jan-82
Jan-84
Jan-86
Jan-88
Jan-90
Jan-92
Jan-94
Jan-96
Jan-98
Jan-00
Jan-02
Jan-04
Jan-06
Jan-08
Jan-10
Date