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Numerical analysis of source-water dynamics for stream-bounded alluvial aquifers

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ABSTRACT

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Alluvial aquifers bounded by streams are water supply sources for numerous communities in the Ohio valley, West Virginia. Groundwater flow models are tools for estimation of source areas, however, existing analytical solutions apply only in settings involving a single stream boundary. A series of numerical experiments was devised for wells near multiple surface sources examining the controlling aspects of well-location and boundary condition interaction on source areas. Local-scale models were constructed representing an alluvial aquifer bounded by a tributary intersecting a large river. Aquifer behavior was examined in response to variations in pumping well location and tributary gradient. Flow within aquifers bounded by a regulated stream was controlled by the presence of the larger river, while aquifers bounded by an unregulated stream derived nearly all source water from tributary infiltration. Source water analysis of alluvial aquifers with multiple bounding streams is best accomplished using simple numerical simulations of this type.

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1. Introduction

1.1 Estimating capture zones for alluvial aquifers

Throughout the United States, it is common to find high-capacity public-supply wells pumping from water-table aquifers in alluvial valleys. Concern regarding the integrity of groundwater used as a primary community source has steadily grown over the last 30 years. In 1974, the Safe Drinking Water Act was implemented to monitor the construction and operational standards of U.S public drinking water supply systems. The Wellhead Protection Program, introduced in 1986 Amendments to the Safe Drinking Water Act (SDWA, Section 1428a), assists states in protecting areas surrounding municipal wells against contaminants. As a result of these amendments, the Source Water Assessment and Protection (SWAP) Program was implemented in West Virginia in 1999 to assess, preserve, and protect source waters supplying public drinking water systems (WVBPH, 1999).

Over eighty percent of the public water systems in West Virginia derive their supply from aquifers (WVBPH, 1999). Commonly used for community supply are alluvial aquifers adjacent to streams. These shallow unconfined aquifers are commonly close to centers of population and supports high-yield wells. They also may be subject to contamination from surface sources, making implementation of source water protection plans appropriate. Alluvial aquifers can have a complex water budget with multiple possible sources of inflow, including (a) vertical infiltration, (b) lateral or artesian inflow from up-gradient bedrock aquifers, and (c) infiltration from surface-water bodies.

"Source water assessment and protection zones for groundwater," as defined under SDWA, are to (a) provide a well field management area in which all potential sources of contamination can be identified, and (b) reduce or eliminate the risk of contamination to public drinking water supplies posed by these sources (WVBPH, 1999). The delineation provides a protection area within which all water supplying the well originates. Methods used for SWAP delineation fall into three main categories: hydrogeologic mapping, volumetric methods, and computer modeling. Of these three methods, the most rigorous is computer modeling, generally reserved for systems supplying a large population or for which there is distinct risk of well contamination. The specific type of numerical model method employed, however, has varied widely.

Two types of models are commonly used in capture zone estimation: analytical models and numerical models. Analytical models solve groundwater flow equations through simple, calculus-based mathematics, generating an exact mathematical solution for the unknown variable. Analytical models generally require simplified conditions, *e.g.*, homogeneity, isotropy and one- or two-dimensional flow. Numerical models calculate solutions to a system of algebraic finite-difference groundwater flow equations, yielding an approximation of the head distribution for transient or steady-state flow conditions. Most field problems are sufficiently complex that, if the field condition is to be modeled to any level of detail, numerical methods must be employed (Taylor and Person, 1998).

1.2 Previous Research

There are numerous studies regarding capture zone delineation and water budget estimation using computer models, both in general and specific hydrogeologic settings. Bair and Roadcap (1992) compared capture zone geometries produced using analytical, semi-analytical, and numerical models in two geologic settings: leaky-confined fractured carbonate aquifers, and buried valley fill aquifers. In both cases, their comparative flow modeling studies showed that a numerical flow model can provide additional insight into the hydrogeologic character of a flow system that cannot be obtained from analytical or semi-analytical flow models. The size and shape of the capture zones computed using the numerical model were more accurate since the model could account for nonuniform hydraulic gradients and transmissivities. They concluded that the most critical factor in selecting a suitable flow model for capture zone delineations is selection of a model that simplifies the flow system as much as possible while still preserving the geologic and hydrologic characteristics of the flow.

Taylor and Person (1998) examined coastal island aquifer systems using analytical, semi-analytical, and numerical models. Their primary focus was on the impact of variable density flow on capture zone geometries. All model types performed consistently at distances greater than 3,000 meters from the coastline; however, the analytical and semi-analytical models were inaccurate in estimating capture zone areas near the coastline.

Studies utilizing solely numerical models have examined the impacts of particular hydrogeologic factors on capture zone geometries and water budget variations. Frind and others (2002) examined capture zone delineations for complex multiple aquifer systems. The heterogeneity in multi-aquifer systems necessitates use of three-dimensional models that can account for varying hydrogeologic characteristics, boundary conditions, recharge, and surface water interactions. Frind and others concluded that numerical modeling was the only approach capable of satisfying all of these objectives for the complex aquifer system. Barlow examined unconsolidated glacial sediments of Cape Cod, Massachusetts (1994), and determined that a combination of factors complicate capture zone delineations in glacial environments including: low pumping rates, well proximity to discharge boundaries, partial penetration of the pumping well, anisotropy within the glacial sediments, and presence of vertical heterogeneity within the aquifer unit. Forster and others (1997) saw similar complications with capture zone variation in their study of alluvial basins in the western United States.

Location of a public supply well adjacent to a stream can induce infiltration toward the pumping well. There are numerous examples of supply wells drilled into alluvium adjacent to a stream or river to purposefully induce infiltration. Zlotnik (1997) and Sophocleous and others (1995) examined water budget variations for a pumping well near a stream. They focused on the effects of partial penetration and aquifer anisotropy on a pumping well's water budget, concluding that overestimation of infiltration volumes occurs if either condition is not accounted for in the numerical model. Chen (2001) studied the travel times and paths of infiltrated stream water to the pumping well and examined variations in these paths due to well location. Chen and Shu (2002) examined variations in stream infiltration causing stream flow depletion, and added an analytical component by calculating the flux of water lost by the stream due to pumping. They acknowledged the strong influence of recharge and well location on induced infiltration volumes; however, they did not account for these parameters in their numerical models.

Computer modeling is widely accepted as a reasonable method for flow system characterization and capture zone delineation. However, with little available field data, validation of numerical model results is difficult or impossible. In the absence of large quantities of data, a simplistic approach (*i.e.,* analytical modeling) may commonly be sufficient. However, there may be situations in which, even in the presence of abundant field data, application of analytical models may lead to erroneous results (Bair and Roadcap, 1992).

Several analytical solutions have been formulated regarding steady-unconfined flow in aquifers adjacent to surface-water bodies (Strack, 1989; Wilson, 1993; Newsom and Wilson, 1988). Changes in induced infiltration volumes supplying a pumping well were attributed to variations in well location, pumping rate, flow direction, and regional hydraulic gradient. The presence of barriers and additional surface-water sources was evaluated to a limited degree examining only barriers and secondary streams parallel to the primary source in question. Solutions for intersecting surface-water bodies of equal potential have also been formulated (Strack, 1989), but these solutions do not account for any recharge sources and assume a constant discharge potential along both stream reaches. These solutions are invalid in situations with steep gradient tributaries discharging into large, low-gradient rivers, a situation very common in the Ohio River valley.

1.3 Purpose and Objectives

The purpose of this study is to examine the dynamics of well location and stream boundary condition interaction in alluvial aquifers with multiple bounding streams. Numerical models will be applied to generalized alluvial settings with a single pumping well, based on water supply systems of the type found in the Ohio Valley of West Virginia. For continuously-used wells, steady-state groundwater flow is generally established, making steady-state analysis by numerical methods appropriate (Chen, 2001). This investigation will employ MODFLOW (Harbaugh and McDonald, 1988) and MODPATH (Pollock, 1989) at two levels of scale: a regional scale (focusing on the areal and volumetric extent of bedrock recharge contributions) and a local scale (focusing on the varying source components, supply areas, and associated volumes for wells located in alluvium). These models will be used to explore variations in capture zone geometry and water budget due to additional tributary influences and changes in supply well location. These numerical model results will be compared to analytical solutions for pumping wells in similar geologic settings.

Objectives include:

1. compilation of available geologic/hydrogeologic data (hydraulic head, well logs, pump tests) into a GIS framework;
2. development of a conceptual hydrogeologic framework including a fluid mass balance for the study area (local and regional-scale);
3. formulation of finite-difference flow models (flow and pathline) for regional and local flow regimes;
4. calculation of fluid mass balance components from numerical model results;
5. sensitivity analysis of fluid mass balance components to additional tributary influences and variations in pumping well distance from the river;
6. calculation of fluid mass balance components from analytical solutions;
7. evaluation of numerical and analytical models as delineation and predictive tools through comparison of fluid mass balance components from each model type.

1.4 Study Area Description

The study area (Figure 1) lies within the Appalachian Plateaus physiographic province, which is characterized by gently-folded to flat-lying Paleozoic sedimentary rocks (Seaber and others, 1988). Figure 2 is a generalized geologic map of the study area, and Table 1 is a generalized stratigraphic column. The majority of the study area is underlain by Permian and Pennsylvanian sedimentary rocks. Narrow bands of Quaternary alluvium appear as either terrace or outwash deposits that follow the major tributaries within the area. The rocks in this area lie within two synclinoria in the Ohio River Valley, the Parkersburg and the Nineveh (Cross and Schemel, 1956). These structures play an important role in oil and gas exploration within this region, but structure does not influence the hydrogeology here as they do in the Valley and Ridge Province to the east (Seaber and others, 1988).

Groundwater occurs primarily in the alluvial sediments bordering the Ohio River and its major tributaries. The high proportion of coarse sand that composes these sediments produces highly-permeable and productive aquifers (Kozar and Mathes, 2001). The Permian and Pennsylvanian rocks underlying the area typically have low permeabilities, but do exhibit some secondary permeability due to jointing and stress-release fracturing (Seaber and others, 1988). The Ohio River alluvium, however, is highly transmissive, far more so than the underlying bedrock. The alluvial aquifer along the Ohio River is believed to be unconfined, with some local semi-confined zones (Kozar and Mathes, 2001).

Topographic relief is relatively extreme along the Ohio River valley, with elevations ranging from approximately 140 to 520 meters above mean sea level. The majority of the area exhibits dissected plateaus, commonly capped by resistant layers (commonly sandstone). Major tributaries include the Kanawha and Little Kanawha rivers, as well as Mill, Fish and Wheeling creeks. Numerous smaller streams contribute to these tributaries, forming a dendritic drainage pattern consistent with the regional geomorphology.

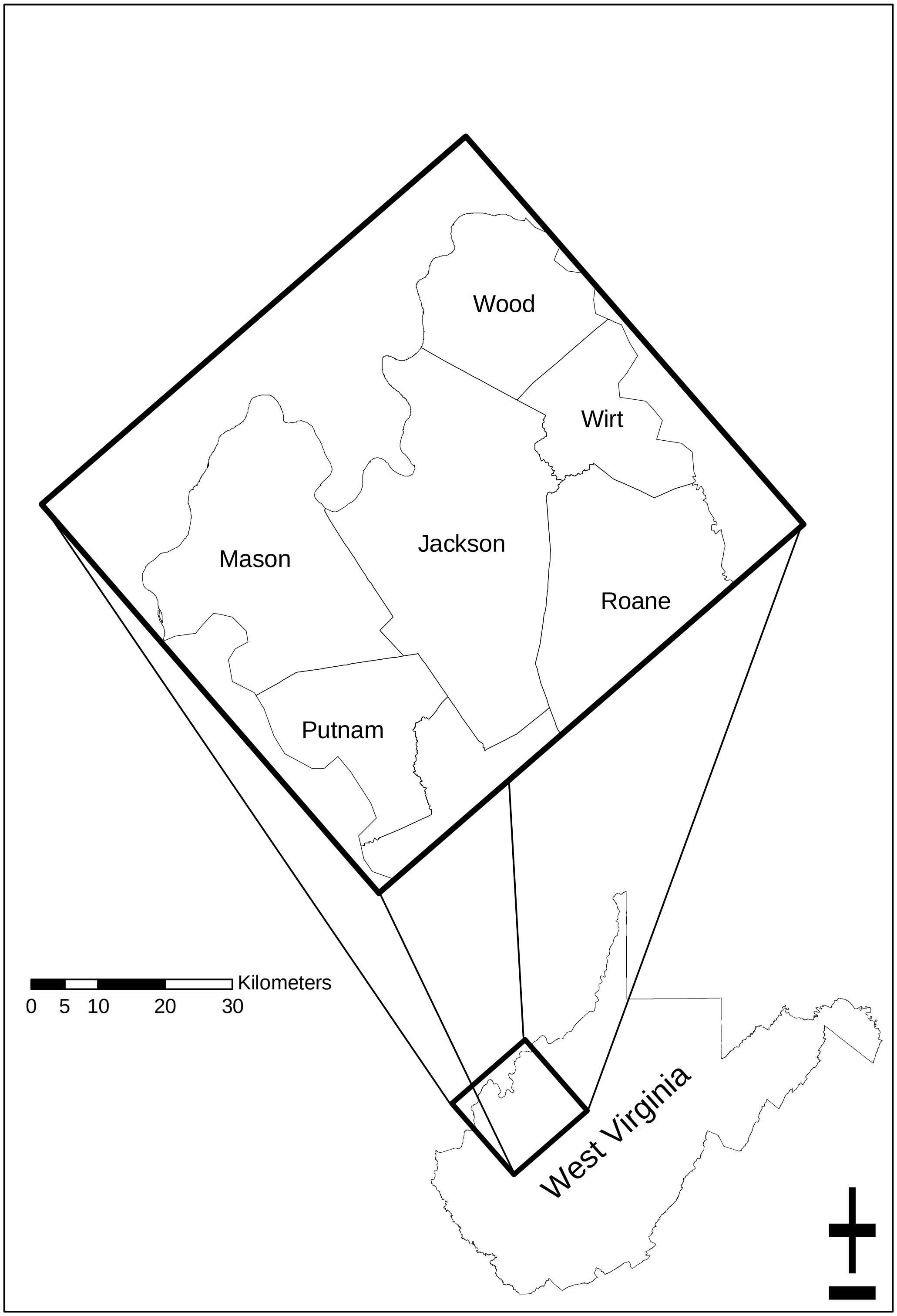


Figure 1. Location of study area.

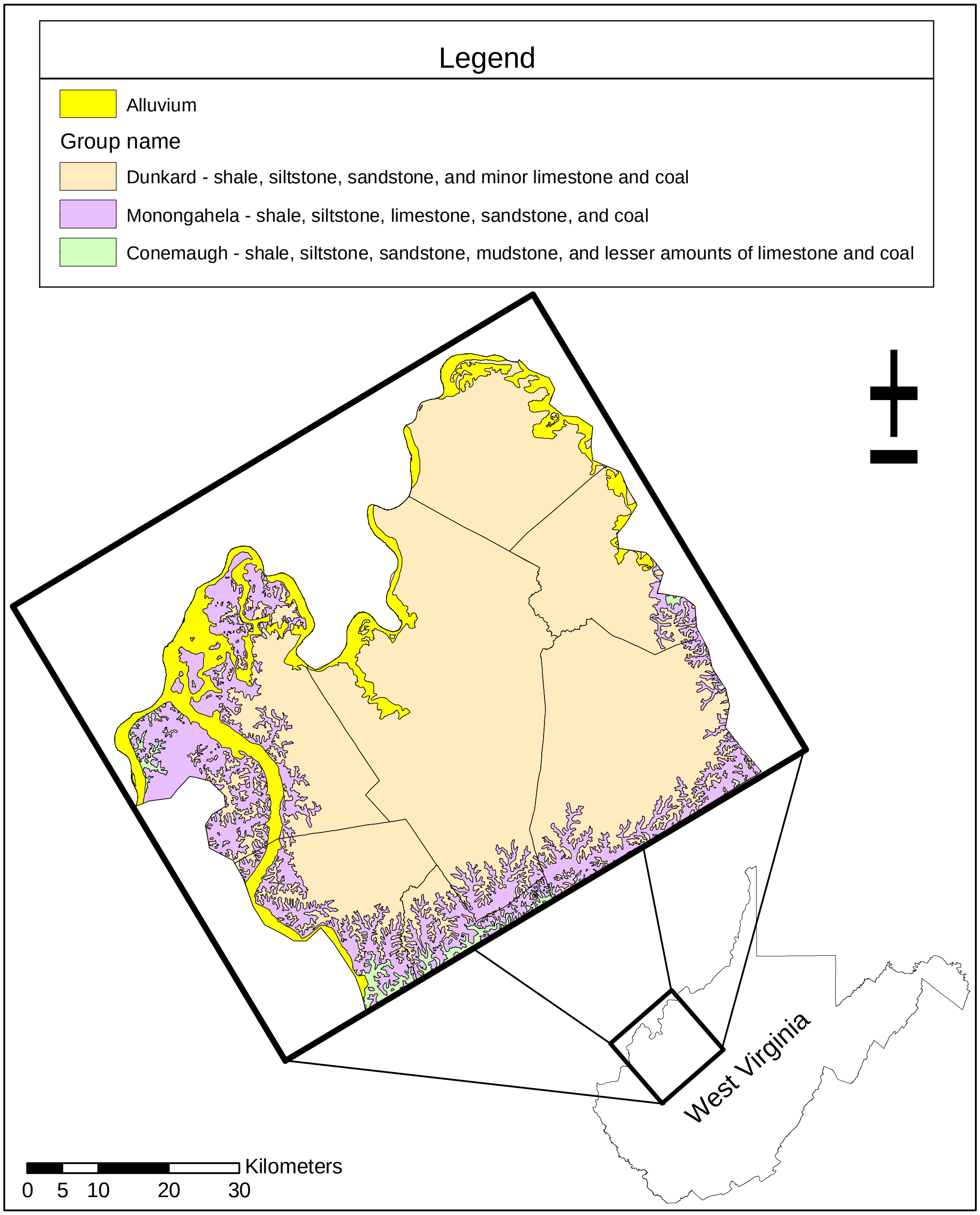


Figure 2. Generalized geologic map of the study area. (After Cardwell et al., 1968).

Table 1. Generalized stratigraphic column of the study area

System	Geologic Unit	Map ID	Formation	Predominant Rock Type
Quaternary	Alluvium	Qal		sand, gravel, silt and clay
(section break)				
Pennslyvanian	Dunkard	Pd		sandstone
			Greene Washington Waynesburg	
	Monongahela	Pm		sandstone
			Uniontown Pittsburgh	
	Conemaugh	Pc		shale and limestone
			Castleman Glenshaw	
	Allegheny	Pa		sandstone
	Pottsville	Ppv		sandstone
			Kanawha New River Pocahontas	

2. Methods

Data useful in characterization of the alluvial aquifer were compiled from several sources including the United States Geological Survey (USGS), the Army Corps of Engineers (ACOE), local well drillers, and the West Virginia Bureau of Public Health (WVBPH). Well lithologic logs and water well levels were obtained for counties included in the study area including Jackson, Mason, and Wood. The primary sources for these logs were the USGS, ACOE, and WVBPH. Well type and usage data were collected from the USGS and WVBPH. WVBPH provided data concerning public supply wells (most drilled in alluvium), while the USGS database contained information for private wells (most drilled in bedrock). Pump test data were obtained from the WVBPH and included information associated with public supply wells located along the Ohio River. Several aquifer characteristics were interpreted from published USGS data (Kozar and Mathes, 2001), which includes estimates of transmissivity, saturated thickness, hydraulic conductivity, and storage properties for most of the major aquifers across the state.

2.1 Interpolated Bedrock Surface

Water well information for alluvium was compiled and interpolated to produce an approximate bedrock surface topography under alluvial portions of the Ohio River valley (see Appendix I), which was used as the base of the alluvial aquifer in the numerical simulations. Production wells are generally drilled to the base of the aquifer unit to increase specific capacity and well yield (Driscoll, 1986). Inverse-distance-weighted (IDW) interpolation was used to model the aquifer's basal surface based on 1,094 reported well depths, taken as an estimate of the depth to the base of alluvium (Figure 3). The IDW algorithm weights nearby values more heavily and works best for modeling a gradually changing surface, such as the bedrock surface (Johnston and others, 2001).

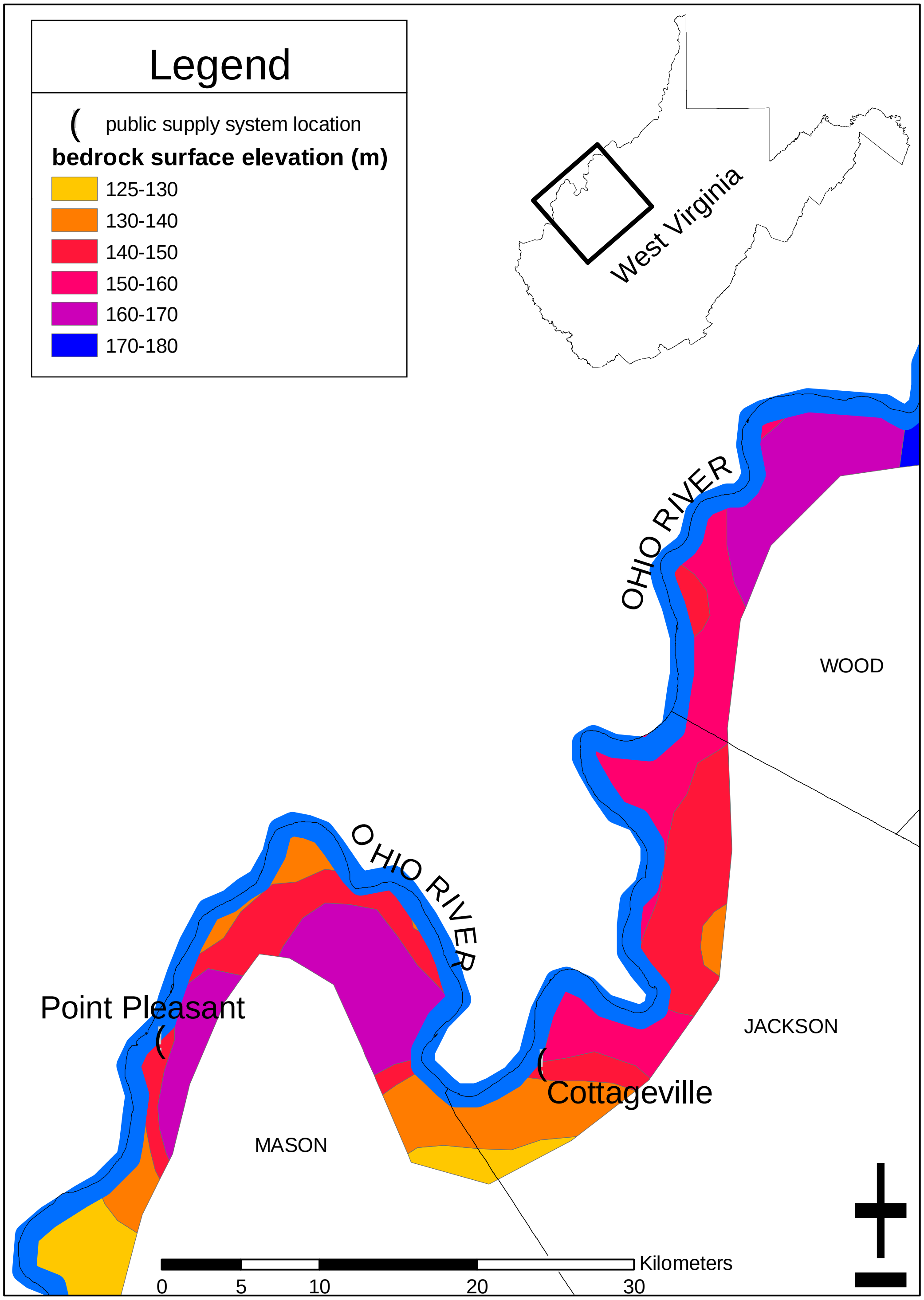


Figure 3. Bedrock surface elevation of the Ohio River valley near the communities of Cottageville and Point Pleasant, generated using IDW interpolation of 1,094 bedrock elevation points (see Appendix I).

2.2 Analysis of Pumping Test Results

Pumping tests are conducted to determine the hydraulic parameters of an aquifer and/or the performance characteristics of a well (Driscoll, 1995). Interpretation of the pump test data leads to estimates of parameters such as transmissivity and storage coefficients. Results from properly-conducted pump tests can be one of the most important tools in groundwater investigations.

Test data were obtained from 26 high-capacity wells in West Virginia water systems from WVBPH. Most of these tests were geared toward determining the performance of the supply well rather than hydraulic parameters of the aquifer. Few had observation well data, and some had no reference static water levels at the pumping well or elsewhere. Lack of quality data made interpretation of aquifer parameters nearly impossible. However, test results give a general idea of aquifer behavior in response to pumping. The time-drawdown plot for the supply well shown in Figure 4a shows a typical response to pumping in an unconfined aquifer located near a river. At approximately 80 minutes, the cone of depression is interpreted to intersect a recharge boundary (i.e., the river) showing the characteristic flattening out of drawdown (Driscoll, 1995). If stream infiltration is sufficient, a pumping well may reach steady-state soon after the break in slope on the time-drawdown curve. This situation was encountered in the Ravenswood, West Virginia, public supply well located in the Ohio River valley alluvial aquifer (Figure 4b). These data indicate the alluvial aquifer in many locations is unconfined and capable of inducing significant infiltration.

2.3 Adjustment of Published Parameter Values

Aquifer parameters taken from Kozar and Mathes (2001) were adjusted to fulfill input data needs for the numerical models. Adjusted parameters include recharge, evapotranspiration, and hydraulic conductivity.

Recharge (R) is precipitation that infiltrates the ground surface and reaches the water table. Recharge estimates specific to the study area were taken from Kozar

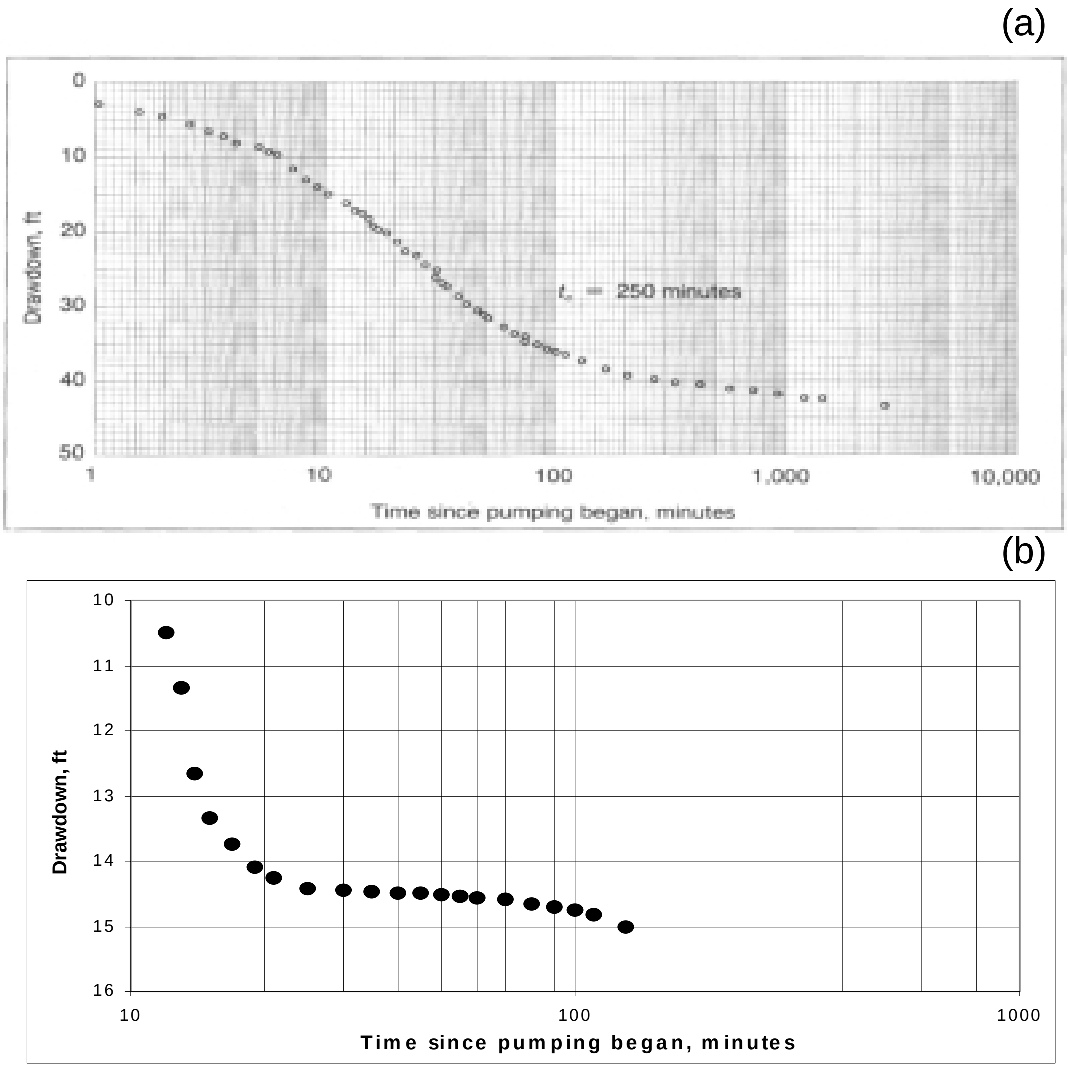
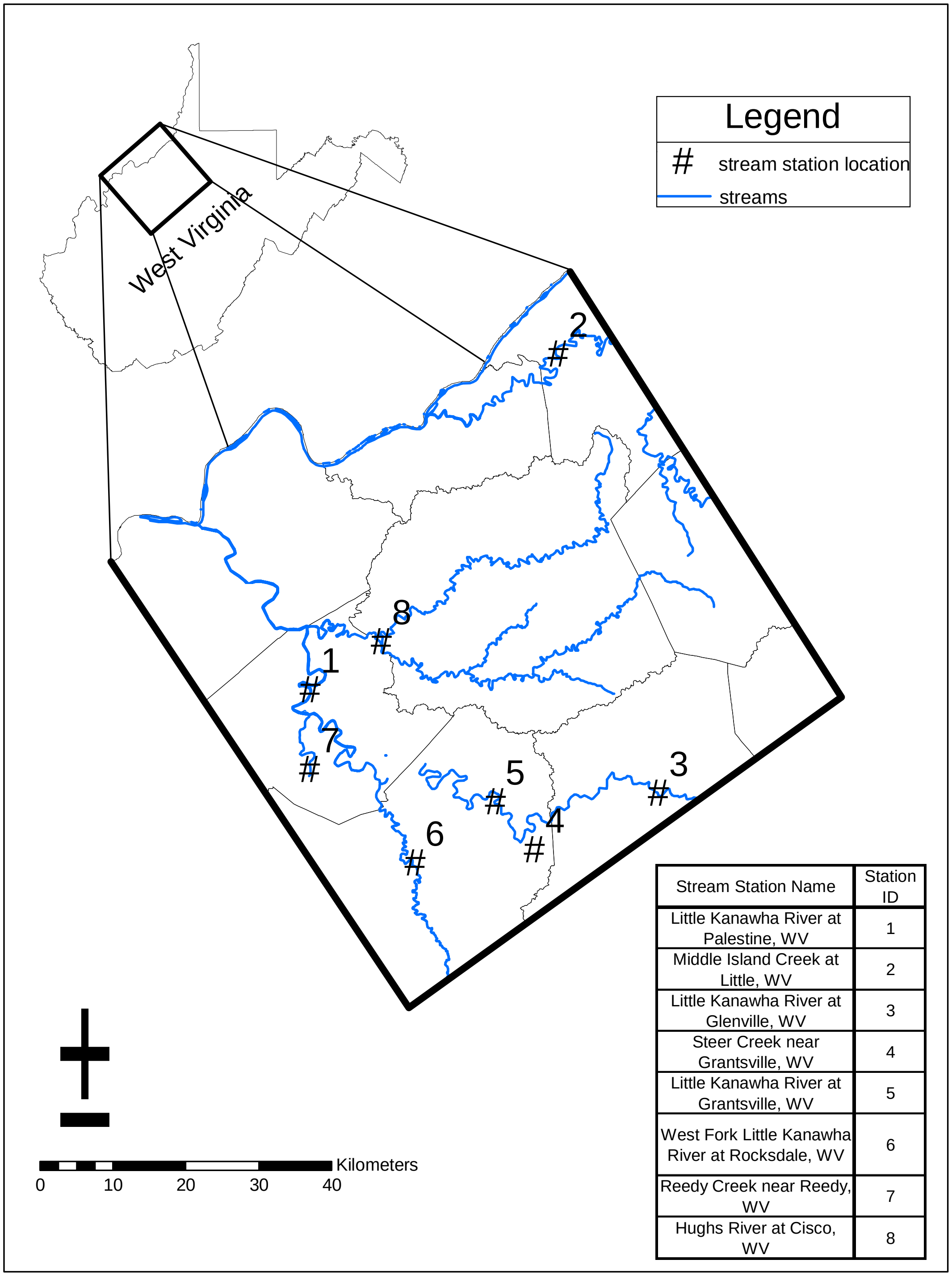


Figure 4. Drawdown versus time curves. (a) Typical time-drawdown curve for a pumping well located near a recharge boundary. (After Driscoll,1986). (b) Time-drawdown curve from the Ohio River valley alluvial aquifer showing an apparent recharge boundary encountered at t=20.

and Mathes (2001). Stream flow data from 41 gaging stations on unregulated streams throughout West Virginia were analyzed using the recession-curve displacement method (Rorabaugh, 1964) to determine mean recharge rates for selected areas (Figure 5). The mean recharge rate for the Ohio Valley region, including the Ohio River, Little Kanawha, and Kanawha rivers, was 23.9 cm/yr (9.4 in/yr) (Table 2). Estimates of hydraulic conductivity (K) for bedrock and alluvial aquifers were derived from the regional results of Kozar and Mathes (2001), based on specific capacities of wells and aquifer test results. Their estimates of transmissivity were divided by local saturated thicknesses, averaged from lithologic logs of wells drilled with Ohio River alluvium, to yield vertically-averaged hydraulic conductivities for alluvium and bedrock.



Stream Station Name	Station ID
Little Kanawha River at Palestine, WV	1
Middle Island Creek at Little, WV	2
Little Kanawha River at Glenville, WV	3
Steer Creek near Grantsville, WV	4
Little Kanawha River at Grantsville, WV	5
West Fork Little Kanawha River at Rocksdale, WV	6
Reedy Creek near Reedy, WV	7
Hughs River at Cisco, WV	8

Figure 5. Location of gaging stations from which groundwater recharge was estimated using the streamflow recession-curve method. (After Kozar and Mathes, 2001).

Table 2. Spatially-averaged groundwater recharge rates, estimated from streamflow data by Kozar and Mathes (2001).

Site	County	drainage area (mi^2)	recharge rate (in/yr)
Ohio River Tributaries			
Wheeling Creek at Elm Grove WV	Ohio	281	9.6
Middle Island Creek at Little WV	Tyler	458	8.0
		mean Ohio River	8.8
Little Kanawha River Basin			
Hughes River at Cisco WV	Ritchie	453	7.1
Reedy Creek near Reedy WV	Wirt	79.4	6.7
Steer Creek near Grantsville WV	Calhoun	162	9.2
West Fork Little Kanawha River at Rocksdale WV	Calhoun	205	8.7
Little Kanawha River at Grantsville WV	Calhoun	913	8.8
Little Kanawha River at Glenville WV	Gilmer	387	9.3
		mean Little Kanawha River	8.3
Kanawha River Basin (western portion)			
Big Coal River at Ashford WV	Boone	391	11.9
Little Coal River at Danville WV	Raleigh	269	11.9
Piney Creek at Raleigh WV	Raleigh	52.7	11.9
		mean Kanawha River	11.9
		global mean	9.4

3. Conceptual Model

Elements of recharge and discharge to Ohio River alluvium include vertical infiltration, lateral or artesian inflow from up-gradient bedrock aquifers, and infiltration from surface-water bodies (Figure 6). The percentage of fluid mass balance for each component varies dynamically according to a number of factors. The magnitude of contribution from vertical infiltration is based upon the recharge rate estimate employed, but will also vary according to capture zone geometry. Contributions to the fluid mass balance from induced infiltration depends on availability of water from bedrock inflow; well pumping rate, and well proximity to stream(s). Therefore, the interaction of these factors makes the water budget highly dependent on covariation between factors.

The heads in for Ohio Valley alluvium are strongly constrained by the pool elevation of the Ohio River. At times of normal pool stage, the alluvial aquifer discharges to the river. At times of high water, when the river rises above the alluvial water table, this gradient may reverse for short periods. At all times however, the river pool forms the bounding head for the alluvial aquifer.

3.1 Bedrock of the Ohio River Valley

The Dunkard Group is the youngest consolidated rock unit found in the Ohio River valley (Cross and Schemel, 1956). It is of Permian age and is dominated by sandstone, limestone, and coal lithologies. The sandstone units within the group, (including the Nineveh, Burton and Fish Creek), are mostly fine- to medium-grained; however the units tend to coarsen down-section. Limestone units, such as the Rockport and Nineveh, originated from freshwater deposition, and contain numerous shale beds throughout the section. Several coal seams occur throughout. The Dunkard Group ranges in thickness from 260 to 586 feet, but in many stream valleys within the study area, the unit has been completely eroded away, leaving the Monongahela Group exposed at land surface.

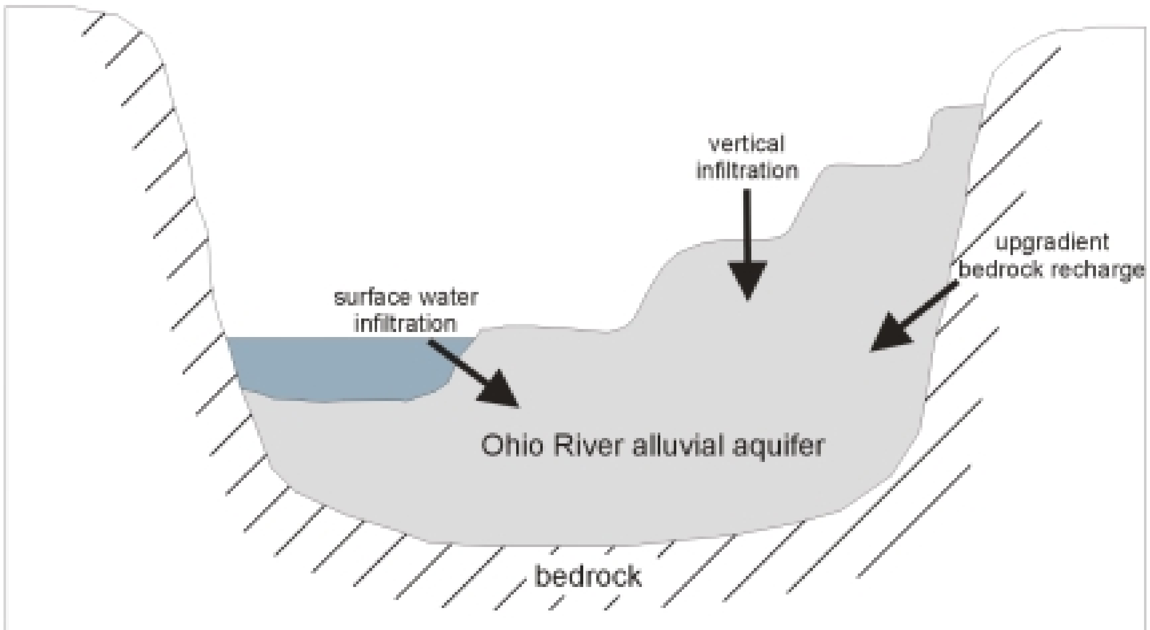


Figure 6. Source components to the alluvial aquifer of the Ohio River valley.

The Monongahela Group of Middle to Late Pennsylvanian age is dominated by shale, sandstone, limestone, and coal lithologies. Sandstone units include the Uniontown, Arnoldsburg, and Sewickley, which tend to be coarse-grained and thick. To the west, the sandstones give way to thick units of lacustrine limestones including the Benwood and Fishpot units. Shales are also quite prominent throughout the group and range from gray and clayey to red and calcareous in nature (Cross and Schemel, 1956). The Monongahela Group ranges in thickness from 248 to 280 feet, and is the dominant exposed bedrock unit near both the Ohio River and the Kanawha River within the study area.

The oldest exposed group within the study area is the Conemaugh Group. It is Middle Pennsylvanian in age and dominated by sandstone, shale, limestone, and coal lithologies. Many of the sandstones are medium- to fine-grained and irregular in thickness and extent. Several thick red-bed deposits are present, including the Clarksburg, Birmingham, and Pittsburgh sequences. The red beds tend to grade into thinner, fresh-water-deposited limestone beds. The Conemaugh Group ranges in thickness from 480 to 540 feet; however, its exposure within the study area is minimal and limited to the southwest near the Ohio River.

3.2 Ohio River Valley Alluvium

While the late-Wisconsinan Lauentide ice sheet extended into the upper Ohio River drainage basin, meltwater transported large quantities of glacial debris, causing aggradation in the valley atop the bedrock floor (Carlston and Graeff, 1956). Following retreat of the glacier during the late Pleistocene, sediment supply reduced greatly and the river began to downcut through the alluvial outwash deposits. During this period of downcutting, floodplains were abandoned at successively lower levels to form the terraces (Kazmann and others, 1960). The terraces are formed in the late-Wisconsinan and Holocene fill, and occur consistently along the length of the river. In most locations today, the Ohio River is still flowing over remaining Wisconsinan fill (Simard, 1989).

The alluvial sediments along the length of the Ohio River compose the primary aquifer unit modeled within this study. Large-scale heterogeneity of river alluvium characterizes the late-Wisconsinan and Holocene alluvial fill in the Ohio River valley. Local differences in depositional facies were caused by irregularities in the old valley floor, in the course of the stream, and in the varying capacity of the river to transport sediments (Kazmann and others, 1960). The primary sediment types overlying the bedrock valley floor include coarse-grained Ohio River alluvium, fine-grained Ohio River alluvium, tributary alluvium, colluvium, and eolian sand and silt (Simard, 1989).

The coarse-grained Ohio River valley alluvium consists of poorly-sorted, well-rounded gravel, sand, and minor silt and clay. This is the dominant facies in the Ohio River valley, but the deposits tend to thin downstream along the river and riverward from the bedrock valley margins (Simard, 1989). Tributary alluvium forms local lenses within the coarser-grained alluvial gravels and is comprised predominantly of flat, subrounded gravels. Tributary alluvium also has more silt and sand than the coarse grained Ohio River alluvium. Colluvium is interbedded with the alluvial deposits near the bedrock valley walls. It consists of angular-sandstone gravels, with shale/siltstone concretions throughout. A fine-grained Ohio River alluvial deposit composed of sand, silt, and clay occurs throughout the region. This facies is most likely a result of overbank or waning flood deposits during the late-Wisconsinan and Holocene periods in the Ohio River valley (Rogers, 1990). Eolian sand and silt are also present atop the older terrace surfaces, however, they do not occur on Holocene active floodplain surfaces (Simard, 1989). Average alluvial thicknesses typically range from 30 to 80 feet, with 100 feet thick deposits beneath terrace surfaces in some locations (ACOE, 1996).

Percentages of clay, silt, sand, and gravel in the alluvium change more or less abruptly throughout the study area. The valley near Parkersburg, West Virginia, contains large amounts of sand in addition to the dominant gravel lithology. Thin silt beds commonly appear atop of the sand and gravel deposits, likely a result of past flooding of the Ohio River (Rogers, 1990). Near Ravenswood, West Virginia, silt and sand dominate the local lithology. At New Haven, West Virginia, fine sand and gravel predominate (Carlston and Graeff, 1956) while coarser sand and gravel dominate the local lithologies near the communities of New Cumberland, Wheeling, Waverly, and Reedsville, West Virginia (Figure 7; ACOE, 1955; ACOE, 1961; ACOE, 1963; ACOE, 1965). Well lithologic logs for the seven localities are shown in Figure 8. The local variability of sediment types causes the conductivity of the water-bearing materials along the Ohio River to vary considerably, both horizontally and vertically. Grain size tends to decrease downstream as the carrying power of the river decreases, correspondingly reducing conductivity (Carlston and Graeff, 1956). The alluvium is stratified horizontally, and interfingering of silt and clay beds within the gravel deposits is common. The silt and clay tend to reduce downward infiltration of precipitation through the vadose zone. Typical conductivity values for sediment types in the Ohio River valley are shown in Table 3.

3.3 The Ohio River Terrace Deposits

The complex set of terraces and floodplains along the Ohio River formed during glacial advances and retreats of the pre-Wisconsinan and Wisconsinan, successive phases of alluvial fills, and incision into the alluvium. The terraces are best developed inside meander bends but are discontinuous along the river's length from bank to bank. At least eight distinct surfaces exist, with other segments present but too small to distinguish on 1:24,000 topographic quadrangles (Simard, 1989).

The impact of local terrace geometry on groundwater flow near the Ohio River is related to the degree of hydraulic continuity between successive terraces. This continuity is thought to depend, in general, on the elevation difference between the top of the lower terrace gravel and the bottom of the higher terrace gravel. If this difference is positive, (i.e., if the top of the younger terrace gravel is above the bottom of the one above it), hydraulic continuity may generally be inferred. Elevation between adjacent terrace levels and stratigraphy are key determining

Figure 7. Well lithologic log location map.

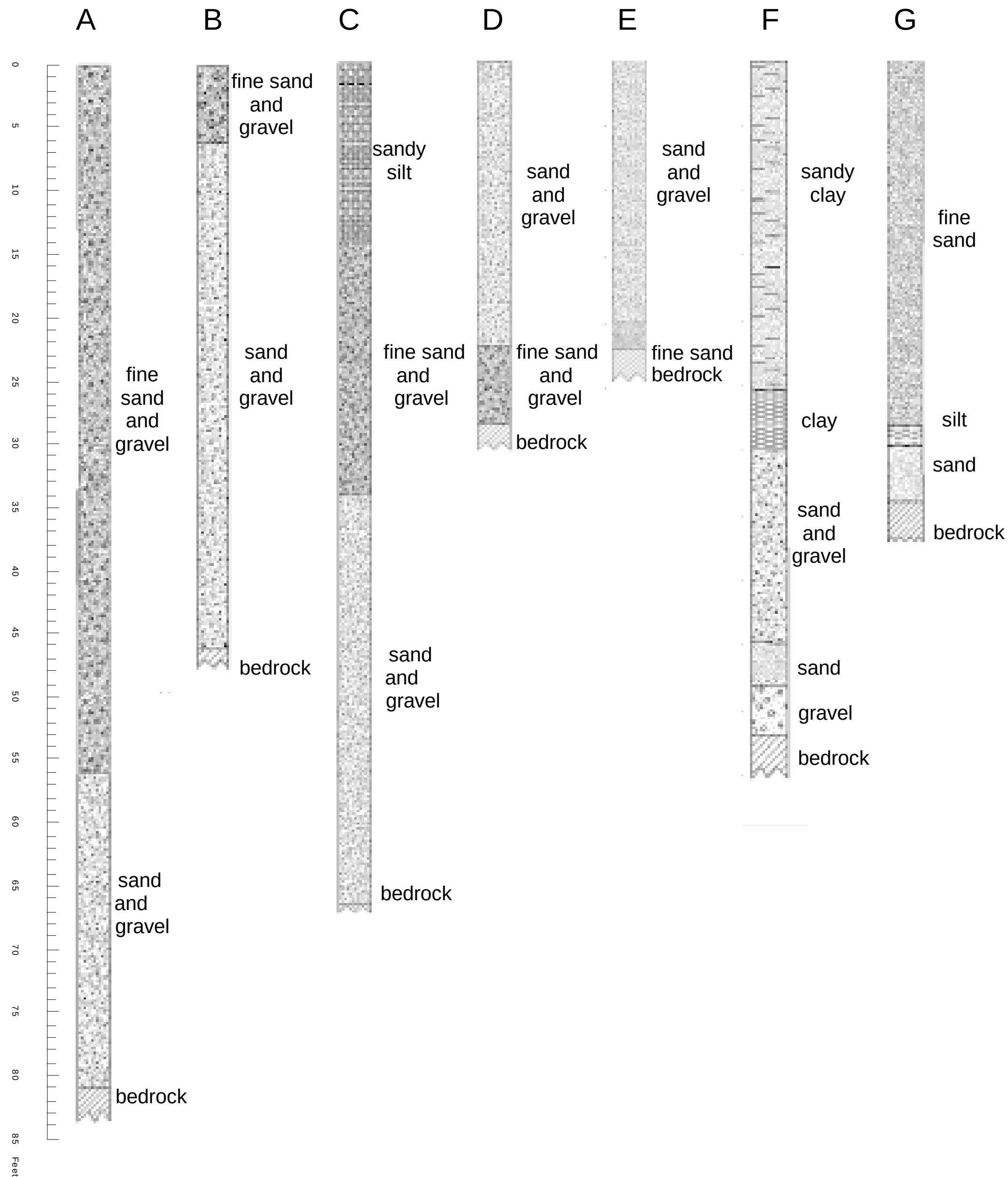


Figure 8. Lithostratigraphic well logs for (A) New Haven; (B) New Cumberland; (C) Waverly; (D) Wheeling; (E) Reedsville; (F) Parkersburg; and (G) Ravenswood, West Virginia.

Table 3. Typical conductivity values for sediment types found in the Ohio River valley.

Material	cm/s			m/d			ft/d		
clay	1.E-09	to	1.E-06	9.E-07	to	9.E-04	3.E-06	to	3.E-03
silt, sandy silts, clayey sands	1.E-06	to	1.E-04	9.E-04	to	9.E-02	3.E-03	to	3.E-01
silty sands, fine sands	1.E-05	to	1.E-03	9.E-03	to	9.E-01	3.E-02	to	3.E+00
well-sorted sands, glacial outwash	1.E-03	to	1.E-01	9.E-01	to	9.E+01	3.E+00	to	3.E+02
well-sorted gravel	1.E-02	to	1.E+00	9.E+00	to	9.E+02	3.E+01	to	3.E+03

factors. Along the Ohio River valley there are a number of different combinations of terrace ages and levels within individual alluvial sequences.

Data from terrace sequences along the Ohio River valley were compiled by Simard (1989). Near Follansbee, West Virginia, two terraces of differing ages, S3 and S5, are exposed (Figure 9a). S3 has been interpreted as having a late-Wisconsinan origin, while S5 is inferred to be slightly older, early Wisconsinan. At Follansbee, a partial hydraulic connection between the coarse sand and gravel deposits in terraces S5 and S3 is inferred to be present based on well lithologic logs from the area (Simard, 1989). Conversely, eight miles downstream at Beech Bottom, West Virginia, hydraulically-*dis*continuous terraces may be inferred. Two terrace surfaces (S2 and S7) are present on the West Virginia side of the river (Figure 9b). Here, examination of valley-side remnants reveals a bedrock exposure between the S2 and S7 surfaces. The Beech Bottom stratigraphy demonstrates the possibility of local terrace discontinuities. Thus, hydraulic continuity of gravels across the base of alluvial terraces frequently exists, but is not assured if the terraces in a specific sequence vary widely in elevation and age.

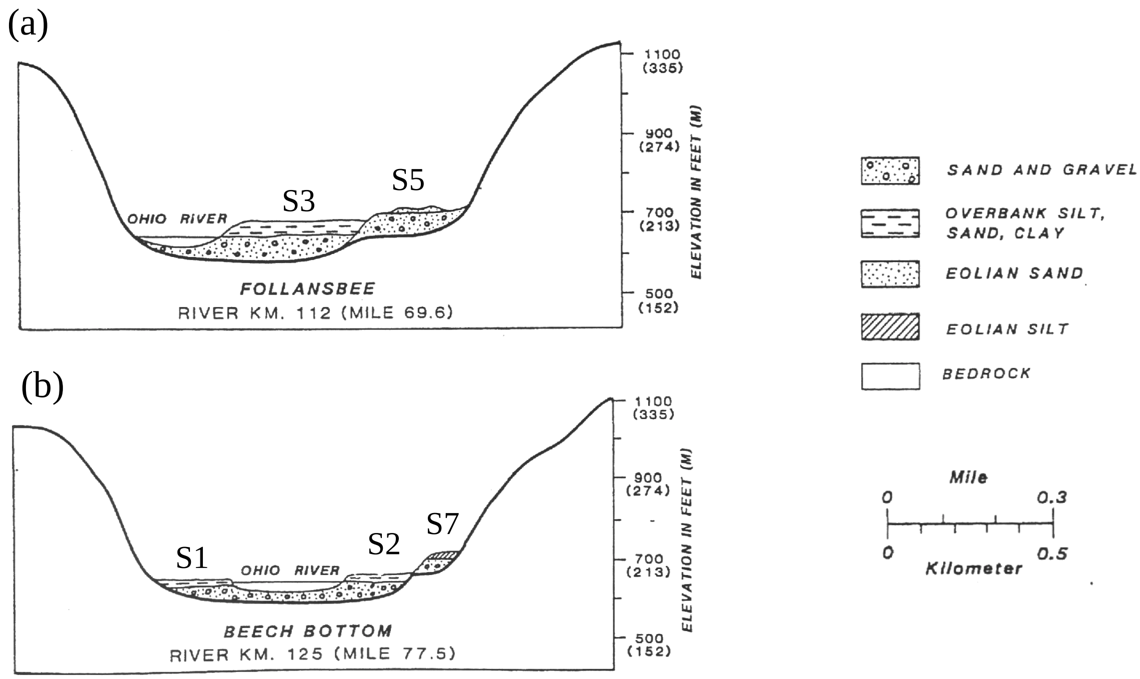


Figure 9. (a) Hydraulically connected Ohio River valley terraces, and (b) hydraulically disconnected Ohio River valley terraces (after Simard, 1989).

4. BACKGROUND: Analytical Models of Capture Zones

Analytical solutions are simplistic "first-cut" tools to solve capture zone problems. Three analytical methods were chosen based on their applicability to alluvial aquifers with tributary influence and varying pumping well locations. All assume horizontal flow only.

4.1 Analytical Solutions of Strack (1989)

Strack (1989) proposed two solutions describing induced infiltration. The first involves a pumping well in an unconfined aquifer near a single long straight river, with regional flow perpendicular to the river flow direction, a situation common in Ohio River valley alluvial aquifers (Appendix III). Using superposition, regional flow and pumping are integrated into a single solution for potential (Φ):

(4.1.1)
$$\Phi = Q_{xo}x + \frac{Q}{4\pi}\ln\frac{(x+d)^2 + y^2}{(x-d)^2 + y^2} + \Phi_0$$

where

Φ = discharge potential
Q_{x0} = x component of uniform flow
x = distance from the river (x coordinate)
y = distance along the river (y coordinate)
d = distance of well from riverbank
Q = discharge of the well
Φ_0 = discharge potential at the river (where x = 0)

Differentiation with respect to x yields

(4.1.2)
$$\frac{\partial\Phi}{\partial x} = -Q_{x0} + \frac{Q}{4\pi}\frac{4d}{d^2 + y^2}$$

Let $S_1 = (0,y_1)$ and $S_2 = (0,y_2)$ be the cartesian location of stagnation points along the river bounding the region of induced flow to the well:

(4.1.3) $$y_{1,2} = \pm\sqrt{\frac{Qd}{Q_{x0}\pi} - d^2}$$

Integration of infiltration between S_1 and S_2 will yield the volume of induced infiltration from the river:

(4.1.4) $$\int_{y1}^{y2} \frac{\partial\Phi}{\partial x}\partial y\bigg|_{x=0} = -Q_{x0}(y_2 - y_1) + \frac{Q}{\pi}\left(\tan^{-1}\frac{y_2}{d} - \tan^{-1}\frac{y_1}{d}\right) + C_1$$

So, let *W* be the fractional infiltration from the river, with respect to the total pumping discharge:

(4.1.5) $$W = \frac{1}{Q}\int_{y1}^{y2} \frac{\partial\Phi}{\partial x}\partial y$$

W will be compared to fractional infiltration volumes calculated from the numerical simulations, to assess the analytical solution's usefulness as a delineation tool.

The second analytical solution reported in Strack (1989) involves a similar setting but between two intersecting rivers, a situation similar to that commonly encountered in the Ohio Valley. Other similar analytical solutions (Ferris and others, 1965; Walton, 1988; Reilly and others, 1987) employ either the other types of boundaries (barrier vs. recharge) or a fixed (45^{o} or 90^{o}) angle of intersection between streams .

The Strack solution allows for a variable angle of intersection between streams. However, Strack's solution disregards spatially-distributed recharge, and was therefore not employed as a comparison with the numerical simulation results.

4.2 Analytical Solutions of Wilson and Newsom (1988)

Wilson (1993) presented analytical solutions for induced infiltration in aquifers with regional flow. He examined three situations: a well in a semi-infinite aquifer bounded on one side by a fully-penetrating stream, a well between a stream and a parallel barrier, and a well between two parallel streams. His solution for the first case is similar to Equation 4.1.1 except for the definition of the coordinate system (Wilson places his stream along the x-axis).

An extension of these analytical solutions incorporated variation in groundwater flow direction (Newsom and Wilson, 1988). This solution was in terms of a stream function (Ψ), with complex conjugate potential function:

(4.2.1) $$\Omega = \Phi + i\Psi$$

where

Ω = complex potential
Φ = discharge potential
Ψ = stream function.

Separating the imaginary and real parts gives:

(4.2.2) $$\Psi = -Q_{x0}(-x\sin\alpha + y\cos\alpha) + \frac{Q}{2\pi}\left(\tan^{-1}\frac{y}{x+d} - \tan^{-1}\frac{y}{x-d} - c\right)$$

(4.2.3) $$\Phi = -Q_{x0}(x\cos\alpha + y\sin\alpha) + \frac{Q}{4\pi}\ln\left(\frac{(x+d)^2 + y^2}{(x-d)^2 + y^2}\right)$$

where

Q_{x0} = x component of uniform flow
x = x coordinate
y = y coordinate
α = angle of ambient groundwater flow
Q = discharge of the well
d = distance of well from riverbank
$c = 0$ for $0 \le x \le d$, and $c = \pi$ for $x \ge d$

Flowline locations vary according to well pumping rate, regional flow rate and direction, and distance from the stream to the well. The flowline that passes through the stagnation points on the river can be estimated by determining their x and y coordinates:

(4.2.4)
$$x = \left(\frac{d^2}{2} \left[\pm (1 - \beta \cos\alpha) + (1 + \beta^2 - 2\beta\cos\alpha)^{1/2} \right] \right)^{1/2}$$

(4.2.5)
$$y = \pm \left(\frac{d^2}{2} \left[\pm (\beta \cos\alpha - 1) + (1 + \beta^2 - 2\beta\cos\alpha)^{1/2} \right] \right)^{1/2}$$

where

x = x coordinate
y = y coordinate
d = distance of well from riverbank
α = angle of ambient groundwater flow
Q_{x0} = x component of uniform flow

and

β = dimensionless pumping rate

(4.2.6)
$$\beta = \frac{Q}{Q_{x0} \pi d}$$

The calculated x and y locations are used in the derived stream function (Eq. 4.2.3) to determine its value at each stagnation point along the stream. The induced infiltration flux to the pumping well can then be calculated using both stream function values:

(4.2.7)
$$Q_s = \left| \Psi_A - \Psi_{STAG} \right|$$

where

Q_s = induced infiltration rate
Ψ_A = flowline bounding the stream capture zone on the upstream side of the well
Ψ_{STAG} = flowline bounding the stream capture zone on the downstream side of the well.

Again, this solution does not account for the presence of a second stream, but it does account for angular regional flow.

5. Numerical Models of Capture Zones

5.1 Regional Simulation

A small-scale regional model, the Kanawha model, was formulated to simulate regional flow adjacent to the Ohio River valley alluvium. The purpose of the Kanawha model was:

1. to infer reasonable recharge and evapotranspiration rates for use in the local models;

2. to infer reasonable hydraulic conductivities for use as initial estimates in the local models; and

3. to estimate the areal extent of bedrock baseflow contribution to the alluvium.

The exposed bedrock units in this area are primarily the Dunkard and Monongahela groups, with small exposures of the Conemaugh group in the southwest portion of the study area. All are dominated by shale, sandstone, coal, and limestone lithologies. Water flows slowly through the bedrock units. Water that occurs near the ground surface in these areas tends to be perched atop clay layers that underlie coal beds. The shale beds have poorly developed fractures and joints, reducing their ability to transmit water. Although the coals and limestones exhibit some permeability, the Dunkard, Monongahela, and Conemaugh groups are considered the poorest quality aquifers within the Ohio River valley region (Friel and others, 1987).

5.1.1 Methodology

A 174 x 168 block-centered finite-difference grid was constructed with a uniform grid spacing of 1,640 feet. The grid was oriented northeast-southwest parallel to the Ohio River (Figure 10). A single-layer flow model representing the bedrock

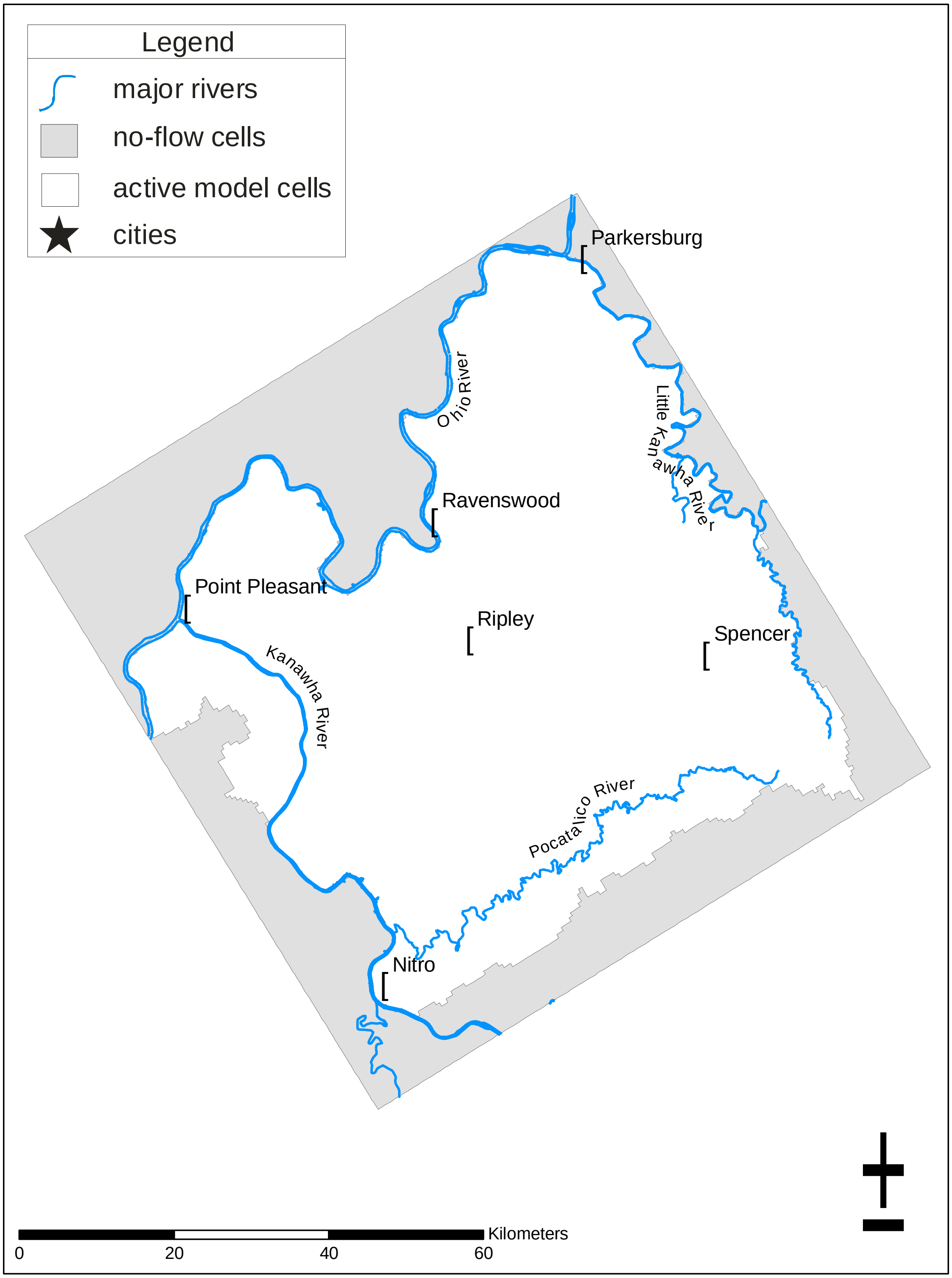


Figure 10. Regional numerical flow model grid orientation.

lithology of the area was simulated. The bedrock units were modeled as a single unconfined (MODFLOW LAYCON “1”) aquifer.

Land surface was represented using USGS 1:24,000 30-meter digital elevation models (DEMs). The lower boundary of the model was represented using two methods. An elevation of 163 meters was arbitrarily assigned for areas outside of the Ohio River alluvium. For areas overlain with alluvial deposits, the interpolated bedrock surface was utilized (see Section 2.1).

Drain cells act to remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and the fixed drain stage elevation, but have no effect if head falls below that level (McDonald and Harbaugh, 1989). The Ohio River was simulated as reach of drain cells along the western boundary of the model, with drain cell elevations obtained from ACOE pool elevation data. Within the Kanawha regional model are two sets of locks along the Ohio River, at Racine and Belleville, West Virginia. Upper and lower pool elevations for the modeled stretch of river can be found in Table 4. Ohio River tributaries were assigned drain cell elevations based on DEM grid values along each associated reach. All modeled streams were verified as perennial using USGS 1:24,000 topographic maps. The northern and southern bounds utilize two major tributaries of the Ohio River, the Little Kanawha River and the Kanawha River, respectively. The eastern boundary coincides with the regional groundwater divide as identified from DEMs. The divide was simulated using a stretch of no-flow cells along the inferred boundary.

Recharge was added at 23.9cm/yr (9.4 in/yr) as the initial rate. Two zones of hydraulic conductivity were employed in the Kanawha model, for alluvium and bedrock, respectively. Zone locations based on exposed geology were estimated using the 1:250,000 state geologic map (WVGES, 1968). Initial hydraulic conductivity estimates were based on transmissivities of Kozar and Mathes (2001) and on regional estimates of saturated thickness averaged from lithologic logs of wells drilled within each modeled unit. The initial K’s used were 100 and 3.5 m/d for alluvium and bedrock , respectively. Initial parameter estimates for the regional

Table 4. Upper and lower pool elevations regulated by the ACOE for the modeled stretch of the Ohio River.

Lock and Dam Name	Nearest Community	Upper Pool Elevation (ft)	Lower Pool Elevation (ft)
Willow Island	Newport, Ohio	602	582
Belleville	Reedsville, Ohio	582	560
Racine	Letart, WV	560	538
Robert C. Byrd	Gallipolis Ferry, WV	538	515

simulation are displayed in Table 5. Variation in initial K was subsequently added to allow model calibration.

5.1.2 Results

Using the above parameter estimates, steady-state simulations were performed for the Kanawha model. Calibration of parameter estimates was achieved by comparing simulated stream fluxes to recorded baseflow fluxes from USGS stream station measurements. One stream station with sufficient flow data, Palestine, West Virginia, is located along the Little Kanawha River within the model domain (Figure 5). Three years of streamflow data were separated to arrive at a reasonable estimate of the average baseflow sustaining the stream. The average baseflow for the Little Kanawha River at Palestine, West Virginia was inferred to be 1.84 x 10^7 m^3/d based upon the stream hydrograph shown in Figure 11. The catchment area reported for this stream station by the USGS is 3,926 km^2; however, the area included within the Kanawha model is only 844 km^2. A ratio of modeled catchment area to USGS catchment area was determined and used to reduce the USGS average baseflow to account for the discrepancies in catchment extent. This discharge was then compared to the modeled fluxes out of the system at the location of the Palestine station.

Based on area-corrected USGS data, the flux out of the Little Kanawha River catchment at the Palestine, West Virginia, stream station should equal 4.00 x 10^5 m^3/d. Modeled flux using the above parameter values (simulation R1, Table 5) totaled 4.73 x 10^5 m^3/d, +18.3% more the expected flux. Additionally, an abundance of flooded model cells occurred due to the presence of a shallow water table in low-lying areas. To correct the lowland flooding, evapotranspiration was added at a rate of 1.5 cm/yr (0.6 in/yr), making the net recharge contributing to groundwater 22.4 cm/yr (8.8 in/yr) in the affected areas. This value is the reported average for the Ohio River tributaries in Kozar and Mathes (2001).

Table 5. Regional-scale numerical model parameters and calibration data.

Simulation	Fluxes Out (m^3/d)			Expected Flux Out (m^3/d)	Variation	ET (m^3/d)	R (m^3/d)	$K_{alluvium}$ (m/d)	$K_{bedrock}$ (m/d)
	Drains	ET	Total						
R1	-445,584	-27,378	-472,962	-399,925	18.3%	4.18E-05	6.54E-04	100	3.5
R2	-412,958	-25,432	-438,390		9.6%	4.18E-05	6.54E-04	100	5

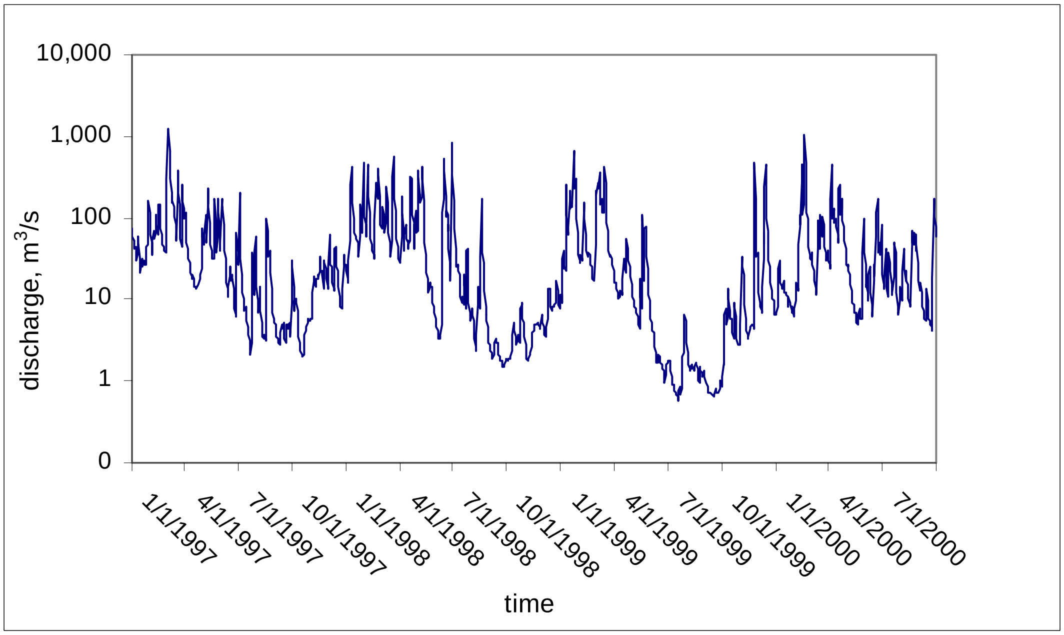


Figure 11. Hydrograph from the Palestine, WV stream gaging station on the Little Kanawha River.

In simulation R2, bedrock hydraulic conductivities were adjusted from 3.5 m/d to 5.0 m/d in an attempt to reduce variation between expected and modeled flux out. Although the potentiometric surface was very similar for both simulations (Figure 12), variation between area-corrected USGS and modeled flux out was +9.7% for R2. Flooding in areas of shallow water table was eliminated. Mass balance error was very low (.0003%), indicating steady-state was achieved. Therefore, run R2 was used as the calibrated Kanawha regional model.

It is reiterated that the primary purpose of the regional model was to develop initial estimates of hydraulic parameters (K, R) for use in local-scale models, as well as to estimate the extent of bedrock contribution to alluvium. A low degree of calibration was considered sufficient for this purpose.

5.1.3 Discussion

Particle tracking using the steady-state head solution from the calibrated regional simulation was used to infer the up-gradient extent of bedrock contribution to alluvium. Single particles were positioned in each drain cell along the reach of the Ohio River. Using MODPATH, the particles were traced backward up the hydraulic gradient for a period of five years. The up-gradient extent of the pathline traces indicates the interfluve divide between the Ohio valley and tributary streams to the east (Figure 13). This divide location will be utilized in local-scale models as a no-flow boundary.

5.2 Local Simulations

5.2.1 Numerical Simulations

Source water assessments and wellhead protection area delineations were performed for 26 public water supply systems along the Ohio River in West Virginia (Figure 14). The Ohio River has numerous minor tributaries of short length and minimal gradient and a few major tributaries with virtually no gradient due to water level regulation with locks and dams. Groundwater sources for

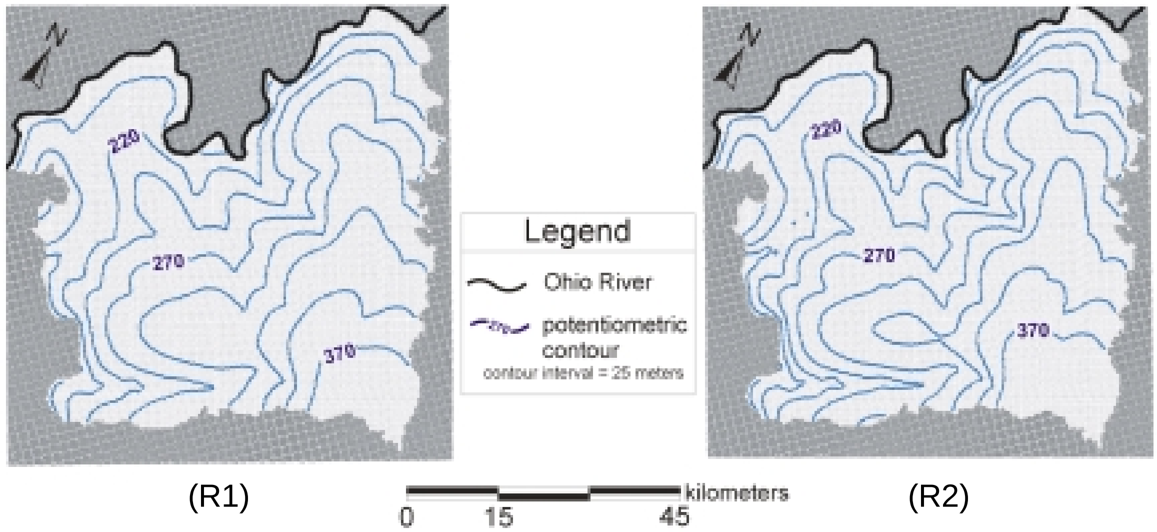


Figure 12. Potentiometric surface map for regional-scale simulation R1 (left), and simulation R2 (right).

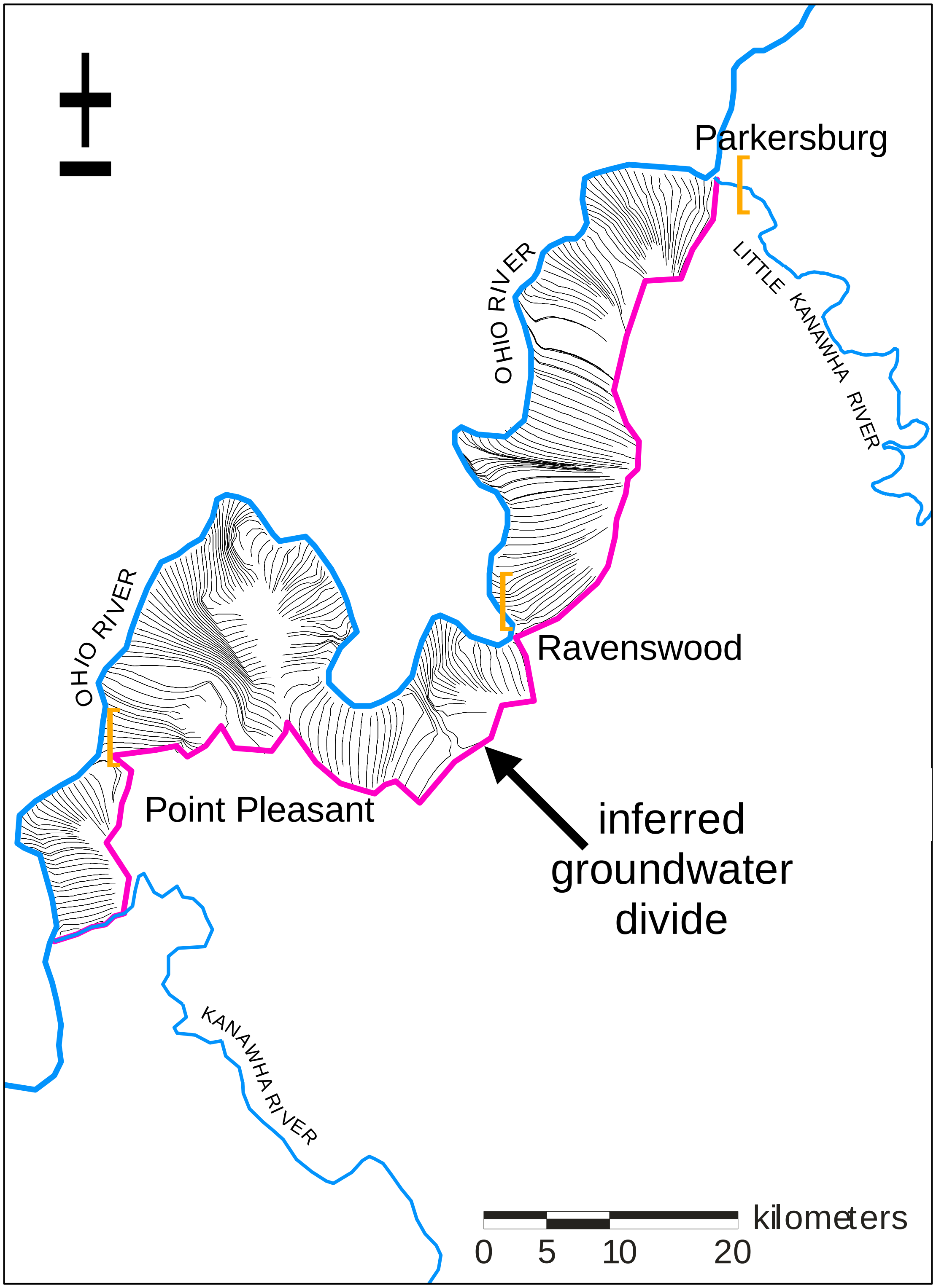


Figure 13. Up-gradient inferred groundwater divide indicating bedrock flow contribution to alluvium.

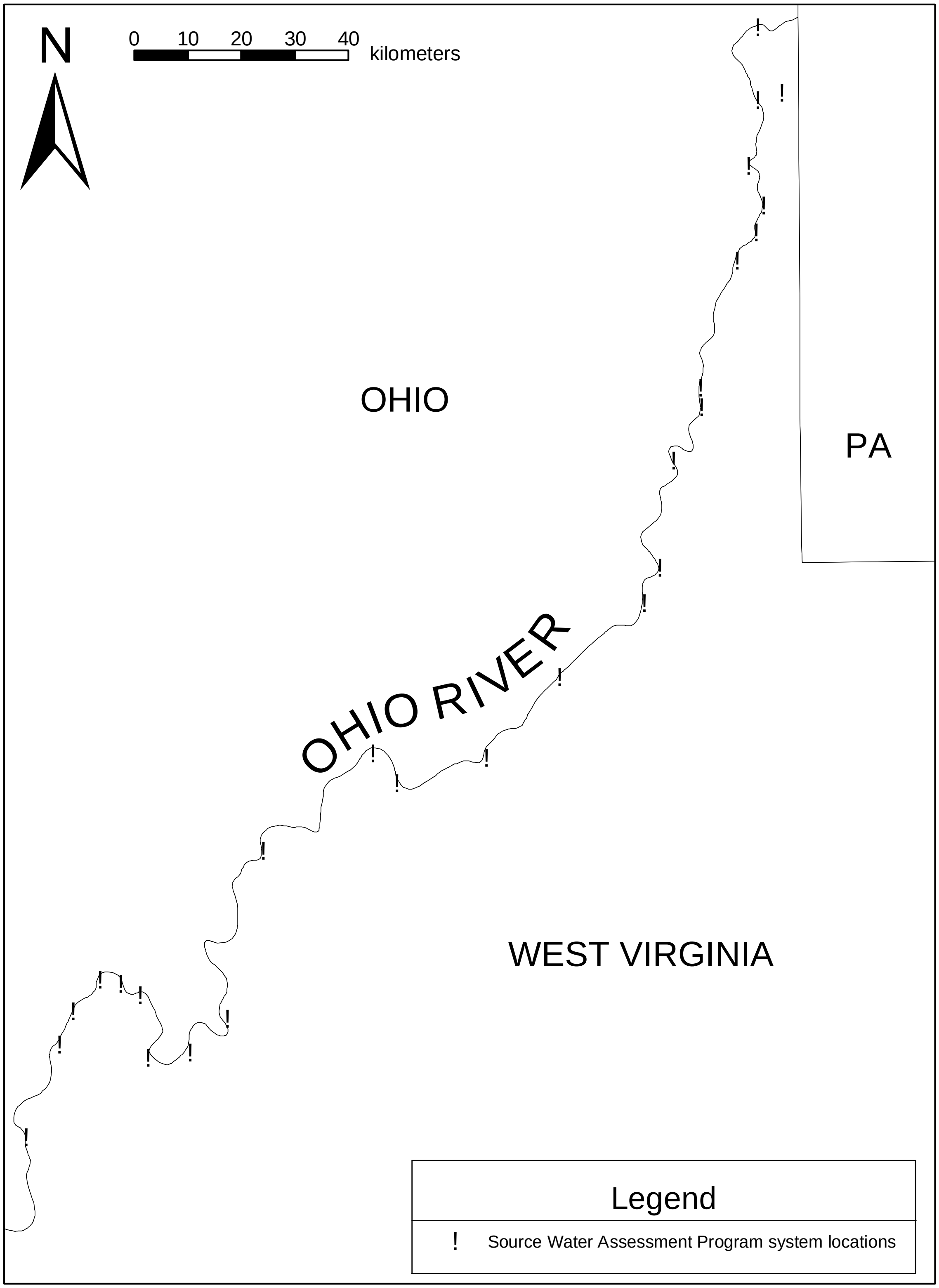


Figure 14. The 26 SWAP systems along the Ohio River in West Virginia, modeled in a previous series of investigations (see Appendix III).

production wells in the Ohio Valley include: 1) induced infiltration from the Ohio River; 2) induced infiltration from associated tributaries; 3) local vertical infiltration of recharge on the terrace surface; and 4) groundwater in bedrock aquifers to the east, which are thought to discharge into the subsurface of the alluvial aquifer. The relative magnitude of contributions from each source varies considerably from system to system, however, close proximity to the river suggests that induced infiltration is likely a very important, perhaps dominant source.

The alluvial aquifers of the Ohio River Valley in West Virginia including those examined in Figure 14 consistently exhibit the following characteristics: the regional bedrock aquifer discharging to the alluvium is composed of bedrock of Upper-Pennsylvanian/Permian age; bedrock transmissivities are considerably less than that of the alluvial deposits, usually by an order of magnitude or more; the proximity of the constant head boundary formed by the Ohio River constrains groundwater discharge elevation and flow in the river alluvium; a spatially-uniform recharge rate to the alluvial aquifer is approximately twice that of bedrock aquifers whose flow discharges into alluvium; and induced infiltration from the Ohio River usually occurs for a well located in close proximity to the river bank. Additionally, there is potential for infiltration to be induced from nearby tributaries by well pumping nearby.

Point Pleasant, West Virginia, located at the confluence of the Ohio and the Kanawha rivers (Figure 15a), is one of many communities in this valley that depends upon an alluvial aquifer for its water supply and exhibits the qualities described above. Pumping from high capacity wells in this alluvium creates a pattern of local gradients that induce water from three of the four groundwater sources to varying degrees. The wellfield is approximately 7,500 meters from the intersecting tributary and apparently does not draw any water from this source.

The Point Pleasant system derives its water from seven wells, drilled as close as possible to the river and designed to encourage induced infiltration. The alluvial deposits near the Point Pleasant well field are composed dominantly of gravelly

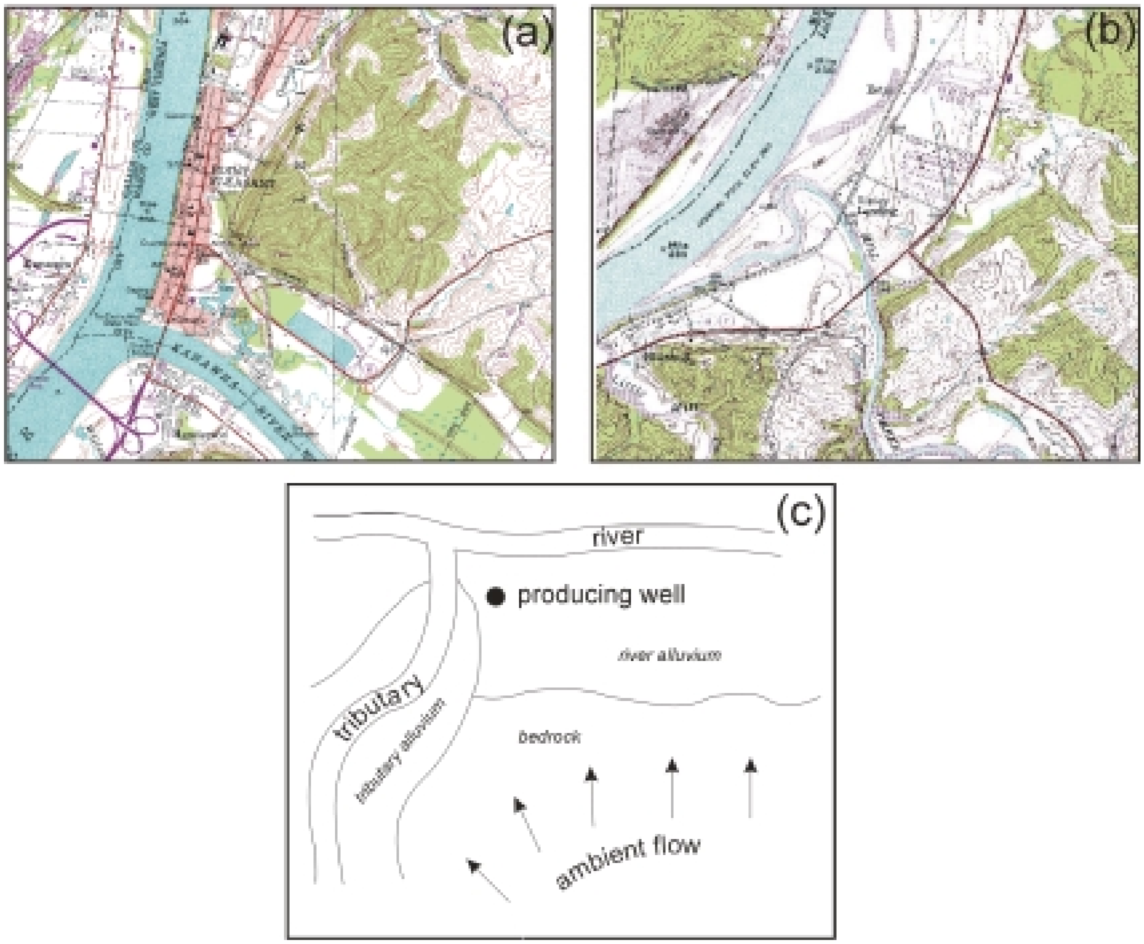


Figure 15. (A) and (b): topographic map of Point Pleasant and Cottageville, West Virginia, which obtain water from an alluvial aquifer bounded by two streams in the presence of regional. (C) schematic of a production well in an alluvial aquifer bounded by two streams in the presence of regional flow.

sand and coarse sand, as shown in Figure 16. Each producing well located in these deposits pumps approximately 600 m^3/d and is located from 335 to 549 meters distant from the river. Operation of the pumping wells is rotated so that only three of the seven are pumping at one time, as is common practice for public supply well fields in the Ohio Valley.

The community of Cottageville, West Virginia also depends upon the alluvial aquifer of the Ohio River valley for its water supply. The Cottageville public supply system consists of two wells located near the confluence of the Ohio River and Mill Creek (Figure 15b). The location of this wellfield is designed to encourage induced infiltration from both surface sources. Each producing well located in the Ohio River alluvial deposits pumps approximately 1,675 m^3/d and is located 762 meters from the river.

5.2.1.1 Conceptual Model

An alluvial flow system bounded by two intersecting surface sources is conceptualized based upon the general characteristics of the Point Pleasant and Cottageville areas and the hydraulic parameters common to many alluvial aquifers adjacent to the Ohio River.

The alluvial aquifer is conceptualized as unconfined, with some semi-confined zones, in which the simulated production wells fully penetrate alluvial deposits. These deposits are dominantly composed of coarse-grained river alluvium with an abundance of slightly finer-grained tributary alluvium near the stream confluence. The up-gradient bedrock aquifer is also included in the conceptualization as it supplies lateral recharge to the alluvial aquifer. Under pumping stress, both surface-water sources may provide additional water to the alluvial flow system depending on production well location and discharge rate.

The alluvial deposits extend along the length of the river and are bounded on their up-gradient side by bedrock valley walls. This creates an aquifer that is much longer than it is wide, as shown in Figure 17. The Ohio River's elevation in the Point Pleasant area is 163.98 meters above sea level. This elevation, regulated by a

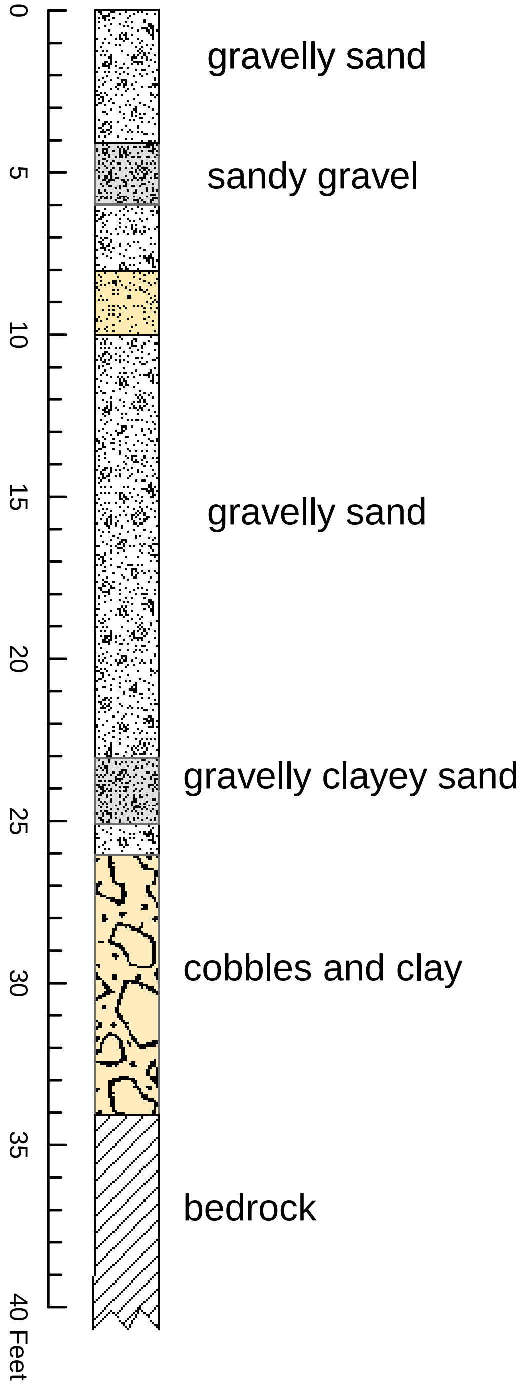


Figure 16. Well lithologic log from Point Pleasant, West Virginia, showing dominant sediment types found within the alluvial aquifer.

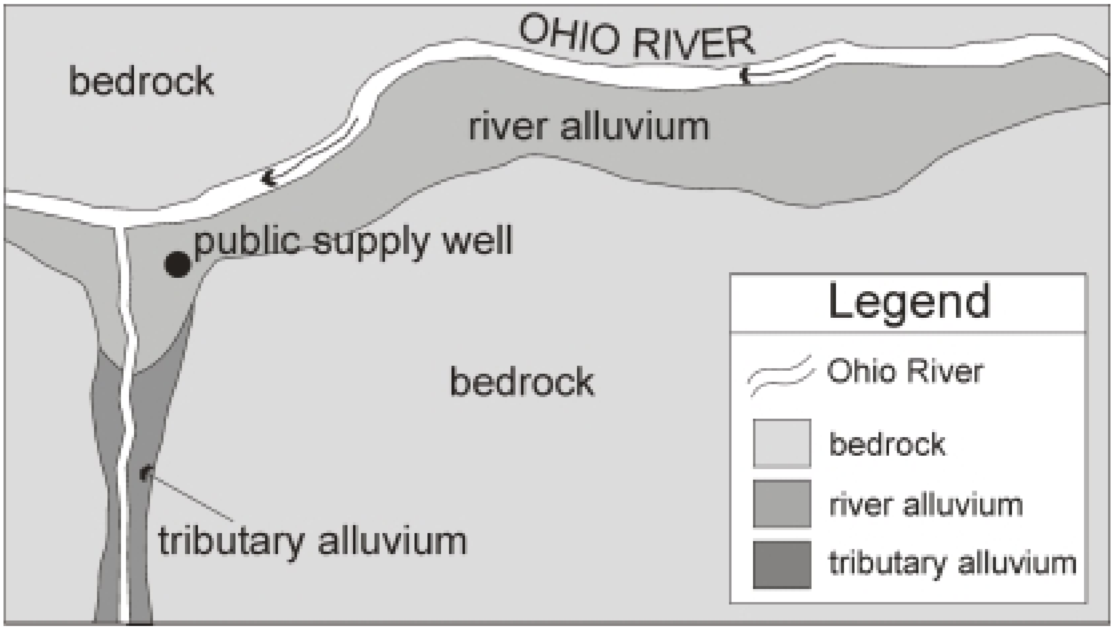


Figure 17. River alluvium deposits forming a thin, strip-like aquifer geometry common to alluvial aquifers of the Ohio River valley.

series of locks and dams, is held constant maintaining a flat-water surface along the river and virtually zero gradient along its length.

In locations of tributary confluence, two situations are common. If the intersecting tributary is large, the water level may be regulated using dams similar to the river. This is situation found at the confluence of the Ohio and Kanawha rivers at Point Pleasant. If the tributary is small, there generally will be no regulation of its water level and it will have its natural gradient along its length. Mill Creek near its confluence with the Ohio River at the Cottageville public water supply wellfield exhibits these conditions. Situations representing both confluence types are modeled here. Although the angle of intersection between both stream reaches

Most municipal wellfields along the Ohio River in West Virginia take advantage of induced infiltration to some degree. Production wells are located 30 to 366 meters from the riverbank. Their discharge amounts vary depending on the population served from 409 to 8,186 m^3/d. The average pumping rate for 26 evaluated public supply systems in West Virginia (Figure 14) is 1,717 m^3/d per pumping well. Both analytical and numerical simulations will utilize this “typical” pumping rate.

Alluvial deposits along the Ohio River in West Virginia are extremely heterogeneous. The sediment types found along the river length, in order of decreasing abundance, include coarse-grained river alluvium, tributary alluvium, colluvium, fine-grained river alluvium, and eolian sand and silt (Simard, 1989). The thickness of these deposits ranges from near zero at the eastern margin of the valley (where the break of slope occurs) to a maximum of about 30 meters in the central portion of the valley. Figure 18 shows a generalized cross section of the Ohio River valley from which the alluvial aquifer geometry is based.

5.2.1.2 Methodology

A single layer model was constructed with 715 columns and 946 rows (676,930 active cells) using MODFLOW (McDonald and Harbaugh, 1984). A uniform 30 x 30 meter grid was used everywhere except around pumping wells, where the grid was telescoped down to as close as 2 meters.

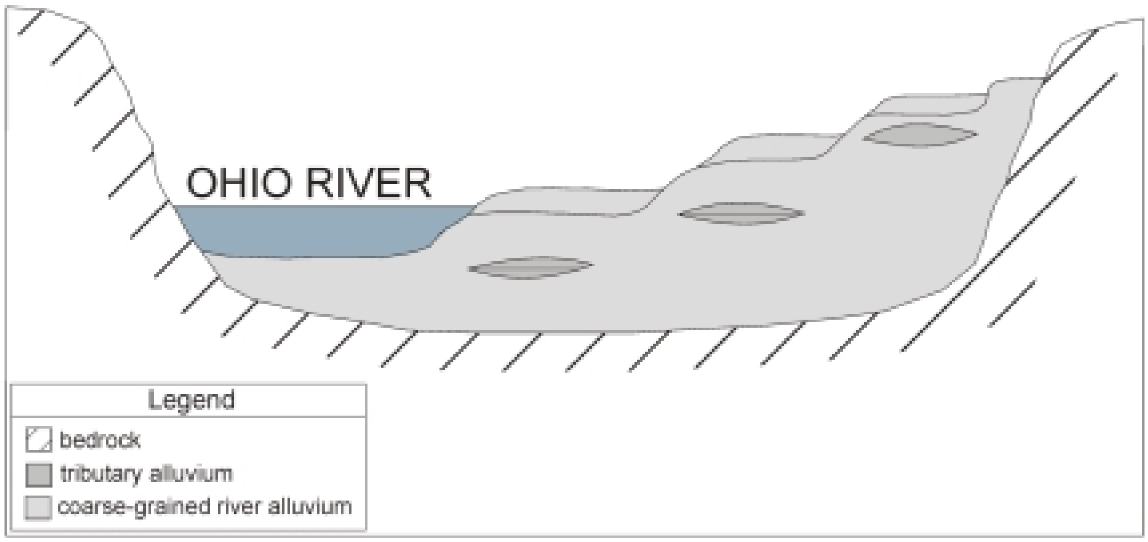


Figure 18. Generalized cross-section (20 times vertical exaggeration) of the Ohio River valley alluvial aquifer (after Simard, 1989).

Land surface interpolated from 30-meter DEMs was employed as the top of the alluvial aquifer. The bottom of the aquifer was set to the interpolated bedrock surface mentioned in Section 2.1. Aquifer-bottom elevation of 163 meters was arbitrarily assigned for areas outside of the Ohio River alluvium.

Hydrostratigraphic zones were constructed for river alluvium, tributary alluvium, and bedrock (Figure 19). Uniform values of hydraulic conductivity and recharge derived from regional simulations were assigned to each zone.

Two different boundary condition combinations were used for this study. Constant head (CH) cells in both simulation sets represented the Ohio River, one of the model's key boundaries. The river's water elevation of 163.98 meters was used as a CH boundary along its entire reach.

Variations in the two boundary condition combinations are found in the representation of the intersecting tributary. Two situations were simulated: one mimicking the a large, regulated, zero-gradient tributary intersecting the river (Type A); and another mimicking a smaller stream with a marked gradient intersecting the river (Type B). The intersection angle of the tributary with the river was oriented at 120^{o} for both simulations. This value was derived from the behavior of Mill Creek near it's confluence with the Ohio River at Cottageville, West Virginia (Figure 15).

The simulations representing the zero-gradient tributary (Type A) utilized RIV cells whose water elevation was set to a CH elevation of 163.98 meters along its length. The thickness of the riverbed sediments was set at 1 meter with a conductivity of 100 m/d. The streambed sediment conductivity was set slightly lower than the 250 m/d conductivity assigned to the alluvial deposits beneath the tributary to simulate lower permeability streambed sediments (Anderson and Woessner, 1992).

The second set of simulations representing the intersecting tributary as a smaller stream with a slight gradient (Type B) also utilized RIV cells. The reach was input as one length with a starting elevation of 173.66 meters, to its confluence with the river at an elevation of 163.98 meters. This change in elevation implemented a

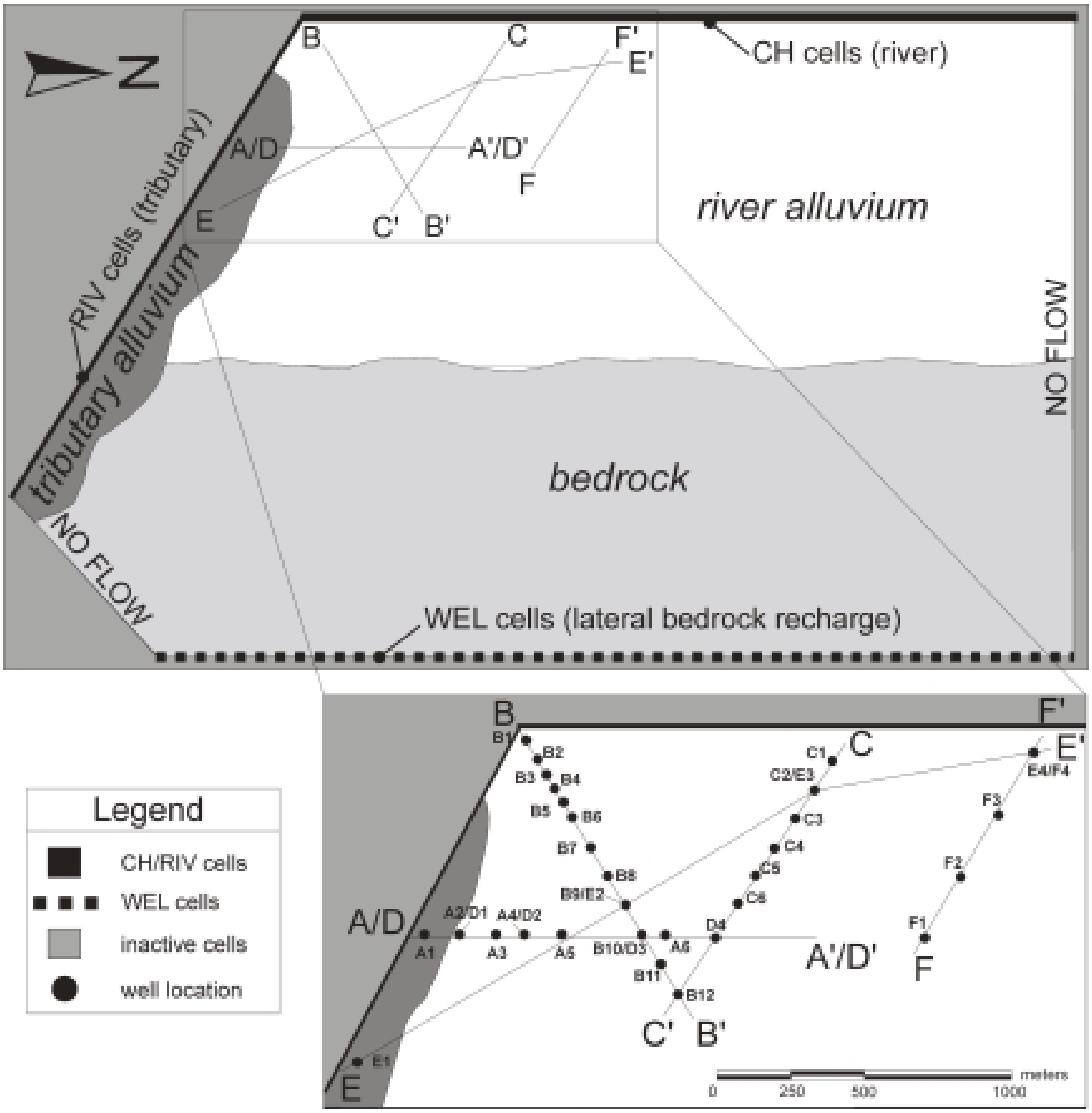


Figure 19. Model discretization showing boundary conditions, conductivity zones, and production well locations for the alluvial aquifer bounded by two streams. Profiles A-A', B-B', and C-C' refer to the Type A alluvial setting. Profiles D-D', E-E', and F-F' refer to the Type B alluvial setting.

gradient of 2.9 m/km (15.3 ft/mi) along the tributary reach, an average value for smaller streams discharging into the Ohio River in West Virginia.

Lateral flow derived from up-gradient bedrock recharge was quantified using results of the regional flow simulations (Section 5.1.2). In the generalized local model, the lateral bedrock recharge was simulated using 678 specified-flux (WEL) cells. This amounted to a total regional flux across the 5-kilometer boundary of 935.33 m^3/d.

The MODFLOW solver package employed in the generic simulations was the preconditioned conjugate gradient (PCG2) algorithm. A convergence criterion of 10^{-4} was used to attain steady-state mass balance errors of less than 1% in all simulations.

Areal recharge was estimated at 17.8 cm/yr for alluvial areas and 7.6 cm/yr in bedrock areas based on stream baseflow separation at 11 stations located within the Ohio River drainage basin for a 20-year period (Kozar and Mathes, 2001), calibrated regional-scale model results, and analyses based on flooded cells in the local-scale simulations. This flux was distributed spatially over the entire domain based upon the surficial geology type and a simplistic sensitivity analysis to flooded cells. Evapotranspiration was held constant in areas of a shallow water table at a rate of 0.15 cm/yr.

Hydraulic conductivity values were derived from the regional simulation results. River alluvium was estimated at 1,000 m/d, and the slightly finer-grained tributary alluvium at 200 m/d. Bedrock was assigned a conductivity of 3.5 m/d. Table 6 lists the values of geologic and hydraulic parameters assigned to each unit.

5.2.1.3 Experiment Design

Six profiles were drawn for the location of single pumping wells, established to perform sensitivity analyses of the alluvial aquifer’s response to pumping stress. These transects are displayed in Figure 19. For each well, a pumping rate of 1,717 m^3/d was assigned, the average from 26 existing community supply wells described

Table 6. Geologic and hydraulic input parameters for the generalized numerical simulations of the alluvial aquifer bounded by two intersecting streams in the presence of ambient flow.

Hydrostratigraphic units	Hydraulic conductivity	Recharge		Evapotranspiration	
	(m/d)	(in/yr)	(m/d)	(in/yr)	(m/d)
River alluvium	1000	7	4.87E-04	0.6	4.18E-05
Tributary alluvium	250	7	4.87E-04	0.6	4.18E-05
Tributary streambed sediments	100	7	4.87E-04	0.6	4.18E-05
Bedrock	3.5	3	2.09E-04	0.6	4.18E-05

in section 5.2.1. Pumping well location was set at varying distances from the tributary and river, and each location was used for a different steady-state simulation of flow. Each pumping well's distance from the river and tributary are listed in Table 7.

The generalized Type A and Type B alluvial settings described in section 5.2.1.2 were modeled using these six well transects. The Type A setting utilizes the profiles A-A', B-B', and C-C', while the Type B setting utilizes profiles D-D', E-E', and F-F'. Well locations in transects for Type A (transects A-A', B-B', and C-C') were located closer to one another than for Type B. For Type B simulations, the well location transects (D-D', E-E', and F-F') extend farther out into alluvium from both streams.

For each run, with a different well location, reverse particle tracking using MODPATH was used to estimate the capture zone and delineate the source supplying each production well location. A ring of initial particle locations was located around each production well and particles were moved by backward tracking from the pumping well. Similar to EPA requirements for source water assessment and protection delineations, a five-year time of travel was employed as the up-gradient limit of particle travel. Both the particle traces and capture zone areas surrounding them were used to calculate source proportions, using either 300- or 30-particle rings. In analyses utilizing the 300-particle traces, each flow tube represents 5.72 m^3/d. The 30-particle flow tubes represent 57.24 m^3/d. For presentation purposes, rings of only 15-30 particles were utilized.

Five-year capture zone areas were used to calculate fluxes of recharge contributing to the pumping well. Alluvial recharge fluxes were calculated using the areal extent of the particle traces originating from each producing well. The area bounded by the outermost particle traces and the bedrock-alluvium contact was determined and multiplied by the recharge rate to alluvium (17.8 cm/yr).

Table 7. Well locations and their associated distances from the river and tributary stream reaches.

Well ID	Distance from river (meters)	Distance from tributary (meters)
A1	700	100
A2	700	200
A3	700	300
A4	700	400
A5	700	500
A6	700	800
B1	50	50
B2	100	100
B3	150	150
B4	200	200
B5	250	250
B6	300	300
B7	400	400
B8	500	500
B9	600	600
B10	700	700
C1	100	1000
C2	200	1000
C3	300	1000
C4	400	1000
C5	500	1000
C6	600	1000
D1	700	200
D2	700	400
D3	700	700
D4	700	1000
E1	1100	100
E2	600	600
E3	30	1000
E4/F4	100	1500
F3	300	1500
F2	500	1500
F1	700	1500

Stream infiltration fluxes were calculated based on the proportion of flow tubes intersecting streams. The flux of bedrock recharge was inferred by mass balance on the pumping rate.

5.2.1.4 Results

Type A and Type B systems differed in behavior, in response to presence or absence of a gradient along the tributary. Figure 20 shows the modeled steady-state head distributions for each simulation type. Bedrock gradients and flow directions remained comparable between both simulations. The major difference was seen in the flow behavior within the region of tributary and river alluvium. The dominant direction of flow within alluvium was reversed for wells close to the tributary when a gradient along the tributary was employed. Dramatic variations in flow direction and hydraulic gradient near the confluence also resulted due to the presence of this tributary gradient.

The impact of a tributary gradient was also seen in the geometry of the particle traces in each simulation. Figures 21 and 22 show particle traces at four production well locations for both Type A and B alluvial settings. Capture zones in the Type A simulations were broad and withdrew most source water from the river and relatively little from the tributary; for these wells, recharge was an important source (Figure 21). In the Type B simulations, the capture zones were narrow and followed the hydraulic gradient straight to the losing tributary (Figure 22). Nearly all water supplying these production wells was derived from tributary infiltration. In locations within 100 meters of the river (Well (d), Figure 22), river infiltration provided a minor flux to the production well. Recharge also provided source water to the producing well, but at an insignificant rate when compared to that derived from tributary infiltration. Tables 8 and 9 present the source water budget for each simulated well location in the Type A and Type B alluvial settings.

Well location had a large impact on source budget in both Type A and Type B settings. In Type A simulations (Figure 23), wells located within 150 meters of the river received much or most of their discharge directly from induced river infiltration. However, wells located within 150 meters of the tributary did not induce tributary infiltration and drew most of their flow from recharge. Additional well locations used to determine dominant source components are presented in Appendix II.

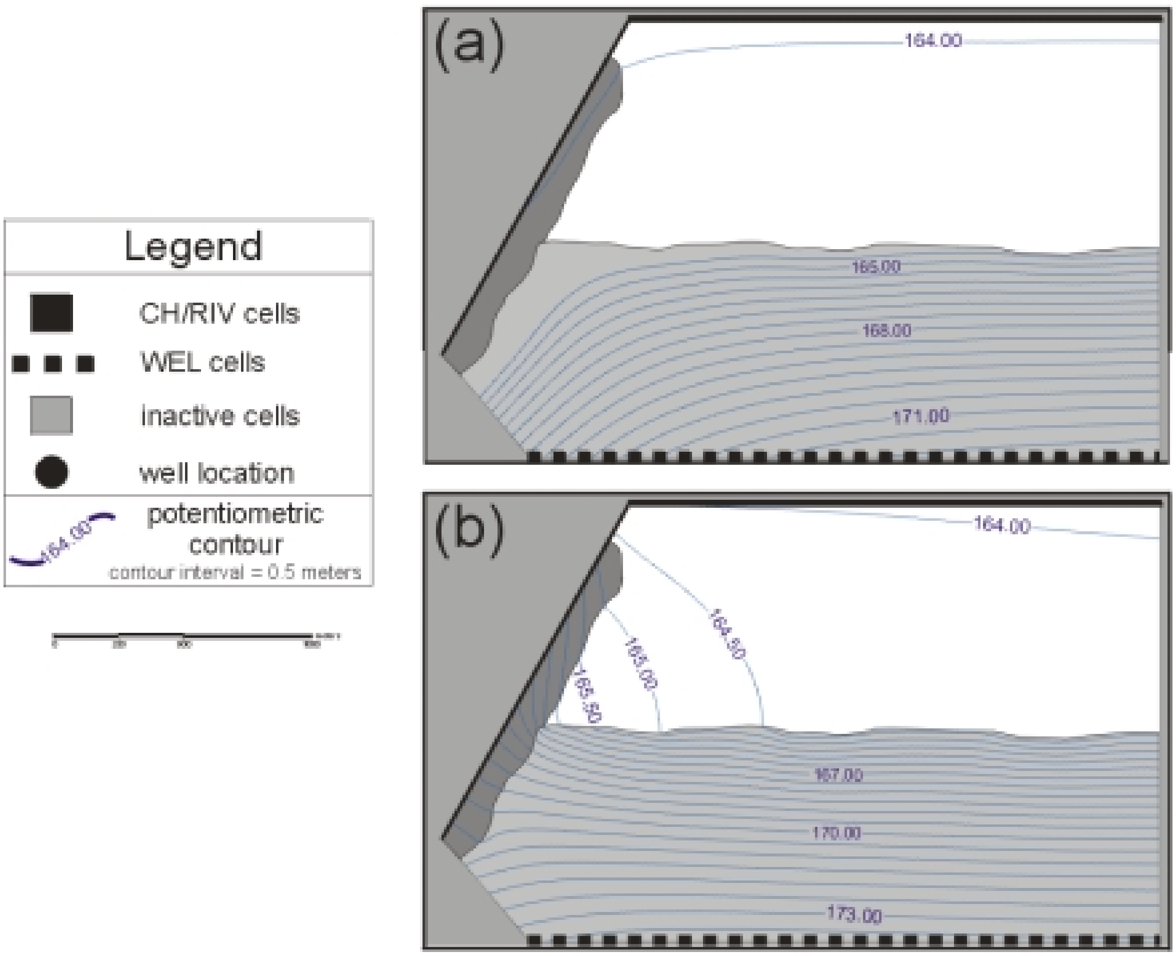


Figure 20. Potentiometric surface shown for both generic surface source intersection simulations: (a) Type A alluvial setting, and (b) Type B alluvial setting.

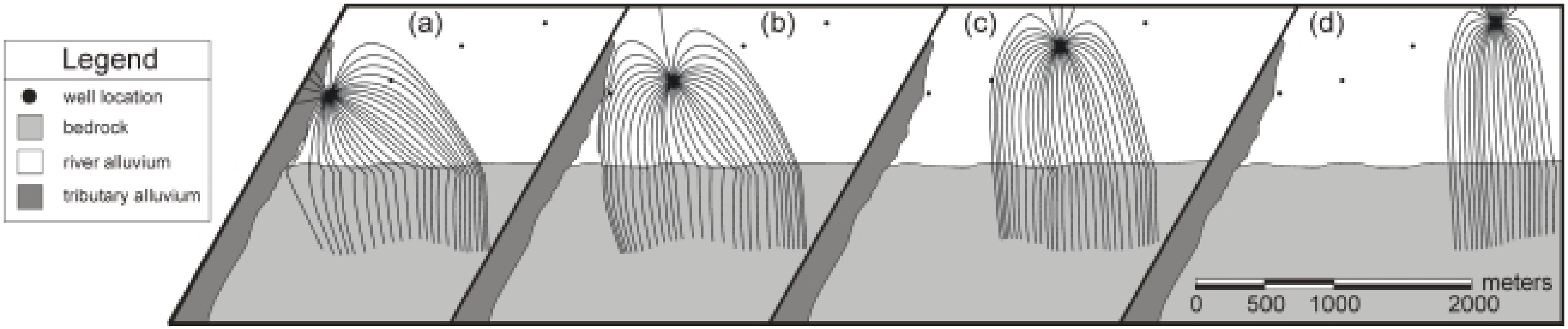


Figure 21. Simulated 5-year particle traces showing variations in capture zone geometry in the Type A alluvial setting. Producing well located at: (a) 700m from river, 200m from tributary; (b) 600m from river, 600m from tributary; (c) 300m from river, 1000m from, tributary; and (d) 100m from river, 1500m from tributary.

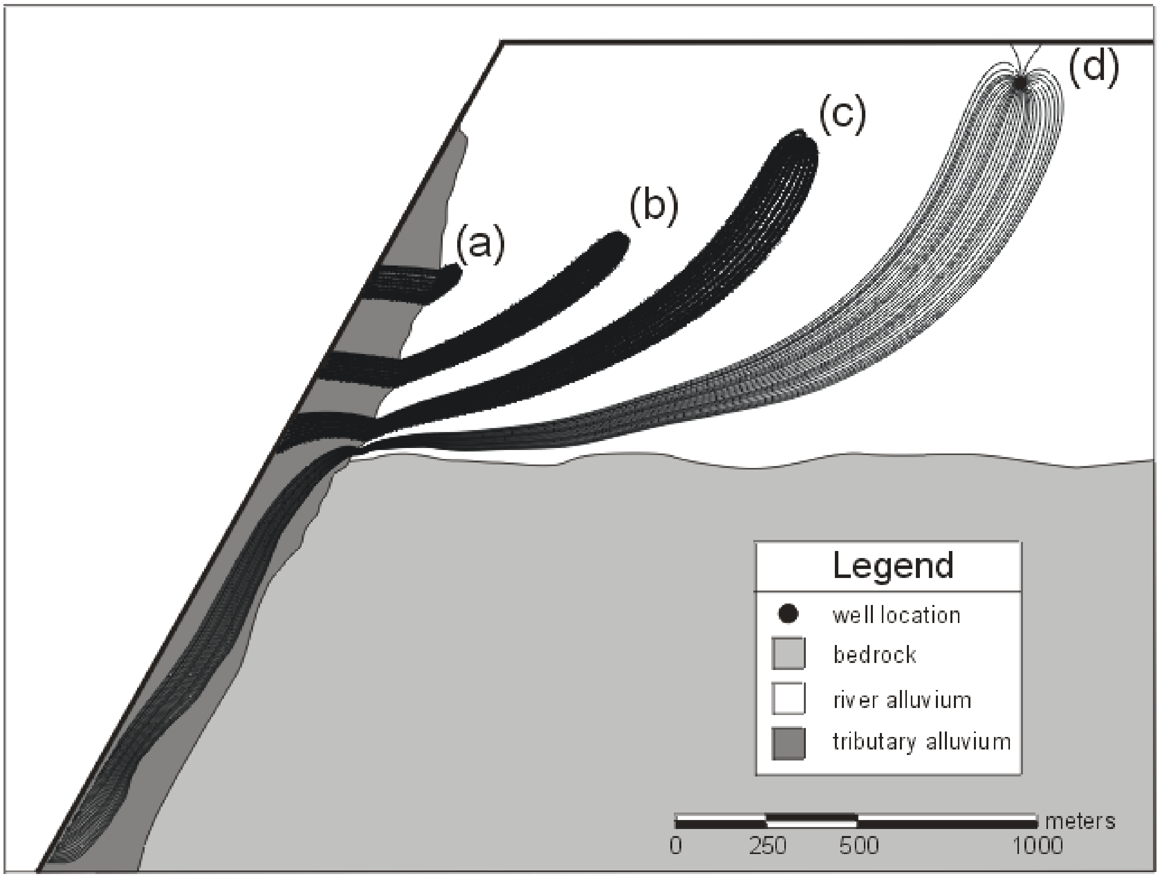


Figure 22. Simulated 5-year particle traces showing variations in capture zone geometry in the Type B alluvial setting. Producing well located at: (a) 700m from river, 200m from tributary; (b) 600m from river, 600m from tributary; (c) 300m from river, 1000m from tributary; and (d) 100m from river, 1500m from tributary.

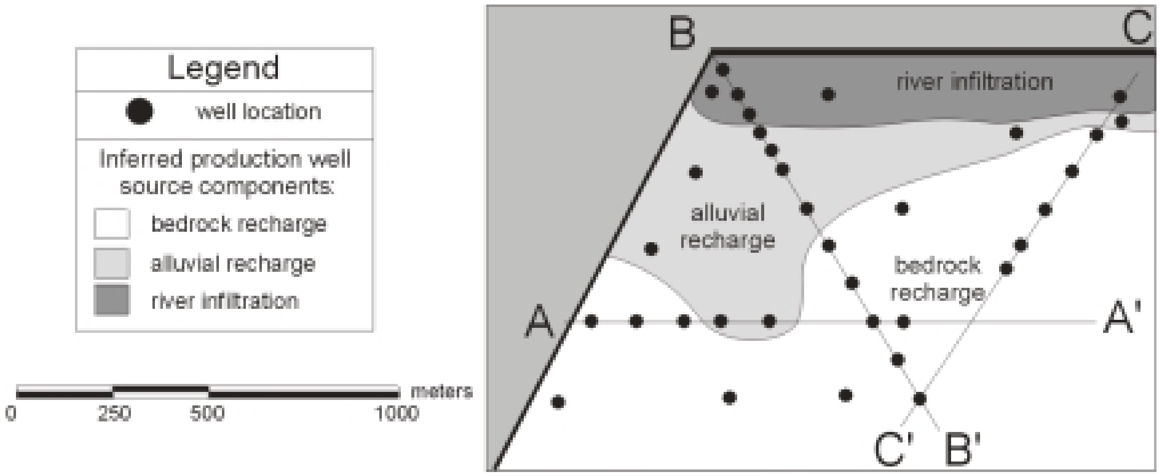


Figure 23a. Dominant source types for producing wells in the Type A alluvial setting. Source types are inferred from numerical simulations treating recharge to alluvium and bedrock as separate source components.

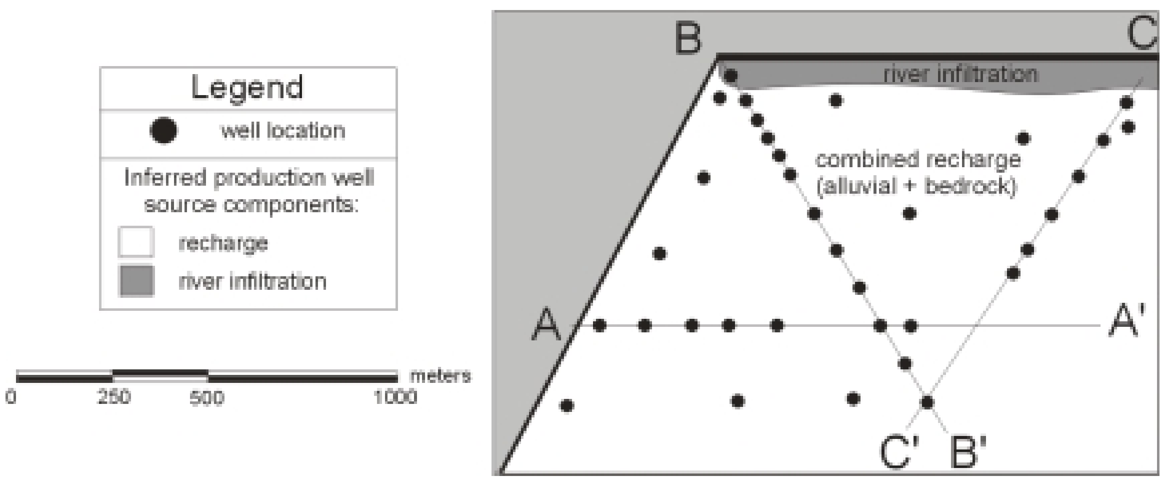


Figure 23b. Dominant source types for producing wells in the Type A alluvial setting. Source types are inferred from numerical simulations treating recharge to alluvium and bedrock as a single source component.

Addition of a tributary with a 2.9 m/km gradient altered the dominant source type for production wells in the Type B setting (Figure 24). In these simulations, the river did not become a dominant source for any production well locations, even at well locations less than 100 meters from its bank. The tributary gradient exerted considerable influence over flow direction within the alluvium. Tributary infiltration was the primary source component at distances up to 1,750 meters from the well. Beyond this distance, bedrock recharge was the dominant source; alluvial recharge was a minor source component for all well locations.

The limit of induced infiltration from both the river and tributary depended heavily upon tributary gradient. In Type A settings the induced infiltration limit extended away from both the river and tributary approximately 700 meters (Figure 25). In Type B settings river infiltration was minor compared to the limit of infiltration from the tributary reach, which extended nearly 1,700 meters into the alluvial aquifer (Figure 26).

5.2.2 Analytical Simulations

The analytical solutions examined here are only applicable to a single surface-water reach without a gradient. Due to these restrictions, the Wilson (1993) and Wilson and Newsom (1988) solutions apply only to the Type A alluvial setting.

5.2.2.1 Results

The Wilson (1993) solution assumes perpendicular regional flow toward the stream. Applying the solution to the river in the Type A setting indicated that induced infiltration would extend up to approximately 360 meters from the river (Figure 27).

Using the Wilson and Newsom (1988) solution oblique flow towards the stream, on average approximately 40 degrees, was simulated in the Type A setting (Figure 28). These results indicated that induced infiltration from the tributary would extend up to 900-1,000 meters from the tributary (Figure 29).

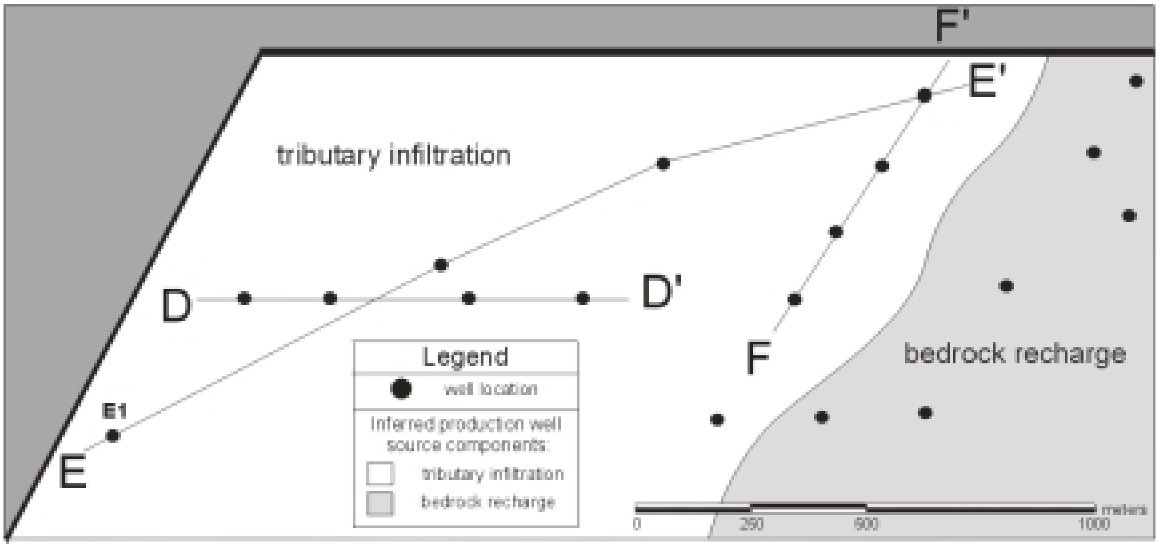


Figure 24a. Dominant source types for producing wells in the Type B alluvial setting. Source types are inferred from numerical simulations treating recharge to alluvium and bedrock as separate source components.

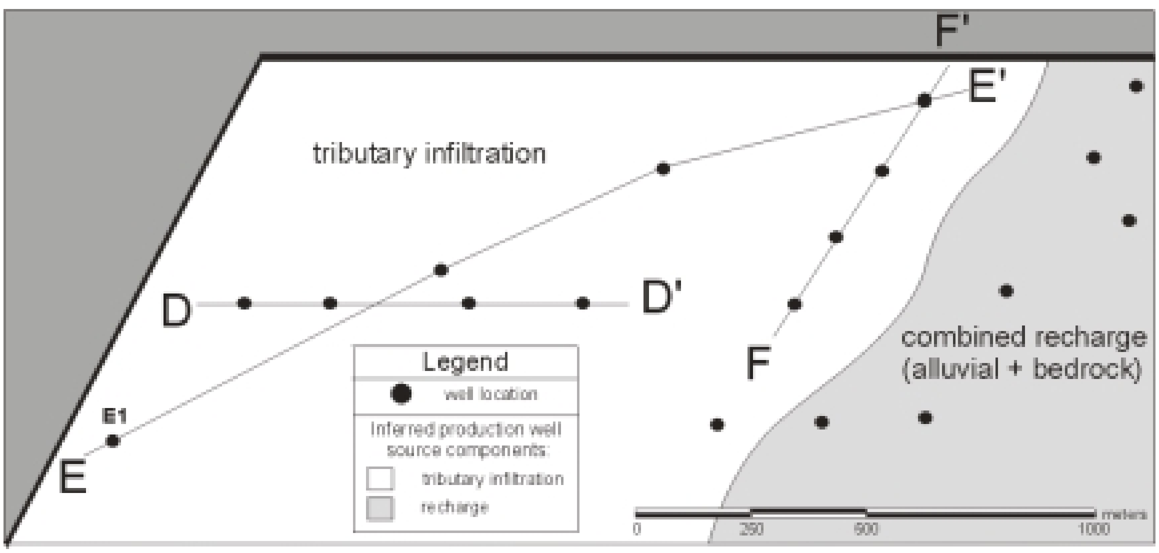


Figure 24b. Dominant source types for producing wells in the Type B alluvial setting. Source types are inferred from numerical simulations treating recharge to alluvium and bedrock as a single source component.

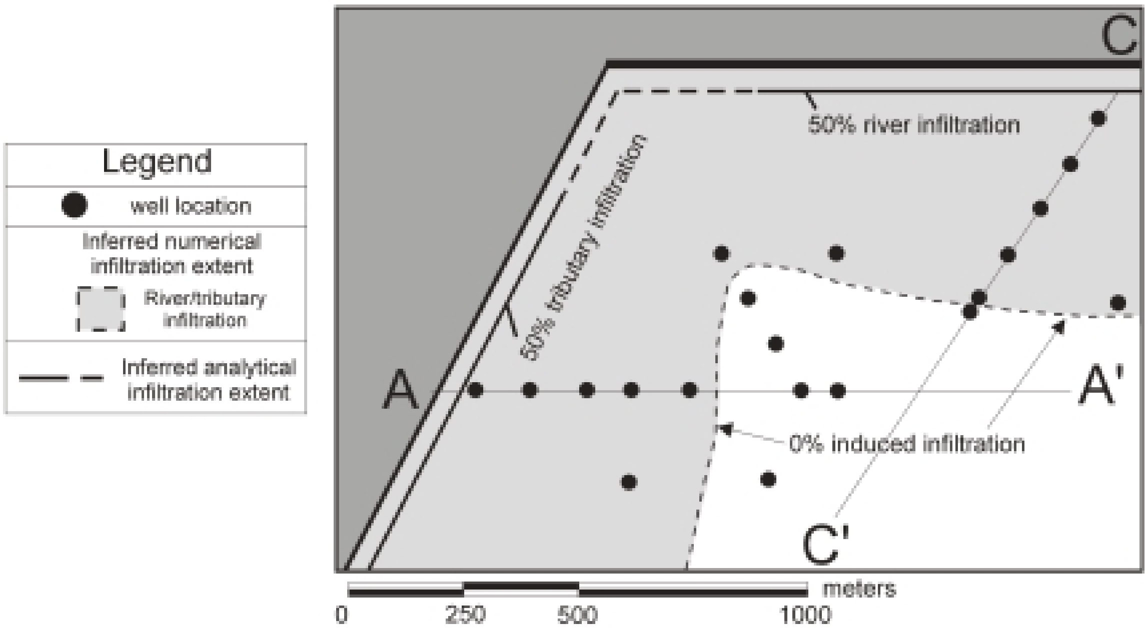


Figure 25. Zero percent river and tributary infiltration extent as inferred from numerical simulations of the Type A alluvial setting.

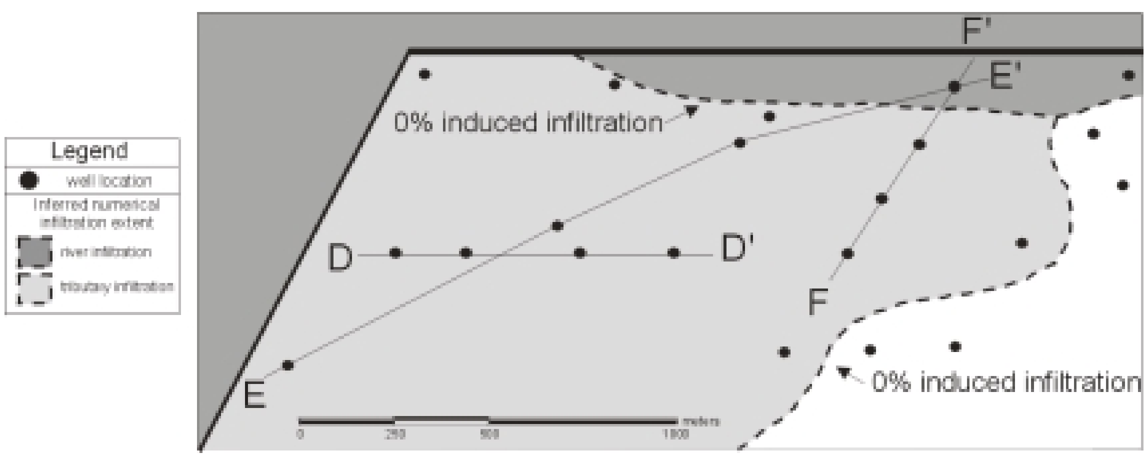


Figure 26. Zero percent river and tributary infiltration extents as inferred from numerical simulations of the Type B alluvial setting.

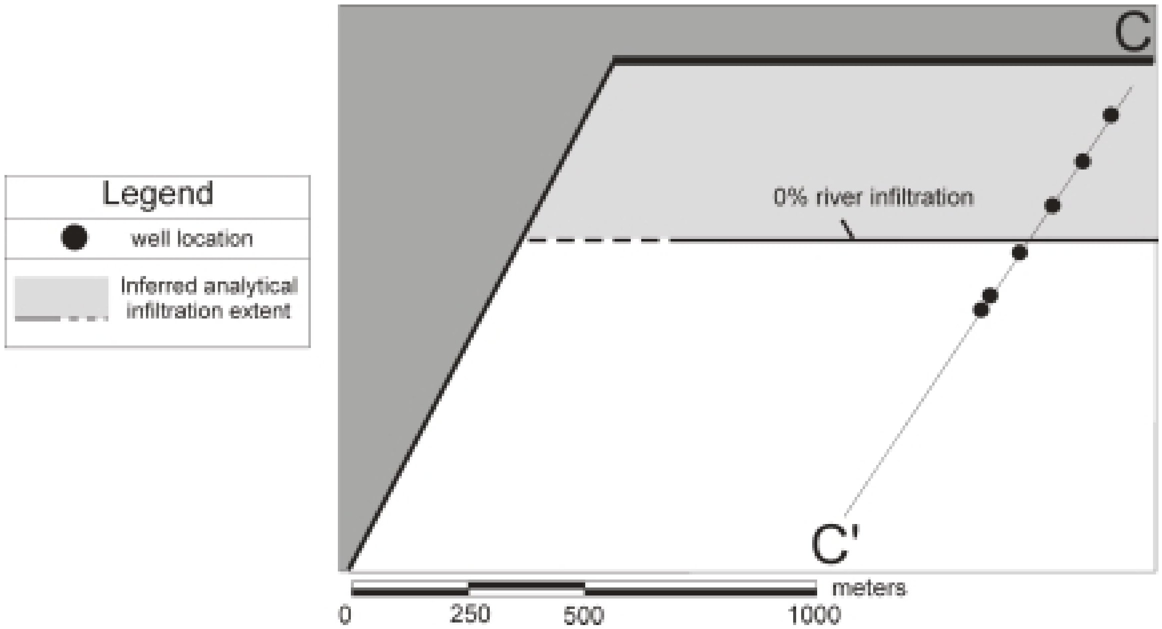


Figure 27. Zero percent river infiltration extent as inferred from analytical simulations of the Type A alluvial setting.

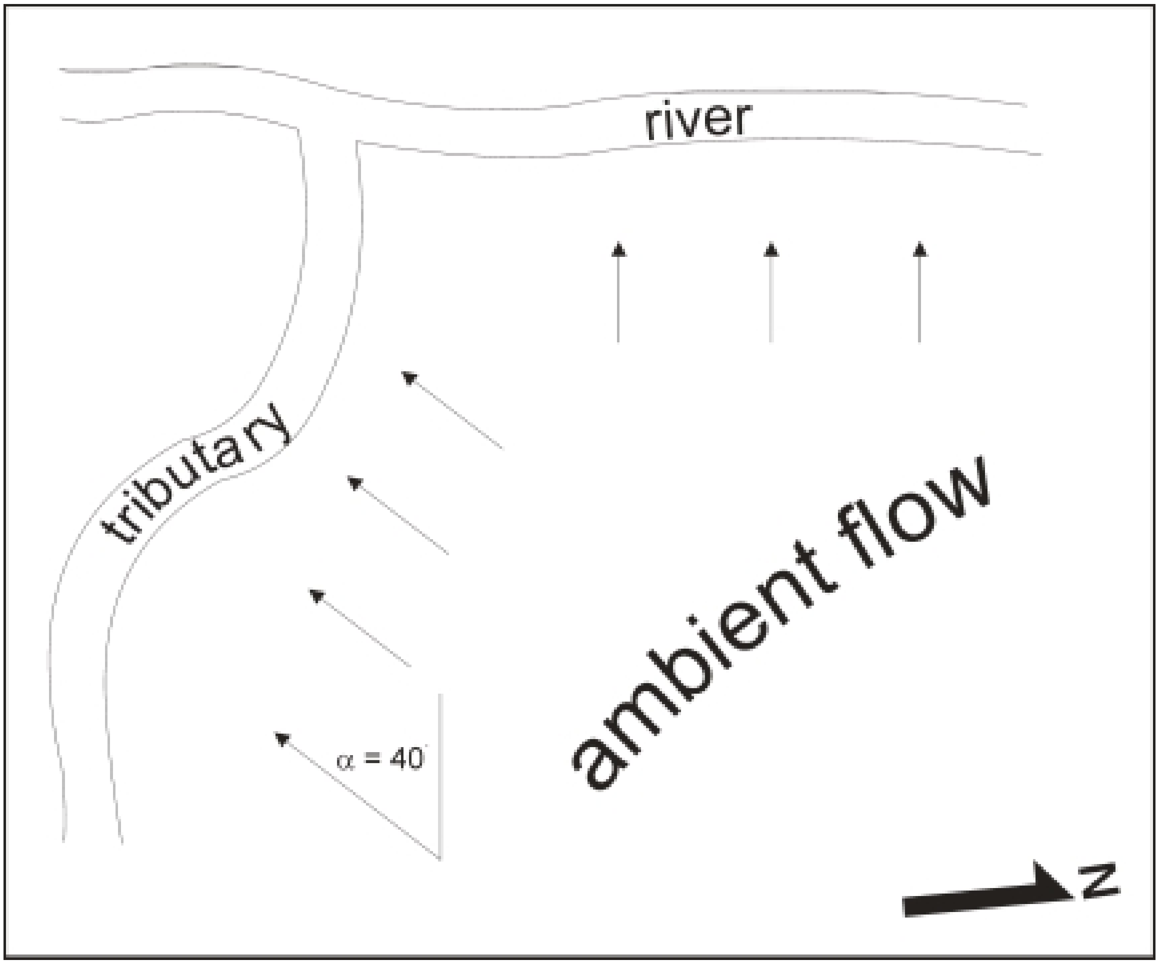


Figure 28. Regional groundwater flow direction toward the river and tributary.

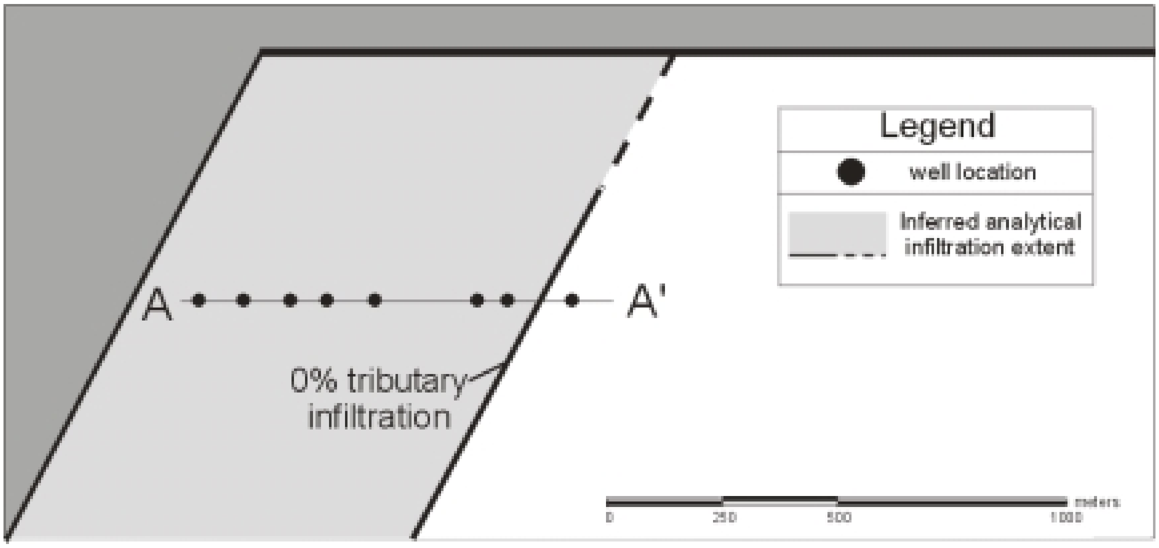


Figure 29. Zero percent tributary infiltration extent as inferred from analytical simulations of the Type A alluvial setting.

Table 10 compares the water budgets for both numerical and analytical simulations of the Type A alluvial setting. The two sets compare closely at distances near the stream banks. However, at distances greater than 200 meters, disagreements in flux became large, although modeled stream exfiltration reaches inferred for each simulation type were in better agreement. Figures 30 and 31 show reverse particle tracks and analytical stream exfiltration reaches for well transects A-A' and C-C' in the Type A setting. Although there is variability in the water budget between numerical and analytical models, there is closer correspondence between their calculated stream exfiltration reaches.

5.3 Discussion

5.3.1 Numerical Simulations

Source dominance supplying production wells located near the intersection of two streams can vary significantly depending on alluvial setting. Despite similar regional groundwater flow conditions in both Type A and Type B simulations, patterns of flow to wells differ drastically depending on the gradient of the intersecting tributary (Figure 20). In Type A, the groundwater pattern is toward both stream boundaries, which are gaining along their entire extent. In Type B, groundwater flow is strongly influenced by the gradient of the tributary stream. The greatest difference with Type A is that, at or near the river alluvium contact, the tributary becomes a losing stream and contributing flow to alluvium and, ultimately, to the river itself. The hydraulic gradient is higher near the river-tributary confluence in Type B compared to Type A.

Variations in particle trace and capture zone geometries may be ascribed to such differences in groundwater flow between Type A and Type B. The shallow hydraulic gradient of Type A (Figure 20a) results in broader well capture zones (Figure 21), with less groundwater flow from up-gradient recharge and more from river infiltration, tributary infiltration, and local recharge.

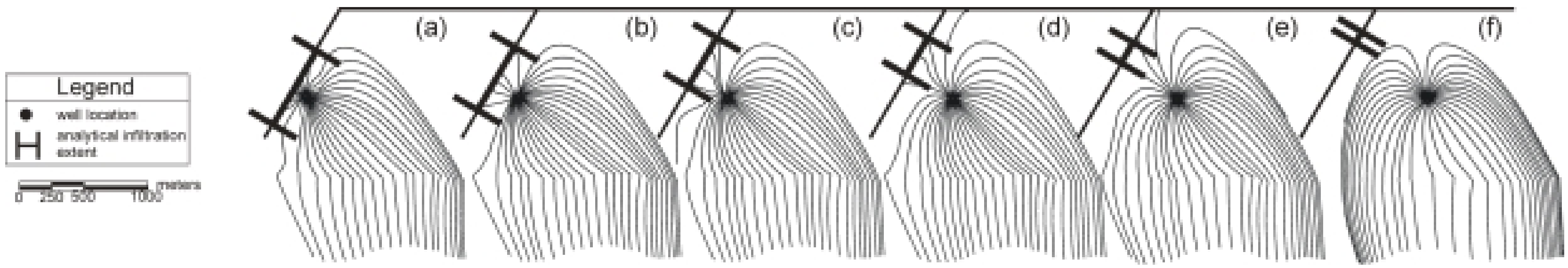


Figure 30. Simulated 5-year particle traces for the Type A alluvial setting showing variations in capture zone geometry due to increasing distance from the tributary. Producing well located at: (a) 100m, (b) 200m, (c) 300m, (d) 400m, (e) 500m, and (f) 700m. Analytical infiltration extent for each producing well also shown.

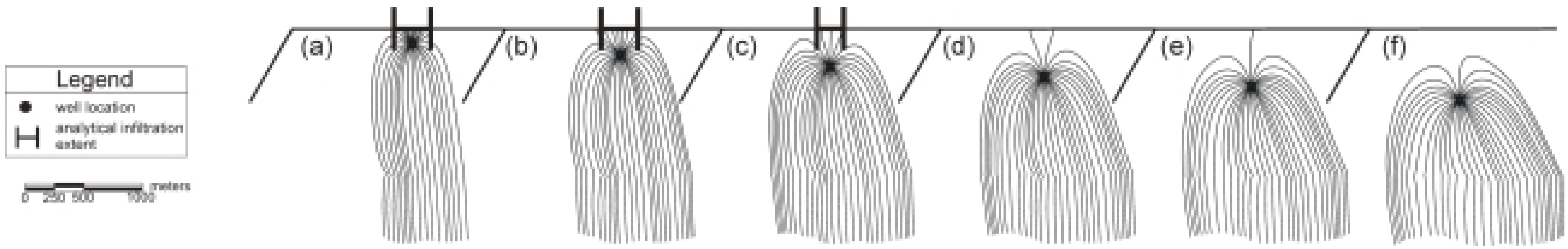


Figure 31. Simulated 5-year particle traces for the Type A alluvial setting showing variations in capture zone geometry due to increasing distance from the river. Producing well located at: (a) 100m, (b) 200m, (c) 300m, (d) 400m, (e) 500m, and (f) 600m. Analytical infiltration extent for wells C1 (a), C2 (b), and C3 (c) also shown.

The particle traces for Type A indicate that river infiltration is dominant over tributary infiltration attributed in part to the low conductivity sediments implemented in the DRN cells for the tributary. The shallow gradient and good hydraulic connection between river and alluvium allow the production well to easily induce infiltration. The rather shallow hydraulic gradient causes capture zones to broaden and indicate greater reliance on areal recharge.

In the Type B alluvial setting, groundwater originated as tributary exfiltration (Figure 20b) supplies far more water to the producing wells than in the Type A setting. This increased tributary exfiltration diminishes the influence of river exfiltration, which supplies producing wells only within 100 meters of the river (Figure 22). Narrowed capture zones indicate a smaller contribution of areal recharge to the producing well, that is, producing wells in Type B were able to draw sufficient volumes of water from tributary exfiltration to reduce the amounts of river infiltration and areal recharge necessary to fulfill pumping demands. Variations in pumping rate and tributary gradient would have a pronounced impact on the source component volumes necessary to supply pumping demands. If one had different stream or well pumping rates in other locations, the results could differ somewhat from those in Figure 20b.

The effects of alluvial setting on groundwater flow heavily influence source water budget for producing wells. Well location also plays a significant role. The highest variation in source component dominance was seen in the Type A setting (Figure 23, Table 8). Wells within 150 meters of the river derive most of their source water from this source. Wells at greater distance (>150 meters) from the river derived their water from up-gradient recharge. This critical distance varies with pumping rate. However, even when wells are close to the river, the sum of up-gradient recharge fluxes exceed the induced infiltration (Table 8). In Figure 23a, areal recharge is divided into alluvial and bedrock components, while in Figure 23b, both recharge sources are combined. As well location moves away from stream sources to the alluvium-bedrock contact, the capture zone areas extend further into bedrock

Table 8. Source water component volumes and percentages for the Type A alluvial setting, profiles A-A’, B-B’, and C-C’.

Well ID	Flux (m^3/d)				% of total discharge			
	R_A	R_{BR}	I_{RI}	I_{TR}	R_A	R_{BR}	I_{RI}	I_{TR}
A1	534.7	610.0	0.0	572.4	31.1	35.5	0.0	33.3
A2	659.6	771.3	0.0	286.2	38.4	44.9	0.0	16.7
A3	714.3	716.6	0.0	286.2	41.6	41.7	0.0	16.7
A4	774.5	713.6	0.0	228.9	45.1	41.6	0.0	13.3
A5	817.3	728.0	0.0	171.7	47.6	42.4	0.0	10.0
A6	718.4	998.7	0.0	0.0	41.8	58.2	0.0	0.0
B1	315.9	256.5	1030.3	114.5	18.4	14.9	60.0	6.7
B2	437.9	420.6	801.3	57.2	25.5	24.5	46.7	3.3
B3	533.0	497.3	629.6	57.2	31.0	29.0	36.7	3.3
B4	570.1	517.4	515.1	114.5	33.2	30.1	30.0	6.7
B5	614.4	530.3	457.9	114.5	35.8	30.9	26.7	6.7
B6	669.3	647.2	343.4	57.2	39.0	37.7	20.0	3.3
B7	751.3	736.8	171.7	57.2	43.8	42.9	10.0	3.3
B8	771.7	774.3	171.1	0.0	44.9	45.1	10.0	0.0
B9	759.1	900.8	57.2	0.0	44.2	52.5	3.3	0.0
B10	723.5	993.6	0.0	0.0	42.1	57.9	0.0	0.0
C1	493.2	479.8	744.1	0.0	28.7	27.9	43.3	0.0
C2	644.9	671.5	400.7	0.0	37.6	39.1	23.3	0.0
C3	724.0	821.4	171.7	0.0	42.2	47.8	10.0	0.0
C4	728.9	873.8	114.5	0.0	42.4	50.9	6.7	0.0
C5	728.7	931.2	57.2	0.0	42.4	54.2	3.3	0.0
C6	718.2	998.9	0.0	0.0	41.8	58.2	0.0	0.0

NOTES:

Simulated pumping rate = 1717.1 m^3/d

R_A = Alluvial recharge

R_{BR} = Bedrock recharge

I_{RI} = Induced river infiltration

I_{TR} = Induced tributary infiltration

and are reduced within alluvium. Induced tributary infiltration is never a dominant source type for the Type A alluvial setting, as this stream is everywhere gaining.

In the Type B setting, less variation in source dominance was seen (Figure 24, Table 9); the losing tributary reach providing water to the producing wells sufficient to meet their pumping demands. Wells located within a large distance from the tributary (1,750 meters) derived the majority of their water from this source. At greater distance, the dominant source was from recharge (Figure 24). Due to the steep hydraulic gradient within the tributary alluvium, the production well capture zones were narrow and, for those that did not induce water directly from the tributary, extended much farther up-gradient into bedrock than those in the Type A simulations (Figure 22). The elongated capture zones reaching into bedrock indicate that the majority of source water originates as areal recharge in bedrock. Alluvial recharge is not a dominant source for wells in the Type B alluvial settings due to the influence of bedrock recharge and tributary infiltration. Some well locations did draw small amounts of water from induced river infiltration, but this flux never exceeded 20% of the water budget (Figure 22, well d).

There is substantial difference in the areal extent of stream exfiltration as shown in Figures 25 and 26. The Type B aquifer is controlled primarily by the simulated tributary gradient, decreasing the importance of induced river infiltration as a supply component to the producing well. Wells in Type B derive source water from river infiltration only when located within 100 meters. At greater distances, the river supplies no water to the pumping wells whose water supply is derived solely from tributary infiltration and areal recharge. Fluxes entering alluvium from the losing tributary make this surface sources a dominant supply component for pumping wells located within 1,750 meters (Figure 26).

Alluvial setting has a greater impact than production well location on source component variations. The presence of a tributary gradient dominates the entire alluvial flow system and primarily controls where a producing well will derive its

Table 9. Source water component volumes and percentages for the Type B alluvial setting, profiles D-D’, E-E’, and F-F’.

Well ID	Flux (m^3/d)				% of total discharge			
	R_A	R_{BR}	I_{RI}	I_{TR}	R_A	R_{BR}	I_{RI}	I_{TR}
D1	12.9	0.0	0.0	1704.1	0.8	0.0	0.0	99.2
D2	24.4	0.0	0.0	1692.7	1.4	0.0	0.0	98.6
D3	50.2	0.0	0.0	1666.9	2.9	0.0	0.0	97.1
D4	74.4	0.0	0.0	1642.7	4.3	0.0	0.0	95.7
E1	5.3	0.0	0.0	1711.8	0.3	0.0	0.0	99.7
E2	43.8	0.0	0.0	1673.2	2.6	0.0	0.0	97.4
E3	108.5	0.0	0.0	1608.6	6.3	0.0	0.0	93.7
E4/F4	332.2	0.0	114.5	1270.4	19.3	0.0	6.7	74.0
F3	215.0	0.0	0.0	1502.0	12.5	0.0	0.0	87.5
F2	231.0	0.0	0.0	1486.0	13.5	0.0	0.0	86.5
F1	296.7	0.0	343.4	1077.0	17.3	0.0	20.0	62.7

NOTES:

Simulated pumping rate = 1717.1 m^3/d

R_A = Alluvial recharge

R_{BR} = Bedrock recharge

I_{RI} = Induced river infiltration

I_{TR} = Induced tributary infiltration

water. Variation of well location causes significant changes in supply component dominance only when both river and tributary streams are regulated.

5.3.2 Analytical Simulations

Induced infiltration fluxes and extents calculated from analytical solutions compare fairly well to the results of numerical simulations in Type A settings. The limits of induced infiltration and the stream exfiltration reaches are similar for both numerical and analytical simulations (Figures 26, 27, 29,30, and 31). In these cases, hydraulic parameters (water level elevations along each stream reach, regional flow, well location variations, well production rate, hydraulic conductivity/transmissivity estimates) could be accounted for in both the numerical and analytical simulations in nearly identical fashion. The analytical solutions, however, were unable to account for variations in aquifer geometry, variations in hydraulic parameters, and the presence of areal recharge. Many variations in fluxes may be due to the inability of the analytical models to account for specific aquifer and hydraulic parameters(Table 10).

Table 10. Comparison of induced infiltration fluxes (m^3/d) from surface-water sources as predicted by numerical and analytical simulations of the Type A alluvial setting.

Well ID	Numerical Simulation		Analytical Simulation	
	I_{RI}	I_{TR}	I_{RI}	I_{TR}
A1	0.0	572.4	0.0	788.9
A2	0.0	286.2	0.0	669.8
A3	0.0	286.2	0.0	569.4
A4	0.0	228.9	0.0	476.5
A5	0.0	171.7	0.0	387.3
B10	0.0	0.0	0.0	218.7
A6	0.0	0.0	0.0	141.9
C1	744.1	0.0	628.6	0.0
C2	400.7	0.0	263.3	0.0
C3	171.7	0.0	59.0	0.0
C4	114.5	0.0	0.0	0.0
C5	57.2	0.0	0.0	0.0
C6	0.0	0.0	0.0	0.0

NOTES:

Simulated pumping rate = 1717.1 m^3/d

R_A = Alluvial recharge

R_{BR} = Bedrock recharge

I_{RI} = Induced river infiltration

I_{TR} = Induced tributary infiltration

6. Conclusions

We have compared the results of numerical and analytical models in quantifying source water budget for production wells in alluvial aquifers bounded by two intersecting streams. Variations in the results of these models occur with (a) changes in well location, and (b) the nature of the alluvial setting.

Although analytical models are useful in determining infiltration extent and flux along a single stream reach, they have limitations as investigative tools for source water investigations. These solutions cannot account for multiple tributary sources or the presence of a gradient along either stream or river. The results of this investigation show that tributaries with sloping gradients can be important sources of induced inflow. Therefore, when dealing with an alluvial aquifer bounded by two intersecting surface sources, especially if near their confluence or if one or both of the sources has a gradient along its length, existing analytical models should be bypassed in favor of simplistic numerical simulations. Source water analysis and protection of dual surface source alluvial aquifers is best accomplished using simple numerical simulations. Variation in the nature of the intersecting tributary is easily implemented using models of this type.

Based upon the evaluated steady-state behaviors, source component analysis, induced infiltration limits, and stream exfiltration reaches, the following conclusions can be made:

- in regulated streams without natural-gradient tributaries (Type A alluvial setting), the river is an alternative source of well water by induced infiltration within 200 meters of the river
- in regulated rivers with natural-gradient tributaries (Type B alluvial setting), the tributary can be a dominant source of well water for wells within a kilometer or more, provided there is good hydraulic connection
- the limit of induced infiltration is equidistant from the river and tributary in Type A, but extends much farther from the tributary than the river in Type B

- Type A results are similar to analytical model results with respect to limit of induced infiltration and stream exfiltration reach
- analytical models are unsuited for regulated streams with sloping tributaries (Type B) because they lack parameters sufficient to describe this type of setting.

Source component identification is a critical factor in source-water assessment and protection evaluations and wellhead-protection area delineations. Communities with limited resources and expertise need options for source water protection modified to suit their needs and capabilities. Comparison between numerical and analytical models indicates that the best way to accomplish source component evaluation and protection in these situations is through simplistic numerical simulation. Alluvial aquifers bounded by intersecting surface sources are common sources for public supply wells in small communities. Current analytical solutions are incapable of representing the complex boundary conditions often encountered in hydrogeologic settings of this type. Numerical simulation is a useful investigative tool in gaining insight into the local controls over the alluvial aquifer's general behavior and response to pumping stress. When little data is available and resources are limited, simplistic numerical simulations are almost always the most accurate option for source component prediction and analysis in source water protection evaluations.

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APPENDIX I

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
391707081333201	-81.56	39.29	568
391750081333201	-81.56	39.30	551
391742081333701	-81.56	39.30	550
391719081333801	-81.56	39.29	545
392029081324201	-81.54	39.34	549
391834081331001	-81.55	39.31	542
401348080391601	-80.65	40.23	598
392049081323201	-81.54	39.35	547
392051081323201	-81.54	39.35	546
391834081331101	-81.55	39.31	545
391947081331201	-81.55	39.33	543
392006081325501	-81.55	39.33	554
391948081331101	-81.55	39.33	544
395641080453101	-80.76	39.94	570
385340081502601	-81.84	38.89	518
391937081330001	-81.55	39.33	549
391937081325901	-81.55	39.33	548
403433080392901	-80.66	40.58	607
400427080380301	-80.63	40.07	840
385023082070101	-82.12	38.84	590
394945080421101	-80.70	39.83	1289
394741080475901	-80.80	39.79	699
400818080390001	-80.65	40.14	858
400400080362301	-80.61	40.07	828
400310080373601	-80.63	40.05	718
385638082010201	-82.02	38.94	638
403603080373301	-80.63	40.60	838
395315080411502	-80.69	39.89	1258
400720080371501	-80.62	40.12	1007
400336080365401	-80.61	40.06	986
385054082063201	-82.11	38.85	631
385130081595001	-82.00	38.86	661
384900082065701	-82.12	38.82	566
394745080430401	-80.72	39.80	726
400530080363701	-80.61	40.09	1045
400538080375301	-80.63	40.09	985
384719081534801	-81.90	38.79	575
384515082070901	-82.12	38.75	745
385239082051401	-82.09	38.88	595
400635080362701	-80.61	40.11	1154
395346080401701	-80.67	39.90	1293
385509081592001	-81.99	38.92	672
385509081592002	-81.99	38.92	672
385344082044401	-82.08	38.90	562
385418082003103	-82.01	38.91	702
400330080383901	-80.64	40.06	721

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
395736080384801	-80.65	39.96	1291
400727080411301	-80.69	40.12	770
400525080391701	-80.65	40.09	1280
400650080392801	-80.66	40.11	1120
385751082013001	-82.02	38.96	487
385542082050001	-82.08	38.93	595
385638082005701	-82.02	38.94	640
385656081595202	-82.00	38.95	725
385418082003102	-82.01	38.91	700
395738080390001	-80.65	39.96	1300
403158080322501	-80.54	40.53	1230
395246080424101	-80.71	39.88	1190
400940080362901	-80.61	40.16	928
400947080401001	-80.67	40.16	1108
401033080402701	-80.67	40.18	1178
400239080370001	-80.62	40.04	738
384625082053301	-82.09	38.77	603
395834080392701	-80.66	39.98	1278
385540081452001	-81.76	38.93	598
401014080345001	-80.58	40.17	1247
395737080384901	-80.65	39.96	1286
391652081220001	-81.37	39.28	846
384855082065001	-82.11	38.82	556
385021082081001	-82.14	38.84	536
401105080395301	-80.66	40.18	626
391358081402901	-81.67	39.23	635
401054080395301	-80.66	40.18	605
400451080360901	-80.60	40.08	915
400239080371501	-80.62	40.04	725
400149080391102	-80.65	40.03	675
385044082040102	-82.07	38.85	660
385159081581901	-81.97	38.87	900
385200082044901	-82.08	38.87	675
384729081560101	-81.93	38.79	875
384743081525901	-81.88	38.80	975
390002082023001	-82.04	39.00	545
395258080404601	-80.68	39.88	775
395027080423201	-80.71	39.84	765
401012080400301	-80.67	40.17	684
385740081584301	-81.98	38.96	664
394756080465301	-80.78	39.80	1184
401100080395201	-80.66	40.18	624
385849082033401	-82.06	38.98	573
385457082032001	-82.06	38.92	553
395217080422001	-80.71	39.87	1283
385345081582801	-81.97	38.90	692

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
400027080383801	-80.64	40.01	692
394845080483901	-80.81	39.81	601
400932080393001	-80.66	40.16	750
401016080361801	-80.60	40.17	1070
400740080393701	-80.66	40.13	1210
400629080385301	-80.65	40.11	1230
400642080392701	-80.66	40.11	990
400408080381601	-80.64	40.07	785
385109082013401	-82.03	38.85	640
385201081582001	-81.97	38.87	895
385742082010801	-82.02	38.96	515
385551081593902	-81.99	38.93	670
385738081584001	-81.98	38.96	660
395207080420701	-80.70	39.87	1260
395324080420301	-80.70	39.89	710
394916080480001	-80.80	39.82	625
401804080325101	-80.55	40.30	700
394918080470202	-80.78	39.82	1099
384943082003201	-82.01	38.83	844
400932080393401	-80.66	40.16	758
400730080374301	-80.63	40.13	948
400248080394101	-80.66	40.05	668
384730081561301	-81.94	38.79	858
385432082043801	-82.08	38.91	587
395940080390401	-80.65	39.99	1197
391603081402902	-81.67	39.27	559
400719080373501	-80.63	40.12	1316
400503080380002	-80.63	40.08	896
400718080365101	-80.61	40.12	1015
400407080382601	-80.64	40.07	785
400425080360301	-80.60	40.07	790
384807082024601	-82.05	38.80	545
384820082075401	-82.13	38.81	830
395734080422001	-80.71	39.96	805
395746080383801	-80.64	39.96	1265
395846080385801	-80.65	39.98	1195
395723080435301	-80.73	39.96	685
395226080423301	-80.71	39.87	1230
394725080494701	-80.83	39.79	640
400728080373901	-80.63	40.12	944
383830082035201	-82.06	38.64	774
400520080401401	-80.67	40.09	843
395658080444801	-80.75	39.95	643
395309080415301	-80.70	39.89	723
400021080380501	-80.63	40.01	702
395722080435201	-80.73	39.96	682

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
395110080431001	-80.72	39.85	732
395127080434501	-80.73	39.86	702
394413080432601	-80.72	39.74	1352
403317080380401	-80.63	40.55	652
390801081441001	-81.74	39.13	561
400624080402401	-80.67	40.11	841
400624080402402	-80.67	40.11	841
400624080402403	-80.67	40.11	841
400227080373201	-80.63	40.04	721
385512082072901	-82.12	38.92	491
391411081411001	-81.69	39.24	560
391455081354801	-81.60	39.25	600
400923080384401	-80.65	40.16	880
400935080365401	-80.61	40.16	876
400940080393801	-80.66	40.16	720
400940080394001	-80.66	40.16	730
400455080393802	-80.66	40.08	1200
400235080374601	-80.63	40.04	690
384956082053001	-82.09	38.83	560
385813082045901	-82.08	38.97	530
385418082003104	-82.01	38.91	680
383838082035600	-82.07	38.64	720
401216080362701	-80.61	40.20	1110
403240080380301	-80.63	40.54	640
395252080411501	-80.69	39.88	749
395325080471801	-80.79	39.89	639
394625080454801	-80.76	39.77	1309
391555081334201	-81.56	39.27	573
401018080350001	-80.58	40.17	1258
385715082055002	-82.10	38.95	498
395202080433301	-80.73	39.87	708
403629080381201	-80.64	40.61	638
395149080460501	-80.77	39.86	1247
391603081402903	-81.67	39.27	547
400240080375001	-80.63	40.04	687
394832080422401	-80.71	39.81	1377
391618081395201	-81.66	39.27	540
394512080451901	-80.76	39.75	1266
400824080412201	-80.69	40.14	1075
400550080431201	-80.72	40.10	615
385959082023901	-82.04	39.00	525
385715082055201	-82.10	38.95	486
385418082003101	-82.01	38.91	675
395257080404301	-80.68	39.88	755
394818080490301	-80.82	39.81	715
403630080380801	-80.64	40.61	635

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
391718081333101	-81.56	39.30	554
390801081440101	-81.73	39.13	554
401217080362701	-80.61	40.20	1104
400503080380001	-80.63	40.08	883
384822082031801	-82.05	38.81	523
385002082082801	-82.14	38.83	517
385736081551601	-81.92	38.96	522
391713081333403	-81.56	39.29	547
400250080375801	-80.63	40.05	681
385741081551901	-81.92	38.96	521
400955080393901	-80.66	40.17	690
384958082081501	-82.14	38.83	525
385030081590501	-81.98	38.84	625
385554082051301	-82.09	38.93	570
385642081544101	-81.91	38.95	525
385715082055004	-82.10	38.95	508
385450082060401	-82.10	38.91	545
400027080383701	-80.64	40.01	670
400030080381402	-80.64	40.01	670
400035080385801	-80.65	40.01	690
395027080420801	-80.70	39.84	760
390446081482801	-81.81	39.08	570
385330081504901	-81.85	38.89	534
401818080354301	-80.60	40.31	600
403629080380802	-80.64	40.61	630
403634080380701	-80.64	40.61	630
401216080362703	-80.61	40.20	1100
391717081333603	-81.56	39.29	549
391714081333401	-81.56	39.29	544
391714081333402	-81.56	39.29	556
391717081333401	-81.56	39.29	551
400425080360401	-80.60	40.07	789
391714081333403	-81.56	39.29	554
391715081333401	-81.56	39.29	555
390658081401601	-81.67	39.12	638
385035082082101	-82.14	38.84	508
400031080381501	-80.64	40.01	668
400913080385201	-80.65	40.15	787
400603080392801	-80.66	40.10	1187
394742080475801	-80.80	39.80	657
391716081333401	-81.56	39.29	546
400851080420301	-80.70	40.15	620
385715082055003	-82.10	38.95	496
385304081554701	-81.93	38.88	546
391710081333301	-81.56	39.29	547
391711081333401	-81.56	39.29	547

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
391712081333201	-81.56	39.29	546
391712081333402	-81.56	39.29	548
391715081333402	-81.56	39.29	554
391719081333902	-81.56	39.29	548
391748081234501	-81.40	39.30	635
400843080405401	-80.68	40.15	1145
385200082004901	-82.01	38.87	670
384836082061101	-82.10	38.81	525
394820080473401	-80.79	39.81	1015
394748080452601	-80.76	39.80	655
403653080373101	-80.63	40.61	630
391618081400801	-81.67	39.27	539
391713081333104	-81.56	39.29	535
400824080423001	-80.71	40.14	594
385726081551301	-81.92	38.96	514
400006080382201	-80.64	40.00	684
401527080361001	-80.60	40.26	624
391717081333802	-81.56	39.29	544
391715081333701	-81.56	39.29	543
400805080423301	-80.71	40.13	603
385304081554501	-81.93	38.88	543
385414082074901	-82.13	38.90	498
395300080405401	-80.68	39.88	743
390221081465101	-81.78	39.04	543
391712081333401	-81.56	39.29	545
400849080390001	-80.65	40.15	762
400348080391601	-80.65	40.06	1102
384812082052301	-82.09	38.80	522
385427082072401	-82.12	38.91	522
401411080390601	-80.65	40.24	622
403039080332301	-80.56	40.51	912
403425080391401	-80.65	40.57	622
391713081333402	-81.56	39.29	540
385327082081201	-82.14	38.89	501
395737080384902	-80.65	39.96	1251
391712081333903	-81.56	39.29	544
391606081400001	-81.67	39.27	536
390731081440301	-81.73	39.13	540
391115081345001	-81.58	39.19	660
400927080343301	-80.58	40.16	960
400546080390201	-80.65	40.10	1240
400619080381001	-80.64	40.11	1110
400213080384401	-80.65	40.04	1240
385035082082102	-82.14	38.84	500
385140082080901	-82.14	38.86	500
384849082064101	-82.11	38.81	510

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
390033081595701	-82.00	39.01	510
385820081560801	-81.94	38.97	540
385858081570101	-81.95	38.98	530
385905081570901	-81.95	38.98	525
385652081595901	-82.00	38.95	620
385716081571501	-81.95	38.95	615
385728081573901	-81.96	38.96	550
385438081582201	-81.97	38.91	635
385503082065501	-82.12	38.92	520
385238082051001	-82.09	38.88	550
385325081560101	-81.93	38.89	540
385332081560101	-81.93	38.89	530
385340081561301	-81.94	38.89	550
394855080473101	-80.79	39.82	640
385738081463001	-81.77	38.96	530
390322081460901	-81.77	39.06	720
384930081470801	-81.79	38.83	540
403039080332201	-80.56	40.51	910
403249080322201	-80.54	40.55	1020
403629080380801	-80.64	40.61	620
391713081333401	-81.56	39.29	544
385759081553601	-81.93	38.97	509
395434080482001	-80.81	39.91	569
400230080425602	-80.72	40.04	778
385110082013001	-82.02	38.85	598
385740081553806	-81.93	38.96	542
385750082012601	-82.02	38.96	493
385608082062801	-82.11	38.94	498
385450082064101	-82.11	38.91	533
395406080403601	-80.68	39.90	1298
395418080481801	-80.80	39.91	570
401538080341901	-80.57	40.26	1128
400655080375401	-80.63	40.12	1227
385009082082301	-82.14	38.84	502
384806082042901	-82.07	38.80	497
395435080401201	-80.67	39.91	1287
400054080374001	-80.63	40.02	1246
385921081564801	-81.95	38.99	536
385326082073801	-82.13	38.89	526
395615080453201	-80.76	39.94	576
391301081312601	-81.52	39.22	535
400934080393101	-80.66	40.16	715
401038080400101	-80.67	40.18	635
400848080353801	-80.59	40.15	985
400408080391901	-80.66	40.07	1235
400427080355301	-80.60	40.07	785

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
400443080360501	-80.60	40.08	815
385041082081901	-82.14	38.84	504
385108081540701	-81.90	38.85	545
385122081595201	-82.00	38.86	595
384932082065101	-82.11	38.83	497
385028082000301	-82.00	38.84	665
385803081552001	-81.92	38.97	512
385902081570001	-81.95	38.98	520
385917081565601	-81.95	38.99	520
385612082054001	-82.09	38.94	540
385612082054002	-82.09	38.94	540
385740081553804	-81.93	38.96	544
395855080440201	-80.73	39.98	595
400035080381201	-80.64	40.01	670
395840080421201	-80.70	39.98	1295
395332080401101	-80.67	39.89	1215
394819080490901	-80.82	39.81	590
395033080460601	-80.77	39.84	1285
394743080453601	-80.76	39.80	605
385653081410701	-81.69	38.95	595
390254081474501	-81.80	39.05	530
401055080384901	-80.65	40.18	1094
401150080395701	-80.67	40.20	595
402912080350101	-80.58	40.49	925
403353080382801	-80.64	40.56	625
403631080380802	-80.64	40.61	615
391008081444301	-81.75	39.17	502
400450080431202	-80.72	40.08	594
385653082060501	-82.10	38.95	499
395609080453001	-80.76	39.94	574
385039082082002	-82.14	38.84	493
385620082054501	-82.10	38.94	543
385627082052801	-82.09	38.94	543
395613080453201	-80.76	39.94	573
395617080453301	-80.76	39.94	573
395503080425501	-80.80	39.92	568
385626081494101	-81.83	38.94	553
401634080364701	-80.61	40.28	593
403238080380401	-80.63	40.54	613
401635080364701	-80.61	40.28	593
400603080370801	-80.62	40.10	1222
400149080391101	-80.65	40.03	632
400216080433803	-80.73	40.04	577
385109082013402	-82.03	38.85	602
385835082044901	-82.08	38.98	502
385916081565601	-81.95	38.99	517

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
395537080451501	-80.75	39.93	574
395540080451701	-80.75	39.93	577
390234081471801	-81.79	39.04	517
401813080325101	-80.55	40.30	662
385216082081101	-82.14	38.87	494
385907081564601	-81.95	38.99	531
385714082055001	-82.10	38.95	500
395609080453002	-80.76	39.94	571
395424080431801	-80.72	39.91	1101
401640080364601	-80.61	40.28	591
394941080415701	-80.70	39.83	1261
390731081440801	-81.74	39.13	515
390819081442101	-81.74	39.14	498
400923080371901	-80.62	40.16	810
400819080414601	-80.70	40.14	970
400853080390001	-80.65	40.15	780
400408080391902	-80.66	40.07	1230
400410080433001	-80.72	40.07	590
400457080373001	-80.62	40.08	1210
400205080434303	-80.73	40.03	575
384959082082801	-82.14	38.83	506
385010082082801	-82.14	38.84	495
385012082054301	-82.10	38.84	490
384827081570701	-81.95	38.81	510
384605082055701	-82.10	38.77	570
385821081561001	-81.94	38.97	525
385843081560201	-81.93	38.98	510
385844081561401	-81.94	38.98	530
385848081560501	-81.93	38.98	510
385849081564501	-81.95	38.98	515
385920081570001	-81.95	38.99	530
385920081570002	-81.95	38.99	515
385729081564901	-81.95	38.96	590
385221082073201	-82.13	38.87	530
395853080440401	-80.73	39.98	580
395621080453401	-80.76	39.94	570
395546080452001	-80.76	39.93	577
394915080485101	-80.81	39.82	600
394918080470201	-80.78	39.82	1060
390443081482401	-81.81	39.08	520
401328080393101	-80.66	40.22	585
401330080392601	-80.66	40.23	590
401336080392501	-80.66	40.23	590
401346080391801	-80.65	40.23	600
401419080390601	-80.65	40.24	600
403531080314001	-80.53	40.59	1110

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
403633080380801	-80.64	40.61	595
391603081402908	-81.67	39.27	563
385657082060301	-82.10	38.95	489
385735082053801	-82.09	38.96	499
385737082053801	-82.09	38.96	489
385739082053601	-82.09	38.96	489
401154080395601	-80.67	40.20	589
401630080364601	-80.61	40.28	589
394729080484401	-80.81	39.79	1169
400843080394601	-80.66	40.15	1168
385259081514701	-81.86	38.88	528
395139080443201	-80.74	39.86	1167
391603081402904	-81.67	39.27	561
391603081402906	-81.67	39.27	561
391603081402907	-81.67	39.27	561
400450080431201	-80.72	40.08	587
385924081593701	-81.99	38.99	527
385450082064601	-82.11	38.91	527
395300080405601	-80.68	39.88	727
402319080374101	-80.63	40.39	597
391603081402905	-81.67	39.27	560
391603081402909	-81.67	39.27	560
385902081570101	-81.95	38.98	516
401507080362201	-80.61	40.25	666
401912080355101	-80.60	40.32	586
402317080373901	-80.63	40.39	596
402007080361501	-80.60	40.34	586
401939080355301	-80.60	40.33	601
402035080363201	-80.61	40.34	586
391752081262801	-81.44	39.30	585
391337081360602	-81.60	39.23	665
400438080373401	-80.63	40.08	1185
385124082080601	-82.13	38.86	505
385124082080602	-82.13	38.86	505
384918082045501	-82.08	38.82	600
385012082053401	-82.09	38.84	515
385020081551101	-81.92	38.84	855
384830082055201	-82.10	38.81	495
384844082063601	-82.11	38.81	545
385510082063501	-82.11	38.92	525
385329081560201	-81.93	38.89	525
395601080452801	-80.76	39.93	565
395137080442901	-80.74	39.86	1155
395156080420601	-80.70	39.87	1225
395305080471001	-80.79	39.88	565
394851080485001	-80.81	39.81	583

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
395027080465101	-80.78	39.84	1145
385741081463002	-81.77	38.96	515
385247081465001	-81.78	38.88	645
385313081504601	-81.85	38.89	510
401913080355103	-80.60	40.32	585
401917080354801	-80.60	40.32	590
401933080355501	-80.60	40.33	575
402319080374301	-80.63	40.39	595
403631080380701	-80.64	40.61	605
403633080380601	-80.63	40.61	607
391603081402900	-81.67	39.27	558
400921080404501	-80.68	40.16	704
400205080434301	-80.73	40.03	569
395315080411501	-80.69	39.89	1194
401210080383901	-80.64	40.20	1124
401627080364702	-80.61	40.27	589
401627080364703	-80.61	40.27	589
403252080335301	-80.56	40.55	1054
403613080382101	-80.64	40.60	604
403716080362901	-80.61	40.62	604
403716080363001	-80.61	40.62	609
403718080362301	-80.61	40.62	609
390436081385501	-81.65	39.08	578
385019082082501	-82.14	38.84	484
395335080471801	-80.79	39.89	638
385454081502801	-81.84	38.92	513
401913080355102	-80.60	40.32	583
401923080355001	-80.60	40.32	599
402040080364000	-80.61	40.34	568
385845081560101	-81.93	38.98	482
385846081560201	-81.93	38.98	482
385918081575601	-81.97	38.99	497
395335080474601	-80.80	39.89	562
385501081502701	-81.84	38.92	512
385628081450601	-81.75	38.94	505
385346081500001	-81.83	38.90	542
402040080364001	-80.61	40.34	567
402040080364003	-80.61	40.34	567
402040080364004	-80.61	40.34	567
402040080364005	-80.61	40.34	567
402040080364009	-80.61	40.34	567
391421081410901	-81.69	39.24	561
391424081410001	-81.68	39.24	561
385804081552503	-81.92	38.97	481
385655081455501	-81.77	38.95	511
401344080392301	-80.66	40.23	581

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
401913080355101	-80.60	40.32	581
391752081334201	-81.56	39.30	505
390932081411701	-81.69	39.16	670
391202081333001	-81.56	39.20	540
400835080354801	-80.60	40.14	1020
400703080392801	-80.66	40.12	1160
400545080364601	-80.61	40.10	1020
400503080413001	-80.69	40.08	620
400230080425601	-80.72	40.04	760
400232080433401	-80.73	40.04	565
385040081582101	-81.97	38.84	595
385055082010001	-82.02	38.85	605
385116081594201	-81.99	38.85	580
385017082073101	-82.13	38.84	485
384842082061501	-82.10	38.81	490
390103082020901	-82.04	39.02	490
385801081552501	-81.92	38.97	480
385802081552601	-81.92	38.97	506
385802081552602	-81.92	38.97	506
385804081552501	-81.92	38.97	480
385804081552502	-81.92	38.97	480
385545082054101	-82.09	38.93	560
385545082054103	-82.09	38.93	560
385626081582101	-81.97	38.94	550
385423082071801	-82.12	38.91	512
385426082070601	-82.12	38.91	500
385430082065201	-82.11	38.91	500
385431082070201	-82.12	38.91	500
385435082065001	-82.12	38.91	515
385438082070101	-82.12	38.91	510
385439082065801	-82.12	38.91	515
385450082064201	-82.11	38.91	515
385459082040001	-82.07	38.92	520
385240081550901	-81.92	38.88	500
385242081551101	-81.92	38.88	500
385253082073401	-82.13	38.88	515
385407082075601	-82.13	38.90	480
395924080400601	-80.67	39.99	1180
394833080480901	-80.80	39.81	580
395025080491501	-80.82	39.84	585
394738080482801	-80.81	39.79	1130
385600081450501	-81.75	38.93	520
385736081462201	-81.77	38.96	540
385922081454301	-81.76	38.99	500
385329081504301	-81.85	38.89	504
401638080364301	-80.61	40.28	590

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
401819080355901	-80.60	40.31	600
402003080360501	-80.60	40.33	590
402620080331901	-80.56	40.44	680
403621080364301	-80.61	40.61	1020
384959082080001	-82.13	38.83	473
385245082025801	-82.05	38.88	619
385419082071701	-82.12	38.91	509
394754080471401	-80.79	39.80	1119
401634080364501	-80.61	40.28	584
400724080354501	-80.60	40.12	1228
400457080433701	-80.73	40.08	598
384848081531901	-81.89	38.81	898
403714080361901	-80.61	40.62	638
403714080361902	-80.61	40.62	638
392359081270001	-81.45	39.40	547
392407081271001	-81.45	39.40	547
392407081271003	-81.45	39.40	547
391551081403201	-81.68	39.26	537
400832080395701	-80.67	40.14	1157
385805082050101	-82.08	38.97	507
385519082061701	-82.10	38.92	567
385416082065801	-82.12	38.90	512
400057080371901	-80.62	40.02	1242
395002080491701	-80.82	39.83	567
392018081301501	-81.50	39.34	786
400234080433501	-80.73	40.04	566
385555081574301	-81.96	38.93	616
385446082061101	-82.10	38.91	566
385421082071801	-82.12	38.91	506
385422082072201	-82.12	38.91	506
394535080453501	-80.76	39.90	576
385420082072101	-82.12	38.91	506
385421082072301	-82.12	38.91	506
385421082072001	-82.12	38.91	506
392407081271002	-81.45	39.40	545
391356081334701	-81.56	39.23	545
391301081312501	-81.52	39.22	515
400857080404601	-80.68	40.15	1185
400910080390401	-80.65	40.15	755
400723080391401	-80.65	40.12	1105
400453080433701	-80.73	40.08	615
385039082082001	-82.14	38.84	475
385027082083201	-82.14	38.84	475
384813082050901	-82.09	38.80	500
384814082050901	-82.09	38.80	500
390033081592401	-81.99	39.01	485

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
385812081560201	-81.93	38.97	495
385823082050201	-82.08	38.97	485
385830081562901	-81.94	38.98	510
385454082024301	-82.05	38.92	545
395646080451101	-80.75	39.95	595
395647080450901	-80.75	39.95	595
395312080451001	-80.75	39.89	1165
394909080485401	-80.81	39.82	565
385741081463001	-81.77	38.96	515
385123081425001	-81.71	38.86	555
392401081265901	-81.45	39.40	545
395337080401901	-80.67	39.89	1274
391550081403401	-81.68	39.26	534
384744082043001	-82.07	38.80	494
384745082041801	-82.07	38.80	494
385837081560001	-81.93	38.98	494
385501082064201	-82.11	38.92	504
385533082054401	-82.10	38.93	554
391613081400801	-81.67	39.27	536
390848081441101	-81.74	39.15	513
400734080354401	-80.60	40.13	1083
400213080380501	-80.63	40.04	1253
385125082080901	-82.14	38.86	473
385007082075001	-82.13	38.84	474
385753081554301	-81.93	38.96	513
385857081570301	-81.95	38.98	503
385533082054402	-82.10	38.93	553
385533082054403	-82.10	38.93	553
385330081555501	-81.93	38.89	498
401622080322101	-80.54	40.27	1153
403224080343501	-80.58	40.54	853
394228080443201	-80.74	39.71	1182
385132082081001	-82.14	38.86	492
385750082045801	-82.08	38.96	472
385451082063501	-82.11	38.91	527
385732081460701	-81.77	38.96	532
385339081502801	-81.84	38.89	522
385340081502701	-81.84	38.89	522
391612081385401	-81.65	39.27	541
400658080420404	-80.70	40.12	561
400714080421302	-80.70	40.12	581
385533082054404	-82.10	38.93	551
385245082025802	-82.05	38.88	611
400049080423401	-80.71	40.01	1151
395300080405602	-80.68	39.88	711
385309081512201	-81.86	38.89	511

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
392400081273401	-81.46	39.40	520
390819081435501	-81.73	39.14	510
400811080405101	-80.68	40.14	990
400652080402801	-80.67	40.11	1110
400658080420401	-80.70	40.12	586
400700080400301	-80.67	40.12	1110
400707080421401	-80.70	40.12	570
400742080392501	-80.66	40.13	1100
400555080381001	-80.64	40.10	990
400648080384101	-80.64	40.11	1170
400445080430501	-80.72	40.08	570
400205080434302	-80.73	40.03	555
385128082080601	-82.13	38.86	495
385202082080801	-82.14	38.87	473
385202082080802	-82.14	38.87	473
385202082080803	-82.14	38.87	473
384951081561801	-81.94	38.83	730
384955082052601	-82.09	38.83	510
385024081550901	-81.92	38.84	830
385034082081701	-82.14	38.84	470
385924081565701	-81.95	38.99	490
390048082020901	-82.04	39.02	490
390051082020801	-82.04	39.02	490
385752081555101	-81.93	38.96	515
385800082050204	-82.08	38.97	500
385808081555101	-81.93	38.97	510
385808081555102	-81.93	38.97	510
385918081563801	-81.94	38.99	510
385549082055801	-82.10	38.93	535
385727082052801	-82.09	38.96	500
385506082050901	-82.09	38.92	530
385338081562001	-81.94	38.89	520
395649080452901	-80.76	39.95	580
395650080453201	-80.76	39.95	580
394831080464001	-80.78	39.81	580
394834080473001	-80.79	39.89	620
394925080485501	-80.82	39.82	585
395003080433901	-80.73	39.83	1280
394737080470001	-80.78	39.79	1120
385500081494001	-81.83	38.92	570
385720081460601	-81.77	38.96	530
385740081461801	-81.77	38.96	530
385328081503101	-81.84	38.89	530
402433080351901	-80.59	40.41	640
402518080353601	-80.59	40.42	645
403648080373701	-80.63	40.61	590

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
400658080420402	-80.70	40.12	559
385718082051201	-82.09	38.96	502
385728082052001	-82.09	38.96	514
385516082062401	-82.11	38.92	559
392227081280201	-81.47	39.37	708
400658080420403	-80.70	40.12	558
400718080420401	-80.70	40.12	568
400649080374501	-80.63	40.11	1268
385206082044401	-82.08	38.87	618
385740081553805	-81.93	38.96	509
385740081553802	-81.93	38.96	507
385536082060201	-82.10	38.93	558
395847080385801	-80.65	39.98	1138
395847080385901	-80.65	39.98	1138
385705081454101	-81.76	38.95	523
385706081454001	-81.76	38.95	523
390202081423101	-81.71	39.03	618
391548081402401	-81.68	39.26	537
391555081405001	-81.68	39.27	517
401056080403101	-80.68	40.18	637
384920082070001	-82.12	38.82	473
385016082081301	-82.14	38.84	467
385920081581901	-81.97	38.99	497
385725082052201	-82.09	38.96	502
385510081592801	-81.99	38.92	597
394639080435101	-80.73	39.78	617
385702081453901	-81.76	38.95	522
385703081453801	-81.76	38.95	522
385705081454001	-81.76	38.95	522
391548081403001	-81.67	39.26	536
385207082075301	-82.13	38.87	486
385212082080801	-82.13	38.87	466
385920081581501	-81.97	38.99	496
385728081552901	-81.92	38.96	506
385223082080801	-82.13	38.87	466
394611080455201	-80.76	39.77	1206
385741081460901	-81.77	38.96	526
385920081581903	-81.97	38.99	490
385752081584201	-81.98	38.96	625
385650082050801	-82.09	38.95	525
395346080401901	-80.67	39.90	1215
403038080332401	-80.56	40.51	875
391547081402201	-81.67	39.26	534
391603081402901	-81.67	39.27	537
385128082080801	-82.14	38.86	494
390041082022501	-82.04	39.01	471

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
390110081595301	-82.00	39.02	469
385721081552501	-81.92	38.96	504
385721081552801	-81.92	38.96	504
395735080384801	-80.65	39.96	1204
403643080341801	-80.57	40.61	604
385726081553201	-81.93	38.96	503
385740081553801	-81.93	38.96	507
385613081494401	-81.83	38.94	523
400048080423601	-80.71	40.01	1143
395437080384301	-80.65	39.91	1242
390013082022901	-82.04	39.00	472
385751081554601	-81.93	38.96	502
395601080451901	-80.76	39.93	542
395610080452501	-80.76	39.94	542
395651080452902	-80.76	39.95	572
394800080473301	-80.79	39.80	1132
385420081502601	-81.84	38.91	517
391252081414501	-81.70	39.21	761
385753081554501	-81.93	38.96	501
391929081325201	-81.55	39.32	540
391931081325001	-81.55	39.32	540
391931081325002	-81.55	39.33	540
391931081325003	-81.55	39.33	540
392242081282701	-81.47	39.38	570
391357081404101	-81.68	39.23	560
391518081411901	-81.69	39.26	520
391522081404901	-81.68	39.26	520
391300081312501	-81.52	39.22	500
400925080415001	-80.70	40.16	560
400951080385701	-80.65	40.16	790
400825080374101	-80.63	40.14	1140
400833080404601	-80.68	40.14	1200
400900080350201	-80.58	40.15	1220
400450080370201	-80.62	40.08	1140
400210080420701	-80.70	40.04	780
385047082041301	-82.07	38.85	590
384923081572201	-81.96	38.82	825
384028082043101	-82.08	38.67	825
385800082050201	-82.08	38.97	490
385800082050202	-82.08	38.97	490
385800082050203	-82.08	38.97	490
385558081545301	-81.91	38.93	500
385655081595901	-82.00	38.95	630
385740081553803	-81.93	38.96	507
385430082043301	-82.08	38.91	510
385448082033901	-82.06	38.91	490

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
385526082062801	-82.11	38.92	530
385527082060001	-82.10	38.92	550
385339081561801	-81.94	38.89	510
395921080390902	-80.65	39.99	1160
395927080381301	-80.64	39.99	1160
395946080391202	-80.65	40.00	1145
395606080452001	-80.76	39.94	550
395608080452301	-80.76	39.94	540
395646080451201	-80.75	39.95	580
395655080453101	-80.76	39.95	550
395502080444201	-80.74	39.92	580
395058080444201	-80.74	39.92	580
395243080423401	-80.71	39.88	890
394854080473001	-80.79	39.82	600
394950080490701	-80.82	39.83	555
385556081500901	-81.84	38.93	500
402535080313001	-80.52	40.43	740
402942080361501	-80.60	40.50	600
403225080344101	-80.58	40.54	850
403629080380701	-80.64	40.61	580
395944080393401	-80.66	40.00	1144
400810080400001	-80.67	40.14	1138
385712082051601	-82.09	38.95	498
383832082035001	-82.06	38.64	708
394904080470901	-80.80	39.82	568
391355081403201	-81.68	39.23	547
400943080365301	-80.61	40.16	844
395506080410601	-80.68	39.92	1177
391031081445201	-81.75	39.18	531
391031081445301	-81.75	39.18	531
400715080393001	-80.66	40.12	1026
400644080362301	-80.61	40.11	1226
385646081551301	-81.92	38.95	511
385335081561801	-81.94	38.89	506
395606080451101	-80.75	39.94	536
392149081295801	-81.50	39.36	535
391403081402501	-81.67	39.23	575
400455080393801	-80.66	40.08	1135
385439081582001	-81.97	38.91	595
385530082060301	-82.10	38.93	545
385241081551001	-81.92	38.88	475
395914080385401	-80.65	39.99	1155
395204080420302	-80.70	39.87	1255
391012081444701	-81.75	39.17	524
385418082064001	-82.11	38.91	494
403447080394601	-80.66	40.58	614

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
391340081405601	-81.68	39.23	513
385413082064301	-82.11	38.90	493
384819082050901	-82.09	38.81	469
385538082045801	-82.08	38.93	507
395132080422801	-80.71	39.86	1182
385503082064001	-82.11	38.92	491
395832080393001	-80.66	39.98	1171
395610080451301	-80.75	39.94	571
391546081401301	-81.67	39.26	525
400950080334301	-80.56	40.16	910
400812080414901	-80.70	40.14	970
400653080371301	-80.62	40.11	1230
400636080381501	-80.64	40.11	1130
384854082065001	-82.11	38.82	470
384624082053801	-82.09	38.77	500
385900082035001	-82.06	38.98	455
385447082033301	-82.06	38.91	480
385503082064002	-82.11	38.92	490
395127080403501	-80.68	39.86	1160
395143080451101	-80.75	39.86	1200
395207080412201	-80.69	39.87	1170
395207080420702	-80.70	39.87	1180
394413080444501	-80.75	39.74	1220
402255080364001	-80.61	40.38	550
385453082063001	-82.11	38.91	504
403444080394501	-80.66	40.58	609
385039081551901	-81.92	38.84	828
385655082050001	-82.08	38.95	513
385445082061001	-82.10	38.91	558
394903080490301	-80.82	39.83	559
385514081495801	-81.83	38.92	527
400652080370201	-80.62	40.11	1231
400213080382501	-80.64	40.04	1186
385739082045801	-82.08	38.96	486
385522082052401	-82.09	38.92	500
385522082052402	-82.09	38.92	500
385524082054401	-82.10	38.92	526
395943080390701	-80.65	40.00	1116
384906082070601	-82.12	38.82	435
384815082053001	-82.09	38.80	465
385545082054102	-82.09	38.93	525
385522082053001	-82.09	38.92	525
395731080390901	-80.65	39.96	1215
395358080402401	-80.67	39.90	1215
395204080420301	-80.70	39.87	1245
401810080351401	-80.59	40.30	485

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
402958080363301	-80.61	40.50	565
402959080363401	-80.61	40.50	565
400450080373101	-80.63	40.08	1164
402014080315201	-80.53	40.34	1024
391444081410601	-81.68	39.25	543
395438080384201	-80.64	39.91	1223
400837080374802	-80.63	40.14	996
385528081495001	-81.83	38.92	542
403434080394301	-80.66	40.58	602
394845080441001	-80.74	39.81	1230
391626081244901	-81.41	39.27	610
400820080395801	-80.67	40.14	1180
400837080374801	-80.63	40.14	980
400404080371601	-80.62	40.07	1080
384742082042401	-82.07	38.80	465
384743082042601	-82.07	38.80	465
385649081595701	-82.00	38.95	610
385526082052801	-82.09	38.92	494
395855080440001	-80.73	39.98	540
395837080392501	-80.66	39.98	1190
395852080435901	-80.73	39.98	540
395853080440001	-80.73	39.98	540
395423080454801	-80.80	39.91	605
385357081500001	-81.83	38.90	520
401110080344201	-80.58	40.19	1110
402127080360101	-80.60	40.36	860
403235080343801	-80.58	40.54	860
394738080470001	-80.78	39.79	1088
385845081555501	-81.93	38.98	453
395837080392401	-80.66	39.98	1188
400150080382201	-80.64	40.03	1167
391929081254401	-81.43	39.32	595
400311080383801	-80.64	40.05	595
384940082003401	-82.01	38.83	755
385845082032701	-82.06	38.98	485
385452082062201	-82.11	38.91	490
395148080460501	-80.77	39.86	1165
394837080441401	-80.74	39.81	1225
394748080470201	-80.78	39.80	1165
384904082040001	-82.07	38.82	534
402404080352901	-80.59	40.40	563
391416081402201	-81.67	39.24	592
403631080380801	-80.64	40.61	554
391422081374401	-81.63	39.24	620
391242081294901	-81.50	39.21	670
400828080360401	-80.60	40.14	1110

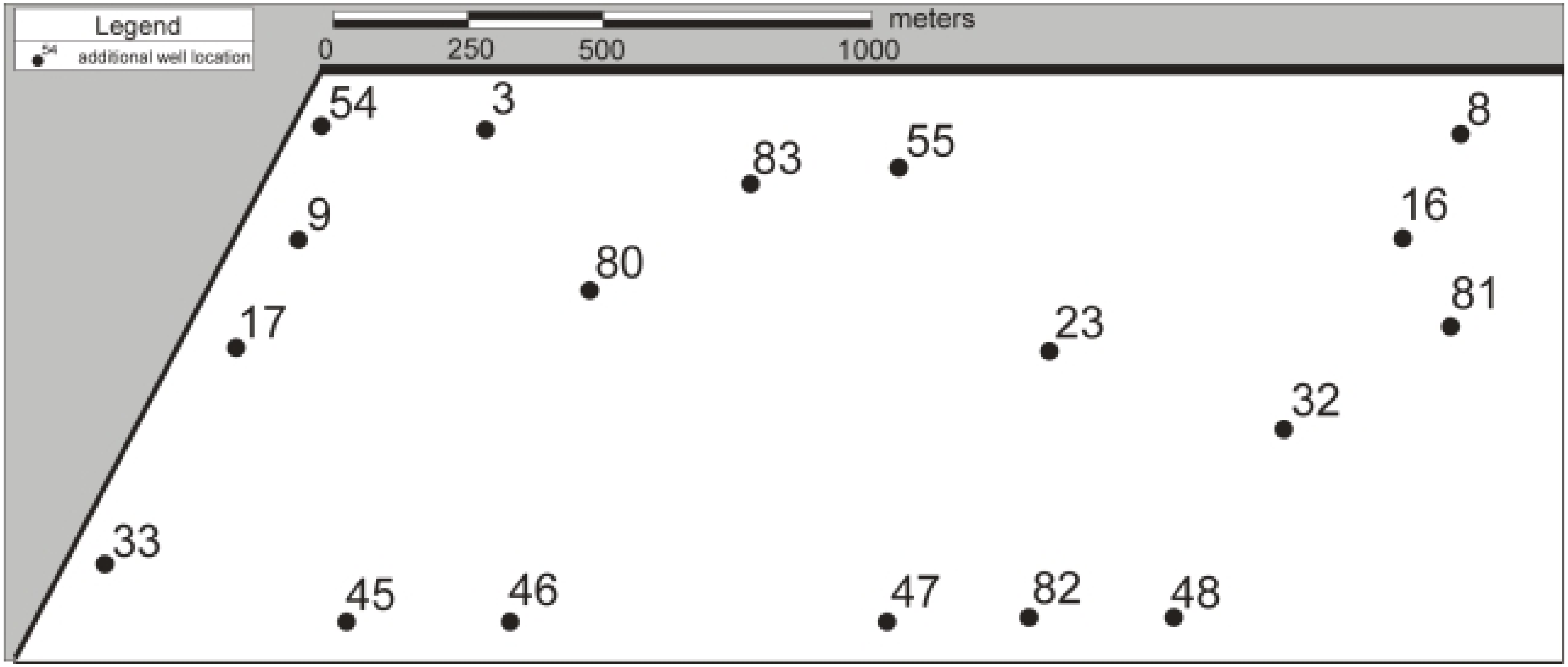
USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
400714080421301	-80.70	40.12	510
400724080394501	-80.66	40.12	1090
385029081591001	-81.99	38.84	545
385029081591301	-81.99	38.84	545
385551081593901	-81.99	38.93	570
385346081584401	-81.98	38.90	660
385400081591001	-81.99	38.90	770
383858082041801	-82.07	38.65	620
400104080370602	-80.62	40.02	1180
395815080431501	-80.72	39.97	1090
395830080395101	-80.66	39.98	1170
395836080393501	-80.66	39.98	1130
385150081493501	-81.83	38.86	470
385450082062001	-82.11	38.91	484
385451082062001	-82.11	38.91	484
385238081555601	-81.93	38.88	448
385124082080901	-82.14	38.86	457
400032080381302	-80.64	40.01	586
384723082035601	-82.07	38.79	531
385520082054901	-82.10	38.92	505
400756080395801	-80.67	40.13	1125
384730082034101	-82.06	38.79	430
384810082051501	-82.09	38.80	445
384811081541701	-81.90	38.80	680
385204081505701	-81.85	38.87	645
402406080352701	-80.59	40.40	555
403200080322401	-80.54	40.53	1115
385623082010901	-82.02	38.94	553
385522082044801	-82.08	38.92	483
395220080422501	-80.71	39.87	1173
385522082061201	-82.10	38.92	501
395833080392601	-80.66	39.98	1160
390539081443301	-81.74	39.09	480
385238081560001	-81.93	38.88	440
400116080403701	-80.68	40.02	1090
385633081453001	-81.76	38.94	443
400024080380601	-80.63	40.01	600
402307080353801	-80.59	40.39	948
395538080395901	-80.67	39.93	1167
395946080391201	-80.65	40.00	1102
391250081312001	-81.52	39.21	455
385934081454101	-81.76	38.99	455
400253080385601	-80.65	40.05	553
385101081420101	-81.70	38.85	492
393049081034001	-81.06	39.51	615
393210080544101	-80.91	39.54	693

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
393212081021101	-81.04	39.54	604
391840081124801	-81.21	39.31	824
393210081021401	-81.04	39.54	593
393212081021201	-81.04	39.54	593
392808081055001	-81.10	39.47	635
392003081214001	-81.36	39.33	605
392058081193801	-81.33	39.35	578
393211081021501	-81.04	39.54	582
392310081144001	-81.24	39.39	602
393100081033301	-81.06	39.52	590
392140081184501	-81.31	39.36	557
392023081212001	-81.36	39.34	556
393203080555501	-80.93	39.53	695
393241081012401	-81.02	39.54	573
392911081024001	-81.04	39.49	693
392834081061101	-81.10	39.48	553
392315081124001	-81.21	39.39	572
392933081052301	-81.09	39.49	572
392856081055901	-81.10	39.48	565
391908081142501	-81.24	39.32	701
393213081021201	-81.04	39.54	575
392628081085001	-81.15	39.44	565
391931081190101	-81.32	39.33	600
392023081212601	-81.36	39.34	550
392059081113901	-81.19	39.35	640
392310081142501	-81.24	39.39	580
393211081021701	-81.04	39.54	564
392830081060601	-81.10	39.48	569
392229081151901	-81.26	39.37	619
393403080593401	-80.99	39.57	568
393502080581401	-80.97	39.58	568
392149081182601	-81.31	39.36	562
392022081213901	-81.36	39.34	547
392022081213201	-81.36	39.34	547
392853081054801	-81.10	39.48	586
393213081021301	-81.04	39.54	565
392344081065501	-81.12	39.40	984
393129081025601	-81.05	39.52	573
393213080572301	-80.96	39.54	723
392150081182701	-81.31	39.36	543
393212081021601	-81.04	39.54	562
391958081074101	-81.13	39.33	772
392240081071301	-81.12	39.38	592
393145081024201	-81.04	39.53	560
393359080511201	-80.85	39.57	740
392557081010901	-81.02	39.43	590

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
392800081062501	-81.11	39.47	585
392846081053101	-81.09	39.48	600
392024081210401	-81.35	39.34	560
392057081194001	-81.33	39.35	560
392425081052601	-81.09	39.41	560
392019081212301	-81.36	39.34	569
392755081062001	-81.11	39.47	578
392842081054501	-81.10	39.48	608
393130081025201	-81.05	39.53	566
392529081100001	-81.17	39.42	576
392201081144501	-81.25	39.37	566
392515081110701	-81.19	39.42	577
392624081090401	-81.15	39.44	545
392625081080801	-81.14	39.44	560
393158081022301	-81.04	39.53	562
392227081164001	-81.28	39.37	582
393214081021001	-81.04	39.54	550
392205081171701	-81.29	39.37	590
392227081170301	-81.28	39.37	560
392230081163502	-81.28	39.38	545
393211081021201	-81.04	39.54	550
392334081121502	-81.20	39.39	567
392334081121501	-81.20	39.39	567
392944081050401	-81.08	39.50	550
393330081000201	-81.00	39.56	625
392536081105201	-81.18	39.43	555
392246081155401	-81.26	39.38	545
392346081120101	-81.20	39.40	565
392714081044401	-81.08	39.45	964
392535081105901	-81.18	39.43	543
393304080595101	-81.00	39.55	612
393607080562601	-80.94	39.60	562
392503081110901	-81.19	39.42	572
392611081041401	-81.07	39.44	522
392247081154901	-81.26	39.38	547
392447081112601	-81.19	39.41	572
393228080534801	-80.90	39.54	660
393338080595001	-81.00	39.56	610
392500081112001	-81.19	39.42	560
392554081101301	-81.17	39.43	550
392633081074501	-81.13	39.44	541
392901081055201	-81.10	39.48	530
392008081215001	-81.36	39.34	560
392014081215901	-81.37	39.34	420
392144081180601	-81.30	39.36	550
392207081172501	-81.29	39.37	540

USGS Alluvial Well ID	Longitude	Latitude	Bedrock Surface Elevation (feet)
392208081172301	-81.29	39.37	540
392252081153201	-81.26	39.38	547
392143081180001	-81.30	39.36	555
392443081112801	-81.19	39.41	565
392256081153101	-81.26	39.38	544
393133081024701	-81.05	39.53	553
393245080541601	-80.90	39.55	633
392823081061001	-81.10	39.47	528
392230081163501	-81.28	39.38	531
393230080540701	-80.90	39.54	630
392810081061801	-81.10	39.47	550
392049081160201	-81.27	39.35	910
392350081115901	-81.20	39.40	560
392953081045601	-81.08	39.50	547
392254081153801	-81.26	39.38	527
392555081100501	-81.17	39.43	546
392240081153301	-81.26	39.38	524
393133081014201	-81.03	39.53	920
393213081020701	-81.04	39.54	560
392858081054701	-81.10	39.48	510
392348081031001	-81.05	39.40	567
393105081032801	-81.06	39.52	525
392023081205501	-81.35	39.34	510
391716081153001	-81.26	39.29	660
392751081061201	-81.10	39.46	504
392148081175501	-81.30	39.36	508
392509081095501	-81.17	39.42	916
393358080564901	-80.95	39.57	944
392741081041901	-81.07	39.46	898
393225080532501	-80.89	39.54	549
393324081001401	-81.00	39.56	494
393203081021201	-81.04	39.53	463
393056081033201	-81.06	39.52	470
392617081064501	-81.11	39.44	878
393505080593301	-80.99	39.58	412
392832081001001	-81.00	39.48	465

APPENDIX II



Additional well locations used to determine dominant source components for the alluvial aquifer bounded by two intersecting streams.

Well ID	Distance from river (meters)	Distance from tributary (meters)
54	100	50
3	100	300
8	100	2000
55	150	1025
83	200	900
9	300	100
16	300	2000
81	370	2100
80	400	700
17	500	100
23	500	1500
32	500	2000
33	900	100
45	1100	500
46	1100	1000
47	1100	1500
48	1100	2000
82	1100	1750

Distances of the additional well locations from the river and tributary stream reaches.

Source water component volumes and percentages for the additional simulated well locations.

Well ID	Flux (m^3/d)				% of total discharge				Simulation ID
	R_A	R_{BR}	I_{RI}	I_{TR}	R_A	R_{BR}	I_{RI}	I_{TR}	
54	408.1	336.0	686.8	286.2	23.8	19.6	40.0	16.7	Type A
3	493.0	480.1	744.1	0.0	28.7	28.0	43.3	0.0	
55	583.1	561.6	572.4	0.0	34.0	32.7	33.3	0.0	
83	663.3	595.9	457.9	0.0	38.6	34.7	26.7	0.0	
9	595.0	492.5	171.7	457.9	34.7	28.7	10.0	26.7	
80	788.6	814.0	114.5	0.0	45.9	47.4	6.7	0.0	
17	650.0	609.2	0.0	457.9	37.9	35.5	0.0	26.7	
23	703.8	1013.3	0.0	0.0	41.0	59.0	0.0	0.0	
33	788.6	814.0	114.5	0.0	45.9	47.4	6.7	0.0	
45	663.6	881.8	0.0	171.7	38.6	51.4	0.0	10.0	
46	624.2	1092.9	0.0	0.0	36.4	63.6	0.0	0.0	
8	412.4	1133.0	171.7	0.0	24.0	66.0	10.0	0.0	Type B
16	343.6	1373.5	0.0	0.0	20.0	80.0	0.0	0.0	
32	243.8	1215.7	0.0	257.6	14.2	70.8	0.0	15.0	
81	348.7	1368.4	0.0	0.0	20.3	79.7	0.0	0.0	
47	176.7	424.3	0.0	1116.1	10.3	24.7	0.0	65.0	
48	162.0	1555.1	0.0	0.0	9.4	90.6	0.0	0.0	
82	158.3	1558.8	0.0	0.0	9.2	90.8	0.0	0.0	

APPENDIX III

References for the "*Source Water Assessment, Delineation, and Protection Plan*" of the 26 previously modeled public water supply systems in West Virginia.

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