EFFECT OF UNCERTAINTY IN RECHARGE AND TRIBUTARY BASIN FLOW ESTIMATE ON PARAMETER ESTIMATION FOR THE SPOKANE VALLEY-RATHDRUM PRAIRIE (SVRP) AQUIFER

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Abstract

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Spokane Valley-Rathdrum Prairie (SVRP) aquifer is the sole source of drinking water to more than 500,000 residents in Spokane County, Washington, and Bonner and Kootenai Counties, Idaho. A model was developed, by employing MODFLOW 2000, to simulate the flow in the SVRP aquifer so that it can be used by regulators and policy makers in decision making with regard to management of this resource. Among the inflows to the aquifer, the recharge and tributary basin flow estimates can be considered to be most uncertain. The objective of this work has been to evaluate the effect of uncertainty in recharge and tributary basin flow estimates on parameter estimation. The evaluation was accomplished by calibrating the model with variable recharge and tributary basin flow estimates. It was found that the primary parameter of concern, hydraulic conductivity of layer 1, increased, in general, with increasing recharge and tributary basin flows. A quantitative expression was developed to relate these variations to the hydraulic conductivity which allows estimation of the parameter for any variation in inflows between -10% and 10%.

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1. INTRODUCTION

Discovered in 1895, the Spokane Valley-Rathdrum Prairie (SVRP) aquifer has turned out to be one of the most important water resources in northern Idaho and northeastern Washington. The US Environmental Protection Agency (EPA) designated this aquifer as a “Sole Source Aquifer” in 1978 (Federal Registrar, 1978). The US EPA (2012) defines such an aquifer as one that supplies at least 50 percent of the drinking water consumed in the area overlying the aquifer to communities which do not have a viable alternative drinking-water source. Several thousand gallons of water per minute can be extracted from the SVRP aquifer rendering it a highly productive one (Hsieh et al., 2007). It serves as the sole source of potable water to more than 500,000 inhabitants within the region of Spokane County, Washington, and Bonner and Kootenai Counties, Idaho. These counties comprise of the cities of Spokane, Spokane Valley, and Liberty Lake of Washington, and Coeur d’Alene and Post Falls of Idaho (Kahle et al., 2007). All of these cities have been subjected to recent rapid expansion of urban, suburban, and industrial/commercial sectors. Similar expansion is also anticipated in the near future. Such expansion is accompanied by increased groundwater abstraction. The average daily water withdrawal from the aquifer is about 146 million gallons (City of Spokane Water Department, 2014). In an attempt to evaluate the impacts of increasing ground-water withdrawal within this area, a comprehensive study of the groundwater flow in the SVRP aquifer was executed in 2004. The study was aimed at providing a scientific basis for efficient management of the aquifer. One of the significant components of the study was to develop a groundwater flow model (Hsieh et al., 2007).

Hsieh et al. (2007) developed a groundwater flow model using MODFLOW-2000 for simulating groundwater flow in the SVRP aquifer from 1990 to 2005. MODFLOW-2000 is a computer program that provides numerical solution to the three-dimensional ground-water flow equation for a porous medium using the finite-difference method (Harbaugh et al., 2007).

Development of the model requires identification and quantification of all the inflows to and outflows from the aquifer. Areal recharge from precipitation constitutes a significant inflow to the aquifer. Areal recharge estimation is, however, quite challenging and is, often, the most uncertain component groundwater flow models. Measurement of areal recharge over large areas is virtually impossible (Bartolino, 2007). The SVRP aquifer also receives inflow from higher altitude regions known as the tributary basins, which are immediately adjacent to the aquifer. This is also an uncertain component of the inflow. Its 67% confidence interval, typically, ranges from 0.4 to 1.6 times the estimated value (Hsieh et al., 2007).

Hsieh et al. (2007) presented a calibrated model for particular recharge and tributary basin flow with the indication that there could be other alternative flow models of similar predictive capability. A systematic analysis of the impact of anticipated variability in areal recharge and tributary basin flow on calibrated parameters is not, however, available. The primary objective of this research has been to evaluate the impact of variability in recharge and tributary basin flow on calibrated hydraulic parameters of the aquifer, primarily horizontal hydraulic conductivity of layer 1.

2. GENERAL DESCRIPTION OF THE AREA

Extent of the area of the SVRP aquifer considered for this study encompasses about 326 mi^2 area that spans from the southern end of Lake Pend Oreille of Idaho and extends westward across the Washington−Idaho state line to near Nine Mile Falls northwest of the City of Spokane, Washington (Kahle et al., 2005). Nine lakes are located along the periphery of the model area as shown in Fig. 1. Lake Pend Oreille and the Coeur d'Alene Lake are the two largest ones among these lakes. Other lakes are the Fernan Lake, the Hauser Lake, the Hayden Lake, the Liberty Lake, the Newman Lake, the Twin Lakes and the Spirit Lake.

Land surface altitude within the study area varies from about 2,600 feet (ft) at the north to about 1,500 ft at the western reach near the Long Lake. The land overlying the aquifer is primarily used for agriculture and urban development. Agricultural land is predominantly used for pasture and for producing grass seeds, barley, wheat, and oats. Major urban areas include the Spokane metropolitan area in Washington and Coeur d'Alene and Post Falls in Idaho. The upland areas surrounding the aquifer area are mostly covered with evergreen trees and residential housing.

Climate changes from subhumid to semiarid condition characterized by warm, dry summers and cool, moist winters (Molenaar, 1988). Among weather stations in the area, mean annual (1981-2010) precipitation ranges from 16.59 in. at the Spokane International Airport, Washington to 34.61 in. at Sandpoint, Idaho (Western Regional Climate Center, 2014).

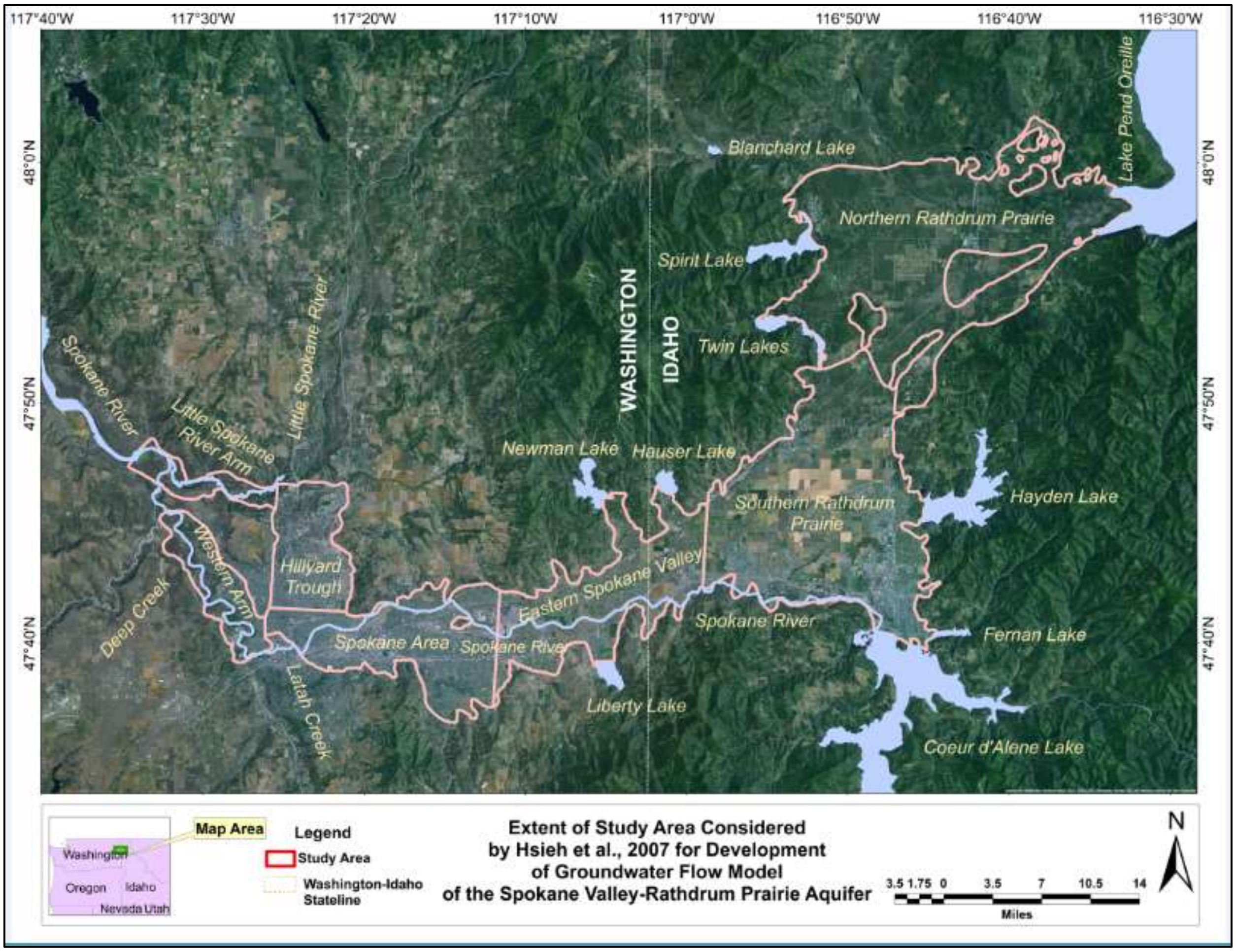


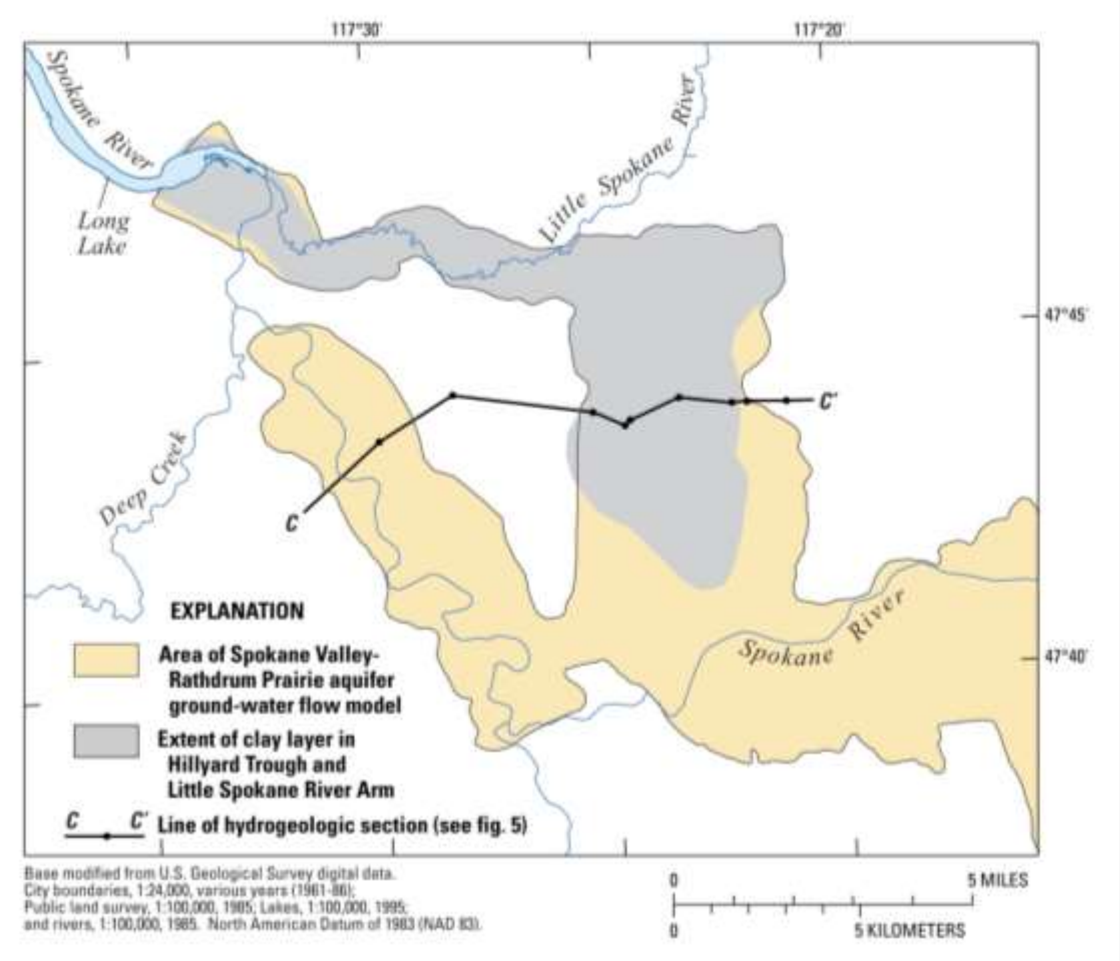
Fig. 1: Extent of the Groundwater Flow Model of the Spokane Valley-Rathdrum Prairie Aquifer Considered by Hsieh et al., 2007

3. THE AQUIFER SYSTEM

The SVRP aquifer system is comprised of three layers. The uppermost layer is the unconfined aquifer. It covers the entire area. The other two layers, a confining layer and a confined aquifer, are of limited extent, which cover only the Hillyard Trough and the Little Spokane Arm areas, as shown in Fig. 1, on the western portion of the aquifer system. The confining layer separates the upper unconfined aquifer from the lower confined aquifer.

The unconfined aquifer primarily comprises of thick layers of coarse-grained sediments such as gravels, cobbles, and boulders (Kahle et al., 2005). Altitude of the base of aquifer varies from about 1,800 ft at the aquifer's origin near Lake Pend Oreille to a little less than 1,200 ft at the aquifer's outlet near Long Lake (Kahle et al., 2007). Hsieh et al. (2007) reported a maximum sediment thickness of about 800 ft in northern Rathdrum Prairie, 500 ft within the vicinity of Washington-Idaho State line, and 700 ft in Hillyard Trough. Depth to groundwater table from land surface in the SVRP aquifer ranges from near land surface to more than 500 ft (Bolke et al., 1979; Berenbrock et al., 1995; Briar et al., 1996; Stone et al., 1996; MacInnis et al., 2000). The largest depth to groundwater occurs in northern Rathdrum Prairie and the shallowest depth, less than 50 ft, is observed near Spokane along the Spokane River (Kahle et al., 2005).

The confining bed is comprised of fine grained soil. Hsieh et al. (2007) referred this layer as the "clay layer" because of its low-permeability characteristics. Areal and vertical extent of this clay layer is depicted in Fig. 2 and 3 respectively. Average thickness of the clay layer is estimated to be 215 ft in Hillyard Trough and 130 ft in the Little Spokane River Arm (Kahle and Bartolino,



Base modified from U.S. Geological Survey digital data.
City boundaries, 1:24,000, various years (1961-86);
Public land survey, 1:100,000, 1985; Lakes, 1:100,000, 1995;
and rivers, 1:100,000, 1985. North American Datum of 1983 (NAD 83).

Fig. 2: Areal Extent of Clay Layer in the Hillyard Trough and the Little Spokane River Arm (from Hsieh et al., 2007)

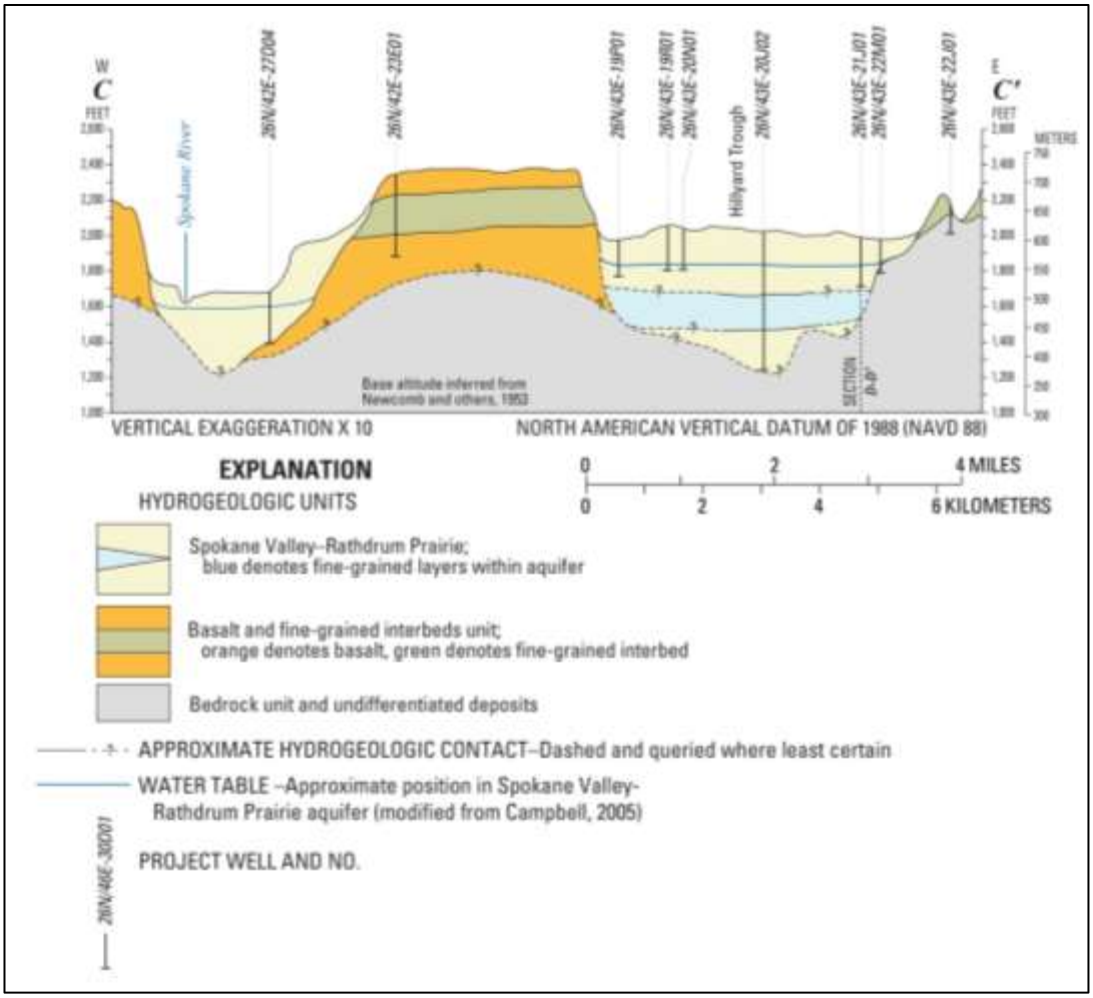


Fig. 3: Hydrogeologic Section of the Spokane Valley-Rathdrum Prairie Aquifer along C-C′ of Fig. 2 (from Kahle and Bartolino, 2007)

2007). Altitude of the top of this clay layer ranges from 1,660 to 1,720 ft at Hillyard Trough, and from 1,500 to 1,700 ft at the Little Spokane River Arm (Hsieh et al., 2007).

4. GROUNDWATER FLOW EQUATION

The following is the generalized equation to describe groundwater flow.

$$\frac{\partial\left(K_{xx}\frac{\partial h}{\partial x}\right)}{\partial x}+\frac{\partial\left(K_{yy}\frac{\partial h}{\partial y}\right)}{\partial y}+\frac{\partial\left(K_{zz}\frac{\partial h}{\partial z}\right)}{\partial z}+W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

In the above equation, K_{xx} is the hydraulic conductivity along the x direction, K_{yy} is the hydraulic conductivity in the y direction, K_{zz} is the hydraulic conductivity in the z direction, h is the hydraulic head, W is volumetric flux representing sources or sinks of water, t is the time, and S_s is the specific storage.

5. SIMULATIING GROUNDWATER FLOW

Groundwater flow is simulated by solving the Eq. 1 numerically. MODFLOW developed by the U. S. Geological Survey (McDonald and Harbaugh, 1988) is one of the most frequently used simulators. The model is designed to simulate flow in multilayered aquifer systems under a variety of boundary conditions and external stresses. It has become the industry standard groundwater flow simulator and is used extensively by regulators and the consulting industry for groundwater resource management and remediation of contaminated aquifers.

MODFLOW requires hydraulic parameters – hydraulic conductivity and storage coefficients, inflow to the aquifer, outflow from the aquifer, initial conditions, and boundary conditions specific to the aquifer system as input to provide the numerical solution.

5.1 Hydraulic Properties

Bolke and Vaccaro (1981) reported a value of about 6000 ft/d for horizontal conductivity in the Post Falls area, about 4300 ft/d in the Spokane Valley, about 2,600 ft/d near Spokane, and about 860 ft/d in the Hillyard Trough and the Little Spokane River Arm. CH2M Hill (1998) reported a range of 100 ft/d to 6,200 ft/d for the west half of the aquifer. Drost and Seitz (1978) reported a transmissivity of 130,000 ft^2/d at the western part aquifer with 13×10^6 ft^2/d adjacent to the Washington – Idaho state line. Storage coefficient was reported to range from 0.1 – 0.2 by Bolke and Vaccaro (1981).

Hsieh et al. (2007) reported a range of 5 – 22,100 ft/d calibrated horizontal hydraulic conductivity for the unconfined aquifer and a range of 207 – 2,000 ft/d for the confined aquifer. Specific yield, the storage coefficient of the unconfined aquifer was reported to range from 0.10 – 0.21.

5.2 Inflows to and Outflows from the Aquifer

Six inflows were considered to develop the SVRP groundwater flow model developed by Hsieh et al. (2007). The inflows are the recharge from precipitation, flows from tributary basins and adjacent uplands, subsurface seepage and surface overflow from lakes along the periphery of the aquifer, flow from losing segments of the Spokane River, return percolation from irrigation, and effluent from septic systems. Major outflows were identified to be withdrawals from wells, flow into the gaining segments of the Spokane River, groundwater outflow to the Little Spokane River and subsurface outflow from the western extreme of the aquifer to the Long Lake.

6. MODEL DISCRETIZATION

The model domain is discretized before MODFLOW can be employed to solve Eq. 1 by using all the associated conditions – initial and boundary. Discretization is also necessary to properly simulate the spatial variability of the input parameters and the inflows to and outflow from the aquifer. The model domain was divided into smaller cells consisting 172 rows and 256 columns. The cells were 1320 ft by 1320 ft. Aquifer thickness, however, was not subdivided. The model was used for simulation for 181 stress periods, each of one month length, from September 1990 to September 2005. It is to be noted that zonation technique was applied to properly simulate spatial variability of hydraulic parameters. A complete treatment of discretization and zonation can be found in Hsieh et al. (2007).

7. PARAMETER ESTIMATION

Hydraulic conductivity of an aquifer or a geological formation is, often times, the most uncertain parameter. An acceptable estimate of this kind of uncertain parameters is normally obtained by adjusting the parameters in such a way that model predictions closely match measured quantities in the field. The measured quantities are, frequently, the hydraulic heads. Measured gains or losses for different segments of the Spokane River and the Little Spokane River were also used. A total 1573 hydraulic head measurements and 313 gain or loss measurements were used for this parameter estimation (Hsieh et al., 2007). The parameter estimation process was completed by employing the PEST, the parameter estimation model developed by Doherty (2004). PEST makes use of a nonlinear least-squares regression method for estimation of model parameters while minimizing the following objective function:

$$\Phi = \sum_{i=1}^{N} (w_i r_i)^2 \tag{2}$$

Where, Φ is the objective function which in fact is sum of the squared weighted residuals, *N* is the number of measurements, w_i is the weight for the i th measured quantity, and r_i is the i th residual (i th measured quantity – i th simulated quantity).

8. EFFECT OF UNCERTAINTY IN RECHARGE AND TRIBUTARY BASIN FLOW ON PARAMETER ESTIMATION

The effect of uncertainty in recharge and tributary basin flow on parameter estimation was evaluated by varying the recharge from -10.0% to 10.0% of the recharge used by Hsieh et al. (2007) with the following intermediate steps: -5%, -2.5%, 2.5%, and 5%. For each variation in the recharge, the tributary basin flow was also varied from -10.0% to 10.0% with the same intermediate values. This variability in recharge necessitated a total of 36 runs of the PEST. The results of the PEST were used to evaluate the effect of uncertainty in recharge and tributary basin flow estimation on parameter estimation, principally the horizontal hydraulic conductivity.

9. RESULTS AND DISCUSSION

9.1 Model Bias

A calibrated model is considered valid when weighted residuals are random with a mean of zero. Consequently, the weighted residuals for a calibrated groundwater model when plotted as a function of simulated hydraulic heads or flows should be evenly distributed about zero and should not show any trend. Weighted residuals of hydraulic heads and flows for all the 36 scenarios were plotted, individually, on similar graphs for the calibrated model as a function of the corresponding simulated values. An examination of plots revealed no apparent bias. It was also found that the new weighted residuals were also very similar to that of the original ones. A graph of weighted residuals of hydraulic heads is presented in Fig. 4 for reference. This graph is very typical of the rest. Graphs for all the thirty six scenarios.

9.2 Effect on Horizontal Hydraulic Conductivity

Layer-1 has been divided into 22 zones, as shown in Fig. 5, to reflect the observed variability in horizontal conductivity. The hydraulic conductivities are HK1-1 through HK1-22. Hsieh et al. (2007) mentioned that, during their model calibration, calibration data were insensitive to HK1-21. As a result, this parameter was assigned with a fixed value from practical considerations rather than estimation by regular calibration process, and thus did not experience any impact due to uncertainty in areal recharge and tributary basin flow. Calibrated values of all other conductivities for the 36 conditions were analyzed to assess their variability in relation to the values reported by Hsieh et al. (2007). The largest positive deviation was observed to be 20.68% for HK1-15 corresponding to -10% change in areal recharge and -10% change in tributary basin flow. This zone, zone 15, is adjacent to the Fernan and the Coeur d’Alene lakes. The maximum

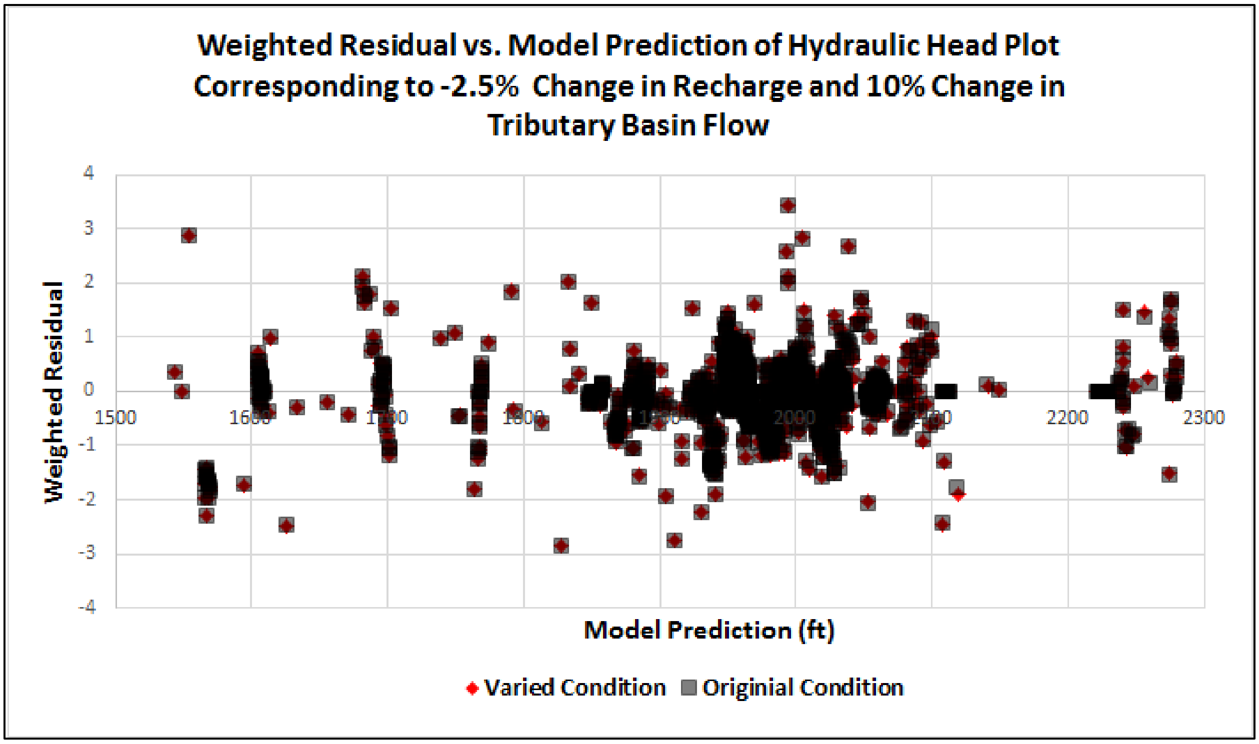


Figure 4: Weighted Residual vs. Model Prediction Plot for Hydraulic Head in the Aquifer

negative deviation of 15.50% was observed for HK1-11, for zone 11, corresponding to -2.5% change in areal recharge and -10% change in tributary basin flow. Zone 11 is adjacent to the Long Lake.

Fig. 6 presents the distribution of monitoring points for flows and hydraulic heads. Flows and hydraulic heads data collected from these points were used for the calibration. Zones 11 and 15 have very few monitoring points. The calibration process estimates the hydraulic conductivity by minimizing the difference between observed and predicted hydraulic head and flows. When there are only few monitoring points in a zone, it is possible for the calibration process to provide a significantly varying estimate of conductivity in response to changes in recharge and tributary basin flows. It can further be influenced by the complex interaction with the neighboring zones.

Linear regression analysis was performed to establish a relationship between calibrated hydraulic conductivities and varying recharge and tributary basin flows. A trend of increasing hydraulic conductivity with increasing recharge and tributary basin flows was generally observed except for zones 9, 11, 15, and 17. An increasing trend is expected for the fact that when there is more flow into the aquifer, the calibration process can minimize the residual only by increasing the hydraulic conductivity to make the predicted hydraulic head smaller and closer the observed value. For zones 9, 11, and 15, calibrated hydraulic conductivities decrease with increasing recharge and tributary basin flows. This decreasing trend is difficult to explain. The calibrated hydraulic conductivity for zone 17, however, increases with increasing recharge and decreases with increasing tributary basin flows. This apparent anomaly can be attributed to the fact that there is no monitoring well at zone 17. Therefore, for zone 17, the calibrated hydraulic

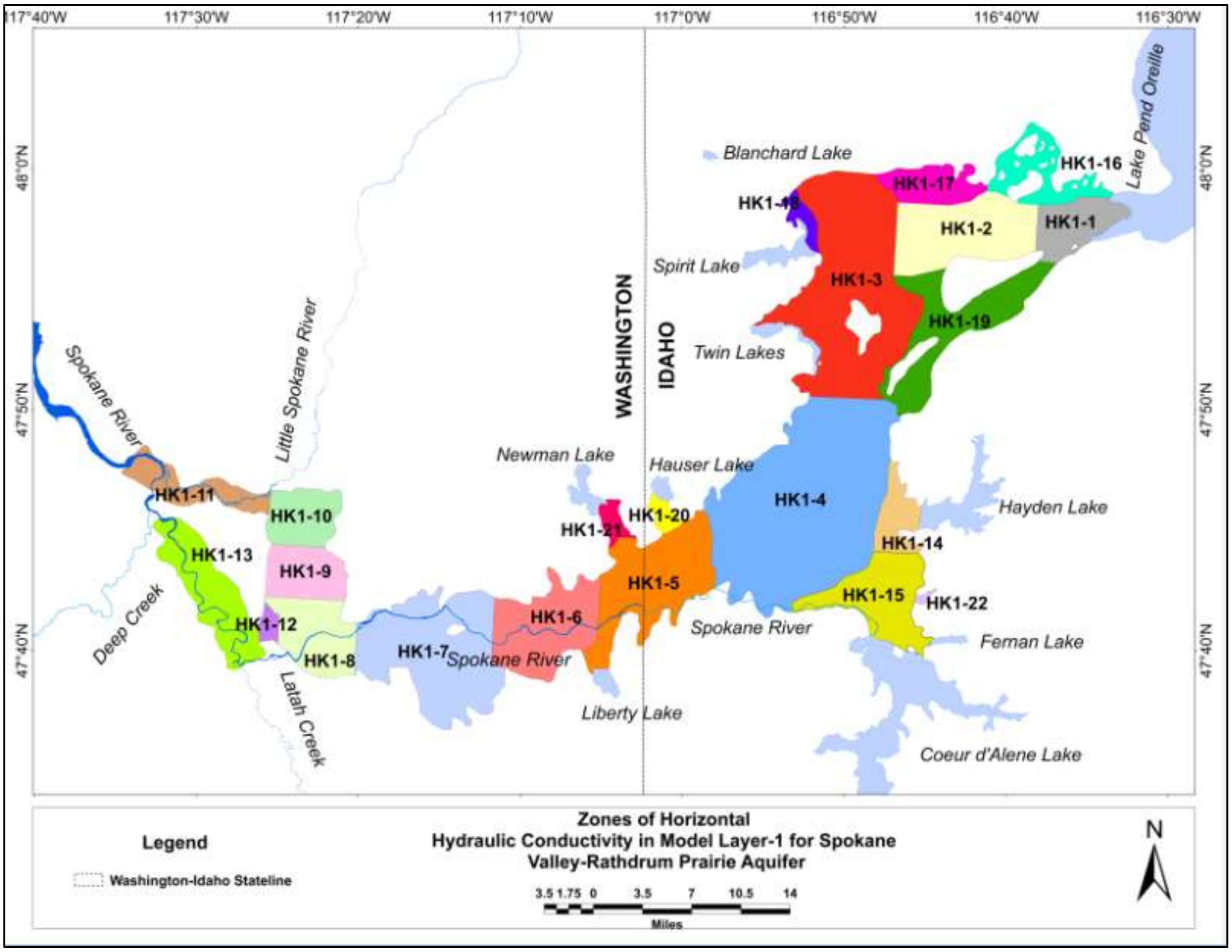


Figure 5: Zones of Horizontal Hydraulic Conductivity in Model Layer-1 for Spokane Valley-Rathdrum Prairie Aquifer (after Hsieh et al., 2007)

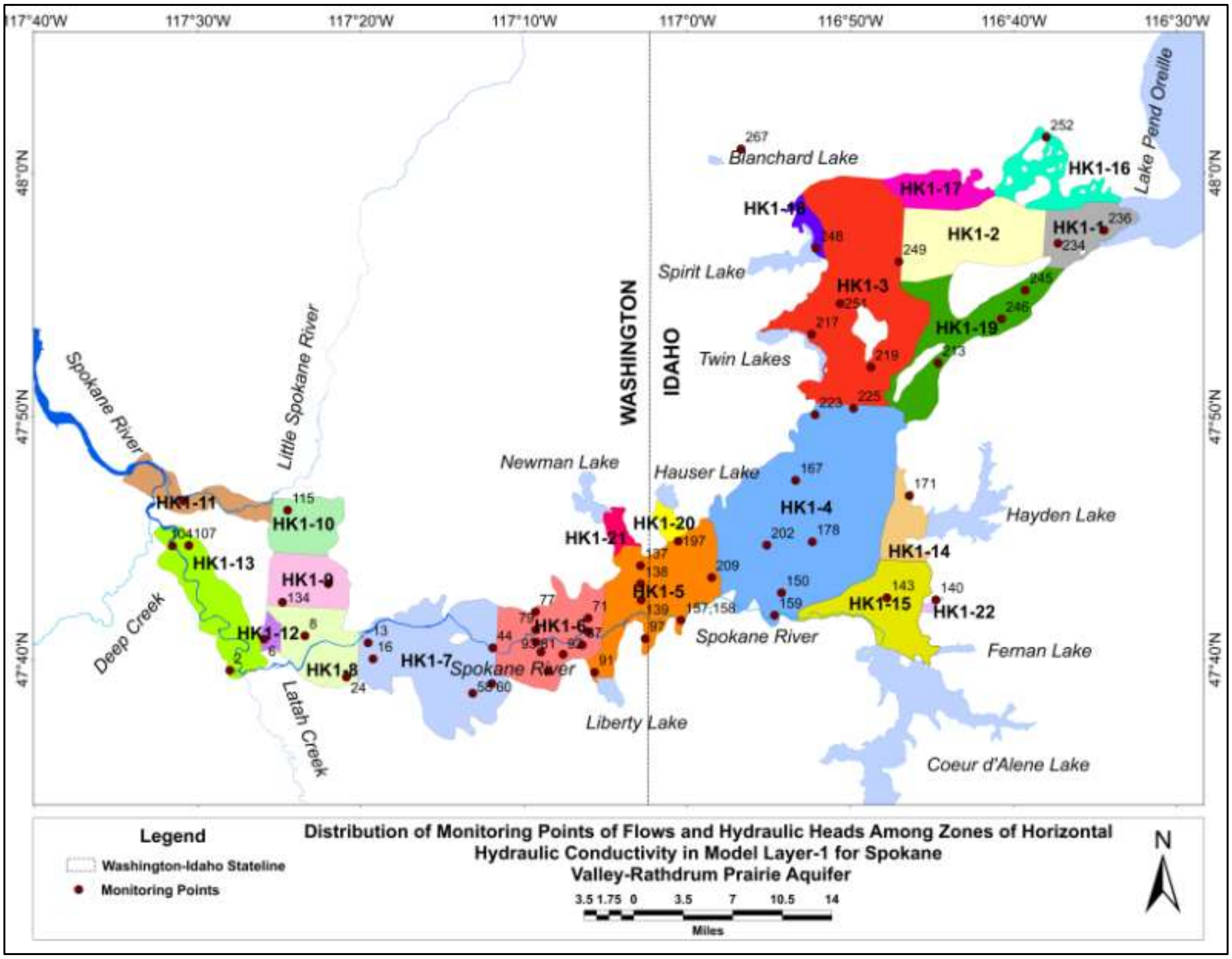


Figure 6: Distribution of Monitoring Points of Flows and Hydraulic Heads Among Zones of Horizontal Hydraulic Conductivity in Model Layer-1 for Spokane Valley-Rathdrum Prairie Aquifer (after Hsieh et al., 2007)

conductivity will be defined by the overall calibration for the whole aquifer, in general, and by the calibration of the neighboring zones, in particular.

The linear regression analysis led to the development of the following equation relating calibrated hydraulic conductivity with changes in recharge and tributary basin flows.

$$HK1 = aR + bT + c \tag{3}$$

Where, $HK1$ is the hydraulic conductivity of layer 1, R is the percent change in recharge, T is the percent change tributary basin flow, with a, b, and c as constants specific to a zone. Constants a, b, and c for layer 1 is provided in Table 1. These values can be used to estimated $HK1$ for any zone of layer 1 and for any anticipated variation in the recharge and tributary basin flows between -10% and 10%. It is evident from the table that tributary basin flow imparts greater influence on this parameter.

Recharge and tributary basin flow are direct input to layer 1. These are not expected to have significant impact on hydraulic conductivities of layer 2 and layer 3. In fact, an analysis of the hydraulic conductivity for layer 3 of all the 36 scenarios confirmed this expectation.

Table 1: Coefficients and Intercept of Multiple Linear Regression for Horizontal Hydraulic Conductivity in Model Layer-1

Location	Coefficient for % Variation in Areal Recharge	Coefficient for % Variation in Tributary Basin Flow	Intercept of Multiple Linear Regression
1	26.32690476	197.047746	13086.12784
2	13.19365079	62.56149683	6187.138432
3	68.13574603	207.7361587	17122.60973
4	11.68104762	28.91085714	12085.77919
5	5.354031746	28.49869841	22132.11486
6	9.066904762	26.78153968	19080.08189
7	4.899979365	12.46306825	7462.883216
8	16.53233492	34.42073968	9496.568189
9	-2.442871429	-2.025655556	2628.162514
10	0.119339683	0.387890476	2181.842189
11	-0.193719048	-0.334460317	1985.480595
12	1.952960794	3.945236667	607.0581189
13	9.172242857	18.24814762	3105.665838
14	0.00484246	0.683762127	89.55535405
15	-8.75207619	-14.86919841	1280.176838
16	0.149722873	0.389891873	54.52772946
17	0.057116265	-0.009394508	4.914867757
18	0.009152968	0.746658873	77.96435784
19	0.167887333	0.779577794	94.68182135
20	0.026441032	0.513784127	64.30984378
22	0.193901429	1.251345397	140.1787892

10. CONCLUSION

For most of the locations of the SVRP aquifer, horizontal hydraulic conductivity in model layer 1 demonstrated a general increasing trend with increasing recharge and tributary basin flows. A quantitative relation was established between these variations of inflow and the hydraulic conductivity which enables computation of the parameter under different varying conditions. Tributary basin flow seemed to have greater influence on estimation of the parameter. This expression can be utilized to estimate the hydraulic conductivity, reasonably accurately, for any variation of recharge and tributary basin flow between -10% and 10%.

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