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A Stream Depletion Factor for the State of Oklahoma

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Student Status	Number	Disciplines
Undergraduate	2	Biosystems and Agricultural Engineering
M.S.		
Ph.D.	1	Biosystems and Agricultural Engineering
Post Doc		
Total	3	Biosystems and Agricultural Engineering

ABSTRACT

Extracting ground water from pumping wells located adjacent to streams can reduce streamflow, known as alluvial well depletion. Primary factors influencing stream-aquifer interaction during alluvial well depletion are the hydrologic properties of the aquifer, the degree of penetration of the stream into the aquifer, and a potential streambed layer with a hydraulic conductivity different than the aquifer conductivity. While the water policy within the state of Oklahoma fails to consider streamflow depletion by groundwater extraction within alluvial systems, a methodology can be developed to assess the importance of this policy limitation. Significant research in the last several years has improved the capability of hydrologists to analyze stream/aquifer interaction during alluvial well depletion through the development of analytical solutions; however, these solutions become mathematically complex. Evaluation of these solutions using field data from multiple regions is needed to assess existing and recently proposed solutions' applicability and predictive capability.

The objective of this research was to develop an Oklahoma stream depletion factor for analyzing the impact of stream depletion of surface water by ground water pumping. Tasks included the following: (1) measuring streambed conductivity in specific stream reaches of two major alluvial river systems in the state of Oklahoma (i.e., North Canadian River and Washita River) using grain size analyses and/or falling head permeameter tests; (2) developing a database of geologic characterization (i.e., depth and extent of the alluvial aquifer) and aquifer parameters for the North Canadian and Washita River alluvial aquifers; (3) long-term monitoring of stream and ground water levels during both recharge and pumping conditions in order to conduct stream/aquifer analysis tests, to evaluate existing analytical solutions, and to determine applicability of the solutions at one field site within each alluvial aquifer; and (4) developing a stream depletion worksheet based on improved analytical solutions for estimating stream depletion by ground water pumping.

In-situ streambed hydraulic conductivity (at both the site of interest and along a several mile reach upstream and downstream of the site) and stream-aquifer analysis tests conducted on the North Canadian River and Washita River in central Oklahoma provided field data that supported the use of and the applicability of simpler drawdown and stream depletion analytical solutions. Support for the simpler solutions was largely based on the fact that both rivers behaved similar to streams with little to no hydraulic resistance provided by a streambed layer. It is suggested to use the Hunt (1999) solution for estimating stream depletion in these alluvial aquifers with a large streambed conductance unless measurements of the streambed conductance suggest otherwise. An appropriate method for estimating reach-scale streambed conductance is to conduct stream-aquifer analysis tests. Stream depletion estimates due to the ground water pumping wells were approximately 40-70% of the pumping rate after five days. Both the hydrogeologic and streambed conditions were more heterogeneous at the Washita River site compared to the North Canadian site; therefore, more care needs to be taken in determining characteristic parameters for the Washita alluvial river system along this reach. An Oklahoma Stream Depletion Factor (OSDF) worksheet was developed to allow water managers to determine the impact of a single pumping well discharging at a constant rate on the streamflow in the adjacent river.

STREAM DEPLETION BY GROUND WATER PUMPING: A STREAM DEPLETION FACTOR FOR THE STATE OF OKLAHOMA

I. PROBLEM AND RESEARCH OBJECTIVES

Quantifying surface water and ground water interaction in stream/aquifer systems has become an increasingly critical issue for water quantity and quality management. Extracting ground water from pumping wells located adjacent to streams can reduce stream flow, known as alluvial well depletion. The depletive effects on a stream caused by irrigation wells must be estimated in order to administer water rights in many of the states in the western United States (Fox, 2007). In addition, new water management strategies, such as managed recharge projects, are being utilized throughout the United States to manage stream and ground water supplies. The two primary factors influencing stream/aquifer interaction are the hydrologic properties of the aquifer and a streambed layer with a hydraulic conductivity different than the conductivity in the aquifer (Fox, 2007).

When a stream and aquifer are hydraulically connected, the stream and ground water intimately interchange water. When the water level in the stream is above the water level in the aquifer, water is discharged from the stream and into the aquifer. In this situation, the stream is classified as a losing stream. If the water level in the aquifer is above the water level in the stream, water is discharged from the aquifer into the stream. The stream is then classified as a gaining stream. However, if the water level in the aquifer is below the bottom of the streambed, an unsaturated layer can form underneath the stream. The stream is said to hydraulically disconnect from the aquifer. When ground water pumping occurs, recharge from the stream satisfies the applied stress created by the pumping well causing water to flow from the stream into the aquifer. While the water policy within the state of Oklahoma fails to consider stream/ground water interactions within alluvial systems, a methodology can be developed to assess the importance of this policy limitation.

Methodologies based on analytical solutions are widely applied in administering tributary groundwater rights (Spalding and Khaleel, 1991). For example, the U.S. Geological Survey standardized a procedure for analyzing the timing of flows between an aquifer and stream called the stream depletion factor (SDF). Jenkins (1968) originally developed the SDF in studying stream depletion by groundwater pumping. The SDF was defined as the time [d] when the volume of stream depletion reaches 28% of the total volume pumped. Mathematically, SDF was expressed as

$$SDF = \frac{L^2 S}{T} \tag{1}$$

where L is the perpendicular distance from the pumped well to the stream [m], S is the storage coefficient, and T is the transmissivity of the aquifer [$m^2\ d^{-1}$].

The SDF methodology makes several simplifying assumptions about the flow regime and stream-aquifer characteristics and, in general, makes use of the Theis (1941) solution. The Theis (1941) solution assumed an infinitely long, straight, completely penetrating stream in a homogeneous aquifer, as shown in Figure 1. Changes in water table elevations were assumed small compared to the saturated thickness of the aquifer, leading to the Dupuit flow assumption. No parameters accounted for a semipervious

streambed layer. Applying the principle of superposition, image wells were used to simulate a constant head boundary condition at the stream, and drawdown was given by:

$$s_w(u) = \frac{Q}{4\pi T}\left[E_1(u) - E_1(u_i)\right] \quad (2)$$

where s_w is the drawdown in the semi-infinite domain [m], Q is the pumping rate [$m^3\ d^{-1}$], T is the transmissivity of the aquifer [$m^2\ d^{-1}$], u is the Boltzmann variable, and $E_1(u)$ and $E_1(u_i)$ are the well functions for the real and image well, respectively.

In addressing limitations of the Theis (1941) equation, Hantush (1965) developed an analytical model that considered the effects of a semipervious streambed, a common feature in many alluvial systems (Landon et al., 2001). The semipervious streambed was represented as a vertical layer of lower conductivity material extending throughout the saturated thickness of the aquifer. The Hantush model was based on the principal of additional seepage resistance due to this semipervious layer. Seepage resistance extended the distance between the well and stream by an effective distance. Therefore, the streambed layer of lower hydraulic conductivity created a flow resistance equal to the ratio between the hydraulic conductivity of the aquifer, K [m d^{-1}], and the streambed conductivity, K_{sb} [m d^{-1}], divided by the streambed thickness, M [m]. As noted by Sophocleous et al. (1995) and Conrad and Beljin (1996), the Theis (1941) and Hantush (1965) analytical models failed to adequately represent the physical conditions representative of alluvial aquifer systems (e.g., streams that do not fully penetrate the aquifer).

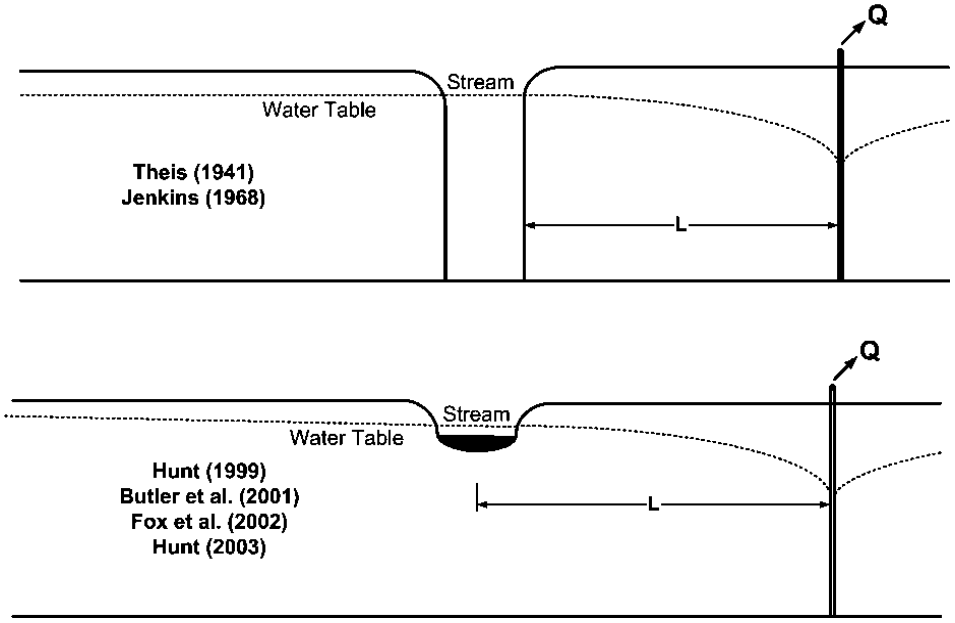


Figure 1. Hydrologic conditions modeled by numerous analytical solutions. Q is the constant discharge rate of the pumping well and L is the distance between the pumping well and stream.

Hunt (1999) developed an analytical model that incorporated streambed conductance and stream partial penetration in the simulation of a groundwater pumping well located near a stream, as shown in Figure 1. Hunt's (1999) model assumed a homogeneous, isotropic aquifer of infinite extent with Dupuit flow. The model also

assumed that changes in water surface elevation due to pumping were small, and vertical and horizontal streambed cross-sections were small compared to the aquifer saturated thickness. Seepage flow rates from the river into the aquifer were assumed linearly proportional to the head gradient between the aquifer and stream, dependent upon the streambed conductance, λ [m d^{-1}]:

$$\lambda = \frac{K_{sb} W}{M} \tag{3}$$

where W is the width of the river (m). The product of λ and the head gradient between the aquifer and river gave the stream leakage per unit length of river. Hunt (1999) derived both a streamflow depletion equation and drawdown equation:

$$\frac{Q_s}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda L}{2T}\right) erfc\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{SL^2}{4Tt}}\right) \tag{4}$$

$$s_w(x,y,t) = \frac{Q}{4\pi T}\left\{E_1\left[\frac{(L-x)^2 + y^2}{4Tt/S}\right] - \int_0^\infty e^{-\theta} E_1\left[\frac{(L+|x|+2T\theta/\lambda)^2 + y^2}{4Tt/S}\right] d\theta\right\} \tag{5}$$

where Q_s is the stream depletion rate [m^3 d^{-1}], E_1 is the well function, S is the aquifer storage coefficient, t is the time since the start of pumping [d], and x and y are the locations within the infinite domain with respect to a datum at the river on a perpendicular line with the well [m]. Additional solutions that expand in complexity have been proposed by Butler et al. (2001) for finite width streams in an aquifer of limited lateral extent, Fox et al. (2002) for finite–width, small streams, Hunt (2003) for semiconfined aquifers, and Chen and Yin (2004) for base flow reduction and stream infiltration.

The benefit of these analytical solutions is that tests can be conducted to simultaneously estimate aquifer and reach-scale streambed parameters in what has been termed a stream-aquifer analysis (SAA) test (Hunt, 1999; Fox, 2004; Fox, 2007). The disadvantage of many of the recent solutions is that most are based on differential equations so mathematically complex that they require numerical inversion of Laplace transforms to derive a semi-analytical solution, with numerous parameters that must be inversely estimated from potentially limited groundwater data.

Predicted K_{sb} from SAA tests has been hypothesized to better represent the spatially variable, reach-scale K_{sb} as opposed to point, in-situ measurements, which can vary significantly for different measurement techniques and across a stream cross-section (Landon et al., 2001; Fox, 2004). However, only a few SAA tests have been documented in the literature and compared to field-measured K_{sb} or λ (e.g., Hunt et al. (2001) in New Zealand, Nyholm et al. (2002) in Denmark, and Fox (2004) in eastern Colorado). Field data from multiple regions are needed to assess the applicability and predictive capability of these analytical solutions.

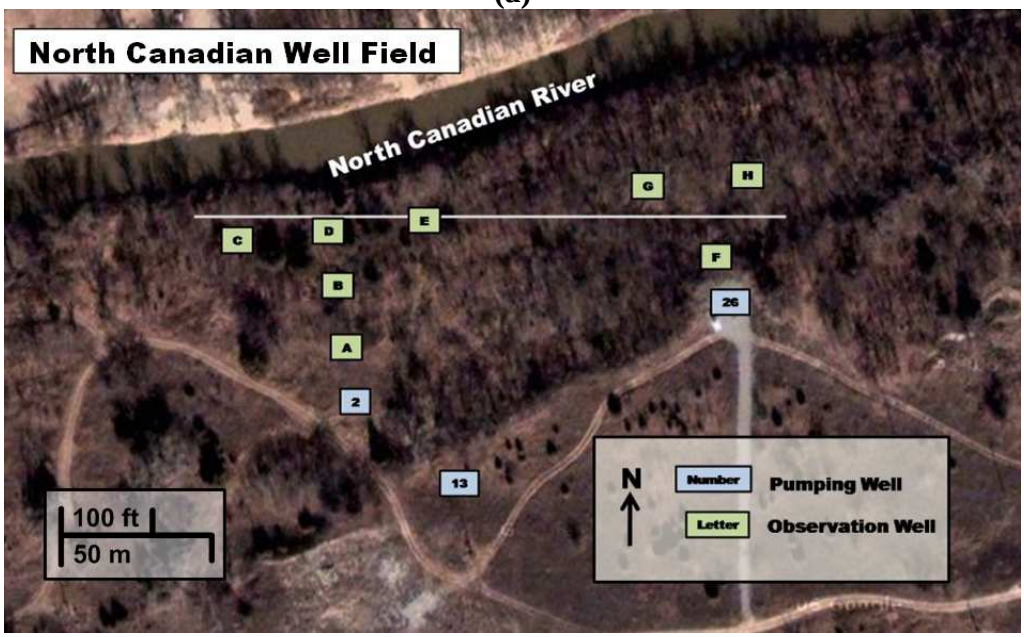
II. METHODOLOGY

2.1 Field Sites

The North Canadian River and Washita River alluvial aquifers were selected for this project due to the magnitude of ground water extractions. The North Canadian River is a sand bed, partially penetrating (incised) stream that does not extend throughout the entire

saturated thickness of the alluvial aquifer. The surface geology is primarily composed of Quaternary alluvial sands and gravels. These deposits are both aeolian and fluvial in origin, usually no more than 15 to 20 m in thickness, and the width extends approximately 1.6 km from the North Canadian River. The specific field site along the North Canadian River for the long-term monitoring and stream-aquifer analysis test was located just north of El Reno, OK (Figure 2).

(a)

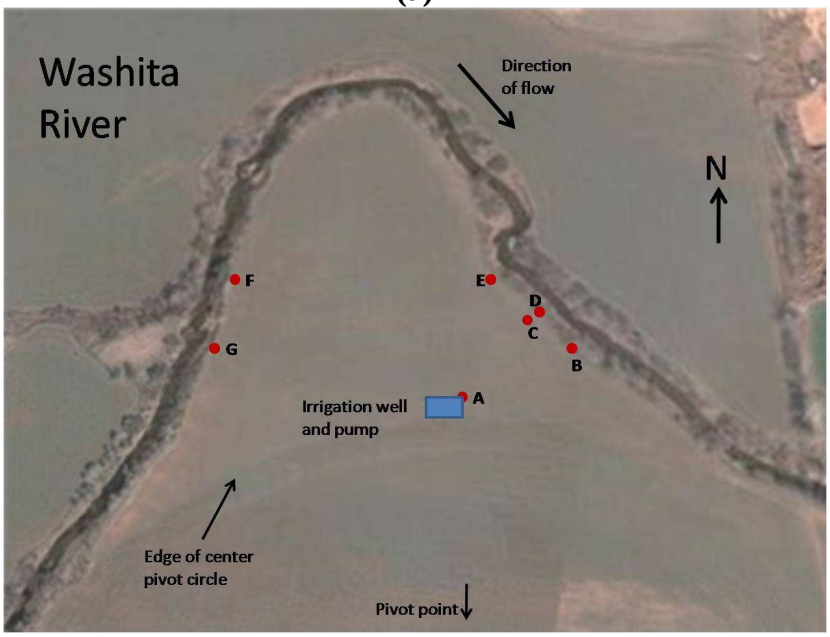


(b)

Figure 2. North Canadian River well field site. Observation wells (letters) were installed around two active pumping wells (#2 and #26). Pumping well #26 was utilized for the stream-aquifer analysis test.

Water from the Washita River alluvium and terraces are used for municipal, irrigation, and industrial uses (Hart, 1965). As discussed by Ryder (1996) and Hart (1965), the alluvium was approximately 64 ft (20 m) thick, consisting of primarily fine-grained sand and clay, and lesser amounts of coarser material. The specific field site along the Washita River for the long-term monitoring and stream-aquifer analysis test was located just north of Clinton, OK (Figure 3).

(a)



(b)

Figure 3. Washita River well field site. Observation wells (letters) were located near the irrigation well and also adjacent to the river to prevent interference with farming operations in the adjacent field.

At both sites, observation wells were installed to a depth of approximately 8 m, constructed of Schedule 40 PVC, and included a 5 m screened section at the base. The observation wells were installed using a Geoprobe (Kejr, Inc., Salina, KS) drilling machine. Drawdown and temperature were measured every 5 minutes using the automated water level loggers (HoboWare, Onset Computer Corp., Cape Cod, MA) installed in each observation well. One logger was also installed in each river to monitor stream stage and temperature.

2.2 Measuring Streambed Conductivity

Streambed sediment samples were acquired from the upper 5 to 10 cm of the streambed and vertical K_{sb} was measured using falling-head permeameter tests near each specific well field and also along a several mile reach upstream and downstream of each site (Figure 4). For the North Canadian site, streambed sediment samples and conductivity measurements at the well field site consisted of three points in the thalweg of the river and two points in sand beds closer to the south bank. At the Washita River well site, streambed sediment samples were obtained at four sampling points: near bank and in the thalweg near observation wells F and G and near observation wells D and E. Falling-head permeameter tests were conducted in the thalweg and near the banks (i.e., in sand bars) of the Washita River at five sampling points. Because of the variability in streambed sediment at the Washita River, falling-head permeameter tests were focused on sampling points that were predominately sand. All reach-scale streambed samples were obtained from near the thalweg of both rivers (Figure 4). Because of the fewer number of sampling sites for the reach-scale Washita River samples, two samples were acquired per sampling site.

Sediment samples were sieved, and the soil texture was determined using ASTM Standard D422-63. The K_{sb} was estimated based on the d_{10} (the effective grain diameter, mm) and d_{50} (the median grain diameter, mm) using the Alyamani and Sen (1993) equation:

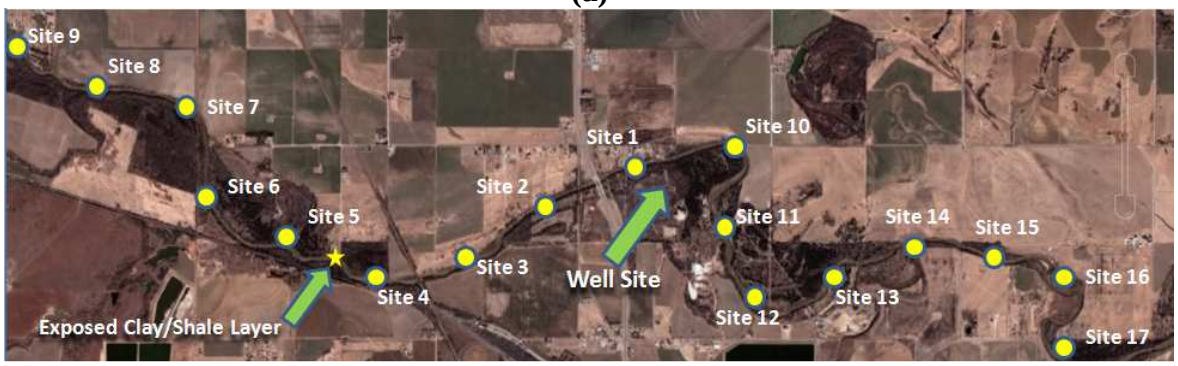
$$K_{sb} = 1300\left[I_o + 0.025\left(d_{50} - d_{10}\right)\right]^2 \tag{6}$$

where I_o is the intercept (mm) of the line formed by d_{50} and d_{10} with the grain-size axis. Permeameter tests were performed by pushing a pipe partially into the streambed (10 to 20 cm) and adding water to induce a hydraulic gradient on the sediments inside the pipe (Figure 5). The water level inside the pipe was allowed to fall while the water level was measured over time. Vertical K_{sb} was calculated using an application of Darcy's equation (Landon et al., 2001; Fox, 2004):

$$K_{sb} = \frac{d}{\left(t - t_0\right)} \ln\left(\frac{H_0}{H(t)}\right) \tag{7}$$

where $H(t)$ is the water level elevation above the stream level at various times during the experiment, t_0 is the initial time, H_0 is the initial water level elevation in the pipe above the stream water level, d is the sediment interval being tested (10 to 20 cm), and t-t_0 is the elapsed time. Each test was performed for at least 5 minutes with measurements of the head inside the pipe approximately every 30 s. Equation (7) was solved for K_{sb} using the t versus $H(t)$ data by minimizing the sum of squared errors (SSE) between measured and predicted $H(t)$.

(a)



(b)

Figure 4. Locations of reach-scale measurements of streambed hydraulic conductivity at the (a) North Canadian River site and (b) Washita River site.

2.3 Hydrogeologic Cross-Sections and Aquifer Parameters

Information was compiled to create generalized hydrogeologic cross sections and the critical alluvial aquifer parameters within the specific stream reaches of interest along the North Canadian River and Washita River. These parameters included the aquifer transmissitivity (hydraulic conductivity and saturated thickness) and the storage coefficient or specific yield. Well logs reported through the Oklahoma Water Resources Board's Water Information Mapping System (WIMS, http://www.owrb.ok.gov/maps/server/wims.php) were used to determine variability in hydrogeologic cross-sections in wells near the selected field sites.

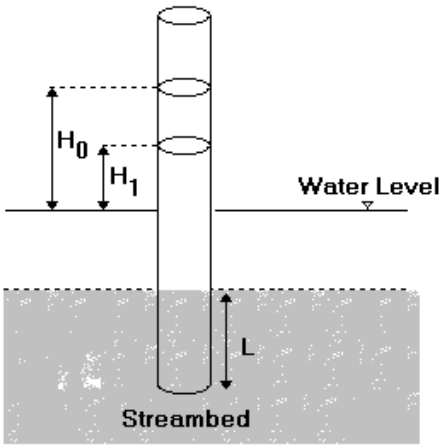


Figure 5. Schematic diagram of falling head permeameter used to measure vertical streambed hydraulic conductivity.

2.4 Long-Term Monitoring and Stream-Aquifer Analysis Tests

For several months prior to the stream-aquifer analysis tests at each site, water levels were monitored in the observation wells every 5 to 15 minutes. This data assisted in determining the most optimal time for the stream-aquifer analysis test and to determine the most suitable observation wells for the test.

At the North Canadian River site (Figure 2), pumping well 2 was pumped continuously; therefore, pumping well 26 was used for the stream-aquifer analysis test with the assumption of a constant, minimum interference between the wells. Pumping well 26, located approximately 85 m from the North Canadian River, discharged water at a constant rate of 2180 m^3/d for 90 hrs from October 18 to 22, 2009 after being off for approximately four days. The drawdown response due to this groundwater extraction was measured in observation wells F, G and H as shown in Figure 2. Spatial locations relative to a coordinate origin at the river and on a perpendicular line with the well are provided in Table 1.

Table 1. Coordinate locations of the pumping and observation wells utilized in the stream-aquifer analysis test along the North Canadian River and Washita River. The origin of the coordinate systems is at the river on a perpendicular line with the well.

Site	Well Identification (Figure 2)	*x* (m)	*y* (m)	*Q* (m^3/d)
North Canadian River	26	85	0	2180
	F	70	0	---
	G	41	-15	---
	H	50	19	---
Washita River	Irrigation Well	200	0	2728
	F	35	50	---
	G	25	-100	---

At the Washita River site, hydrologic conditions were complicated by numerous factors: (1) greater hydrogeologic variability, (2) the site was within a meander bend, and (3) the irrigation well did not pump at a steady, constant rate. The hydraulic gradient was typically directed from observation well A to observations wells B, C, D, and E, even during pumping, which violates the assumption of existing, transient stream depletion models. Future work must be devoted to developing analytical solutions for the condition of base flow reduction through reducing the ground water gradient. Therefore, the stream-aquifer analysis test focused on observation wells G and F, during a time period of August 8-9, 2010 and a pumping rate of 500 gpm (2728 m^3/d) for the irrigation well located approximately 200 m from the stream. Spatial locations for this site are also provided in Table 1.

Predicted drawdown using the Hunt (1999) solution was fit to the observed drawdown measured in the observation wells for each test site. The Hunt (1999) solution required estimates of T, S_y, and λ. Parameter estimates where derived by attempting to minimize the difference between the predicted and observed drawdown. A quantitative index based on an acceptance criterion as quantified by a normalized objective function (*NOF*) (Pennell et al., 1990; Hession et al., 1994) was utilized. The NOF is the ratio of the standard deviation of differences (*STDD*) to the overall mean (X_a) of the observed parameter. The NOF has been used in the past for model evaluation (Pennell et al., 1990; Hession et al., 1994; Fox et al., 2006). In general, 1%, 10%, and 50% deviations from the observed values results in NOF values of 0.01, 0.10, and 0.50, respectively. Inverse estimation was deemed acceptable when minimizing the NOF.

For the Hunt (1999) solution which utilizes partial differential equations for confined flow as estimates for unconfined flow (valid when the drawdown is small compared to the saturated thickness), the fit was confined to the late-time drawdown data as delayed yield effects were neglected. This procedure is reasonable in cases where the goal is to predict aquifer and streambed parameters for long-term water management (Fox, 2004). Using parameter estimates, stream depletion due to ground water pumping during the stream-aquifer analysis test was predicted.

2.5 Development of a Stream Depletion Worksheet

The final task of this project was to develop an Oklahoma Stream Depletion Factor (OSDF) worksheet based on the results of the earlier tasks. The OSDF is an automated solution tool that solves for stream depletion by a pumping well based on Hunt's (1999) solution shown in equation (4). The OSDF is based in Excel, allowing the user to easily input the streambed conductance (λ), aquifer parameters (T, S_y), the pumping rate (Q), and the location of the pumping well relative to the stream (L). The program will then estimate the stream depletion in terms of stream infiltration into the alluvial aquifer.

III. PRINCIPLE FINDINGS AND SIGNIFICANCE

3.1 Measuring Streambed Conductivity

3.1.1 North Canadian River

All streambed sediment samples in the North Canadian River were classified as coarse sand. Approximately 99% of each of the five streambed samples was sediment with particle sizes greater than 0.075 mm (Figure 6). The Alyamani and Sen (1993) equation estimated K_{sb} as approximately 30 m/d based on d_{50} = 0.37 mm and d_{10} = 0.19 mm. Streambed K_{sb} estimates from the falling-head permeameters had low variability (i.e., coefficient of variation of 0.2) for this reach of the North Canadian River (Figure 7), especially compared to previous data sets reported in the literature (Landon et al., 2001; Fox, 2004). Only small differences were estimated in thalweg versus edge of channel (i.e., sand bar) measurements. The three thalweg permeameter tests estimated K_{sb} in the range of 13.9 to 20.6 m/d, with the K_{sb} estimated for the sand bars within this range (i.e., 14.6 and 19.0 m/d).

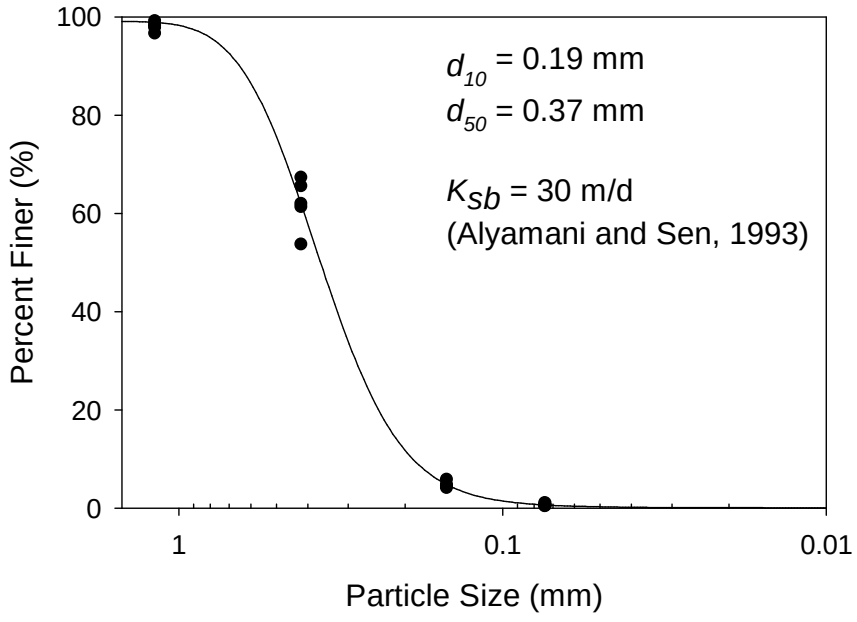


Figure 6. Grain-size distribution measured from five streambed sediment samples in the North Canadian River. The best-fit trend line was used to derive the representative grain size diameters (d_{10}, and d_{50}).

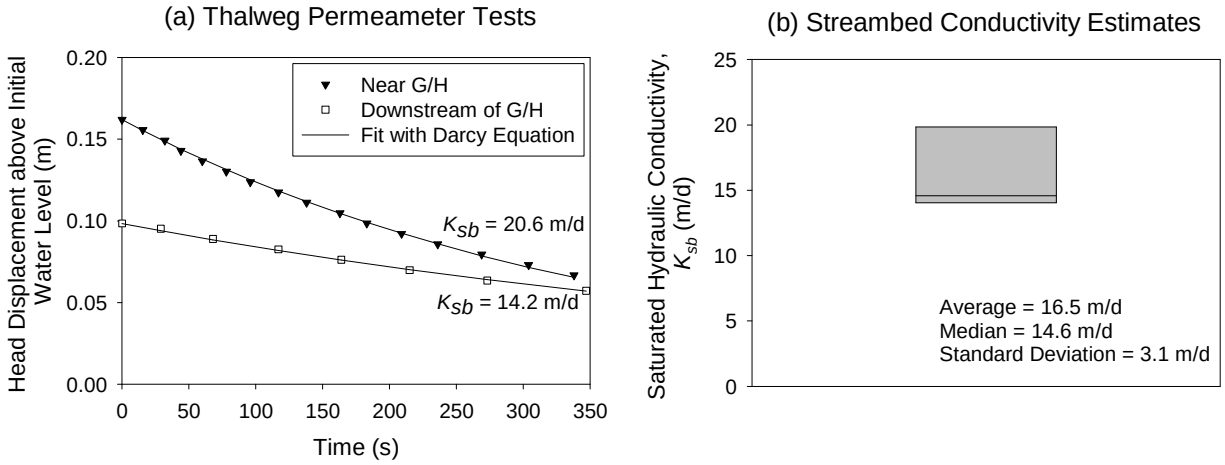


Figure 7. (a) Data from the streambed hydraulic conductivity, K_{sb}, measurements using falling-head permeameter tests in the North Canadian River including the resulting fit of the data with the Darcy equation. (b) Box plot of K_{sb} measurements for both thalweg and sand bar measurements.

Reach-scale K_{sb} estimates were similar to those measured at the specific North Canadian field site. The grain-size distributions from the streambed samples were relatively uniform within the study reach with approximately equivalent d_{10} and d_{50} to the samples at the field site (Figure 8). One exception was an exposed shale/clay layer upstream of the site, with samples from this location not included in the analysis (Figure 4). Falling-head permeameter tests along this reach of the North Canadian River suggested even higher K_{sb} than previous tests (Figure 9).

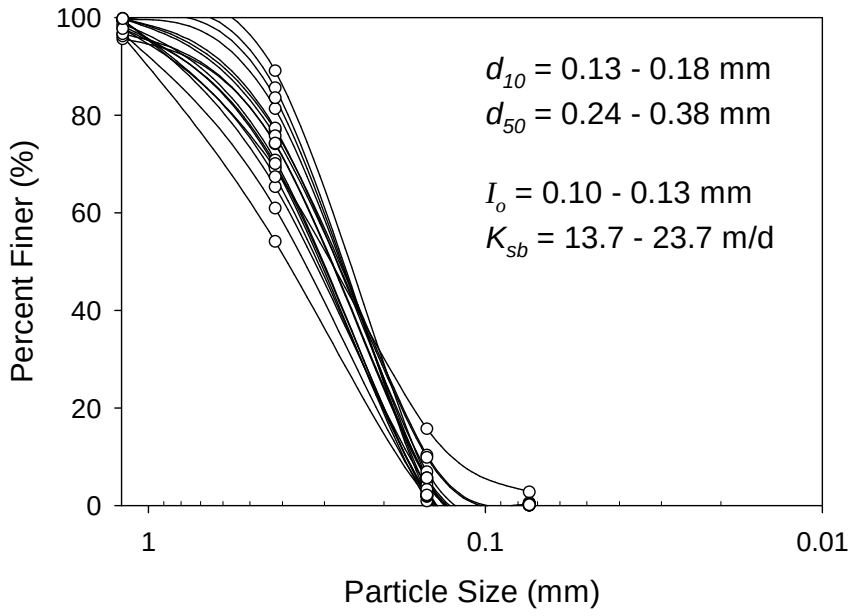


Figure 8. Particle size distribution curves for reach-scale streambed samples along the North Canadian River. Sampling sites are shown in Figure 4(a). The saturated hydraulic conductivity (K_{sb}) was estimated using equation (6).

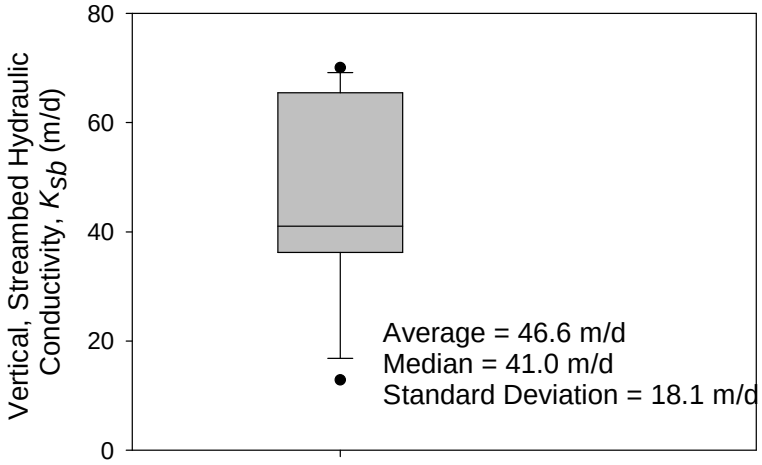


Figure 9. Streambed hydraulic conductivity (K_{sb}) from falling-head permeameter tests measured along the North Canadian River near the El Reno field site. Measurement sites are shown in Figure 4(a).

In general, the North Canadian River K_{sb} measurements were on the same order of magnitude of K for the aquifer material suggesting minimal hydraulic restriction at the streambed. With such high K_{sb}, it was difficult to identify any streambed restriction layer and therefore challenging to estimate M. The W of the North Canadian River was typically between 20 and 25 m. Based on equation (3), the estimated λ was on the order of 10^3 to 10^4 m/d.

3.1.2 Washita River

Streambed samples in the Washita River were more variable than corresponding samples in the North Canadian River. This variability was not surprising considering pictures of the stream at the site (Figure 3b). Samples collected in the thalweg were classified as sand with a d_{50} near 0.4 mm; samples near the banks were classified as sandy loam with a d_{50} near 0.1 mm. The K_{sb} estimated from grain size distribution curves reflected the differences in the streambed samples (Figure 10), with an approximate four-order magnitude difference in estimated K_{sb}. The falling-head permeameter tests also suggested a considerable variability (i.e., 0.3-27.4 m/d), even when trying to measure the K_{sb} of sand dominated locations (Figure 11).

Rach-scale estimates of K_{sb} from the falling-head permeameter tests and particle size distributions were even higher than K_{sb} measured at the site (Figure 12). Falling-head permeameter tests estimated K_{sb} ranging from 8.5 to 185.0 m/d. These estimates support the idea that the Washita River's K_{sb} are on the same order of magnitude of K for the aquifer material, suggesting minimal hydraulic restriction at the streambed.

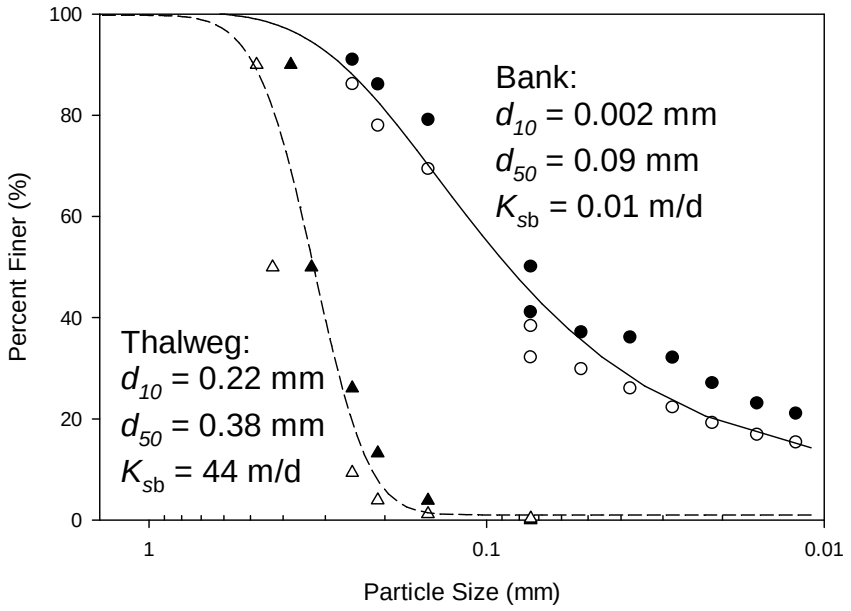


Figure 10. Grain-size distributions measured from four sampling points (two in the thalweg and two in near-bank sediment) in the Washita River. The best-fit trend line was used to derive representative grain size diameters (d_{10} and d_{50}).

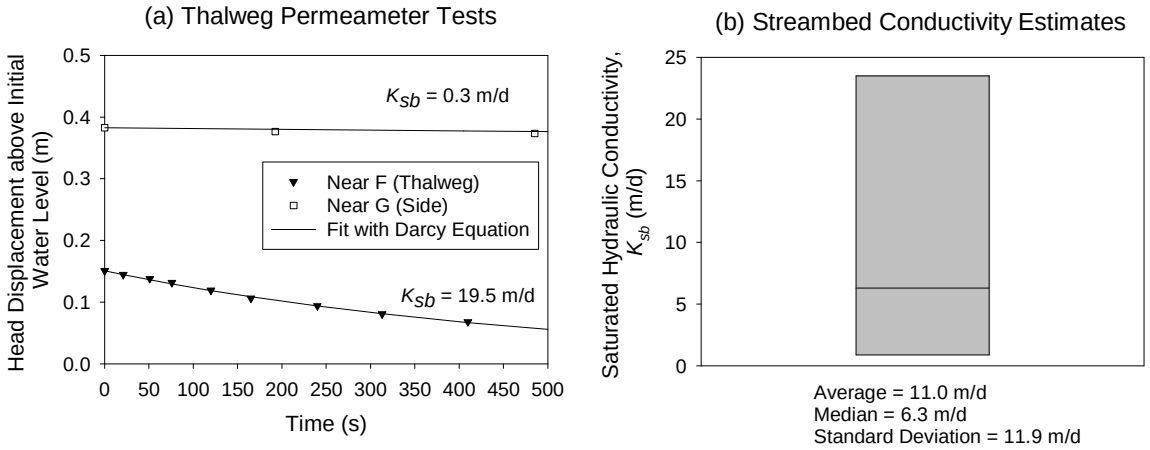


Figure 11. (a) Data from the streambed hydraulic conductivity, K_{sb}, measurements using the falling-head permeameter tests in the Washita River including the resulting fit of the data with the Darcy equation. (b) Box plot of K_{sb} measurements for both thalweg and side channel measurements.

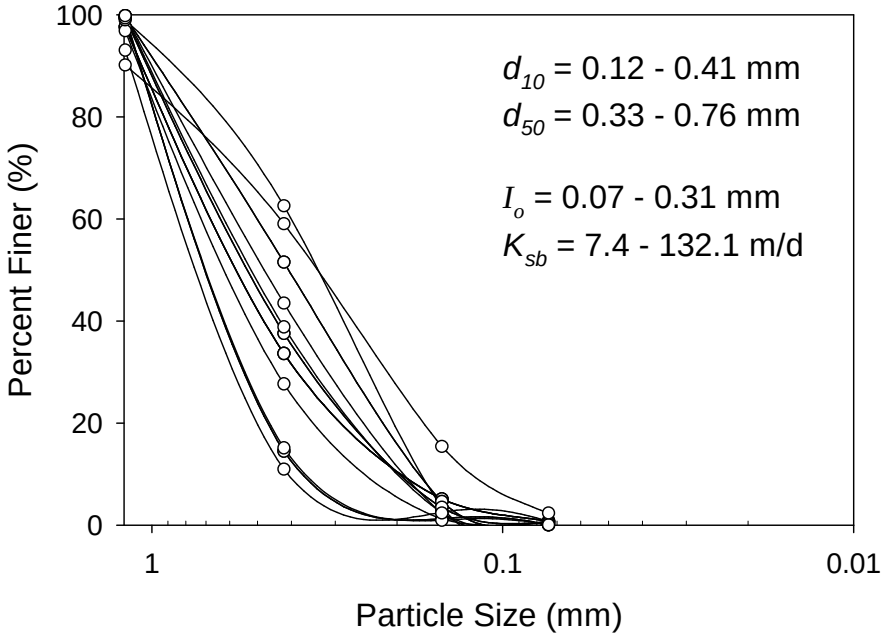


Figure 12. Particle size distribution curves for reach-scale streambed samples along the Washita River. Sampling sites are shown in Figure 4(b). The saturated hydraulic conductivity (K_{sb}) was estimated using equation (6).

3.2 Hydrogeologic Cross-Sections and Aquifer Parameters

Limited data was available on typical parameters for characterizing the alluvial aquifers at both sites. For the North Canadian site, driller's logs reported mostly fine sand with interdispersed clay (ACOG, 2009). Schoff and Reed (1951) reported an aquifer transmissivity, T = 870 m^2/d near in the alluvium near Oklahoma City and El Reno. Ryder (1996) reported specific yield and hydraulic conductivity estimates of 0.29 and 48 m/d.

For the Washita River alluvium, Ryder (1996) and Hart (1965) both mention that the alluvium in the area downstream of the field site was approximately 64 ft (20 m) thick, consisting of primarily fine-grained sand and clay, and lesser amounts of coarser material. Kent (1978) reported depths to bedrock of 12 to 30 m, T of 100 to 400 m^2/d, and S_y of 0.30 for the alluvium between Anadarko and Alex, OK.

Hydrogeologic cross-sections were investigated from well logs from the Oklahoma Water Resources Board's Water Information Mapping System and located adjacent to both field sites (Figures 13 and 14). The well logs demonstrated similar results to the streambed samples in that the Washita River alluvium was much more complex and variable compared to the North Canadian River alluvium at the field sites. The North Canadian alluvium at this location consisted of a large component of fine and coarse sand with interdispersed clay. However, many of the Washita River wells possessed considerable depths of clay and shale with interdispersed sand and coarse gravel (Figure 14).

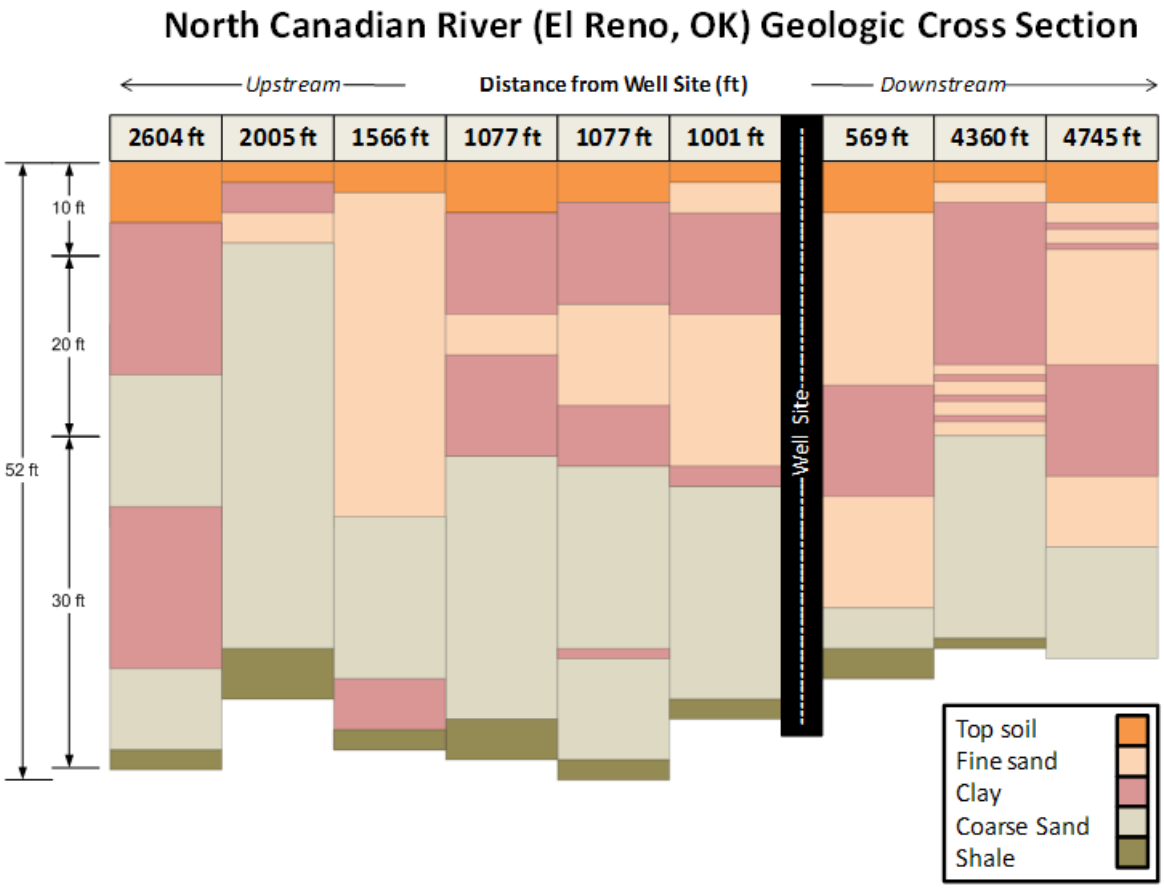


Figure 13. Hydrogeological cross-sections for wells near the North Canadian River field site. Data used to generate the graph is from the Oklahoma Water Resources Board's Water Information Mapping System.

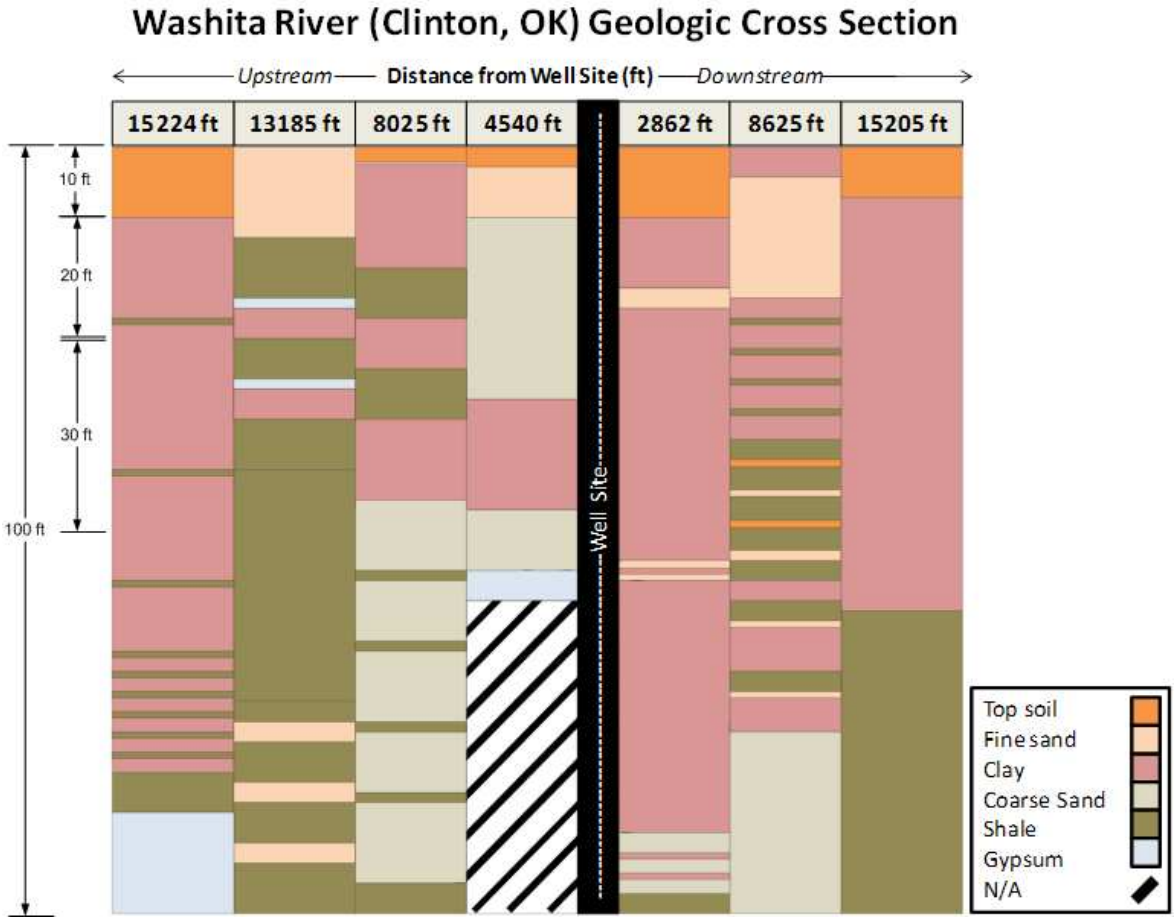


Figure 14. Hydrogeological cross-sections for wells near the Washita River field site. Data used to generate the graph is from the Oklahoma Water Resources Board's Water Information Mapping System.

3.3 Stream/Aquifer Analysis Tests

3.3.1 North Canadian River

For the stream-aquifer analysis (SAA) test period at the North Canadian River site, the initial gradient was directed from the stream and into the alluvial aquifer (i.e., a stream depletion condition), as shown in Figure 15. The initial hydraulic gradient was 0.017 m/m based on a transect from the stream through observation wells G and F.

Late-time drawdown data was typically greater than 1000 minutes based on an appropriate fit of the Hunt (1999) solution to the observed data within ranges of T and S_y that matched previous investigations in the ground water system. Inversely estimated T and S_y ranged from 790 to 950 m^2/d and 0.19 to 0.28, respectively (Figure 16). Descriptive statistics of the fit between observed and predicted late-time (i.e., t > 1000 minutes) drawdown data are shown in Table 2. In general, the NOF for all three observation wells were less than 0.02.

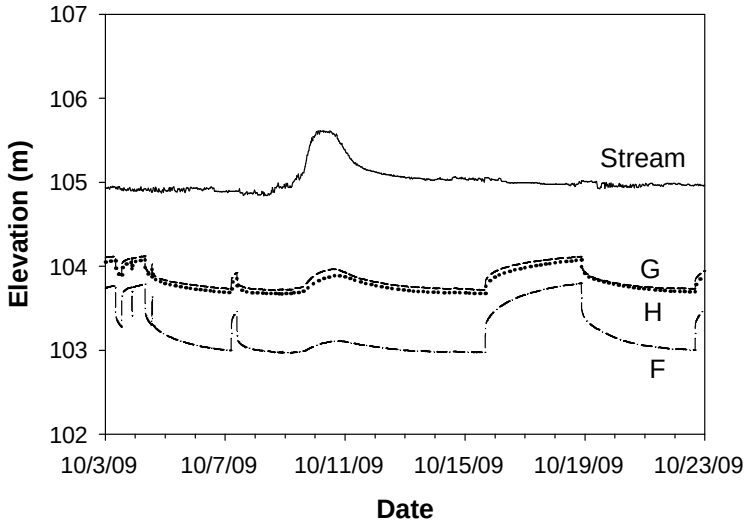


Figure 15. Water levels in the North Canadian River and observation wells during October 2009. The stream-aquifer analysis test was performed from October 18-22, 2009.

Estimates for λ suggested that the North Canadian River at this site was equivalent to a fully penetrating stream with little to no streambed conductivity resistance. Drawdown from observation well F was the first to be utilized and suggested that λ greater than 600 m/d was reasonable. As λ increased in the Hunt (1999) solution, equation (5) converged to the Theis (1941) solution for a fully penetrating stream with no streambed resistance. In fact, predictions by the Theis (1941) solution with image wells using the inversely estimated T and S_y closely matched the predictions by the Hunt (1999) solution with λ greater than 600 m/d, as shown in Figure 16a. Also included in this figure is the predicted drawdown response due to pumping the well without consideration for the stream (i.e., the Theis (1935) solution). It is apparent from this figure that the stream definitively provided a recharge source for the pumping well. Estimates of λ when using observations wells G and H, located closer to the stream, were even higher (i.e., greater than 1500 m/d) than corresponding estimates from observation well F. These observation wells provided data at locations closer to the river where the interaction of the stream and aquifer was more pronounced. This is one reason why Fox (2007) emphasized the use of multiple observation wells, including ones closer to the stream, when performing stream-aquifer analysis tests.

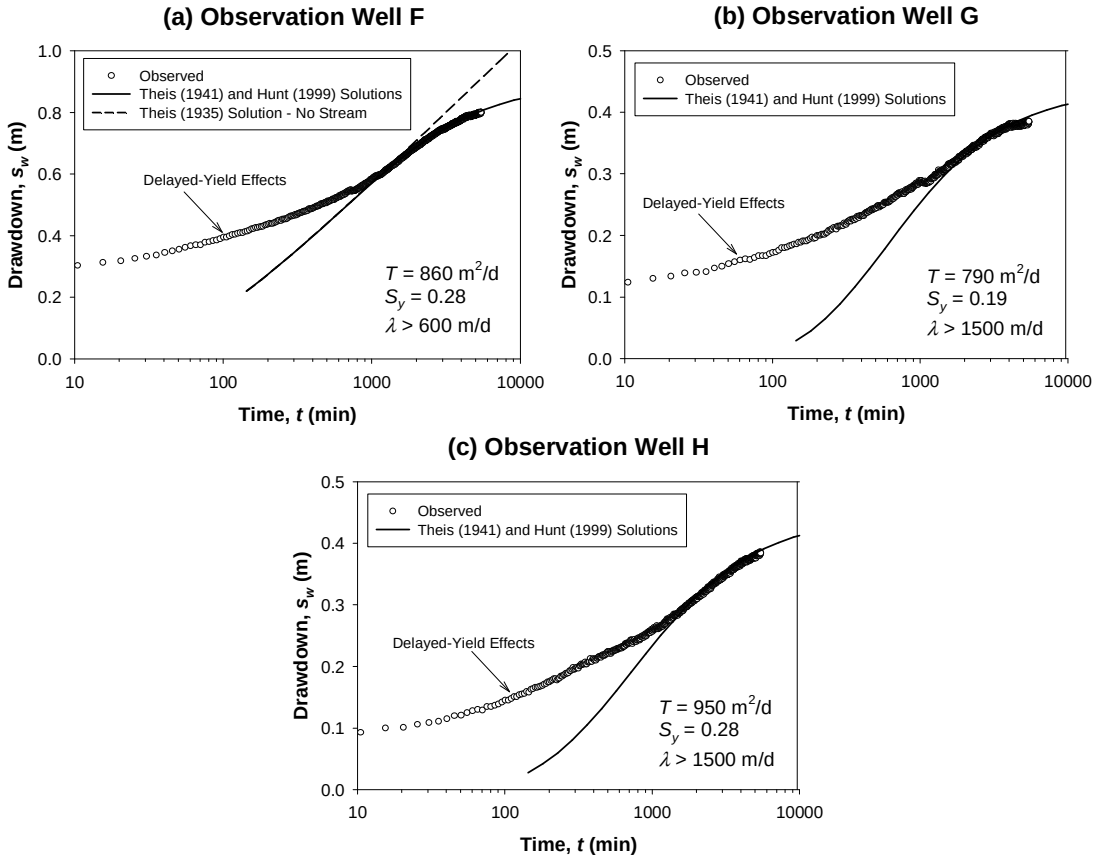


Figure 16. Inversely estimated aquifer transmissivity (T), specific yield (S_y), and streambed conductance (λ) derived from fitting the Hunt (1999) analytical solution to the observed drawdown during the stream-aquifer analysis test at the North Canadian River.

Table 2. Descriptive statistics of the fit between predicted and observed drawdown (late-time data) when using the Hunt (1999) solution. SSE = sum of squared errors; STDD = standard deviation of differences; X_a = average observed drawdown; NOF = normalized objective function.

Well Identification (Figure 1)	SSE	N	STDD	X_a	NOF
F	0.09	891	0.01	0.73	0.01
G	0.07	891	0.01	0.35	0.02
H	0.07	891	0.01	0.34	0.02

Estimated stream depletion based on the Hunt (1999) solution, i.e., equation (4), using the inversely estimated parameters from observation wells F, G, and H were as high as 30% to 35% of Q after one day of pumping and approached 60% to 70% of Q approximately five days after initiation of pumping (Figure 17). Since λ was relatively large, equation (4) simplified to equation (8), which is the equation obtained when analyzing stream depletion from a fully penetrating stream with no streambed resistance:

$$\frac{Q_s}{Q} = erfc\left(\sqrt{\frac{SL^2}{4Tt}}\right) \tag{8}$$

For this reach, it is suggested that this equation should be used as a first estimate of stream depletion unless site-specific conditions (i.e., measurements of λ being small) suggest otherwise. Then, the full depletion solution, i.e., equation (4), should be used.

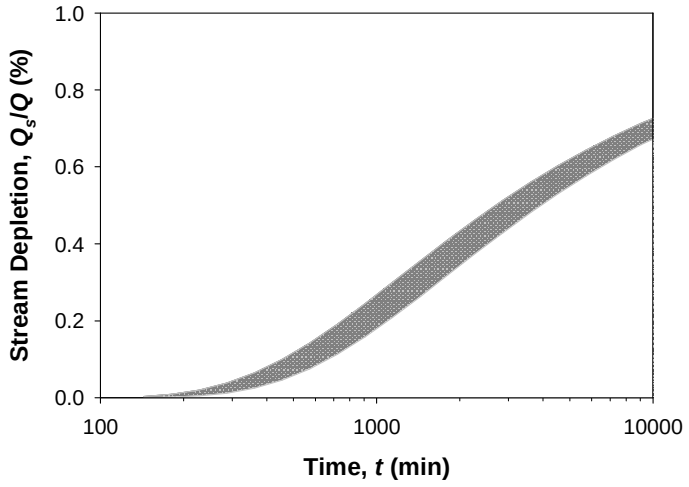


Figure 17. Estimated stream depletion due to pumping well 26 during the stream-aquifer analysis test. Stream depletion was estimated using the Hunt (1999) solution with inversely estimated aquifer and streambed parameters from observation wells F, G, and H (gray area).

3.3.2 Washita River

Long-term monitoring from the Washita River site indicated a greater degree of heterogeneity within this system; i.e., even during times of irrigation well discharge, water levels in observation well A were consistently higher than water levels in some observation wells closer to the stream (Figure 18). This condition suggested preferential flow through coarse material near the irrigation well at the field site. Such conditions created a non-ideal situation for using stream-aquifer analysis tests to estimate aquifer parameters and the streambed conductance. First, observation wells B, C, and D could not be used due to the fact that the water table gradient was directed from A to B, C, and D throughout the test (Figure 18). In other words, the irrigation well did not have enough influence on the ground water system to create a stream depletion scenario, but rather a capture of return base flow. While this condition may be common in many ground water systems, the analytical models utilized in this research are not capable of simulating transient dynamics for this condition. Therefore, the stream-aquifer analysis test focused on observation wells G and F, during a time period of August 8-9, 2010 and assuming a pumping rate of 500 gpm (2728 m^3/d) for the irrigation well located approximately 200 m from the stream.

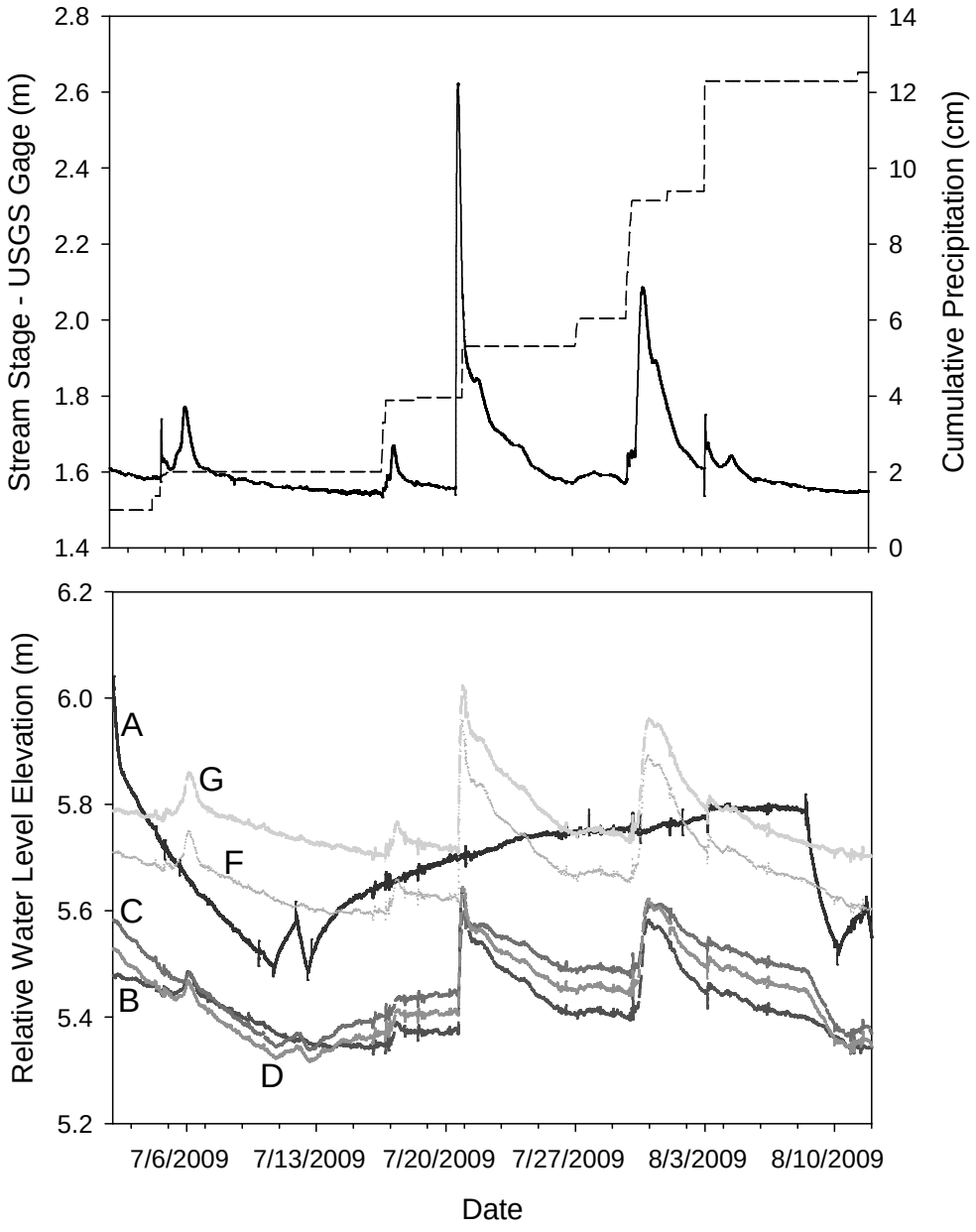


Figure 18. Stream stage as measured at the USGS gage on the Washita River in Clinton, OK, cumulative precipitation, and water level elevations in observation wells at the Washita River site.

Since only observation wells F and G were used in the analysis, drawdown was only observed in these observation wells during late-time data. Inversely estimated T and S_y ranged between 400 to 450 m^2/d and 0.07 to 0.08, respectively (Figure 19), and these values were consistent with limited literature values for the Washita River alluvium. The NOF for both observation wells was approximately 0.30. The larger NOF for the Washita compared to the North Canadian River was due to the dependence of the metric on the

average of the observed data; the average of observed drawdown for these two observation wells were small compared to the drawdown observed at the North Canadian River field site. Further attempts at calibrating parameters for the model were not successful in significantly reducing the NOF while at the same time maintaining reasonable parameter values. More complex analytical solutions may be warranted for the Washita River due to the heterogeneity within the system, but these complex solutions required a user to inversely estimate a multitude of other parameters for which reasonable parameter values were unknown.

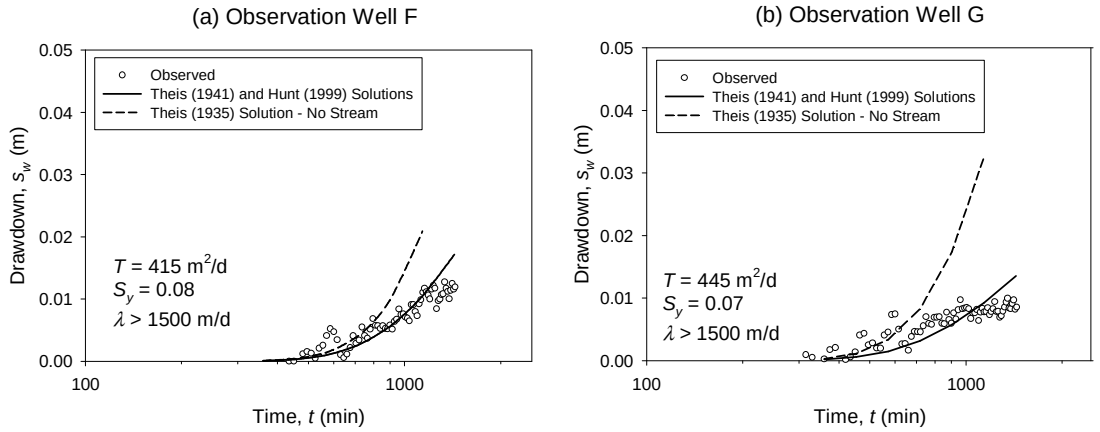


Figure 19. Inversely estimated aquifer transmissivity (T), specific yield (S_y), and streambed conductance (λ) derived from fitting the Hunt (1999) analytical solution to the drawdown during the stream-aquifer analysis test at the Washita River.

Estimates for λ suggested that the Washita River at this site, similar to the North Canadian River site, was equivalent to a fully penetrating stream with little streambed conductivity resistance. Estimates of λ from both observation wells were approximately 1500 m/d, with greater λ resulting in approximately equivalent drawdown profiles. As shown in Figure 19, the Hunt (1999) solution mimicked data from the Theis (1941) solution for a fully penetrating stream and no streambed resistance. Also, as shown in Figure 19, the predicted drawdown response due to pumping the well without consideration for the stream (i.e., the Theis (1935) solution) was significantly different, serving as another indicator of the importance of intense stream-aquifer interaction on the drawdown profiles.

Estimated stream depletion based on the Hunt (1999) solution, i.e., equation (4), using the inversely estimated parameters from observation wells F and G were approximately 10% of Q after one day of pumping and approximately 50% of Q after one week of pumping (Figure 20). It can be noted that these numbers are smaller than the corresponding stream depletions estimated using data from the North Canadian River site. The primary reason was the location of the pumping well relative to the stream; the pumping well at the Washita River site was 115 m further from the river than the pumping well at the North Canadian River. Similar to the North Canadian River site, it is suggested that equation (8) can be used as a first estimate of stream depletion unless site-specific conditions (i.e., measurements of λ being small) suggest otherwise.

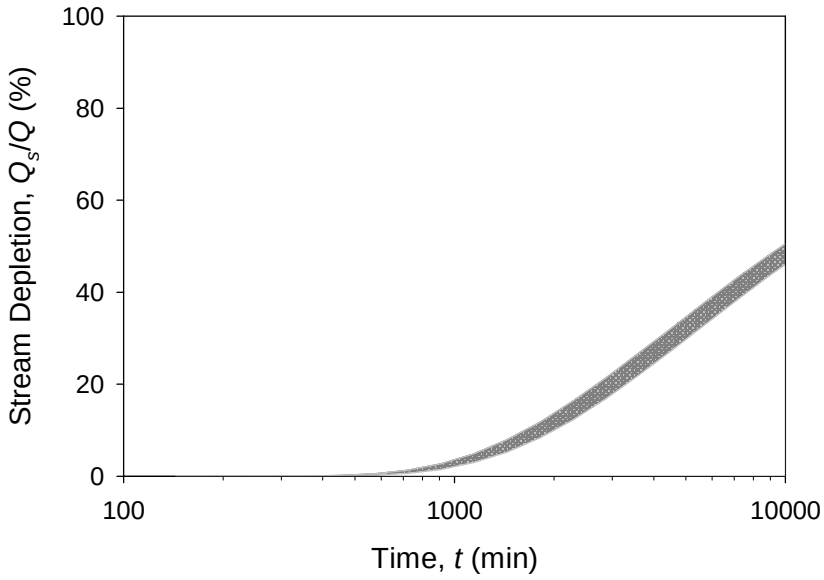


Figure 20. Estimated stream depletion due to the irrigation well at the Washita River site during the stream-aquifer analysis test. Stream depletion was estimated using the Hunt (1999) solution with inversely estimated aquifer and streambed parameters from observation wells F and G (gray area).

3.4 Oklahoma Stream Depletion Factor (OSDF) Worksheet

Stream-aquifer analysis test results have indicated that both the North Canadian River and Washita River sites have intense stream-aquifer interaction during alluvial well depletion. To assist water managers with estimating stream depletion using equations (4) or (8), the stream depletion factor worksheet can be used. The interface of the worksheet is shown in Figure 21. Technical information is provided in a tab in the worksheet. Users can also access the values used to generate the figures for cumulative stream depletion (in ft^3/s) or the stream depletion factor (Q_s/Q) shown on the main page through a calculations tab. This spreadsheet is intended to serve as an initial tool for determining the impact of a single alluvial pumping well discharging at a constant rate on the adjacent streamflow. This spreadsheet tool can be obtained free of charge by contacting Dr. Garey Fox at garey.fox@okstate.edu or by downloading the program at http://biosystems.okstate.edu/Home/gareyf/OSDF.htm.

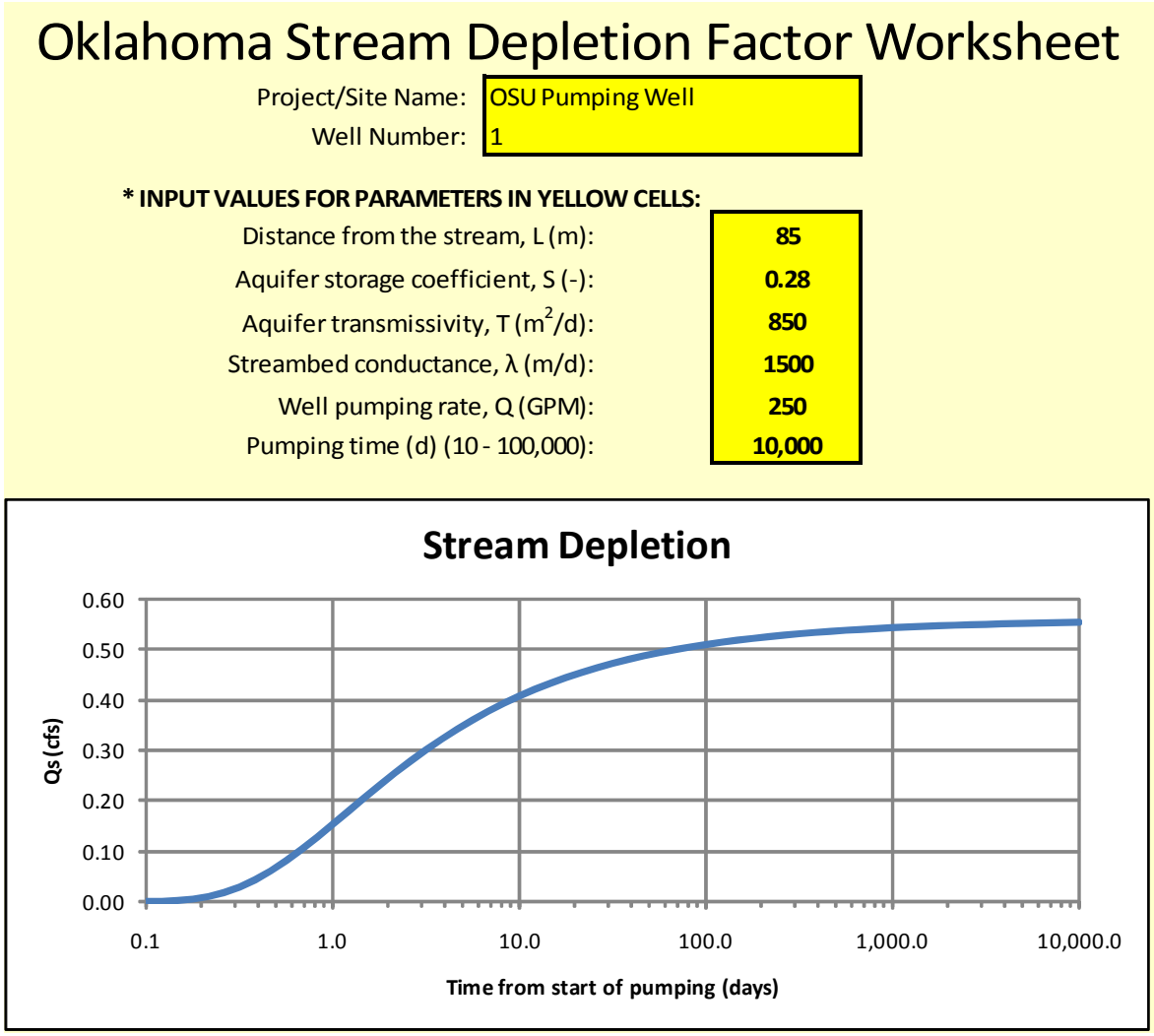


Figure 21. Oklahoma Stream Depletion Factor Worksheet main page. Users can enter the aquifer and streambed parameters, location of the pumping well from the stream, and pumping rate. The worksheet solves for the stream depletion over time. The program can be downloaded from http://biosystems.okstate.edu/ Home/gareyf/OSDF.htm.

IV. Conclusions and Future Work

The stream-aquifer analysis tests conducted on the North Canadian River and Washita River in central Oklahoma provided field data that supported the use of and the applicability of simpler drawdown and stream depletion analytical solutions. Support for the simpler solutions was largely based on the fact that both rivers behaved similar to fully penetrating streams with little to no hydraulic resistance provided by a streambed layer. Estimates of streambed hydraulic conductivity from grain-size analyses and falling-head permeameter tests indicated that at both sites the conductivity of the streambed was on the same order of magnitude as the conductivity in the aquifer. The Washita River streambed hydraulic conductivity was much more variable, potentially due to the variability in the geological system through which the river is flowing.

Because of the large values of field measured and inversely estimated streambed conductance, simpler analytical solutions proposed by Theis (1941), Jenkins (1968) and Hunt (1999) were appropriate for the rivers at the site locations. Even though the streams only physically partially penetrated into the alluvial aquifers, the lack of hydraulic resistance created streams that intensely interacted with their alluvial aquifers. In fact, estimates of stream depletion were as high as 40 to 70% of the pumping rate after only five days of pumping. Predicted streambed hydraulic conductivity from stream-aquifer analysis tests were similar to streambed hydraulic conductivity measured in situ using falling-head permeameter tests and grain-size distribution empirical equations. The advantage of the stream-aquifer analysis tests is that they provide a reach-scale integrated estimate of the streambed conductivity, less influenced by local-scale spatial heterogeneity within the river.

It should be noted that inversely estimated parameters from the observed drawdown were based on only late-time drawdown data, thereby neglecting delayed yield effects of the unconfined aquifer. This was reasonable because of the interest in long-term (i.e., multiple days to months) pumping effects. With this realization, more complex solutions are not warranted for this system, which considerably simplifies the mathematical complexity of analytical solutions to be used and the number of parameters required to be estimated to parameterize the stream-aquifer interaction. These simpler solutions were used to develop an Oklahoma Stream Depletion Factor (OSDF) worksheet to allow water managers to determine the impact of a single pumping well discharging at a constant rate on the streamflow in the adjacent river.

V. ACKNOWLEDGEMENTS

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