Streamflow Depletion by Wells - Understanding and Managing the Effects of Groundwater Pumping on Streamflow

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Introduction

Groundwater is an important source of water for many anthropogenic activities. Most of the time, it is the only source of water in arid and semi-arid regions. Streamflow depletions caused by pumping have become an important water-resource management issue because of the negative impacts that reduced flows can have on aquatic ecosystems, the availability of surface water, and the quality and aesthetic value of streams and rivers. However, it is difficult to observe and measure because it depends on the amount of water available in the stream and in local aquifers, as well as the subsurface geology. Over the past decades has made important contributions to the basic understanding of the processes and factors that affect streamflow depletion by wells. In this context, the decision-making process has been playing a significant role in management and political decision to get the most suitable solutions between different stakeholders. In its simplest sense, decision-making is the act to select the best alternatives under multiple and often conflicting criteria by reducing uncertainty which has many different types of sources. In this more extensive process of problem-solving could lead to a conflict between stakeholders. For these reasons, the purpose of this investigation is to use Hantush's analytical solution to determine streamflow depletion caused by pumping wells in complex scenarios to create a suitable and tangible decision-making process between stakeholders.

Methodology

Accomplish integrated watershed management for mitigating streamflow depletion induced by wells is necessary to use modelling techniques to calculate the mathematical representation of human-environment interactions, improving the decision-making process, and encouraging stakeholder agreement. Previous modelling studies in the water management literature have explored conjunctive use strategies aimed at improving streamflow conditions by using simple analytical models. Hantush (1965) derived an analytical solution to estimate streamflow depletion caused by pumping wells. This solution conceptualizes a stream fully penetrates the aquifer with streambed resistance. The governing equation of the Hantush method is:

$$Q_r = Q \cdot \{erfc(U) - exp[-U^2 + (U+w)^2] \cdot erfc(U+w)\}$$

$$U = \sqrt{\frac{d^2 \cdot S}{4 \cdot T \cdot t}}$$

$$w = \sqrt{\frac{T \cdot t}{S \cdot a^2}}$$

Where, Q_r is rate of river depletion at any time since pumping started (cubic length per time), Q is the constant discharge of the well (cubic length per time), t is time since pumping began (time), and d is the distance from the well to the stream (length).

The transmissivity of the aquifer is defined as:

$$T = K \cdot b$$

Where, T is transmissivity (square length per time), K is hydraulic conductivity of aquifer (length per time), and b is the thickness of the aquifer (length).

The storativity or specific yield of the aquifer is express as:

$$S = s \cdot b$$

Where, S is storativity (dimensionless), s is aquifer specific storage (length^{-1}), and b is aquifer thickness (length).

Methodology

The streambed leakance or retardation coefficient of the streambed is estimated as:

$$a = \frac{K \cdot b'}{K'}$$

Where, a is streambed leakance (length), K' is hydraulic conductivity of streambed (length per time), and b' is thickness of streambed (length).

The assumptions used to development the analytical model are: a) groundwater flow toward the pumping wells is horizontal with no vertical hydraulic gradient component, assuming a constant depth of the aquifer (Dupuit, 1863); b) the aquifer is homogeneous, and isotropic; c) discharge of the well (pumping rate), transmissivity, storativity, and streambed leakance values do not change through time; c) there is no streambank storage; d) the stream fully penetrates the aquifer with streambed resistance.

We tested the analytical solution with four different pumping rate conceptual models. The first case considers the well's flow rate constant throughout the year. In the same context, we defined that the second, third, and fourth configuration the well only pumps water for the first 6, 3, and 1.5 months per year, respectively, expecting a streamflow recovery period since pumping stopped. These configurations has developed to quantify the effects of seasonal changes in pumping rate over time. Simulation time did set to five years, and the time step is daily. The seasonal variation for the second, third and fourth configuration simulation means that the well operates the first 282, 90, and 45 days and then shuts down for each simulation year. Also, the pumping rate values for each simulation scenario has defined based on the total annual pumping flow. In other words, the total amount of water pumped per year is equal in each simulation configuration. The pumping rate value for the first, second, third, and fourth configuration is 10, 20, 40, 80 m^3/d, respectively. Furthermore, we defined several values for the distance between the wells and the river. Thus, simulations can be evaluated depending on the same groundwater extraction and well distance values or by defining specific designs.

The hydrologic properties values used as input data for the models varies over a wide range to simulate various sites with diverse soil and aquifer characteristic. It is an attempt to replicate areas with complex nature of groundwater flows. From that perspective, we carefully selected the maximum and minimum value for all the variables, trying to replicate the most complicated and simple conditions for water flow. Furthermore, Python was the programming language used to define functions, visualization, and analysis data. Also, Python code iterate over all possible combinations, generating a robust data set.

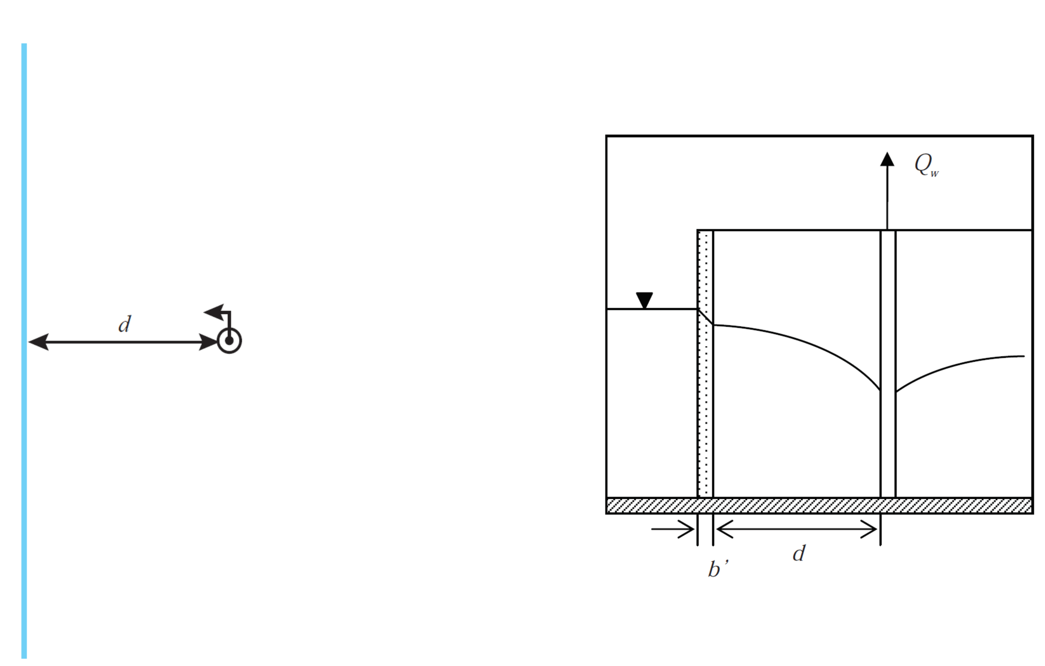

Figure 1. Hantush equation conceptual model.

Results

The streamflow depletion simulation generated 288 streamflow events for each pumping rate configuration. The results stated the pumping rate configuration has a direct influence on streamflow depletion distribution over the simulation period. Streamflow variation is more susceptible to higher pumping rates. If we compare the two oppositive cases, 12 and 1.5 months of pumping water per year, the results show that the final streamflow values during the whole simulation have a similar distribution pattern, displaying a skewed left distribution. In other words, the left tail (smaller values) is much longer than the right tail (larger values). However, the streamflow range value is significantly different, obtaining lower streamflow values when the pumping rate has a higher value. Figure 2 shows the streamflow depletion distribution over 5 years of simulation under four different pumping rate configuration.

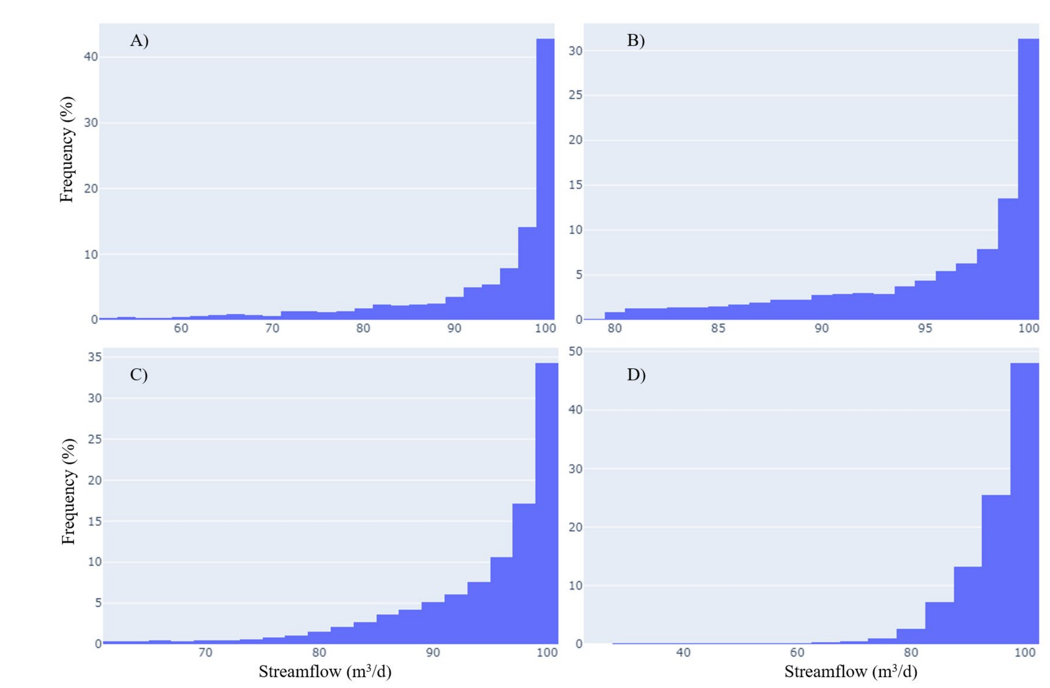

Figure 2. Streamflow depletion distribution over 5 years of simulation under four seasonally conceptual models (A): 12, (B): 6, (C): 3, and (D): 1.5 months of pumping per year.

Figure 3 shows the correlation between the maximum and minimum streamflow value obtained in four different pumping rate values under four seasonally conceptual models (12, 6, 3, and 1.5 months of pumping per year) in the last year of simulation. The results stated the maximum streamflow values show a strong correlation with the minimum streamflow values, independently of the pumping rate value. These results suggest that any stakeholder can estimate the maximum and minimum streamflow value by only knowing the pumping rate value. An empirical equation has been developing to represent this correlation. Figure 4 shows the correlation between the pumping rate and the minimum streamflow value for the second seasonally conceptual model. We are developing and improving different equations for several seasonally conceptual models and initial streamflow values; we have been getting promises results. The principal purpose is to create one equation that allows us to estimate several conceptual models.

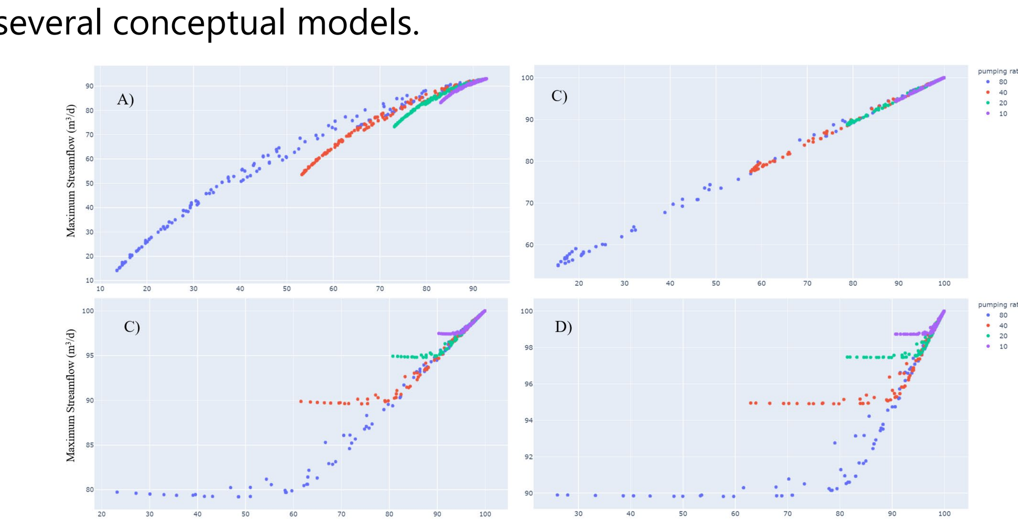

Figure 3. Correlation between the maximum and minimum streamflow value obtained in four different pumping rate values under four seasonally conceptual models (A): 12, (B): 6, (C): 3, and (D): 1.5 months of pumping per year.

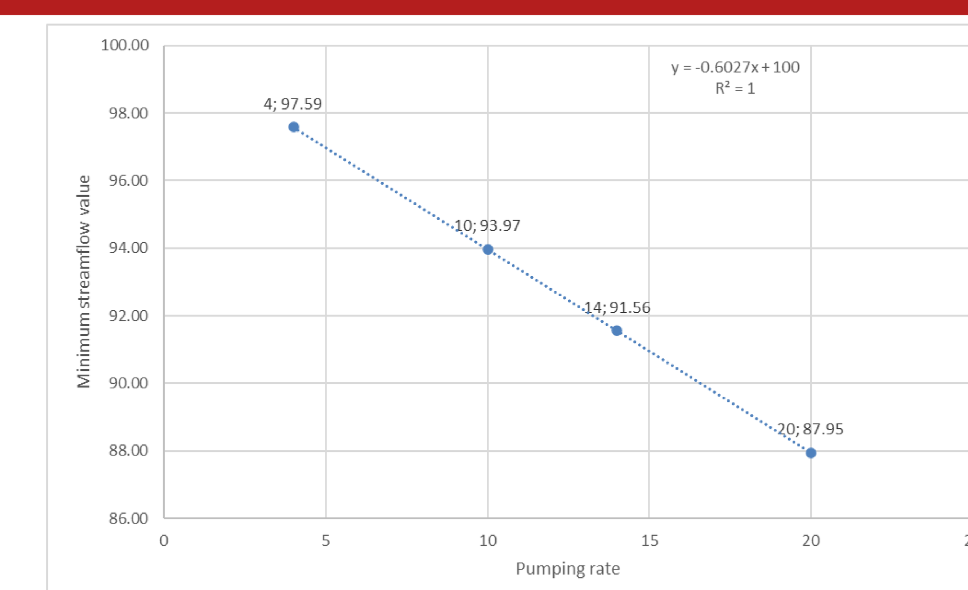

Figure 4. Correlation between the pumping rate and the minimum streamflow value for the second seasonally conceptual model.

One application of this equation is to estimate the cost-benefit for different stakeholders. Figure 5 shows a revised cost-benefit equation for the farming sector and the town center management by using data obtained during various investigations. Also, it displays the correlation between streamflow and cost. This information is vital to understand the economic impact of the streamflow variation. Besides, we can determine the exact streamflow value where the cost will be equal for both parts. In the same context, we can illustrate when the cost of one stakeholder is higher than the other (Figure 5 – point A and B).

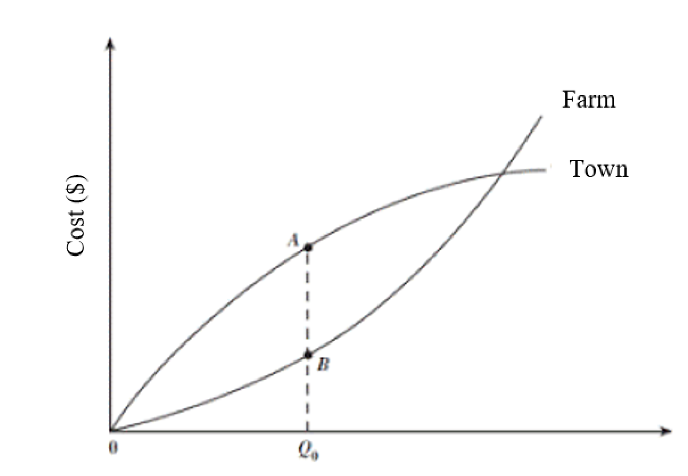

Figure 5. Correlation between streamflow and cost.

In summary, we have used a reliable hydrology equation to estimate streamflow depletion caused by wells in several conceptual models, changing well design characteristics (e.g. well distance, pumping rate, etc...) and hydrology properties (e.g. hydraulic conductivity of aquifer, Thickness of streambed, etc...). Those results have been used to develop a new simple equation to estimate the streamflow depletion based on the pumping rate. Finally, it is reasonable to estimate the cost-benefit for several stakeholders by estimating the streamflow depletion.

Conclusions

- Use of the Hantush solution incorporates simplifying assumptions, including that all flow is horizontal. Also, the analytical solution uses values for horizontal soil permeability, initial saturated aquifer thickness, specific yield, basin length, basin width, and duration and magnitude of recharge rate. It is a simple and reasonable method to estimate streamflow depletion caused by well.
- Pumping rate configuration plays an important role to estimate the maximum and minimum streamflow value distribution.
- Pumping rate, maximum and minimum streamflow values over the whole simulation period have a strong correlation between them. It is possible to predict the streamflow distribution range only knowing the pumping rate value. This correlation will help any stakeholder to predict and analyse the streamflow variability.
- In the same context, it is possible to estimate the cost-benefit for each stakeholder based on streamflow value, improving the decision-making process.