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Characterization of Aquifer-Stream Systems and Preliminary Groundwater Drought Indicators in the Okanagan Basin, BC

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Summary

When assessing drought, it is important to consider the nature of the hydraulic connection between the stream and groundwater system. This project characterized aquifer-stream systems in the Okanagan region as being recharge-driven or streamflow-driven. Observation wells were paired with nearby hydrometric stations to generate hysteresis plots that identify whether streamflow or groundwater level leads the response. A cross correlation analysis was carried out to determine the strength of the correlation and the time lag. A preliminary groundwater drought indicator analysis was also completed using three different metrics: 1) the 30-day minimum groundwater level, 2) monthly means, and 3) the day of water year when 75% of the total annual cumulative groundwater level occurs. The third metric was found to be the best indicator of drought conditions in 2015 (a notable drought year in the province), for both the recharge-driven systems and the streamflow-driven systems. The approaches used in this research will be expanded to examine groundwater drought across BC, develop a quantitative groundwater drought indicator, and explore how drought affects different types of aquifer-stream systems.

Introduction

British Columbia (BC) experienced a severe drought in 2015. By August 20th, 2015, Level 4 drought conditions were declared in the Okanagan and surrounding water basins (BC River Forecast Centre 2015; Coulthard et al. 2016; Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2019). The BC Drought Response Plan uses the 7-day average streamflow as one of the core indicators during the drought season; groundwater level is used only as a supplemental qualitative indicator (BC Ministry of Environment and Climate Change Strategy (ENV) 2018). The primary motivation for this study was to develop a quantitative groundwater indicator of drought that can be used province wide. However, drought in mountainous regions is a complex process due to the geographic, geologic, climatic, and hydrologic diversity across various scales. Moreover, the variable nature of the hydraulic connection between surface water and groundwater (Winter et al. 1999, Viviroli et al. 2003) requires an understanding of the dynamics of the aquifer-stream system. Differences in aquifer-stream system type may affect how aquifers respond during periods of drought.

Allen et al. (2010) identified two end members for aquifer-stream systems: recharge-driven systems and streamflow-driven systems. In recharge-driven systems, diffuse recharge to the aquifer results in groundwater that discharges into the stream as baseflow (Figure 1a; Allen et al. 2010). Therefore, changes in streamflow lag behind changes in groundwater level in recharge-driven systems. In contrast, streamflow-driven systems exhibit bi-directional flow, such that the rise and fall of the streamflow drives the rise and fall of the groundwater level (Figure 1b).

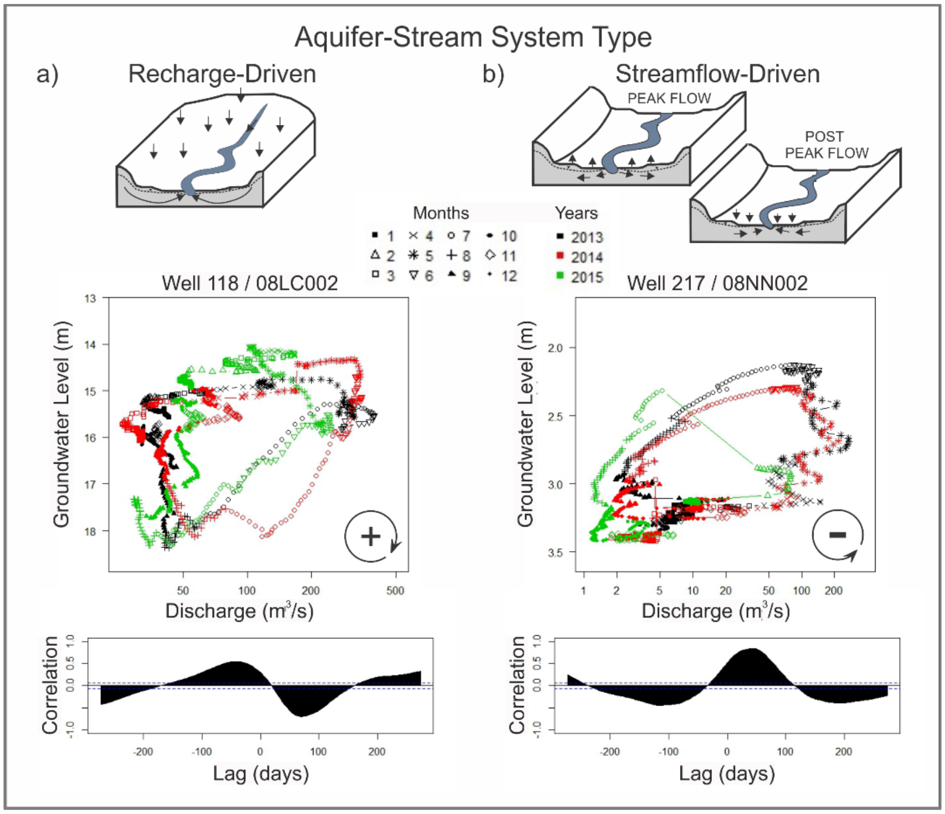

Figure 1. Schematic diagram showing the two end-member aquifer-stream systems, as well as example hysteresis and cross correlation plots used in the characterization. a) In recharge-driven systems, changes in streamflow lag behind changes in groundwater level creating a positive or clockwise hysteresis loop b). In streamflow-driven systems, the water flows from the stream to the aquifer during peak flow, and from the aquifer to the stream post peak flow. Therefore, changes in the groundwater level lag behind changes in the streamflow, creating a negative or counter-clockwise hysteresis loop (Schematics from: Allen et al. 2014)

This study first explores groundwater level and streamflow responses in different aquifer-stream system types in the Okanagan Basin, BC. The Okanagan Basin is a mountainous region with variable topography (steep mountains and flat valley bottoms), a range of stream orders (headwater to a mainstem lake and river system), and complex hydrogeology (multiple aquifers and aquitards). The study then qualitatively evaluates different statistical metrics that may serve as groundwater drought indicators.

Method

Groundwater level data from 24 observation wells in the Okanagan Basin and surrounding area, and stream discharge data from the nearest hydraulically connected hydrometric station were analyzed. Hysteresis plots, cross correlation plots, and the characteristics of the observation wells and aquifers were used to characterize the aquifer-stream system type (Allen et al. 2010). Hysteresis plots indicating that temporal changes in groundwater levels occur before changes in streamflow (clockwise direction) suggest that the aquifer-stream system is recharge-driven (Figure 1a). In contrast, hysteresis plots indicating that changes in streamflow occur before groundwater levels (counter-clockwise) suggest that the aquifer-stream system is streamflow-driven (Figure 1b). Cross correlation plots (Figure 1a and 1b) were used to determine the strength of the correlation and the time lag.

The groundwater level records were analyzed for any irregularities during the 2015 drought year to determine possible indicators of groundwater drought. Three indicators were tested: 1) the difference from the mean of the 30-day minimum groundwater level, 2) the difference from the mean for the monthly means of July, August, September, and October, as well as 3) the difference from the mean and median of the day of water year (DoY) 75% total annual cumulative groundwater level. The DoY 75% total groundwater level is the day of the water year when 75% of the total water level rise for the water year has been reached.

Results and Discussion

The aquifer-stream system type was identified for 20 of the 24 observation wells analyzed in the study area. Of the 20 wells, 11 were characterized as streamflow-driven and 9 as recharge-driven systems. The four remaining wells had insufficient data or possibly the aquifer was not connected to the surface water to allow for characterization. Interestingly, shorter distances between streams and observation wells did not appear to favour streamflow-driven systems, although the sample size was rather small.

The selection of the hydrometric station was important for correctly identifying the aquifer-stream system type. In some cases, the closest hydrometric station was not strongly connected to the aquifer system, and stations located further away with higher correlation coefficients were used. Using observation wells and hydrometric stations that are not located in a hydraulically connected system will mis-characterize the aquifer-stream system. Indeed, the hysteresis plots can become very messy in such cases, with no clear hysteresis pattern. Ideally, hydrometric stations that are situated on streams that are hydraulically connected to the aquifer in which the observation well is located should be used. This limits the number of observation wells that can be characterized with these methods. It is also important to note that the aquifer-stream system characterization is a sliding scale with two end members; recharge-driven systems and streamflow-driven systems. Difficulties in clearly identifying the aquifer-stream system type may be caused by blended responses due to, for example, topographic or geologic variability.

The groundwater drought indicators did not all indicate that a significant drought had occurred in 2015. The differences from the mean 30-day minimum groundwater level were only lower in the 2015 drought for 36% of the wells analyzed. The July, August, September and October monthly means had groundwater levels lower than the mean for 77%, 68%, 77%, and 36% of the wells, respectively (Figure 2). For the 2015 drought year, 19 of the wells (86%) had DoY 75% medians or means less than the median and mean for each well (Figure 2).

The differences from the means were greater for the recharge-driven systems when using the difference from the mean of the 30-day minimum groundwater level and the difference of the mean for the monthly means (Figure 2). The differences from the mean and medians of the DoY 75% total groundwater level was comparable between the recharge-driven systems and the streamflow-driven systems (Figure 2). Therefore, the DoY 75% indicator is useful for both streamflow-driven and recharge-driven wells. Whereas, the 30-day minimum groundwater level and the difference from the mean for the monthly means is not very useful for the streamflow-driven systems. The differences in magnitudes between the streamflow-driven systems and the recharge-driven systems may also indicate that the 2015 drought may have had a larger impact on the recharge-driven wells.

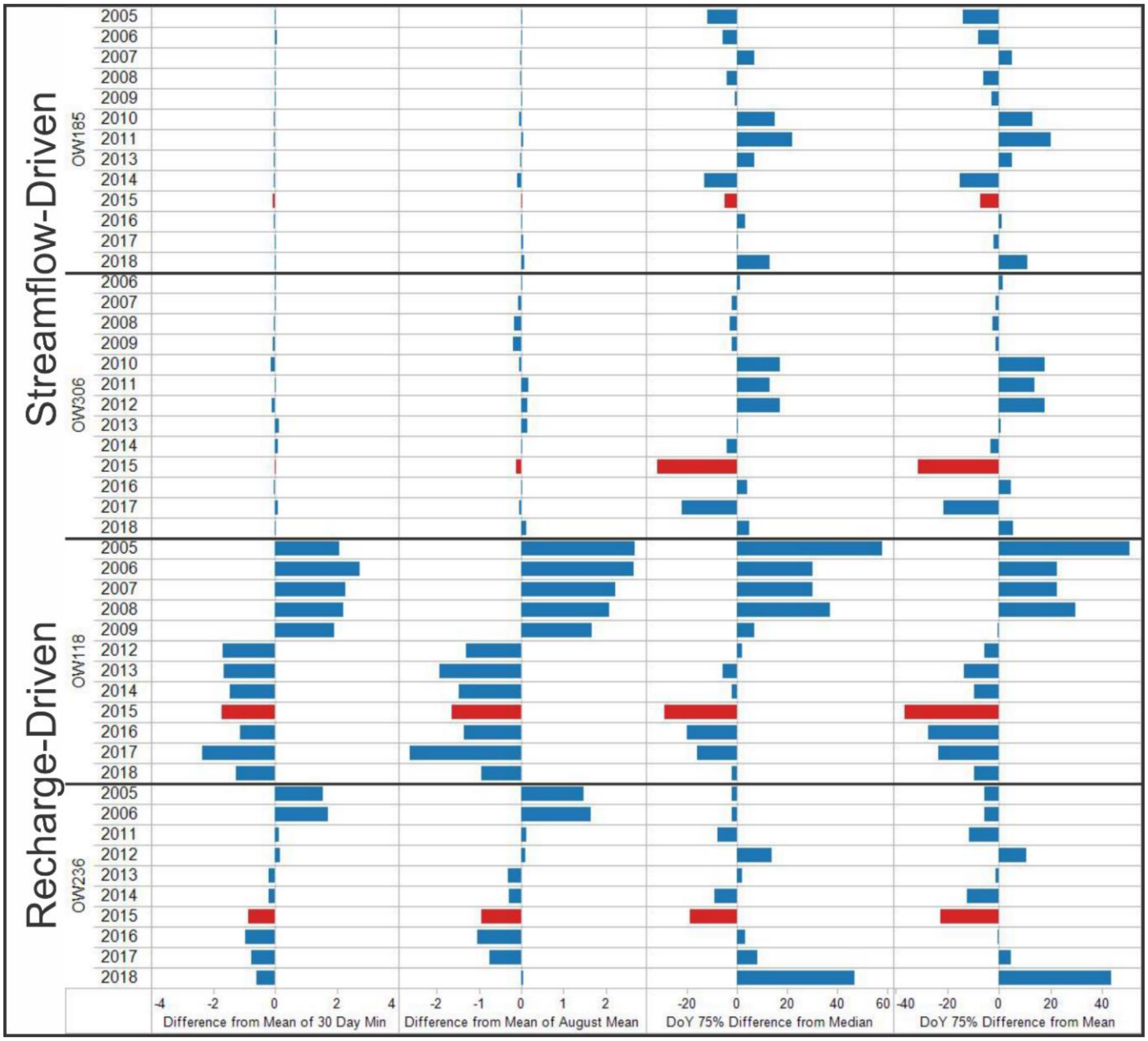

Figure 2. The indicators used to test for irregularities during the 2015 drought for two streamflow-driven wells (OW306 & 185), and two recharge-driven wells (OW236 & OW118). The 2015 water levels are represented by the red bars. The streamflow-driven wells (OW185 & OW306) have smaller magnitudes of variance from the means for the 30-day minimum and the monthly means. The DoY 75% difference from the median and mean was better at indicating that a drought had occurred in 2015 for both the stream-driven and recharge-driven systems.

Conclusions

Characterization of the aquifer-stream systems in the Okanagan Basin and surrounding region was an important first step in understanding how and why the groundwater level responds the way it does under natural conditions. Ultimately, however, there is uncertainty in associating groundwater level responses with a particular aquifer-stream system type. This characterization required a combination of hysteresis plots and cross correlation analysis, a suitable hydrometric station, as well as knowledge of the aquifer characteristics. No single method could be relied upon to characterize the system.

Several preliminary groundwater drought indicators were qualitatively compared. While they did not all indicate that a significant drought had occurred in 2015, the DoY 75% indicator was useful for both streamflow-driven and recharge-driven wells.

Further research will expand the characterization of aquifer-stream system for all observation wells in BC, as well as testing other statistical metrics for a groundwater drought indicator.

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