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Watershed-Scale Response of Groundwater Flow System to Decadal Fluctuations of Meteorological Condition

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1. Introduction

Groundwater flow system can be seen as a unit of water management consisting of recharge, storage, and discharge. Recharge and discharge occur at the interface between surface water and groundwater. In semi-arid regions of North America, where precipitation and evapotranspiration are tightly balanced, interannual and interdecadal wet-dry fluctuations of weather can stress the groundwater flow system. This poster presents a case study in the Canadian Prairies examining the watershed-scale response of a groundwater (GW) flow system to wet-dry fluctuations. Specific questions are:

1) **How does the GW flow system respond to wet-dry fluctuations?**
2) **How are the three components of the GW flow system connected?**
3) **How resilient is the GW flow system?**

2. Study Area – West Nose Creek Watershed

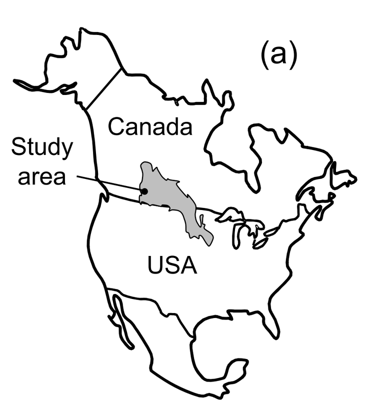
West Nose Creek is located in the northwestern edge of the Northern Prairies region (**Fig. 1a**), near Calgary, Alberta. The physiography is characterized by:

- **Cold, semi-arid climate**:
  - Annual precipitation ~480 mm, annual potential evapotranspiration ~700 mm
  - Cold winter – soil is frozen to 1-1.5 m during November-April.
- **Glaciated terrain**:
  - Clay-rich, low-permeability till overburden up to 20-30m thick.
  - Numerous closed topographic depressions collecting runoff.
- **Heterogeneous aquifers**:
  - Paleocene bedrock aquifer (many small sandstone units encased in aquitards)
  - Pre-Pleistocene gravel deposits.

The watershed has a gross drainage area of 250 km^2 (**Fig. 1b**). The land use is mostly agricultural, roughly equal areas of cattle grazing and annual crop production without irrigation (barley, wheat, oil seeds, etc.).

The creek has perennial flow sustained by discharge from springs (e.g., **Fig. 2b**). Except during snowmelt and occasional summer storms, the creek has steady baseflow (**Fig. 2a**) of 0.1-0.4 m^3 s^{-1} or 10-40 mm y^{-1} normalized by drainage area.

Most residents of the watershed have relied on groundwater for household water use (**Fig. 3a**) and for cattle water supply (**Fig. 3b**) for many years.



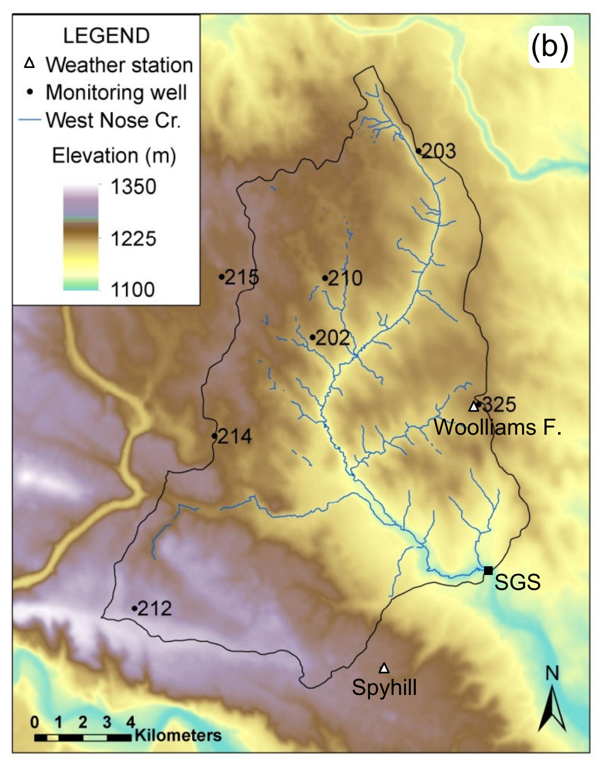


Fig. 1 (a) Map of North America showing the extent of the Northern Prairies region and location of the study area. (b) Elevation map of the West Nose Creek watershed (bounded by solid black line) and the surrounding area. Location of bedrock monitoring wells, automatic weather stations, and stream gauging station (SGS) are shown in the map (Hayashi and Farrow, 2014).

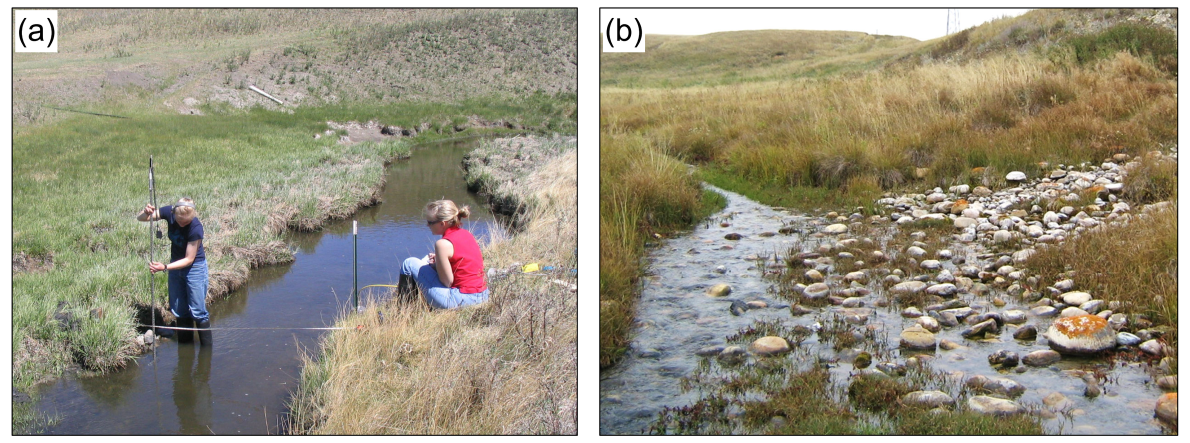
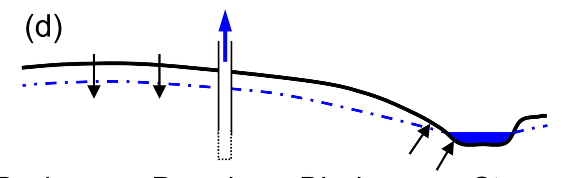


Fig. 2 (a) Baseflow of West Nose Creek at the gauging station. (b) A spring discharging from a gravel aquifer. This spring provides ~50% of creek baseflow.

In recent decades, many farms in the region have been sold and subdivided to develop residential complexes relying of groundwater supply from new wells (**Fig. 3c**). Increasing usage of groundwater has raised concern about the sustainability of groundwater resources in the watershed. To evaluate the sustainability, it is important to consider the balance of groundwater at a scale of the entire watershed under the present and future climates (**Fig. 3d**). Therefore, it is essential to conduct **<u>long-term monitoring of groundwater flow system</u>** with respect to **<u>recharge, storage, and discharge</u>**.

Fig. 3 (a) Household water supply well. (b) Well for cattle watering. (c) Development of rural residential complex, each house equipped with a well. (d) Concept of watershed-scale water balance.



3. Methodology

The West Nose Creek (WNC) hydrological observatory was established during 2004-2005 with installation of a stream gauging station, weather/soil monitoring stations, and a network of bedrock aquifer monitoring wells (**Fig. 2b**).

The WNC monitoring well network was established using existing household water supply wells in the community (**Fig. 4a**). The well monitoring was later expanded to the rural municipality of Rocky View County (**Fig. 4b**) and became a **<u>community-based</u>** network using **<u>citizen-science</u>** approach (Little et al., 2016). Some wells are measured manually by well owners, and others are monitored by pressure transducers. Most of the water level data used in this presentation were collected using pressure transducers.

Weather stations were equipped with soil moisture sensors and an eddy-covariance system to monitor the energy balance and evapotranspiration fluxes. These data were used for the calibration and validation of the soil water balance model.

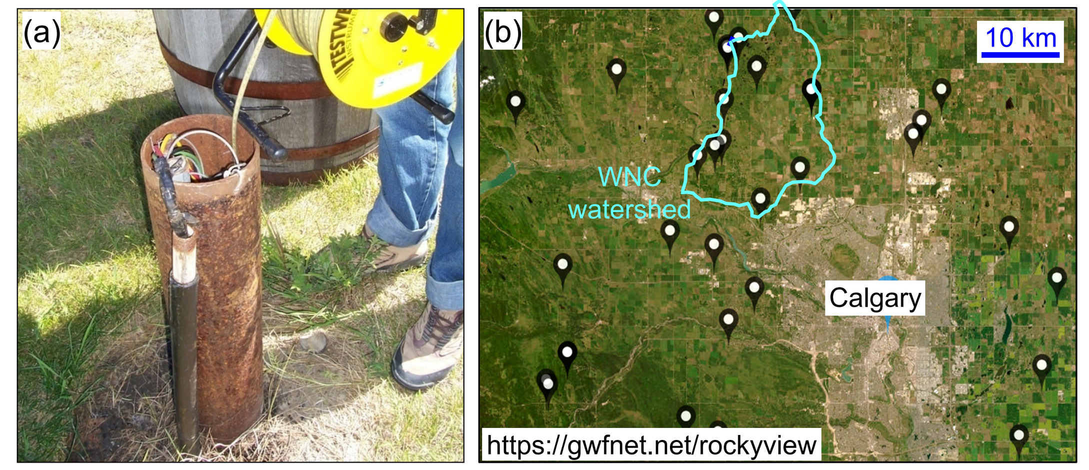


Fig. 4 (a) Water level measurement in a house well. (b) Location of wells in the community-based groundwater monitoring program: Rocky View Well Watch (Little et al., 2016).

Groundwater recharge in the watershed is focussed under topographic depressions (**Fig. 5a**). A soil water balance model was specifically developed for the estimation of depression-focussed recharge (DFR) at daily time steps (**Fig. 5c**) and field-tested using the data from the WNC hydrological observatory (Negm et al., 2021).

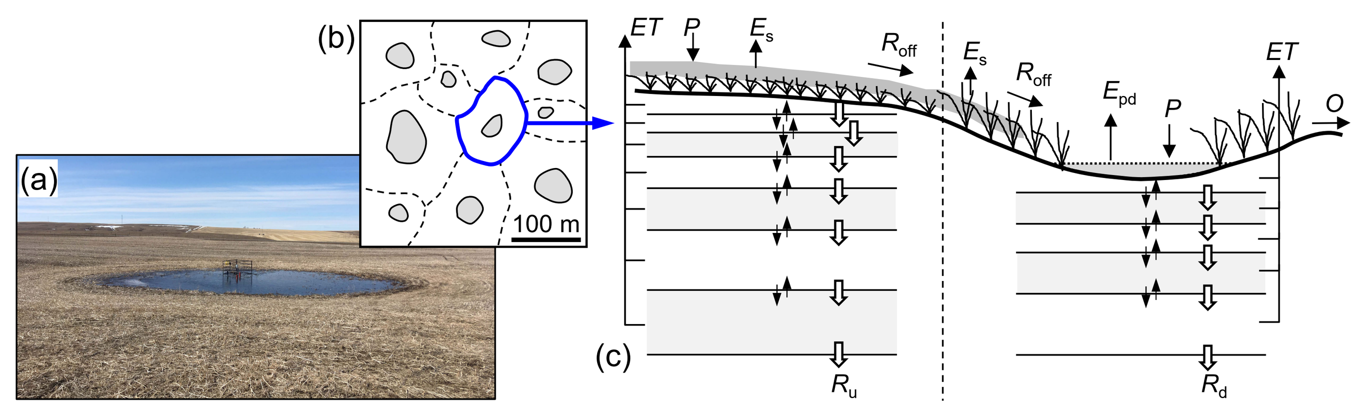


Fig. 5 (a) Depression filled with snowmelt runoff. (b) Numerous depressions (~10-100 per km^2) occur in the Northern Prairies. A depression-catchment system is represented by a soil water balance model. (c) Versatile Soil Moisture Budget (VSMB) model consisting of a depression receiving runoff (R_{off}) from the upland (Negm et al., 2021). Other water balance components are: precipitation (P), snow sublimation/evaporation (E_S), soil evapotranspiration (ET), pond evaporation (E_{pd}), and overflow (O) to the neighboring catchment. Gravitational drainage (thick open arrows) and moisture diffusion (thin solid arrows) redistribute soil moisture. The drainage from the bottom of the soil column is considered recharge from upland (R_u) and depression (R_d).

4. Results and Discussion

Groundwater levels in the WNC watershed showed consistent patterns (Fig. 6) despite being measured in disconnected sandstone aquifers, indicating similar responses to decadal-scale wet-dry fluctuations: i.e. little recharge in dry years (2009-2010, 2017-2019, 2022-2023) and high recharge in wet years (2007-2008, 2013-2014. 2020-2021).

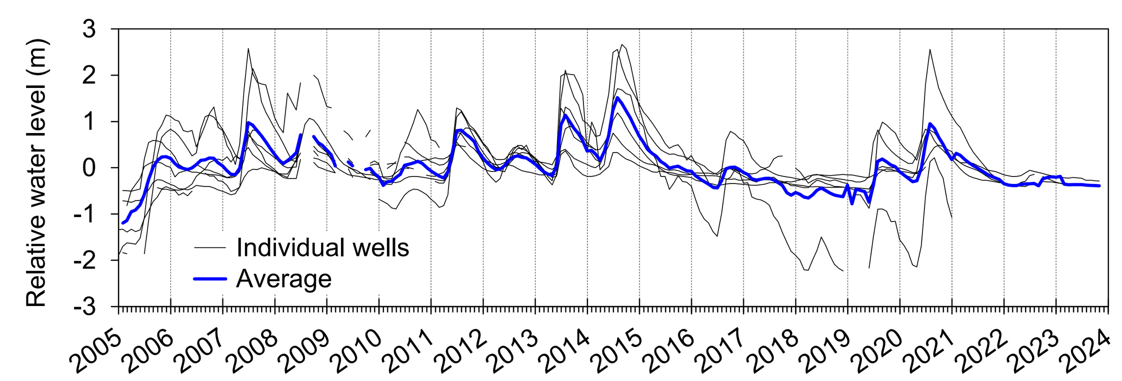


Fig. 6 Water levels in the WNC monitoring wells (see Fig. 1 for locations). Values are relative with respect to the long-term mean of each well. The thick line indicates the average of all wells with available data. Major tick marks on the horizontal axis indicate January 1.

Daily recharge fluxes simulated by the VSMB model were passed through a simple linear reservoir model (**Fig. 7a**) to demonstrate the effects of wet-dry fluctuations on groundwater recharge. Model-simulated aquifer water level had a decadal-scale pattern (**Fig. 7b**) resembling the observed water level in the watershed (**Fig. 6**).

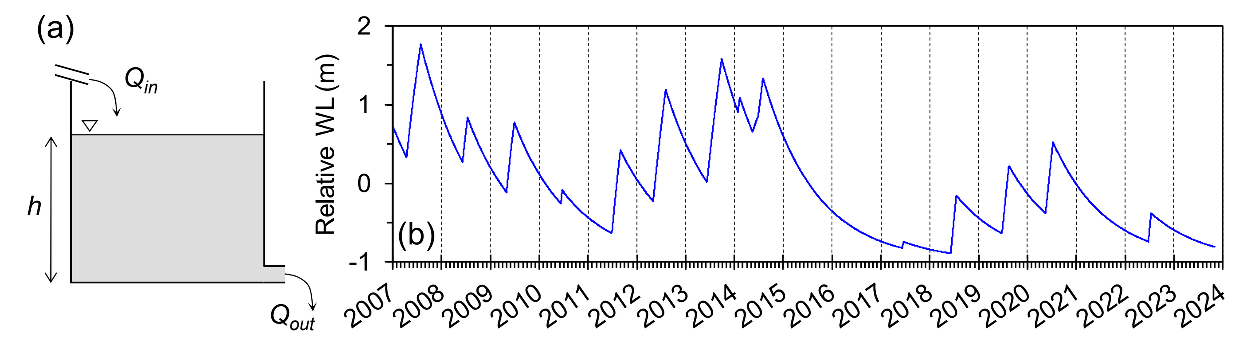


Fig. 7 (a) Simple linear-reservoir model representing the watershed-scale aquifer storage, consisting of recharge input (Q_{in}), discharge output (Q_{out}), and water level (h). (b) Response of the linear-reservoir aquifer response to interannual variability in recharge simulated by VSMB.

The summer baseflow in West Nose Creek is strongly influenced by evapo-transpiration uptake by dense riparian vegetation. Therefore, groundwater discharge is best represented by October baseflow (Hayashi and Farrow, 2014). The baseflow had strong inter-annual and inter-decadal variability, which was visibly correlated with the variability of groundwater level (**Fig. 8a**). This demonstrates the response of groundwater flow system to wet-dry fluctuations, which is indicated by the standard precipitation index (SPI) (**Fig. 8b**).

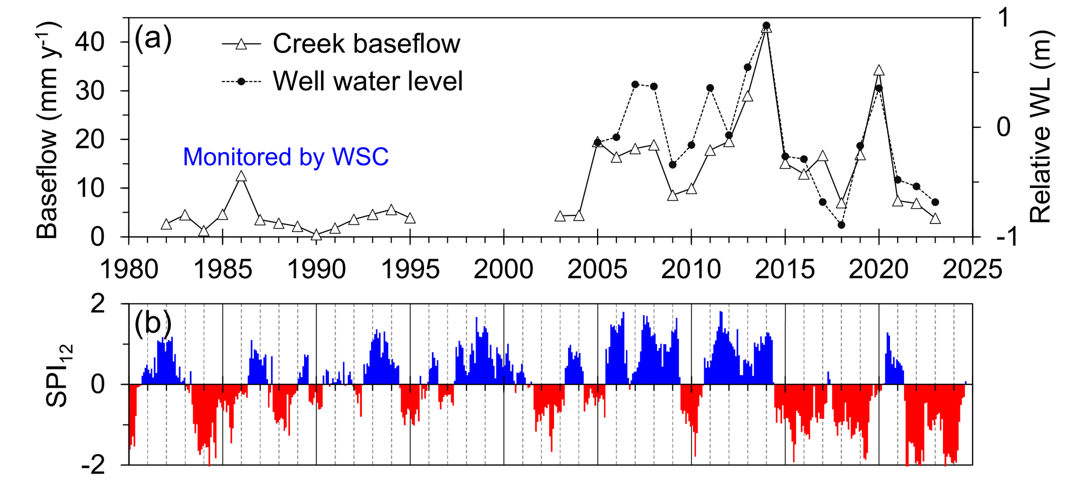


Fig. 8 (a) West Nose Creek (WNC) baseflow and the average water level WNC monitoring wells in October of each year. (b) Standard precipitation index (SPI) in Calgary, calculated with a 12-month leading period. Flow was monitored by the Water Survey of Canada (WSC) at the same location during 1982-1995 until the station was discontinued.

5. Conclusions

The groundwater flow system in prairie watersheds responds to wet-dry fluctuations at interannual and interdecadal scales. The system appears to have resilience to withstand multiple years of drought, sustaining the water supply and creek baseflow under the current climate and land use.

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