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Quantification of groundwater recharge using the chloride mass balance method in a semi-arid mountain terrain, South Interior British Columbia, Canada

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ABSTRACT

Groundwater recharge is essential to groundwater resources availability to economy and society development in semiarid areas. Chloride mass balance method to assess groundwater recharge have been review and was employed to quantify groundwater recharge in North Okanagan which is a semiarid mountainous terrain, southern interior British Columbian, Canada. Chloride concentration in precipitation was summed from the historical data observed by Environment Canada. Chloride concentration in groundwater associated with surface water was determined from groundwater samples and previous studies. The results indicated that estimate recharge at valley bottom as 10-16 mm/yr (1.1-1.9%) of precipitation and 7-11 mm/yr (1.8-2.7%) of precipitation on mountain areas appear useful. Errors in the estimated recharge rate maybe large because of the limited data used in this analysis.

Keywords: Chloride Mass Balance; Recharge; Semi-arid areas; Mountain Terrain

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INTRODUCTION

Recharge is the most important factor in evaluating groundwater resources in arid and semiarid environments, but it is often the most difficult parameter of the water balance to quantify. Groundwater recharge is defined as the entry into the saturated zone of water made available at the water-table surface, together with the associated flow away from the water table within the saturated zone. Groundwater recharge can also be defined generally as addition of water from the overlying unsaturated zone or surface water body.

The techniques of estimation of recharge in arid and semiarid regions include geochemical methods, isotopic methods, physical measurements, water-balance techniques, and temperature profiles, electromagnetic and modeling approaches. These techniques have been utilized and reviewed in previous studies [1-6].

The North Okanagan which consists of Deep creek watershed (DCW) and Fortune creek watershed (FCW) aquifer system is composed of valley bottom unconsolidated aquifers surrounded by bedrock highlands of variable composition, geological history and geometric configuration. MSR consists of several components. Runoff from the mountains that creates localized recharge of water to the alluvial aquifer system at the mountain front is termed mountain-front recharge (MFR). Diffuse recharge through the uplands leads to percolation through the mountain bedrock that reaches the basin via the movement of deep groundwater (mountain-block recharge, hereafter MBR).

The acronym MFR has traditionally been utilized to describe both processes collectively but recent literature has moved to separate the terms MFR and MBR.

This paper uses available historical data, and recent groundwater sampling to perform watershed scale chloride mass balance of the Deep Creek and Fortune Creek watersheds. The two watersheds are considered together as hydrogeological evidence indicates that moderate and deep depth groundwater flow within the Fortune Creek watershed passes southwards into the Deep Creek Watershed.

METHODOLOGY

Chloride is perhaps the most informative ion from a hydrochemical perspective. Due to the conservative nature of chloride, chloride mass balance (CMB) techniques are the most widely utilized approach for estimating recharge in unsaturated and saturated zones [7-12]. Scanlon et al summarized ~70 studies of groundwater recharge [13] which have applied of CMB methods in watersheds located across the globe.

The Deep Creek Watershed (hereafter DCW) and Fortune Creek Watershed (FCW) consist of mountain areas composed of bedrock with minimal coverage of Holocene soils, and valley bottom areas with considerable thicknesses of glacial and post-glacial clastic sediments ranging up to 450 meters thick. CMB is employed to improve the conceptual and quantitative understanding of recharge within this system which includes both MSR recharge from the bedrock uplands and recharge from the valley bottom via precipitation and stream losses.

The basic equation for quantifying recharge using the CMB method [4] is:

$$R = (P)(Cl_{wap})/Cl_{gw} \qquad \text{(Eqn. 1)}$$

Where R is the really averaged recharge flux to groundwater (mm/y); P is mean annual precipitation (mm); Cl_{wap} is the weighed average chloride concentration (wet and dry) in precipitation (mg/l); Cl_{gw} is the average chloride concentration in groundwater.

The precipitation-weighted average-chloride (Cl_{wap}) can be calculated using the following equation:

$$Cl_{wap} = \frac{\sum_{i=1}^{n} P_i Cl_{pi}}{\sum_{i=1}^{n} P_i} \qquad \text{(Eqn. 2)}$$

Where Cl_{pi} is chloride in precipitation (mg/l) of the sample; P is precipitation (mm/yr) of the sample; and n is the number of samples

Both Cl_{wap} and Cl_{pi} include the effects of both wet deposition of chloride ions at the ground surface, and dry deposition of chloride. Wet deposition of chloride occurs when chloride ions are dissolved in falling precipitation, and that precipitation is recorded at a ground surface precipitation gauge. Additional chloride mass may be a really deposited at the ground surface as dry deposition. This chloride is the result of dry solids deposited within the area such as windblown soil or dust particles, as well as chloride left behind by evaporation of water not recorded in the rainfall gauge. For example, precipitation falling on tree branches which does not reach the ground or water that adsorbed to dust particles suspended in the air column may subsequently evaporate and leave chloride within the watershed, but the precipitation volume is not recorded as the bulk precipitation. The weighted average chloride concentration must include chloride mass aerially distributed to the ground surface by both wet and dry processes.

Wet deposition can be measured via capture within a rain sampler that is only opened during precipitation events, and remains closed at other times, preventing dry deposition. Dry deposition is not easily directly measured. Bulk air sampling with filtering equipment can determine the mass of chloride contained within the air column as particulate or other forms. Calculation of dry deposition then requires consideration of the rate at which that the suspended particles/chloride mass settles to the ground surface during different climactic conditions. Computer modeling is used to determine dry deposition.

Cl_{wap} is therefore an equivalent concentration of chloride dissolved in precipitation that when multiplied by precipitation gives the correct really distributed mass flux of chloride to the ground surface.

Application of equation (1) requires several assumptions described the following conditions:

First, the only source chloride is from precipitation. This implies that the chloride concentration in groundwater reflects the degree to which the chloride in precipitation has been concentrated by evaporation, transpiration or sublimation.

Second, the aquifers system receives recharge only by direct precipitation on the surface and subsequent recharge through the vadose zone. This implies that there is no water leaving from the aquifers areas and there is no flow from underlying or adjacent aquifers.

Third, chloride must behave as a conservative species; chloride is not absorbed by the plant roots and soil, and does not react with any minerals, mineral surfaces or organic materials along the recharge flow path.

Equation (1) has been applied to estimate recharge in many regional and local aquifers where recharge to the aquifer is distributed really, and only occurs through net infiltration through the soil profile above the water table. In contrast, the DCW and FCW areas are different from these other studies. The valley basin aquifers system receives recharge from infiltration of precipitation on the valley bottom and recharge from the adjacent mountains (MSR). Surface runoff leaves from the aquifers area via Deep Creek and Fortune Creek. Groundwater within basin aquifers discharges into Okanagan Lake. The chloride mass balance method must therefore be re-written to reflect a basin scale chloride mass balance.

Based on basin scale water-balance approach, equation (1) can be modified to:

$$Cl_{gw} \times R_{tot} = (P_{tot}^{v} \times Cl_{wap}^{v}) + (P_{tot}^{m} \times Cl_{wap}^{m}) - (R_{s} \times Cl_{was}) \qquad \text{(Eqn. 3)}$$

Where Cl_{gw} is the average chloride concentration of groundwater within the two watersheds (mg/l); R_{tot} is the chloride weighted total precipitation recharge rate (mm/yr); $P^{v}{}_{tot}$ is the precipitation on valley bottom; $Cl^{v}{}_{wap}$ is the weighted chloride concentration on the valley bottom; $P^{m}{}_{tot}$ is the precipitation on the mountain areas; $Cl^{v}{}_{wap}$ is the weighted chloride concentration on the mountain areas; R_s is the mean annual surface runoff leaving from the two watersheds areas (mm); Cl_{was} is the weighted average chloride concentration of surface runoff water (mg/l).

Use of Equation 3 assumes that precipitation inputs to groundwater chloride and stream flow discharges of chloride have reached a steady state condition in which the concentration of chloride in groundwater is unchanging.

The surface water runoff weighted average-chloride (Cl_{was}) can be calculated using the following equation:

$$Cl_{was} = \frac{\sum_{i=1}^{n} R_{si} Cl_{si}}{\sum_{i=1}^{n} R_{si}} \qquad \text{(Eqn. 4)}$$

Where Cl_{si} is the chloride concentration in a surface runoff (mg/l) sample; R_{si} is the spatially averaged runoff (mm) that corresponds to the sample; and n is the number of samples. The chloride concentration in precipitation must be weighted to include both wet and dry chloride deposition, as discussed below.

The chloride mass balance method therefore assumes that all chloride in the groundwater of a basin aquifer system only comes from precipitation and that any increase in chloride concentration in groundwater over the concentration in precipitation occurs as the result evaporation from rainfall and snowmelt or sublimation of precipitation from snow. The assumptions necessary for successful application of this method in the DCW and FCW are:

(1) precipitation is the only source of chloride;
(2) chloride does not participate in any chemical reactions during water movement;
(3) steady-state conditions are maintained with respect to long term precipitation quantity and chloride concentration in that precipitation;
(4) chloride always dissolves into the water which implies that chloride is not absorbed by the soil or clay and plant roots when precipitation infiltrates into the vadose zone and chloride is not deposited or retained as halite in any above or below ground forms;
(5) no recycling of chloride occurs within the watersheds; and
(6) There is no permanent snow and thus all snow melts into water each year.

Two potential sources of chloride exist in the North Okanagan. Anthropogenic chloride is introduced for road salting, and in wastewater. Geological sources of chloride in the subsurface are possible if the bedrock contains evaporates, incompletely leached marine sediments, or porous rocks that have been in contact with the ocean.

DATA

Effective Chloride concentration in Precipitation

A literature survey and survey of Okanagan databases and prior studies was made to determine historical precipitation chemistry monitoring programs with data on precipitation chloride. This included NAtChem: National Atmospheric Chemistry Database/Precipitation Chemistry Database system, Canadian. The NAtChem Database system was set up by Environment Canada's Meteorological Service of Canada (MSC) in 1987 as a Canadian central database and analysis facility to accommodate and maintain diverse and variable precipitation sampling network data and combine them together in one centralized Canadian database.

The British Columbia provincial government maintained a precipitation chemistry monitoring programs during the mid 1980’s as far as the mid-1990. The long-term precipitation chemistry from the Kelowna and Kamloops precipitation sampling stations were available from NAtChem and are 0.288 mg/L and 0.357 mg/L.

Precipitation chemistry on mountain areas

The chloride concentration in precipitation in mountainous areas is typically lower than at the valley bottom. Data for Kelowna and Kamploops would overestimate high elevation precipitation chloride. Examination of the NAtChem database did not reveal any data from Canadian stations with a similar climate to the study area that were located at higher elevations. Data from NADP/NTN was used to estimate chloride in precipitation from two higher elevation stations (Table 1) located immediately south of the Okanagan valley in Washington and Idaho which are 0.077 mg/l and 0.053 mg/l.

Compensation for Dry Deposition

A total of eight of the 74 locations consisted of measures of both wet and dry deposition in Nevada [14-15]. The average concentration for the eight locations was 0.6 mg/l. The mean value for the other 66 locations where just wet deposition was measured was 0.4 mg/l. Dry deposition is estimated to be half of the wet deposition here. Murphy et al, 1996 indicate that dry deposition of chloride in semi-arid areas is approximately 60% of the total. Gates et al similarly estimated dry deposition to be 50% of total chloride input in studies within China [16].

Chloride in wet deposition in precipitation in the valley bottom in DCW and FCW was estimated to be between the measurements from the Kelowna and Kamloops stations.

The dry chloride deposition in study areas was estimated based on the studies above. The estimated range of precipitation-weighted average-chloride were presented in Table 1.

Table 1 Estimated range of precipitation-weighted average-chloride (Cl_{wap}, mg/l) within the study area valley bottom

Location	*Measured Cl concentration, Wet deposition*	*Estimated Dry deposition*		*Total deposition*	
		Min (60% total)	*Max (70% total)*	*Min*	*Max*
Kelowna	*0.288*	0.432	0.672	0.72	0.96
Kamloops	*0.357*	0.536	0.833	0.893	1.19
DCW&FCW	*0.288~0.357*	*0.432~0.536*	*0.672~0.833*	*0.72~0.893*	*0.96~1.19*

The effective chloride concentration in precipitation at the valley bottom in the DCW and FCW was estimated to range from 0.72 mg/l to 1.19 mg/l.The determination of chloride inputs on mountain areas are presented below in table 2.

Table 2 Determination of chloride concentration in precipitation on Mountain areas

locations	*Wet deposition*	*Dry deposition*		*Total deposition*	
		Min(60% total)	*Max(70)% total)*	*Min*	*Max*
WA15	*0.077*	0.116	0.18	0.193	0.257
ID02	*0.053*	0.08	0.124	0.133	0.177
DCW&FCW	*0.053~0.077*	*0.08~0.116*	*0.124~0.18*	*0.133~0.193*	*0.177~0.257*

Chloride concentrations in the historical station records increase northwards. Chloride concentrations within the study area likely should be higher than those reported in Washington and Idaho. The calculation above utilizes the higher estimate of dry deposition rate applicable for semi-arid areas for the sub-humid upland area. This leads to an upper estimate of chloride of 0.257 mg/l. This value will be utilized to estimate the recharge. The higher concentration of chloride leads to a greater estimate of recharge.

Groundwater and surface water Chloride Concentrations

A total of 42 groundwater samples were collected for geochemical analysis in the study area between March to November, 2007, and in July 2008. This included sampling of unconfined, moderate confined, deep confined and bedrock aquifers utilizing domestic, agricultural, Ministry of Environment observation and artesian wells. An additional 34 historical groundwater chemical analyses were collected from other sources for the areas of interest. The average chloride concentration in groundwater is 5.7 mg/l. The mean chloride concentration is 2.53~5.7 mg/l.

RESULTS

Based on the determination of the parameters above, equation (3) was applied. The estimated minimum recharge in the whole watershed is R_{tot} is 17.2 mm/yr. The estimated maximum recharge, R_{tot} , is 26.9 mm/yr. The groundwater in the valley bottom aquifers comes from Mountain System Recharge and infiltration of precipitation on valley bottom.

A two end-member mixing calculation was utilized to identify the percentage of recharge by MSR and valley bottom precipitation. Mixing between MSR and valley bottom precipitation infiltration can be quantified using equation (5)

$$Cl_g = x \bullet Cl^v_{wap} + (1-x)Cl_{MSR} \tag{5}$$

Where, Cl_g is the chloride concentration in groundwater within valley bottom aquifers, Cl_{MSR} is the concentration of chloride in bedrock.

Cl^v_{wap} is between 0.72 mg/l to 1.19 mg/l, Cl_{MSR} is 12.95 mg/l, Cl_g is 5.7 mg/l. Equation(5) is applied. Cl^v_{wap} is from 5.27 mm to 8.96 mm, MSR is from 11.91 mm to 17.90 mm, representing 1.1 -1.9% of long-term average annual precipitation on valley bottom and 1.8-2.7% of long-term average annual precipitation on mountain areas.

At a basin scale, the ratio between valley bottom recharge and mountain system recharge is approximately 40/60.

DISCUSSION

The parameters of chloride concentration in precipitation at the valley floor and on mountain areas, the chloride concentrations in surface water and in groundwater may all have variability. The records of precipitation chemistry monitoring in Kelowna and Kamloops are short (~10 years and ~5 years respectively) in comparison to the assumption of groundwater chloride reflecting a long term steady state average of groundwater recharge. It is likely that there is variability from year to year, and over millennia that is unaccounted for in our calculations. Redistribution of halite applied to Okanagan roadways in winter time was noted in the local precipitation samples obtained in both Kelowna and the study area.

Uncertainty in the recharge estimate is therefore large. The values of chloride in groundwater used in this estimation maybe vary by as much as 10-30% from the average value due to the aquifers' complex geology and subsequent heterogeneity of the aquifer materials. The "representative" value of chloride in Deep Creek may have little error based on the long-term chloride monitoring but the mean annual runoff volumes to Okanagan Lake maybe have 30-50% error due to lack of long term data.

The chloride concentration and runoff in Fortune Creek may also have 50% error in short of long term data. However, the result is reasonable comparison with studies at a global scale in arid and semi-arid regions.

CONCLUSION

The chloride mass-balance method applied at a watershed scale appears to offer a useful method to rapidly estimate groundwater recharge. The calculations above estimate recharge at valley bottom as 10-16 mm/yr (1.1-1.9%) of precipitation and 7-11 mm/yr (1.8-2.7%) of precipitation on mountain areas appear useful. However, errors in the estimated recharge rate maybe large because of the limited data used in this analysis.

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