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Investigation of Groundwater Contribution to Stream Flow under Climate and Land Use Changes: A Case Study in British Columbia, Canada

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Author's contribution

The author carried out all the analyses, developed the model, and prepared the manuscript.

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ABSTRACT

Groundwater contributes a significant proportion of stream flow, and its contribution varies temporally throughout the year. The objective of this study was to investigate the temporal dynamics of groundwater contribution to stream flow under the effects of climate and land use changes. A study area of the Mainstem sub-watershed of the Kiskatinaw River watershed, British Columbia, Canada was used as a case study. A physically conceptual model, Gridded Surface Subsurface Hydrologic Analysis (GSSHA), was developed for the study area. One greenhouse gas (GHG) emission scenario (i.e., B1: more integrated and environmental friendly world) was used for climate change study for 2012-2016, and land use changes scenarios were generated for short-term period (2012-2016) due to limited future projected land use data. The simulation results revealed that climate change affects significantly the temporal patterns of mean groundwater contribution to stream flow. Due to precipitation variability, these contributions varied monthly, seasonally, and annually. When land use changes (i.e., increasing forest clear cut area, and decreasing forest and agricultural areas) were combined with climate change scenarios, these contributions were decreased due to changes in the flow patterns to the regime with more surface runoff and stream flow but less groundwater discharge. Compared to the reference period (2007-2011), the mean annual groundwater contribution to stream flow from 2012 to 2016 under the B1 climate change scenario and the combined effects of B1 scenario and land use changes is expected to decrease by 1.8% and 4.3%, respectively, due to increased precipitation (on average 3.6% under the B1 scenario) and temperature (on average 0.36°C under the B1 scenario), and land use changes. The results obtained from this study will provide useful information for seasonal and annual water extractions from the river and allocation to the stakeholders for future water

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supply, as well as ecological conditions of the stream, which will be beneficial to aquatic ecosystems. They will also provide how land use changes can impact the groundwater contribution to stream flow, which will be useful for planning of water resources management considering future climate and land use changes.

Keywords: Groundwater contribution; stream flow; climate; land use; GSSHA.

1. INTRODUCTION

Groundwater provides one of the major sources of stream flow by contributing water to stream flow, and plays a vital role in maintaining the health of surface water bodies (e.g., stream, river, lake) because groundwater and surface water are closely linked components of the hydrologic system. This contribution occurs throughout the year, and it varies temporally over the year. Therefore, it is very important to understand and quantify the exchange processes between these two components for sustainable water resources management [1]. It has been recognized that the water resources system is extremely vulnerable to climate change [2-3]. The IPCC (Intergovernmental Panel on Climate Change) reported that the global atmospheric concentrations of greenhouse gases (GHG) will continue to increase in the following decades and lead to continuing climate change [4]. Climate change impact studies have been conducted by more focusing on surface water bodies than on groundwater because groundwater is less visible and has a more complex relationship with climate [5-6]. Due to the importance of groundwater resources, climate change impact studies on groundwater have received increasing attention from many scientists during the last decade. For example, Scibek et al. [5] conducted a case study of an unconfined aquifer in the Grand Forks valley in south-central British Columbia, and they developed a methodology for linking climate models, hydrologic model (i.e., HELP), and groundwater flow model (i.e., Visual MODFLOW) in order to investigate the impacts of climate change on groundwater resources. Van Roosmalen et al. [7] used the DK model (The National Water Resource model for Denmark) based on MIKE SHE code to study climate change impacts on groundwater system for two study areas in Denmark. Krause et al. [8] used the IWAN (Integrated Water Balance and Nutrient Dynamics Model) model to simulate exchange fluxes between surface water and groundwater of a riparian floodplain in Germany. Jenkins [9] used the GSSHA (Gridded Surface Subsurface Hydrologic Analysis) model to investigate groundwater-surface water interaction in the floodplain of Rio Grande River, New Mexico, USA during high and low flows in Rio Grande River. Dams et al. [10] used a coupled model of WetSpa and MODFLOW to study climate change impacts on the groundwater system in the Kleine Nete basin in Belgium. Vansteenkiste et al. [11] compared the estimations of climate change impacts on the flow regime in the Grote-Nete catchment in Belgium by using two spatially distributed models, MIKE SHE and WetSpa. In general, most of the previous studies reported how the mean annual groundwater level and groundwater recharge or discharge (i.e., mean of 20 to 40 years) would change under different climate change scenarios. Only a few studies reported how these variables show monthly variation between current and projected future climates [7,10-11]. There is little knowledge regarding how the mean monthly groundwater contribution to stream flow will change under different climate change scenarios. In addition, land use changes can also significantly affect groundwater recharge and discharge, and surface water flow patterns by altering soils' infiltration rates [12]. For example, increasing urban area resulted in decreasing groundwater discharge, and increasing stream flow and surface runoff [13-17]; the conversion of perennial vegetation to seasonal growing crops in the Mississippi River Basin resulted in increased groundwater discharge and stream flow, and decreased surface runoff [18-19]; changing agricultural area into grasslands in a sub catchment of Havel River, Germany, resulted in decreased groundwater discharge [20]; the conversion of grassland into forest in the western part of Jutland, Denmark, resulted in decreased groundwater discharge [21]. In general, previous studies reported how the mean annual groundwater recharge and discharge, stream flow, as well as groundwater level would change under different land use change scenarios. However, little attention was paid to investigate how the mean monthly, seasonal and annual groundwater contributions to stream flow will change under both changing land use and climatic conditions. In fact, such information could determine the monthly status of groundwater resources and site conditions for groundwater-dependent terrestrial ecosystems [22]. They will also determine the monthly, seasonal and annual variations of stream flow dependency on groundwater, and these will provide useful information for both short and long-term water supply decisions making.

This research attempts to investigate groundwater contribution to stream flow under climate and land use changes effects using a study area along the river of the Mainstem sub-watershed of Kiskatinaw River Watershed (KRW) in north-eastern British Columbia as a case study through the developed GSSHA model. The monthly, seasonal and annual groundwater contributions to stream flow under the B1 GHG emission scenario and the combined effects of the B1 GHG emission scenario and land use changes were investigated for a short-term period of 5 years (2012 to 2016) due to limited future projected land uses data. The annual land use maps from 2012 to 2016 were used in the developed GSSHA model.

2. MATERIALS AND METHODS

2.1 Details of Study Area

The study area (213.82 km^2) is a part of the Mainstem sub-watershed, which is a sub-watershed of the Kiskatinaw River Watershed (KRW) and located in north-east British Columbia, Canada (Fig. 1). The KRW is divided into 5 sub-watersheds, including (a) Mainstem (433 km^2), (b) East Kiskatinaw (996 km^2), (c) West Kiskatinaw (1005 km^2), (d) Halfmoon-Oetata (194 km^2), and (e) Brassey (208 km^2) [23]. The City of Dawson Creek has been drawing water from Kiskatinaw River for drinking purpose since the mid-1940s because the groundwater in this region contains high total hardness [24]. In addition, the drinking water intake of the water supply system for Dawson Creek is situated at Arras in the study area. The study area has an elevation ranging from 687 m to 950 m and an average slope of 7.8% [25]. Clay loam covers the majority of the study area. Clay loam, silt loam and sandy loam cover 91%, 6%, and 3%, respectively of the study area (Fig. 2a) [25]. Forest, forest clear cut, agriculture, wetland, water, and built up area cover 68%, 18.7%, 8%, 2%, 1.8%, and 1.5%, respectively of the study area (Fig. 2b).

During the last 40 years, the City of Dawson Creek has experienced steady water demand growth with an average annual growth rate of about 3.2% [24]. In addition to providing a community water supply, the KRW has many other values, such as timber harvesting, agriculture, oil and gas, wildlife, recreation, and potential mineral resources development. In particular, a large and increasing scale of timber harvesting, oil and gas exploration/production, and agricultural activities in recent years have caused growing concerns to various water users. The KRW is a rain dominated hydrologic system with peak flows occurring from late June to early July. On average, it receives an annual precipitation of 499 mm, consisting of 320 mm of rainfall, and 179 mm of snow [24]. Based on the regional groundwater flow field of the study area, groundwater contributes to the river system in the major parts of the study area [25]. However, there is no available information about groundwater contribution to river flow in this study area as well as in the KRW which is very important to develop future water resource management and water allocation plan under changing climatic and land use conditions.

2.2 Data Collection

Observed precipitation, temperature and other meteorological data (i.e., wind speed, relative humidity, and solar radiation) collected from nearby three weather stations in the KRW were averaged to get daily distribution of those parameters for 2000 to 2011. Stream flow data at Arras site (i.e., outlet of the study area) during 2006-2011 were collected from nearby Water Survey Canada station. A digital elevation model (DEM) data in 13.74 m by 23.81 m grid was collected from Canadian Digital Elevation Data (CDED). Due to the limited available information regarding the stratification of soils of the study area, the soils of the study area were assumed as isotropic. Land use maps (30 m by 30 m grid) for the study area in 1999 and 2010 were generated from Paul's [26] results using Arc GIS. The details of this land use map generation can be found in Paul [26]. It is to be noted that in this study land use map in 2010 was kept constant to all other years due to lack of maps on those years for maintaining simplicity for model calibration and validation, as well as future climate change effects on groundwater contribution to stream flow.

2.3 GSSHA Hydrological Model

GSSHA is a physically based, distributed parameter, and structured grid based hydrologic model that simulates the hydrologic response of a watershed given hydrometeorological inputs. It simulates major processes include spatially and temporally varying precipitation, snowfall accumulation and melting, precipitation interception, infiltration, evapotranspiration, surface runoff routing, unsaturated zone soil moisture accounting, saturated groundwater flow, overland flow, sediment erosion, transport and deposition and instream sediment transport. Each process simulated has its own time-step and associated update time. During each time-step the update time is compared with the current model time, and when they match, the process is updated and the information is transferred to dependent processes. This formulation allows the simultaneous simulation of processes that have dissimilar response times, such as overland flow, evapotranspiration, and lateral groundwater flow. The details of GSSHA can be found in Downer [27]. In this model, infiltration is calculated using the Green and Ampt infiltration with redistribution (GAR) method [28]. Overland flow routing is simulated using the alternating direction explicit (ADE) finite difference method, and channel routing is simulated using an explicit solution of the diffusive wave equation. Water flux between the stream and the saturated groundwater is calculated based on Darcy's law.

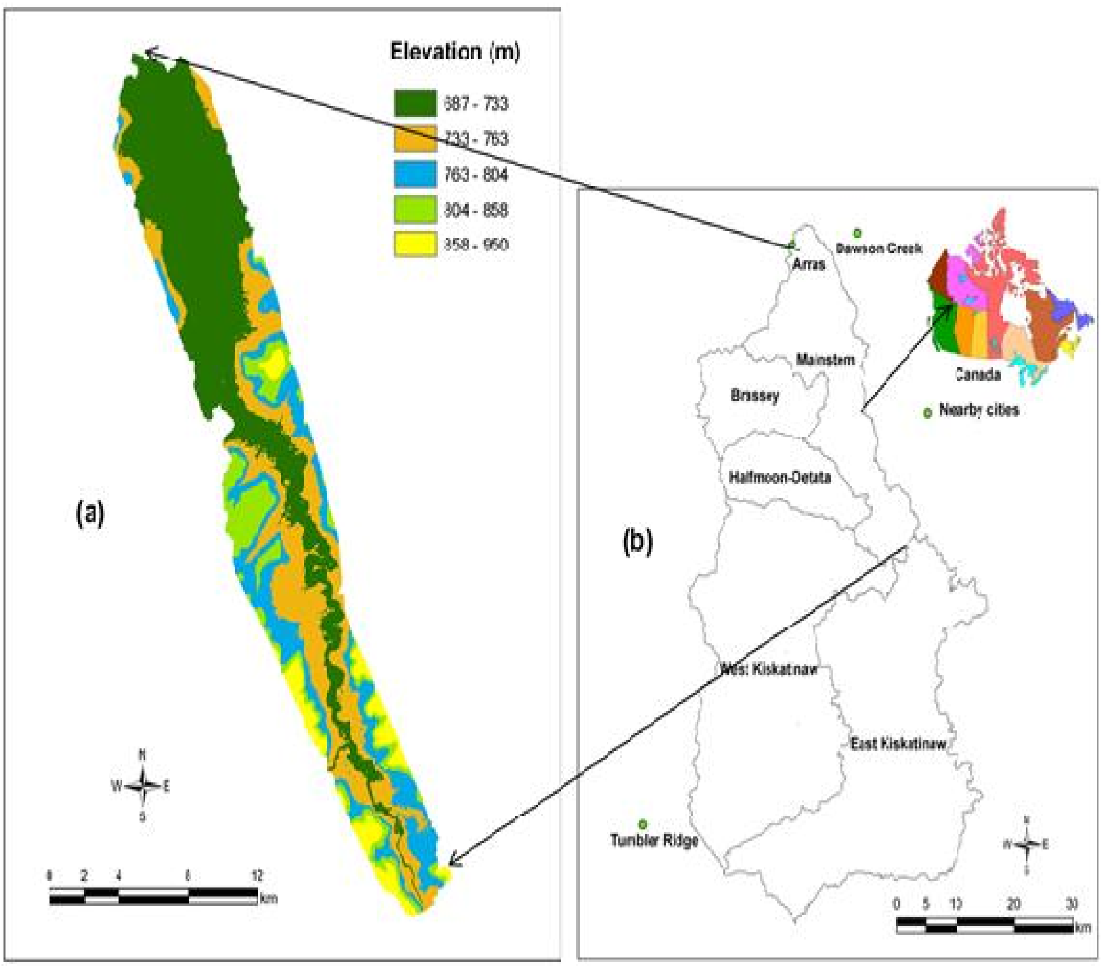

Fig. 1. (a) Digital elevation map of the study area, and (b) its location in the KRW as well as in Canada

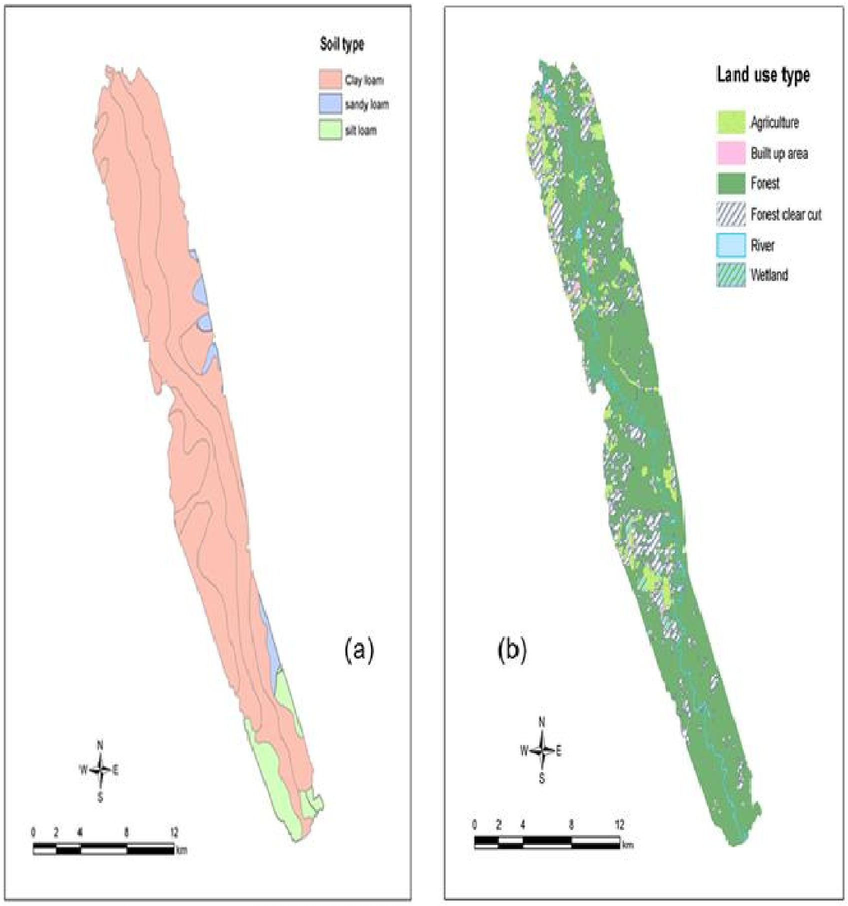

Fig. 2. (a) Soil type and (b) year 2010 land use maps of the study area

2.4 Model Development

During GSSHA model development, Watershed Modeling System (WMS) Version 8.4, a graphically-based software environment, was used for delineating watershed, importing land use map and segmentation, defining segment cross section parameters, developing reach segment parameters, defining climate and meteorological input time series data. Using WMS, a 2-D GSSHA grid with spatial resolution of 30 m by 30 m was chosen for simulation based on available grid sized DEM and land use maps. In a distributed model like GSSHA, land use and soil type data are needed to convert into index maps so that parameter values can be easily assigned to each individual grid cell. In this study, three index maps were prepared for parameter assignment at the grid level: a soil type index map, a land use index map and a combined land use and soil type index map. In addition to these maps, aquifer bottom and initial groundwater table maps were prepared to simulate groundwater contribution to stream flow using GSSHA model. Initial groundwater table map in the study area was prepared using inverse distance weighted (IDW) interpolation method and observed groundwater table data collected from groundwater monitoring network. Aquifer (unconfined) bottom map in the study area was prepared using IDW interpolation method and bore log data of a few existing wells in the KRW and its surrounding area collected from the database of British Columbia Water Resources Atlas [29]. The distance between aquifer bottom elevation and ground elevation was then used to create the vertical layer of the modeling domain. Since the GSSHA model only provides 2-D grid, therefore, vertical discretization of the modeling domain is not necessary. Before using these collected groundwater table data, barometric pressure correction was applied on those data because groundwater table fluctuates by atmospheric pressure with altitude change [30]. The barometric pressure correction was made according to the technical guidelines of Solinst [31]. The barometric pressure data were collected from the three nearby weather stations because no barologger was used in this study.

2.5 Model Calibration and Validation

In GSSHA there are two types of boundary conditions; one is for groundwater boundary condition around the perimeter of the study area, and the other is groundwater boundary condition for stream. For groundwater boundary condition around the perimeter of the study area, no flow boundary condition was assumed based on previous studies results [32]. For stream routing, flux river was chosen as groundwater boundary condition for stream because a significant amount of water goes into the subsurface (groundwater) flow from stream network. After developing the model, it was calibrated using automated calibration because manual calibration takes long time to pick parameters and tedious. Generally, the GSSHA model is calibrated and validated using observed stream flow. However, due to lack of sufficient data, the GSSHA model in this study was calibrated and validated using observed stream flow, and groundwater contribution to stream flow. The developed GSSHA model was calibrated using measured stream flow by changing soil parameters (i.e., hydraulic conductivity, and porosity), overland surface roughness, channel roughness, overland retention depth, initial soil moisture, and soil moisture depth. The coefficient of determination (R^2), and coefficient of efficiency (NSE: Nash-Sutcliffe efficiency) were used to evaluate the goodness-of-fit of this hydrologic model. Due to limited observed stream flow data, the model calibration was performed from October 15th, 2010 to December 31st, 2011, and validation was performed from October 15th, 2006 to October 15th, 2010. It is to be noted that there was flood in 2011, and the model calibration was performed to assess the performance of the model during flooding year, and model validation was performed in normal precipitation years. During calibration of the developed model (Fig. 3a), R^2= 0.65, and NSE=0.61 were found. Santhi et al. [33] and Van Liew et al. [34] mentioned that R^2 value greater than 0.5 is considered as acceptable for model evaluation. In addition, the United States Environmental Protection Agency (US EPA) [35] stated that R^2 value between 0.6 and 0.7 shows fair performance for hydrologic models. Based on these evaluation statistics guidelines, the developed model fulfills all the criterion. During validation (Fig. 3b), R^2= 0.62, and NSE=0.59 were found.

The GSSHA model was also calibrated and validated using the calculated mean monthly groundwater contribution to stream flow based on the PART base flow separation program of the USGS [36]. In the PART program, groundwater contribution to stream flow is expressed as a base flow index. This program estimates daily base flow by considering it to be equal to stream flow on days that fit a requirement of antecedent recession, and then linearly interpolating it for other days in the stream flow record. Based on these daily values, the mean monthly groundwater contribution to stream flow was calculated. On the other hand, the GSSHA model estimates monthly total volume of stream discharge (flow) and groundwater discharge, and based on those values the mean monthly groundwater contribution to stream flow was calculated [37]. The calculated groundwater contribution to stream flow in the study area by PART program for the period of January 2007 to December 2009 was used for GSSHA model calibration, with R^2 = 0.92 and NSE = 0.74. The PART-calculated groundwater contribution to stream flow in the study area for the period from January 2010 to December 2011 was used for GSSHA model validation, with R^2 = 0.71 and NSE = 0.55. As a result, the developed GSSHA model holds satisfactory modeling performance. The comparison of mean monthly groundwater contribution to stream flow from January 2007 to December 2011 calculated by the PART program and simulated by GSSHA model is shown in Fig. 4.

2.6 Generation of Climate Scenario

In this study, precipitation and temperature for the short-term (2012-2016) period were downscaled from CRCM 4.2 (Canadian Regional Climate Model) modeling outputs of CCCma (Canadian Centre for Climate Modeling and Analysis) using the delta change method under the B1 greenhouse gas (GHG) emission scenario of SRES (Special Report on Emissions Scenarios) of the Intergovernmental Panel on Climate Change (IPCC) [38]. The details of all GHG emission scenarios are presented in Table 1.

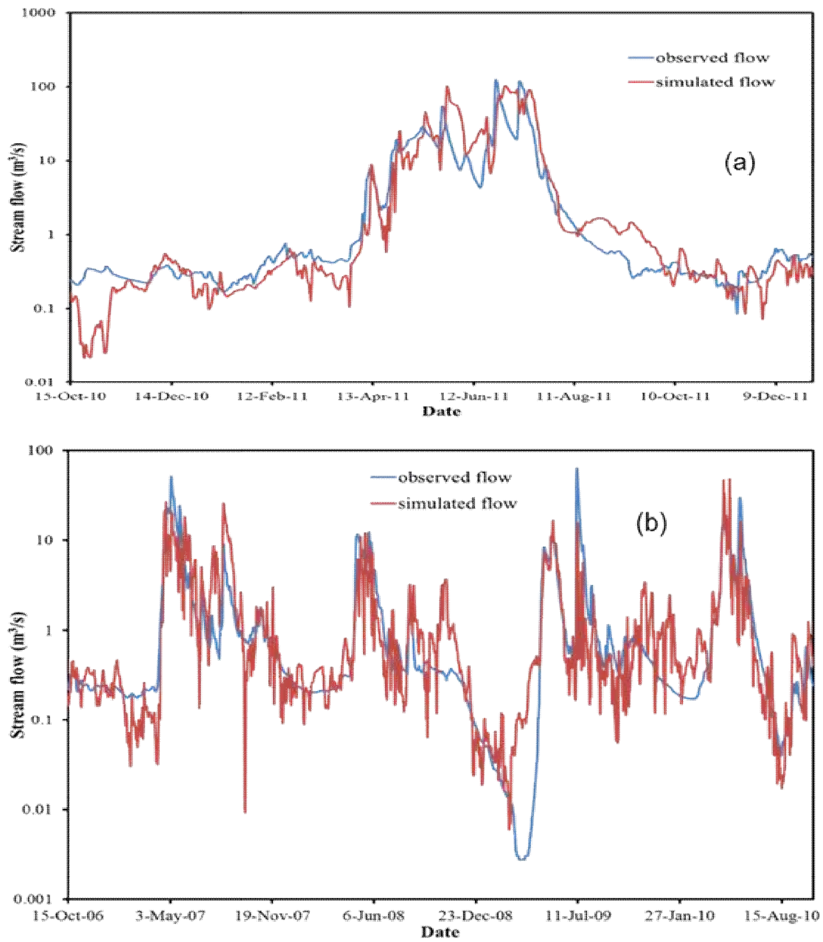

Fig. 3. Comparison of observed and simulated stream flows by GSSHA model at the outlet of the study area during (a) calibration and (b) validation periods

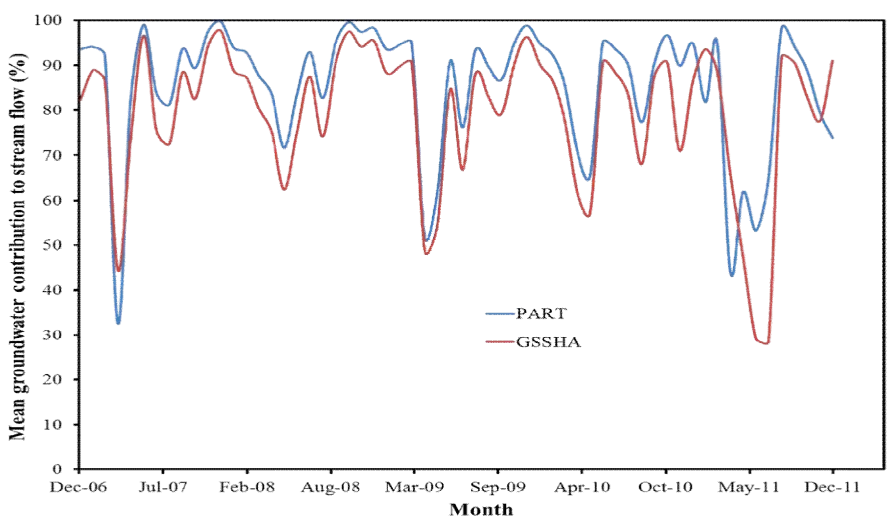

Fig. 4. Comparison of mean monthly groundwater contribution to stream flow calculated by the PART program and simulated by the GSSHA model

Table 1. GHG emission scenarios [38]

Emission scenario	Description
A1	• The A1 scenario describes a convergent world that becomes more homogeneous with increased social and cultural interactions • Very rapid economic growth • Global population reaches peak in 2050 and then gradually decreases • Quick introduction of new and more efficient technologies • The A1 scenario is divided into 3 subsets based on their energy sources: fossil intensive (A1FI), non-fossil intensive (A1T), and balanced of all sources (A1B)
A2	• The A2 scenario describes a very heterogeneous world with self-reliance and preservation of local identities • Economic development is regionally oriented • Global population is increasing continuously • More fragmented and slower technological change than other scenarios
B1	• The B1 scenario describes a more integrated and environmental friendly world • Emphasis is given on global solutions to economic, social and environmental sustainability • Global population that peaks in mid-century and thereafter declines • Rapid change in economic structures in service and information economy due to the reduction of material intensity and the introduction of clean and resource-efficient technologies
B2	• The B2 scenario describes a heterogeneous world • Global population increases continuously but at a lower rate than under the A2 scenario • Emphasis on local solutions to economic, social and environmental sustainability • Less rapid and more diverse technological changes than under the A1 and B1 scenarios

In this study, the B1 scenario was chosen because it describes a more integrated and environmental friendly world, which is characterized by lower population and global solutions to economic, social and environmental stability. The output from the CRCM (45 km grid) is monthly means for the B1 GHG emission scenario. These monthly mean values were distributed as daily value for every day in the particular month using delta change downscaling method, which is a commonly applied method to cope with biases when using climate model outputs in hydrological impact studies at catchment or sub-watershed scale [39-40]. It is a simple way of transferring the change in a meteorological variable, as simulated by the climate model, to an observed data set to create a scenario climate data set. A number of studies used the delta change method for hydrological impact assessments in Scandinavia [41-45]. In this study, the monthly delta change values for precipitation and temperature were determined for the watershed scale from the CRCM 4.2 simulation outputs because these outputs are from a 45-km horizontal grid-size mesh [46]. Absolute changes were used for temperature because it is a state variable and not a flux, whereas the relative change factors were applied for precipitation because it is a flux [47]. For temperature, the procedure of delta change method is as follows:

$$T_{\Delta}(i,j) = T_{obs}(i,j) + \Delta_T(j), \quad i = 1, 2 \ldots 31; \; j = 1, 2 \ldots 12 \qquad (1)$$

where T_{Δ} is the temperature input for the future hydrological scenario simulation, T_{obs} is the observed temperature in the historical period, (i, j) stand for day and month, respectively, and Δ_T is the change in temperature. This Δ_T value is calculated by Eq. 2.

$$\Delta_T(j) = \overline{T}_{scen}(j) - \overline{T}_{ctrl}(j), \quad j = 1, 2, 3 \ldots 12 \qquad (2)$$

where $\overline{T}_{ctrl}$ (j) is the mean daily temperature for month j and it is calculated as the mean of temperature of all days in month j for all 12 years of the reference (i.e., control) period; $\overline{T}_{scen}$ (j) is the mean daily temperature for month j of each particular year from 2012 to 2016. The indices "scen" and "ctrl" stand for the scenario period (2012-2016) and the control period (2000-2011), respectively. This led to 12 monthly delta change values for each year from 2012 to 2016, and they were used to adjust the observed daily temperature within the individual months for future temperature input.

For precipitation, the delta change method can be described as follows:

$$P_{\Delta}(i,j) = \Delta_p(j) * P_{obs}(i,j),$$

$$i = 1, 2 \ldots 31;\ j = 1, 2 \ldots 12 \quad (3)$$

where P_{Δ} is the precipitation input for the future hydrological scenario simulation, P_{obs} is the observed precipitation in the historical period, (i, j) stand for day and month, respectively, and Δ_p is the change in precipitation, which can be calculated by:

$$\Delta_p(j) = \frac{\overline{P}_{scen}(j)}{\overline{P}_{ctrl}(j)}, \quad j = 1, 2 \ldots 12 \quad (4)$$

where $\overline{P}_{ctrl}$ (j) is the mean daily precipitation for month j and it is calculated as the mean of precipitation of all days in month j for all 12 years of the reference period, and $\overline{P}_{scen}$ (j) is the mean daily precipitation for month j of each particular year from 2012 to 2016. The indices "scen" and "ctrl" stand for the scenario period (2012-2016) and the control period (2000-2011), respectively. One of the advantages of the delta change method is that a bias correction of the RCM data is not necessary because the change in variables between the scenario and the control period is used and the bias is assumed equal for both the control and scenario simulations. Another advantage of the delta change method is that an observed database is used as the baseline resulting in a consistent set of scenario data, whereas the use of climate model output directly could result in unrealistic dynamics in input variables due to climate model variance. On the other hand, the use of an observed database is also a drawback of this method because information on the changes in variability and extremes in the future climate as simulated by the climate model is lost. Therefore, the delta change method is more applicable for impact studies on groundwater systems than surface water systems because groundwater systems are more sensitive to changes in means than to changes in extremes [47].

2.7 Results of Climate Change

Fig. 5a presents the projected monthly precipitations from 2012 to 2016 under the B1 scenario. The future monthly precipitations of the study area under the B1 scenario show variable patterns annually due to the anthropogenic increases in the atmospheric concentrations of greenhouse gases [38,48]. On average, the mean winter, spring, summer, and fall precipitations from 2012 to 2016 are 112 mm (σ=15 mm), 94 mm (σ=8 mm), 164 mm (σ=13 mm), and 140 mm (σ=11 mm), respectively. This shows that the mean winter, spring, summer, and fall precipitations from 2012 to 2016 under the B1 scenario is expected to increase by 3 mm (2.5%), 1 mm (1%), 6 mm (4%), and 2 mm (1%), respectively, in relation to the mean winter, spring, summer, and fall precipitations from 2000 to 2011. Similarly, due to the anthropogenic increases in the atmospheric concentrations of greenhouse gases, these types of variable trends are found [38,48]. The mean annual precipitation of 2012-2016 under the B1 scenarios is 510 mm (σ=11 mm), and this number is above the mean annual precipitation of 2000-2011 by 12 mm (2.5%). Similar types of increase precipitation patterns were predicted in northern British Columbia by BC Ministry of Forests and Range [49].

The trend of mean monthly temperatures is similar in every year under the B1 scenario (Fig. 5b), with the highest and lowest mean monthly temperatures occurring in July and January, respectively, which are similar to those of 2000-2011. On average, the mean winter, spring, summer, and fall temperatures from 2012 to 2016 are -13.03ºC (σ=0.89ºC), 3.19ºC (σ=0.45ºC), 17.54ºC (σ=0.42ºC), and 4.12ºC (σ=0.29ºC), respectively, which are corresponding to an increase by 0.53ºC, 0.03ºC, 0.11ºC, and 0.12ºC, respectively, as compared to those of 2000-2011. Similarly, due to the anthropogenic increases in the atmospheric concentrations of greenhouse gases, these types of variable trends are found [38,48]. The mean annual temperature also increases as compared to that of 2000-2011. On average, the mean annual temperature from 2012 to 2016 is 2.99ºC (σ=0.18ºC), which is increased by 0.29ºC from that of 2000-2011. Similar predictions were done in northern British Columbia by BC Ministry of Forests and Range [49].

2.8 Land Use Changes Analysis

The land use changes in the study area between 1999 and 2010 are shown in Table 2. In this table, land use change per year was calculated considering linear land use change in every year due to limited information available. The results show that the major land use changes occurred in forest clear cut and wetland. As compared to that in 1999, forest clear cut area increased by about 735% in 2010, while wetland area decreased by about 59%. The rapid change in forest clear cut area was due to a large scale of oil/gas exploration and production, while the rapid change in wetland area may have occurred due to the shift of vegetation and oil/gas exploration/production in the study area. It is also found that river (including small channels) and built up area (e.g., road, house, industrial infrastructures) increased by about 20% and 96%, respectively, from 1999 to 2010, while agriculture (e.g., cropland and pasture) and forest decreased by 44% and 11%, respectively.

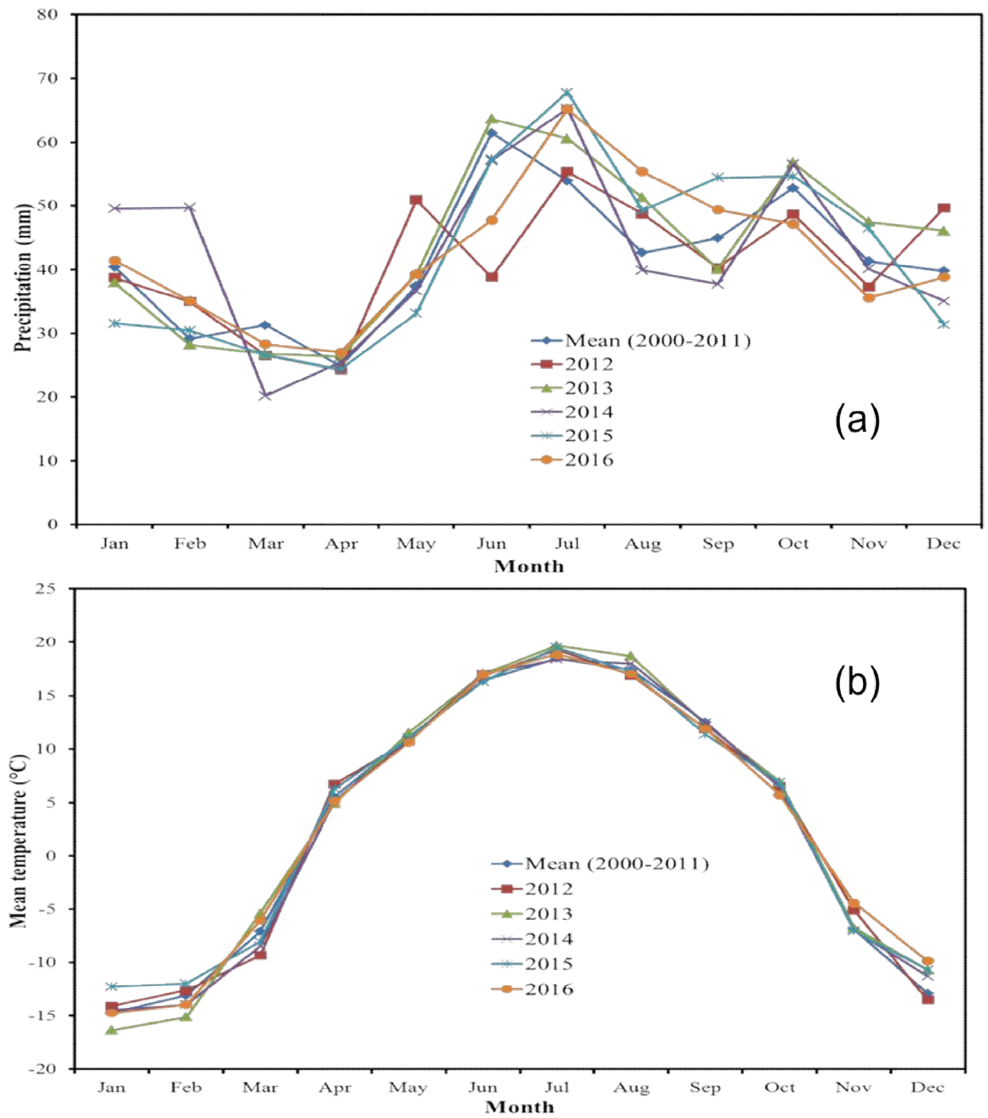

Fig. 5. Projected (a) monthly precipitations and (b) mean monthly temperatures of the study area in KRW from 2012 to 2016 under B1 scenario

Table 2. Land use changes from 1999 to 2010 in the study area. Change (%) = [(Area of 2010 land use - Area of 1999 land use)/ Area of 1999 land use] × 100

Land use type	Area (km^2) in 1999	Area (km^2) in 2010	Change (km^2)	Change (%)	Change/year (km^2/year)
Forest	163.36	145.35	-18.01	-11	-1.64
Agriculture	31.42	17.74	-13.68	-44	-1.24
Forest clear cut	4.78	39.89	35.11	735	3.19
Wetland	9.58	3.94	-5.64	-59	-0.51
River	3	3.6	0.6	20	0.05
Built up area	1.68	3.3	1.62	96	0.15
Total	213.82				

2.9 Future Land Use Scenarios

Based on land use change analysis between 1999 and 2010, future annual land use index maps from 2012 to 2016 were generated using Arc GIS and GSSHA through the following considerations. Due to the unavailability of land use map for year 2011, year 2010 land use data were assumed for year 2011.

- Future annual land use index map considers the annual change of only forest clear cut, forest and agriculture areas because they cover 18%, 68%, and 8% of the study area, respectively, based on the 2010 land use map. It is to be noted that large-scale shale gas exploration/production activities have started in the KRW since 2005 [50]. In addition, Forest Practices Board [51] also predicted an increase of forest clear cut area in the KRW until 2017.
- Due to limited data availability, the future annual land use index map was developed by assuming that the forest and agriculture areas are converted into forest clear cut area at the conversion rate shown in Table 2 (i.e., forest and agricultural area will be reduced by 1.64 km^2 and 1.24 km^2 annually, respectively). The summation of annual forest and agricultural areas reduction was added to the annual increase of forest clear cut area. Drohan et al. [52] also found a similar conversion of agricultural and forest areas in Pennsylvania into gas well pads, which is a part of forest clear cut area in this study. The projected land use types from 2012 to 2016 are then presented in Table 3. A similar rate of linear land use changes from 2000 to 2020 was also used in Dams et al. [16].
- In this study, the annual conversion of forest and agriculture areas into forest clear cut area was assumed in May of every year since in the study area, most of the snowmelt occurs in April. In addition, temporal land use changes during the year are difficult to detect due to lack of proper information (e.g., clear monthly satellite images).
- The spatial allocation of future land use changes was determined based on the change of a particular land use type and how much of that particular land use type has changed spatially between 1999 and 2010. For example, the reduced agriculture area at a particular site between 1999 and 2010 was used to calculate the future annual agriculture area reduction around that site. Special attentions were paid to allocate future land use types as per the guidelines of Kiskatinaw River Watershed Management Plan by Dobson Engineering Ltd. et al. [24], especially in the areas that are close to Kiskatinaw River. In addition, the major land use changes occurred in 0 – 4.6% slope areas in the study area because topography also plays a major role in soil erosion, for example, steeper slope area is more susceptible to higher soil erosion during heavy rainfall events than milder slope area [53-54]. The future annual land use index maps of 2012 and 2016 shown in Figs. 6a and 6b, respectively, considering seasonal tributary drains of the study area were generated in GSSHA based on its digital elevation map and the above considerations. In these land use index maps, different types of land uses overlap river networks, especially seasonal tributary drains. This occurs because only the main river was considered in the original land use map due to the resolution of remote sensing images (i.e., 30 m by 30 m), and the seasonal tributary drains are very narrow compared to Kiskatinaw river.

Table 3. Projected land use types from 2012 to 2016 with respect to base line of 2011

Year	Forest (km^2)	Agriculture (km^2)	Forest Clear cut (km^2)
2011	145.35	17.74	39.89
2012	143.71	16.5	42.77
2013	142.07	15.26	45.65
2014	140.43	14.02	48.53
2015	138.79	12.78	51.41
2016	137.15	11.54	54.29

3. RESULTS AND DISCUSSION

3.1 Groundwater Contribution to Stream Flow under B1 Scenario

During the study of climate change effects on groundwater contribution to stream flow, land use of the study area was kept constant, and the land use map of year 2010 was used. The simulated results were analyzed on a mean monthly basis. Fig. 7 illustrates the mean monthly groundwater contributions to stream flow under climate change condition of B1 GHG emission scenario for 2012-2016. It is shown that the mean monthly groundwater contribution patterns vary annually due to monthly precipitation fluctuations, which result in variable monthly stream and groundwater discharges [7,55-58]. Therefore, climate change significantly affects stream and groundwater discharges, as well as the patterns of mean monthly groundwater contribution to stream flow. The 2012 mean monthly groundwater contribution to stream flow ranges between 45% in May and 99% in December. The remaining portion comes from surface runoff. Similar trends are expected for years 2013 to 2016. These results demonstrate that stream flow depends mostly on groundwater flow in those months when there is highest groundwater contribution to stream flow, and vice versa [59].

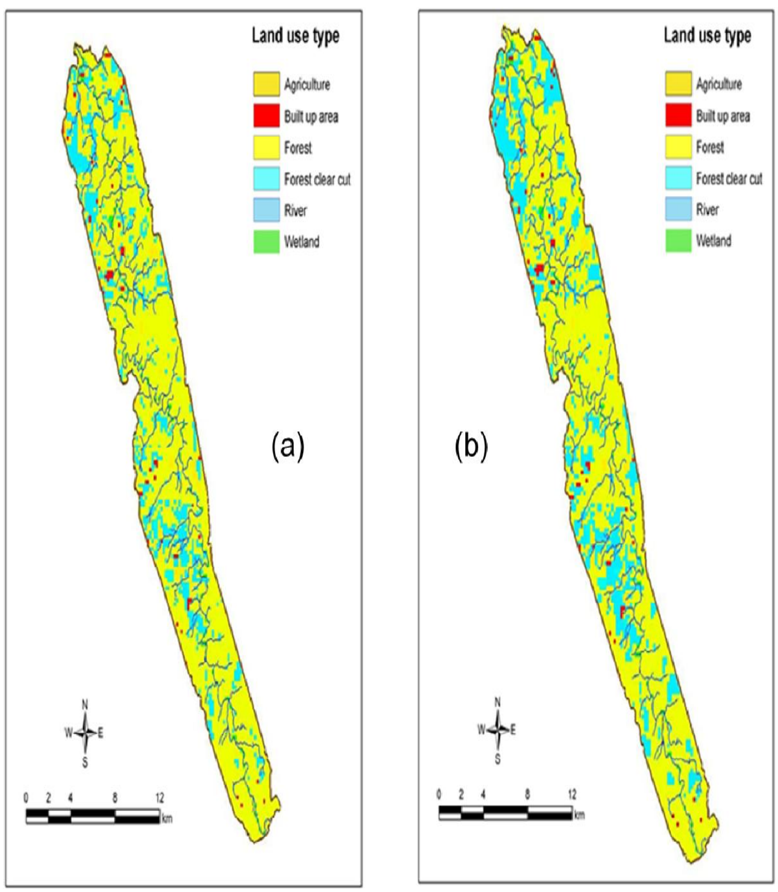

Fig. 6. Land use index maps of year (a) 2012 and (b) 2016

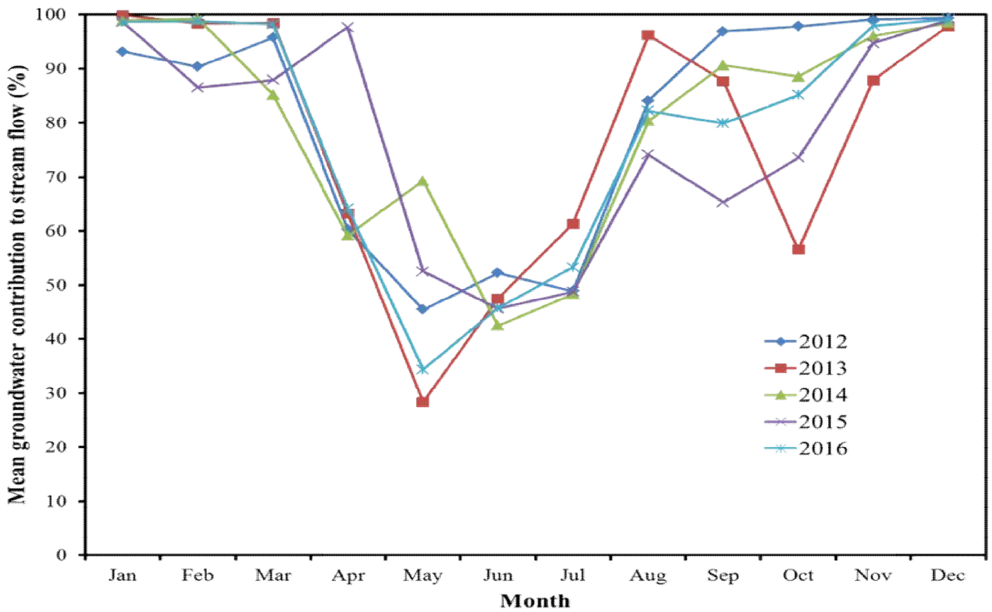

Fig. 7. Mean monthly groundwater contributions to stream flow under climate change of B1 GHG emission scenario for 2012-2016 simulated by the GSSHA model

From the seasonal point of view, on average, the mean groundwater contribution to stream flow during winter, spring, summer, and fall from 2012 to 2016 is 97% (σ=2.4%), 70% (σ=4.3%), 61% (σ=4.8%), and 88% (σ=5.1%), respectively. These results demonstrate that the mean groundwater contribution to stream flow is the lowest and highest during summer and winter, respectively. Hence, stream flow depends mostly on groundwater flow during winter, but at a lesser extent during summer. Consequently, the highest and lowest water extraction from the river for future water supply could be possible during summer and winter, respectively, due to the highest (i.e., on average 6.06 m^3/s) and lowest (i.e., on average 0.23 m^3/s) mean stream flow rates during summer and winter, respectively. Similar seasonal variations of mean groundwater contribution to stream flow were found in other studies [60-61]. However, these variations differ from area to area depending on the type and temporal pattern of precipitation around the year. For example, in western and northern Europe (e.g., United Kingdom, Belgium, Denmark) more precipitation occurs during winter as rainfall, and therefore, results in higher surface runoff compared to groundwater discharge [7,16], and lower groundwater contribution to stream flow during winter than other seasons, which is opposite to the finding of this study. Therefore, the seasonal variations of mean groundwater contribution to stream flow depend on the type and temporal pattern of annual precipitation in the particular area.

3.2 Groundwater Contribution to Stream Flow under B1 Scenario with Land Use Changes

Fig. 8 presents the mean monthly groundwater contributions to stream flow under the B1 GHG emission scenario with land use changes during 2012-2016. Similar to the climate change effects, the groundwater contributions under the combined effects show variable annual patterns due to monthly precipitation fluctuations [55-58] and land use changes. The mean monthly groundwater contribution to stream flow in 2012 ranges from 45% in May to 98% in December. Similar trends are found for years 2013 to 2016. Similar to the climate change effects, stream flow depends mostly on groundwater flow in those months when there is the highest groundwater contribution to stream flow, but at a lesser extent during the months when there is the lowest groundwater contribution.

On average, the mean groundwater contribution to stream flow during winter, spring, summer, and fall from 2012 to 2016 is 96% (σ=2.1%), 66% (σ=4.1%), 57% (σ=5.5%), and 86% (σ=6.5%), respectively. Similar to the results under the B1 scenario, stream flow depends mostly on groundwater flow during winter, but at a lesser extent during summer. Consequently, the highest and lowest water extraction from the river, and allocation to the stakeholders for future water supply could be possible during summer and winter, respectively, due to the highest (i.e., on average 6.30 m^3/s) and lowest (i.e., on average 0.235 m^3/s) mean stream flow rates during summer and winter, respectively.

3.3 Comparison of Groundwater Contribution to Stream Flow under B1 Scenario and the Combined Effects of B1 Scenario and Land Use Changes

Fig. 9 shows the comparison of mean monthly groundwater contributions to stream flow of 2012-2016 under climate change of B1 GHG emission scenario and the combined effects of B1 scenario and land use changes with respect to the reference period (2007-2011). Here, the period of 2007-2011 was used as reference period because the calibration and validation of the model was done during that time period. The results illustrate that the mean monthly groundwater contributions to stream flow of 2012-2016 are lower under the combined effects of B1 scenario and land use changes than that under the B1 scenario due to land use changes. The lowest and highest mean monthly groundwater contributions to stream flow of 2012-2016 under the B1 scenario are found in May (i.e., 46%) and December (i.e., 99%), respectively. On the other hand, the lowest and highest mean monthly groundwater contributions to stream flow in 2012-2016 are found in May (i.e., 40%) and December (i.e., 97%), respectively, under the combined effects of B1 scenario and land use changes. Therefore, the trends of mean groundwater contribution to stream flow are similar in both cases. However, the only difference occurs in the magnitude of mean groundwater contribution to stream flow, and this variation occurs due to land use changes, which result in increasing surface runoff and stream flow, and decreasing groundwater discharge due to increasing forest clear cut area of low hydraulic conductivity soil. Similar types of decreasing groundwater discharge and increasing surface runoff and stream flow due to increasing built up area of low hydraulic conductivity soils were found in other studies [13-17]. Therefore, combined climate and land use changes have offsetting and additive impacts on water resources systems.

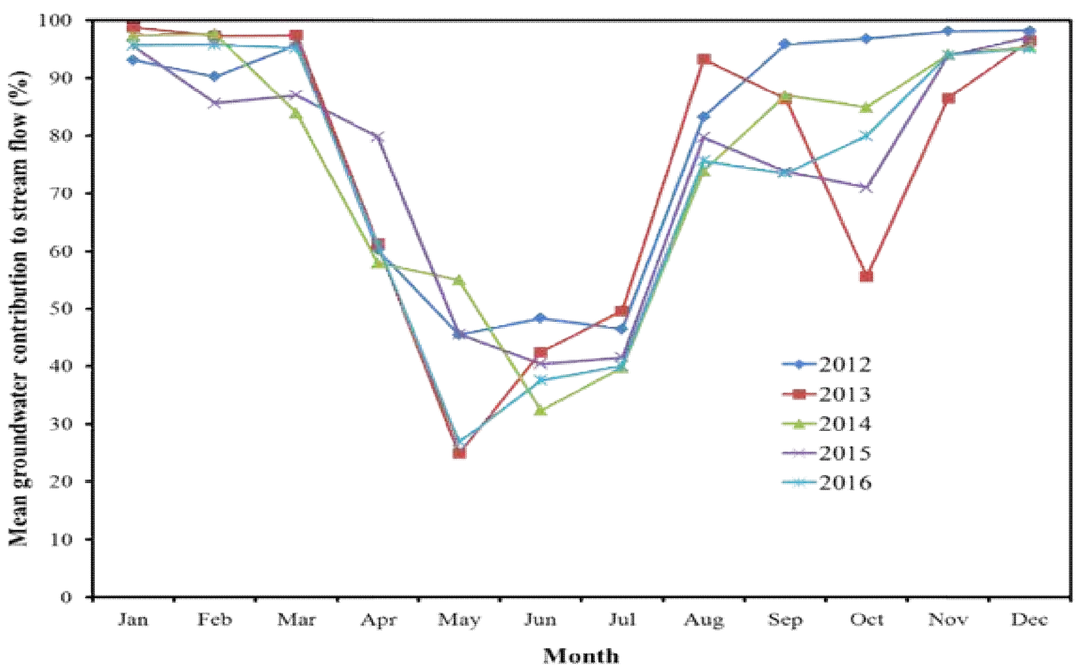

Fig. 8. Mean monthly groundwater contributions to stream flow during 2012-2016 under the combined effects of B1 GHG emission scenario and land use changes

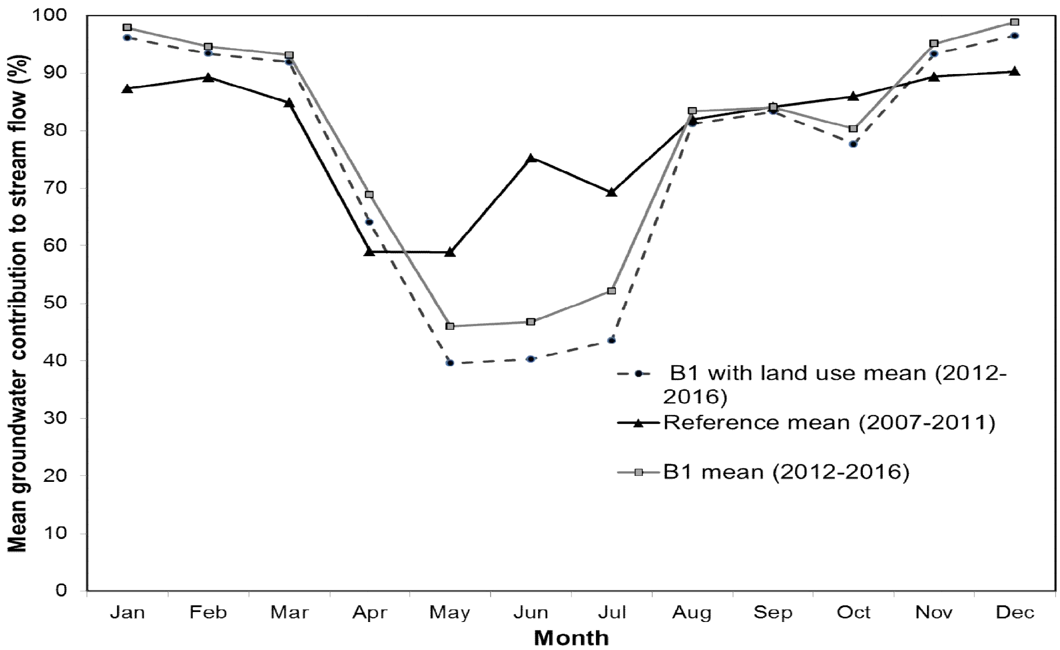

Fig. 9. Comparison of mean monthly groundwater contributions to stream flow of 2012-2016 under B1 GHG emission scenario and B1 scenario with land use changes, with respect to reference period (2007-2011)

The results also show that the mean monthly groundwater contributions to stream flow of 2012-2016 under climate change of B1 GHG emission scenario and the combined effects of B1 scenario and land use changes are lower in late spring and summer than under the reference period (2007-2011) due to increased precipitation and temperature predicted under those scenarios during those seasons with respect to the reference period. During other months, especially in winter and early spring, however, the mean monthly groundwater contributions to stream flow of 2012-2016 under climate change of B1 GHG emission scenario and the combined effects of B1 scenario and land use changes are almost higher than that under the reference period due to variable precipitation observed in those months of reference period. Therefore, climate change, as well as combined climate and land use changes influence the patterns of mean monthly groundwater contribution to stream flow significantly.

The comparison of the mean annual groundwater contributions to stream flow from 2012 to 2016 under climate change of B1 GHG emission scenario and the combined effects of B1 scenario and land use changes with respect to year 2011 is presented in Fig. 10. Under the B1 scenario, the highest and lowest mean annual groundwater contributions during 2012-2016 are found in 2012 (i.e., 80.2%) and 2013 (i.e., 77%), respectively, due to the lowest (i.e., 494 mm) and highest (i.e., 524 mm) precipitation predicted in those years. On the other hand, the highest and lowest groundwater contributions to stream flow during 2012-2016 are found in 2012 (i.e., 79.3%), and 2016 (i.e., 72.9%), respectively, under the combined effects of B1 scenario and land use changes. On average, the mean annual groundwater contribution to stream flow of 2012-2016 under the B1 scenario and the combined effects of B1 scenario and land use changes is 78.2% (σ=1.25%) and 75.7% (σ=2.4%), respectively. Compared to the climate change effects only, this contribution is lowered by 2.5% (i.e., absolute value) under the B1 scenario with land use changes, while the stream flow and surface runoff increased averagely 2.8% and 17.8%, respectively, under the combined effects of B1 scenario and land use changes, but groundwater discharge decreased averagely 0.5% under the combined effects of B1 scenario and land use changes. In addition, on average, it was found that the mean annual groundwater contribution to stream flow during the reference period (2007-2011) is approximately 80%. With respect to the reference period, the mean annual groundwater contribution to stream flow from 2012 to 2016 under the B1 scenario and the combined effects of B1 scenario and land use changes is expected to decrease by 1.8% and 4.3%, respectively, due to increased precipitation (on average 3.6% under the B1 scenario) and temperature (on average 0.36ºC under the B1 scenario), and land use changes. Walvoord et al. [62] also found similar type of change in the mean annual groundwater contribution to stream flow in the Yukon River basin due to changing climate. The climate change would result in increased stream flow and groundwater discharge but the major increases occurred in surface runoff. However, under the combined effects of climate and land use changes, stream flow and surface runoff are expected to increase but groundwater discharge is expected to decrease compared to only climate change effect. Therefore, climate and land use changes significantly affect stream and groundwater discharges, and surface runoff, as well as the mean annual groundwater contribution to stream flow. Table 4 presents a summary of mean annual stream flow, surface runoff, and groundwater discharge under the reference period, B1 scenario and the combined effects of B1 scenario and land use change for the short-term period. This decreased groundwater contribution to stream flow under both cases may result in warmer stream temperature, lower dissolved oxygen in stream, and increased nutrient concentrations in stream (e.g., Dissolved organic carbon (DOC) and nitrogen (DON)) that may promote excessive growth of habitat-choking algae by increasing surface runoff and soil erosion [63-64], with respect to the reference period. These results demonstrate that those above mentioned impacts will be lower in the B1 scenario as compared to the combined effects of B1 scenario and land use changes due to higher annual groundwater contribution to stream flow under the climate change of B1 scenario. These results also demonstrate that stream flow is more dependent on groundwater flow under the B1 scenario than under the combined effects of B1 scenario and land use changes. Therefore, more annual water extraction from the river, and allocation to the stakeholders for future water supply could be possible under the combined effects of B1 scenario and land use changes than under the B1 scenario without causing a negative impact on regional groundwater level as well as aquatic ecosystems, compared to the reference period.

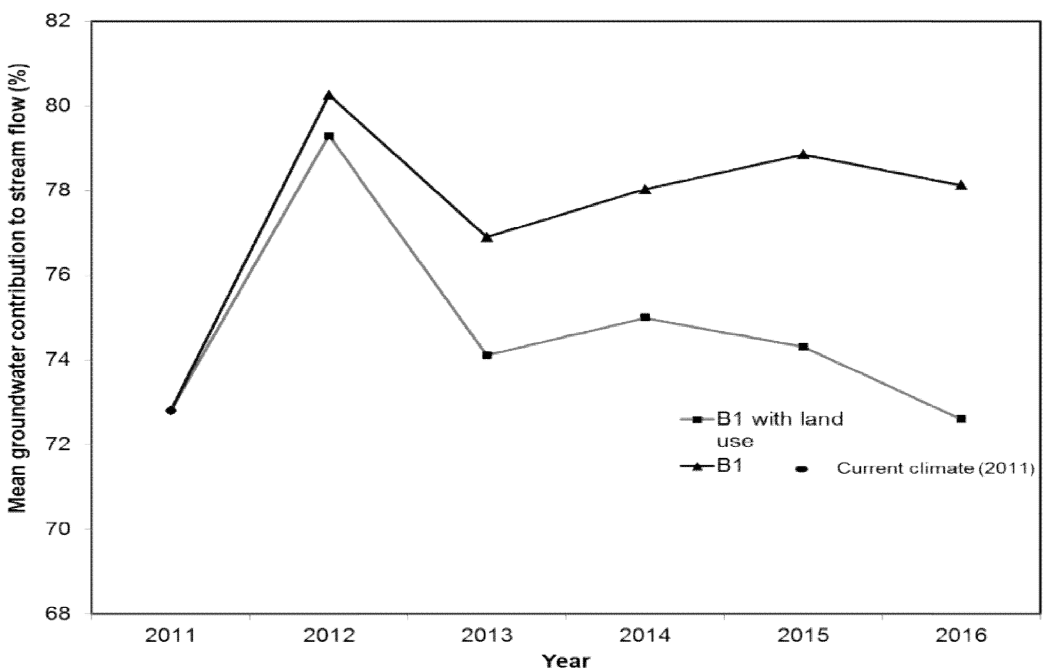

Fig. 10. Comparison of mean annual groundwater contributions to stream flow from 2012 to 2016 under climate change of B1 GHG emission scenario and the combined effects of B1 scenario and land use changes with respect to year 2011

From the seasonal point of view, as compared to the period of 2007 to 2011, the mean groundwater contribution to stream flow during winter, spring, summer, and fall from 2012 to 2016 is expected to decrease by 1%, 2%, 1%, and 1% under the B1 scenario, respectively (Table 5). This is due to increased precipitation and temperature predicted under B1 scenario as compared to the reference period. Therefore, the effect of climate change on the mean seasonal groundwater contributions to stream flow is significant. The most decrease occurs in spring. On the other hand, as compared to the period of 2007 to 2011, the mean groundwater contribution to stream flow during winter, spring, summer, and fall from 2012 to 2016 is expected to decrease by 2%, 6%, 5%, and 3% under the B1 scenario with land use changes, respectively. These decreased seasonal groundwater contributions to stream flow under both cases may result in seasonal warmer stream temperature, lower dissolved oxygen in stream, and increased nutrient concentrations in stream, with respect to the reference period.

The mean groundwater contribution to stream flow during all seasons under the combined effects of B1 scenario and land use changes is lower than that under the effect of only climate change by 1%-4% (i.e., absolute values). This variation occurs due to increasing surface runoff and stream flow, and decreasing groundwater discharge resulting from annual increasing forest clear cut area of low hydraulic conductivity soil from 2012 to 2016. These results indicate the significant role of land use changes in stream flow, surface runoff, groundwater discharge, as well as the mean seasonal groundwater contributions to stream flow. Similar decreasing groundwater discharge, and increasing stream flow and surface runoff were found due to urbanization (area of low hydraulic conductivity soils) in other studies [13-17]. Therefore, this decreased groundwater contribution to stream flow may result in more warmer stream temperature, lower dissolved oxygen in stream, and increased nutrient concentrations in stream than those under the sole climate change effects. The most decrease occurs in spring and summer under the B1 scenario with land use changes due to increasing forest clear cut area of low hydraulic conductivity soil and more precipitation predicted during summer and snow melting during spring.

Table 4. Mean annual precipitation, temperature, stream flow, surface runoff, and groundwater discharge under the reference period (2007-2011), B1 scenario and the combined effects of B1 scenario and land use changes for the short-term period (2012-2016). The values within the parentheses are relative changes except for temperature, where absolute changes were calculated

Scenario	Mean annual precipitation (mm)	Mean annual temperature (ºC)	Mean annual stream flow (m^3/s)	Mean annual groundwater discharge (m^3/s)	Mean annual surface runoff (m^3/s)
Reference period	492	2.63	3.08	2.46	0.62
B1	510 (3.6%)	2.99 (0.36)	3.18 (3%)	2.49 (1.2%)	0.69 (11.2%)
B1 with land use	510 (3.6%)	2.99 (0.36)	3.27 (5.8%)	2.48 (0.7%)	0.80 (29%)

Table 5. Mean seasonal groundwater contributions to stream flow under the reference period (2007-2011), B1 scenario and the combined effects of B1 scenario and land use changes for the short-term period (2012-2016). The values within the parentheses are absolute changes.

Scenario	Winter	Spring	Summer	Fall
Reference period	98%	72%	62%	89%
B1	97% (1%)	70% (2%)	61% (1%)	88% (1%)
B1 and land use change	96% (2%)	66% (6%)	57% (5%)	86% (3%)

4. CONCLUSION

In this study, the impacts of climate change and the combined effects of climate and land use changes on groundwater contribution to stream flow were examined using a study area along the river of the Mainstem sub-watershed of KRW as a case study through the developed GSSHA model for the short-term period (2012 to 2016). The future land use scenarios were generated based on the changes of land use types between 1999 and 2010, and B1 climate change scenario was chosen. Based on the simulation result it was found that groundwater contributes significantly to stream flow in the study area under both cases. It was also found that climate change influences significantly the temporal patterns of mean groundwater contribution to stream flow. These contributions showed monthly, seasonal, and annual variations due to precipitation variability. Under the combined effects of climate and land use changes, similar results to those under the effect of only climate change were found, but with a decreasing rate in the mean groundwater contribution to stream flow. This indicates that land use change has an important role in the groundwater contribution to stream flow by shifting the flow patterns to the regime with more surface runoff and stream flow, but less groundwater discharge. The results obtained from this study will provide useful information for seasonal and annual water extractions from the river and allocation to the stakeholders for future water supply, as well as ecological conditions of the stream, which will be beneficial to aquatic ecosystems. They will also provide how land use changes can impact the groundwater contribution to stream flow, which will be useful for planning of regional groundwater resource management, as well as water resources management considering future climate and land use changes.

Since future climate change scenarios are full of uncertainty [65], uncertainty analysis of climate change should be incorporated in further study to assess the average impact of climate change scenarios on groundwater contribution to stream flow. Therefore, the results obtained in this study should be considered as some trends and orders of magnitudes rather than exact predictions. The results obtained from this study may be different in another region where monthly precipitation trend and land use types are different than to this study area. Therefore, the results obtained in this study should be compared to another climatic region and watershed with different land use types. In addition, different climate models may give different scenarios of future precipitation and temperature trend in B1 GHG emission scenario. Therefore, other climate models predicted precipitation and temperature should be used for comparing the results obtained from this study. Finally, for accurate future land use projections, economic model (e.g., Wonderland model, World3) should be used with land use changes.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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