MODELING THE WATER BALANCE PROCESSES FOR UNDERSTANDING THE COMPONENTS OF RIVER DISCHARGE IN A NON-CONSERVATIVE WATERSHED

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ABSTRACT. *The study was conducted in the Shibetsu watershed, eastern Hokkaido, Japan, to examine the possibility of using the Soil and Water Assessment Tool (SWAT) model in a non-conservative watershed (the surface watersheds are lying on a discontinuous impervious horizon) with external contribution (EXT). After confirming the capability of model simulation, the EXT was estimated to understand the components of river discharge. The EXT is difficult to measure directly and simulate by SWAT due to its subsurface circulation. In this study, the EXT was roughly estimated from the water balance equation using measured data. The average daily flux of EXT (1.38 mm d^{-1}) was assumed as a point-source discharge in SWAT. The simulation of daily streamflow during the calibration and validation periods produced satisfactory results, with R^2 values of 0.65 and 0.66, respectively. In addition, the simulated daily baseflow, monthly streamflow, surface runoff, and evapotranspiration (ET) all showed good agreement with the corresponding observations. Our simulation suggested that the EXT assigned as the assumed discharge in SWAT can help us to reasonably simulate the streamflow in the Shibetsu watershed. The EXT was then investigated indirectly by considering the difference between the observed streamflow and simulated streamflow using calibrated SWAT without adding the assumed EXT. The result indicated that the EXT was an important water source in the Shibetsu watershed, accounting for 47% of streamflow during the study period.*

Keywords. *External contribution, Point-source discharge, Streamflow, SWAT, Water balance.*

A number of hydrological model types are described in the literature, such as lumped, distributed, physical, and stochastic. However, all surface hydrological models, in general, reach their limit of applicability in complex hydrological environments, such as those where the surface watershed does not correspond to the hydrogeological watershed (Eisenlohr et al., 1997; Labat et al., 1999, 2000; Larocque et al., 1998; Le Moine et al., 2007, 2008; Salerno and Tartari, 2009). This situation occurs frequently in non-conservative watersheds where the surface watersheds are lying on a discontinuous impervious horizon (Le Moine et al., 2008). Non-conservative watersheds may either leak (losing water to neighboring watersheds or to the sea) or gain water (originating from outside the watershed). There are many well-known physical reasons for the existence of non-conservative watershed. Karstification of limestone is perhaps one of the most widespread reasons worldwide; however, similar water transfers may exist in volcanic substrata as well as in chalk horizons (Le Moine et al., 2007).

In non-conservative watersheds, the possible application of a hydrological model would not take into account the underground fluxes because watersheds are systems with too many unknowns. For example, two sources of output (evaporation and leakage) are mostly unobservable, and the underground fluxes cannot be directly measured. Therefore, only the measurable precipitation and streamflow can be computed into the water balance, which could lead to an under- or overestimation of the streamflow. Because of this shortage, only a few hydrological models are applied in these types of complex watersheds. Le Moine et al. (2007, 2008) attempted to use rainfall-runoff models (GR4J, a daily four-parameter rainfall-runoff model with an explicit intercatchment groundwater flow representation, and SMAR, the Soil Moisture Accounting and Routing model) to handle underground fluxes. They presented a review of solutions that may theoretically account for non-conservative behavior and a case study of validation by GR4J. However, many more similar cases are needed to validate GR4J's structure. Salerno and Tartari (2009) examined the possibility of using the Soil and Water Assessment Tool (SWAT) in karst environments, with validation by wavelet analysis, whereby the underground flux was calculated from the difference between the

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observed streamflow and the streamflow simulated by SWAT. The few other available examples are generally theoretical or conceptual or black-box models where the applications are usually in karstic areas.

Physical models are based on hydraulic laws that represent different flow processes in porous media. These models are usually hard to implement due to the extensive data collection required to characterize the distributed aquifer properties, such as aquifer geometry, position and direction of fractures and open channels, and hydraulic properties. Conceptual models are based on a simplified but as accurate as possible representation of hydrological systems, using water balance equations and the limited amounts of available data, such as precipitation, potential evapotranspiration (PET), and streamflow. Conceptual models are easier to apply and can be used for studying the underground fluxes in non-conservative watersheds (Rimmer and Salingar, 2006). However, these models cannot assess the temporal patterns of underground fluxes over a short time scale because the water balance equation ($P - ET = Q$) is based on the assumption that the difference in catchment soil water storage becomes negligible only when the time scale is large, such as annual. In addition, when the precipitation occurs as snow, the time lag of snow to streamflow or the time lag of water release in some topographically and geologically complicated watersheds makes both the instantaneous and annual capture of the underground fluxes impossible. Therefore, the streamflow and its components in non-conservative watersheds are really not clearly understood due to the inherent difficulty in both measurement and simulation. Especially when underground fluxes do not exist in the visible karstic areas, such as in volcanic substrata or in chalk horizons, the underground fluxes are usually neglected by attributing them to the inaccurate streamflow observation or evapotranspiration, which is hard to measure.

The overall problem for a hydrological model applied in a non-conservative watershed is how to simulate the underground fluxes, and how to validate the model, because the underground fluxes are not directly measurable and the hydrological model cannot compute the additional contribution due to subsurface circulation. The main objective of this study, therefore, was to test a method that can indirectly simulate the underground flux with a hydrological model to further understand the components of the river discharge in a non-conservative watershed with volcanic substrata.

Methods

Watershed Description

The Shibetsu watershed is located in eastern Hokkaido, Japan (fig. 1). The watershed covers an area of approximately 672 km^2, with 29% as mountainous area. The Shibetsu watershed is very flat, so we defined the mountainous area as the area with slopes greater than 10% and elevation ranging from 295 to 1059 m. The mountainous area located at the upper streams is dominated by forest and covered by Brown Forest soil; other areas with flat terrain (slopes less than 10%) are mainly covered by agricultural land. Kuroboku and Regosolic Kuroboku soils are the major soil types. Summarized by land use information, the Shibetsu watershed consists of forest (53.7%), agriculture (40.8%), urban (4.5%), and water (1.0%). The dominant forest vegetation is Japanese larch (*Larix kaempfer* L.). Pasture (mainly *Phleum pretense* L.) occupies more than 95% of the agricultural land area, and the remainder is cultivated with maize (*Zea mays* L.), sugar beet (*Saccharum officinarum* L.), potato (*Solanum tuberosum* L.), and Japanese radishes (*Raphanus sativus* L.). This region has a hemi-boreal climate, characterized by warm summers and cold winters. During 1980-2008, the average annual precipitation averaged 1128 mm and the annual mean temperature was 5°C. The lowest mean monthly temperature was in February (-8.3°C), and the highest mean monthly temperature was in August (18.0°C) (Japan Meteorological Agency, www.jma.go.jp).

The underlying rocks in the mountainous area are andesite, tuff, volcanic breccia, tuff breccia, and clastic; volcanic ashes dominate the flat areas. Although the geology is not well known, according to our investigation, the presence of springs (the survey showed more than 30 spring points) indicates that the geology is likely to present a comprehensive picture of a rich underground water network. In addition, the volcanic substrata may lead to formation of a non-conservative watershed with an underground flux (Le Moine et al., 2007). The presence of springs and volcanic substrata indicate that the water source may be complicated, and the water may not only come from the watershed itself but also from areas outside the watershed. For example, Lake Mashu, which is located in the western part of the Shibetsu watershed (fig. 1), may be one of the spring sources. Although there are no surface rivers, streams, or ditches to discharge water from Lake Mashu, research has shown that the lake loses water via underground channels (about 700 mm year^{-1}; National Institute for Environmental Studies, 2006). Our aim in this work was to determine if the spring sources from outside the watershed, such as groundwater from Lake Mashu, contribute significantly to the Shibetsu watershed discharge.

Annual Water Budget

The water balance of a watershed is a deterministic relationship between the various components of the water balance, which are random variables in time and space whose probability distributions are generally unknown. In a watertight (no water leaks or gains) watershed, the independent input variable is precipitation, and the dependent output variables are evapotranspiration, streamflow, soil storage change, and groundwater storage. The volumetric water balance per unit area can therefore be expressed as:

$$P - ET - SS - GS = Q \quad (1)$$

where P is the precipitation, ET is the actual evapotranspiration, SS is the soil water storage, GS is the groundwater storage, and Q is the streamflow (Eagleson, 1978). All the terms except P are dependent on the soil moisture redistribution, which is generally not measured. Assuming the storage change to be negligible over an integration interval spanning a full year, substituting the expected values gives the following average annual water balance equation (Milly, 1994; Everson, 2001):

$$P - ET = Q \quad (2)$$

We used equation 2 to balance the water in the Shibetsu watershed and observed a mean difference of 504.32 mm year^{-1} between observed streamflow (Q_{obs}) and streamflow

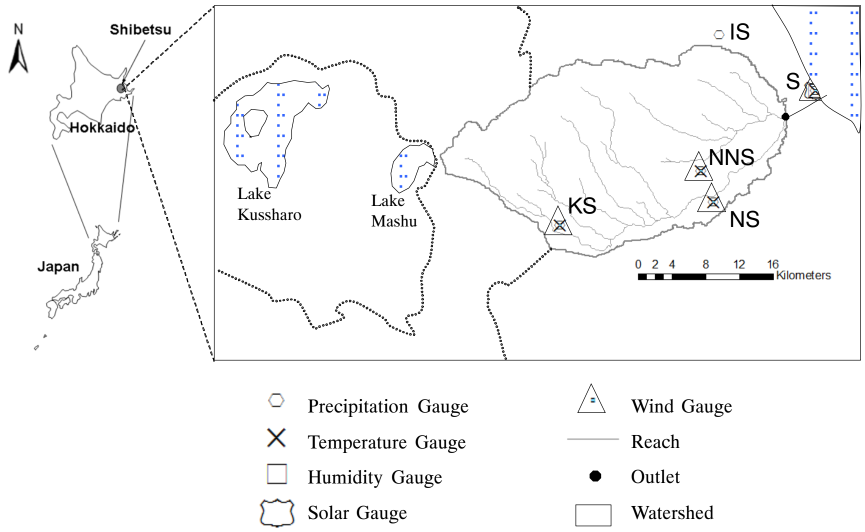

Figure 1. Locations of the Shibetsu watershed and the weather stations.

Table 1. Annual water balance in the Shibetsu watershed for 1980-2008.

Year	Q_{obs} (mm)	P (mm)	ET[a] (mm)	$Q = P - ET$ (mm)	$Q_{obs} - Q$ (mm)	$(Q_{obs} - Q) / P$
1980	773.760	890	548.172	341.828	431.932	0.49
1981	1368.965	1441	546.010	894.99	473.975	0.33
1982	928.326	933	564.604	368.396	559.930	0.60
1983	968.158	1010	526.917	483.083	485.075	0.48
1984	789.117	867	559.988	307.012	482.105	0.56
1985	953.760	1086	573.957	512.043	441.717	0.41
1986	905.282	919	527.422	391.578	513.704	0.56
1987	807.367	1060	542.123	517.877	289.490	0.27
1988	953.273	1036	511.216	524.784	428.489	0.41
1989	1208.645	1478	547.589	930.411	278.234	0.19
1990	1320.959	1513	554.633	958.367	362.592	0.24
1991	1112.161	1117	549.825	567.175	544.986	0.49
1992	1128.478	1317	525.059	791.941	336.537	0.26
1993	1235.997	1187	527.071	659.929	576.068	0.49
1994	1234.566	1183	601.491	581.509	653.057	0.55
1995	1064.642	1147	541.996	605.004	459.638	0.40
1996	1145.753	1106	529.033	576.967	568.786	0.51
1997	1117.443	1198	532.357	665.643	451.80	0.38
1998	1245.114	1391	514.564	876.436	368.678	0.27
1999	1065.601	1088	576.578	511.422	554.179	0.51
2000	--	1263	528.083	734.917	--	--
2001	--	932	526.918	405.082	--	--
2002	--	1264	538.007	725.993	--	--
2003	1257.974	1276	509.679	766.321	491.653	0.39
2004	967.338	931	578.738	352.262	615.076	0.66
2005	1102.754	975	531.267	443.733	659.021	0.68
2006	1642.429	1329	547.174	781.826	860.603	0.65
2007	1123.214	1038	613.956	424.044	699.17	0.67
2008	698.945	751	577.971	173.029	525.916	0.70
Mean	1081.539	1128	546.634	581848	504.324	0.47
SD	209.965	196	25.795	203.652	130.511	0.15

[a] ET was calculated from the Penman-Monteith equation.

(Q) calculated by equation 2 during 1980-2008. The difference accounted for an average of 47% of the annual precipitation (table 1). The above discrepancy could either represent the uncertainty in P, ET, and Q_{obs} or indicate that some other water contribution exists in addition to precipitation.

Precipitation

The average annual precipitation from five rain stations located in or near the watershed was 1128 mm from 1980 to 2008 (Japan Meteorological Agency, www.jma.go.jp). Although there were no rain stations in the mountainous area, the precipitation there might be higher, which could explain some part of the discrepancy (47%) between the observed and measured water balances. However, according to Sawano et al. (2005), the precipitation in the forested area was about 330 mm higher than that in the agricultural area in Japan during 1979 to 2003. Another study conducted in Hokkaido, northern Japan, showed that the precipitation in the mountainous area was significantly correlated with elevation (Yamada et al., 1995). We used the empirical equation from Yamada et al. (1995) to predict the precipitation, which, in our mountainous area, was about 38% higher than the observation from five stations, which accounted for 11% of the observed discrepancy in the water balance.

Evapotranspiration (ET)

The potential evapotranspiration (PET) during 1997-2001 was estimated by a pan evaporation equation (Snyder, 1992) using observed daily pan evaporation data (from Nemuro old weather station, near station NNS, not shown in fig. 1). The Penman-Monteith equation, as recommended in FAO Paper 56 (Allen et al., 1998), was also used to estimate the PET during 1980-2008. The estimated PET data from 1997 to 2001 by the two methods were compared and yielded a high coefficient of determination ($y = 0 .8085x - 0.2201$, $R^2 = 0.73$). The comparison indicated that the Penman-Monteith equation can accurately simulate the PET in the Shibetsu watershed. The actual ET can be calculated by experimental data based on leaf area index and PET. However, in our study area, this information was not available; thus, the PET estimated by the Penman-Monteith equation was used. Kondo et al. (1992) estimated the ET in Japan by the heat budget method and found that the ET in the Nemuro area (including the Shibetsu watershed) was about 486 mm year^{-1}. The value of ET is therefore lower than the PET that we estimated with the Penman-Monteith equation (546.63 mm year^{-1}, table 1). Therefore, replacing ET with PET in the water balance equation could not explain the discrepancy in the water balance.

Discharge

The annual discharge was obtained from the Japanese Ministry of Land, Infrastructure, and Transport (www1.river.go.jp). Daily discharge was calculated from the daily stream water table (monitored at the outlet of the Shibetsu watershed) and calibrated *H-Q* equations (quadratic curve), which are the relationships between streamflow (Q) and the water table (H) (Tachibana and Nasu, 2003). The *H-Q* curve, which was obtained from the measurement of stream velocity and river section in three periods (monthly baseflow, daily snowmelt, and daily storm events, measured at the outlet), yielded an R^2 greater than 0.95 every year, showing the reliability of the estimated river discharge.

External Contribution (EXT)

When the possibility of an invalid estimation of the magnitude of precipitation, evapotranspiration, and discharge is excluded, the difference in the annual water balance (Q_{obs} - Q) can be reasonably considered as an additional water contribution (underground flux) to that of precipitation. The external contribution (EXT) is therefore used to describe the underground flux in the Shibetsu watershed hereafter.

SWAT Model

SWAT is a basin-scale, continuous-time model that operates at annual, monthly, and daily time steps and is designed to predict the impact of management on water, sediment, and agricultural chemical yields in ungauged watersheds. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria including pathogens, and land management (Neitsch et al., 2005). In SWAT, a watershed is divided into multiple subbasins, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use and soil and terrain characteristics. The water and nutrient cycles are simulated separately for each HRU, aggregated at the subbasin, and then routed to calculate the outlet streamflow and pollutant delivery. The overall hydrologic balance is simulated for each HRU, including canopy interception of precipitation, partitioning of precipitation, snowmelt water, irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers. Therefore, SWAT is a surface watershed model that simulates hydrology and nutrients, taking into account the spatial variability of data for weather, soil, topography, land use, vegetation, and management by means of a GIS interface (Neitsch et al., 2005).

Data Availability

Daily weather data for precipitation, maximum and minimum temperature, wind speed, and relative humidity were obtained from the records of the weather stations (fig. 1, table 2) from 1997 to 2008. The solar radiation data were calculated with the Angstrom formula (Allen et al., 1998) using the observed sunshine hours from Shibetsu station (S) during 1997 to 2008.

Digital elevation model (DEM) data were prepared using a digital map with a 50 m grid elevation created from a 1:25,000 topographic map published by the Japanese Geographical Survey Institute (GSI, http://nlftp.mlit.go.jp/ksj/jpgis/jpgis_datalist.html). A land use map (1:25,000) based on 2005 was obtained from the GSI. According to SWAT classification, the land use was reclassified into five classes (fig. 2a). GIS-referenced soil data were extracted from a 1:50,000 soil map of the Fundamental Land Classification Survey developed by the Hokkaido Regional Development Bureau (www.agri.hro.or.jp/chuo/kankyou/soilmap/html/map_index.htm). The soil types are shown in figure 2b, and the main soil characteristics are listed in table 3.

Table 2. Weather station used in the SWAT simulation.

Station	Longitude (°)	Latitude (°)	Elev. (m)	Period
Nemuronakashibetsu (NNS)	E 144.96	N 43.58	65	2003-2008
Kamishibetsu (KS)	E 144.75	N 43.52	181	2003-2008
Nakashibetsu (NS)	E 144.98	N 43.54	50	1997-2008
Shibetsu (S)	E 145.13	N 43.67	3	1997-2008
Itokushibetsu (IS)	E 144.99	N 43.72	115	1997-2008

Observed daily streamflow datasets (2004-2008) were downloaded from the website of the Japanese Ministry of Land, Infrastructure, and Transport (www1.river.go.jp). Daily baseflow was the streamflow during days of no rainfall (2004-2008). Monthly surface runoff (2004-2008) was estimated with the baseflow filter program, which estimates baseflow and groundwater recharge from streamflow records using the methodology outlined by Arnold and Allen (1999) and Arnold et al. (1995), using daily discharge data. PET (1997-2001) was estimated with the pan evaporation equation using observed pan evaporation data.

Simulation Approach

Simulation of EXT in SWAT

Although SWAT is a sophisticated surface hydrological model, the groundwater from outside the watershed is difficult to accurately simulate due to the subsurface circulation. In non-conservative watersheds, especially karst systems, the black-box model is usually applied, which only considers the physical processes that transform input to output. This is because black-box models do not require any information about the internal structure of an aquifer nor the mathematical relationships between the input and output. Considering that there is not much information about the EXT (the investigations and measurements for spring), and SWAT cannot simulate the EXT directly in this study, the idea of the black-box model was blended into SWAT. We therefore neglected the process of the EXT contributions to the watershed. The EXT is not simulated by SWAT but is added as a point-source discharge in SWAT. In this simulation, the EXT is an input. Combined with the other SWAT inputs, the model produces the output of streamflow, which can then be compared with the observed streamflow.

In the SWAT model, there is no groundwater inflow, so the EXT was added as the point-source discharge. As mentioned above, this study only focused on the output of streamflow. For understanding the river discharge components, the baseflow should be the simulated baseflow in SWAT plus the EXT. According to the appearance of springs, the mountainous area might be where the EXT joins the watershed, so several points in the mountainous area were chosen as the assumed point sources in SWAT.

Calculation of Point-Source Discharge

The point-source discharge was equated to the EXT, and it was calculated as follows:

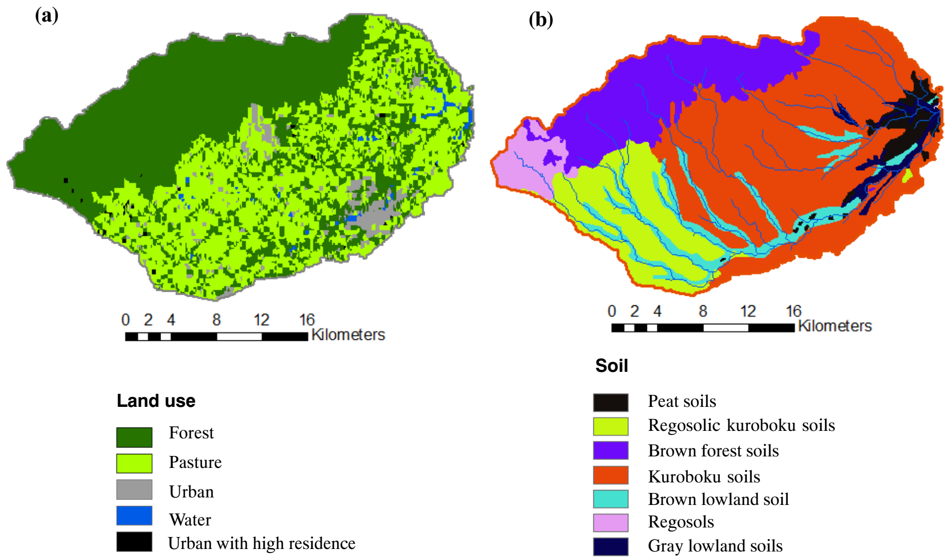

Figure 2. Maps of land use types and soil types.

Table 3. Soil input data about main attributes.

Name	Area (%)	Layer	Depth (mm)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Organic C (%)	Total N (%)
Peat soils	2.96	2	380	6.60	32.71	60.69	0.00	2.47	0.25
Regosolic Kuroboku soils	14.49	10	830	33.51	3.73	63.66	0.00	3.54	0.24
Brown forest soils	30.28	4	630	19.36	16.26	54.63	9.75	1.70	0.10
Kuroboku soils	45.00	9	1000	4.98	30.16	64.87	0.00	4.30	0.25
Brown lowland soil	0.10	2	250	3.30	31.77	64.93	0.00	3.40	0.27
Regosols	4.56	2	400	2.35	12.42	85.23	0.00	2.51	0.16
Gray lowland soils	2.67	2	260	5.45	42.36	52.19	0.00	3.19	0.31

$$EXT = Q_{\text{obs}} - (P - ET) \quad (3)$$

where EXT is the external contribution (mm), Q_{obs} is the observed streamflow (mm), P is the measured precipitation (mm), and ET is the evapotranspiration (mm). The observed data of annual precipitation and discharge from 1980 to 2008 were used for the calculation, and annual ET was estimated from the Penman-Monteith equation (table 1). For simplification, we added the EXT as a constant (the average value from 1980 to 2008 was 1.38 mm d^{-1}) without any temporal dynamics.

SWAT Calibration and Validation

Calibration and validation of the SWAT model are necessary, as the model is composed of a large number of parameters that define various watershed characteristics and flow processes that are not accurately characterized by default input parameters or easily measured in the field. However, in this study, the EXT as an assumed input is also required for calibration. How to calibrate the EXT, in addition to the SWAT model itself, is a big question. Therefore, we first calibrated the EXT and SWAT model together by using streamflow. Then the surface runoff, baseflow, and ET provided benchmarks to calibrate the SWAT model itself. According to the water balance equation ($P - ET + EXT = Q$, where Q is the streamflow, which includes surface runoff and baseflow, including EXT), if we calibrate the surface runoff and baseflow (including EXT) and compare the ET as well, then the baseflow (excluding EXT) would be calibrated indirectly by the water balance equation. As streamflow includes baseflow (excluding EXT), EXT, and surface runoff, the EXT was calibrated when the streamflow, baseflow (excluding EXT), and surface runoff all were calibrated. Therefore, the calibration in our study would be streamflow, surface runoff, baseflow, and ET.

The SWAT model was applied to the Shibetsu watershed from 1997 to 2008 at a daily time step. A database of parameters supplied with SWAT aided the initial model parameterization and was augmented by inputs from previous literature and the Shibetsu watershed characteristics (Hao et al., 2006; Somura et al., 2009; Stratton et al., 2009). For example, the temperature lapse rate in mountainous areas was set at -6.5°C km^{-1}, and the ELEVB (elevation at the center of the elevation band) and ELEVB_FR (fraction of subbasin area within the elevation band) were set as well. Similarly, an average precipitation lapse rate of 573 mm km^{-1} was computed by analysis of six years of annual precipitation (2003-2008) from the five weather stations. After the initial parameterization, the preliminary model results were used for sensitivity analysis with a Latin hypercube one-at-a-time (LH-OAT) method (Van Griensven et al., 2006). A total of 14 parameters (the sensitive parameters were the same, regardless of adding EXT or without EXT) were selected from the results of this analysis based on their effects on the flow (table 4). An auto-calibration process was then conducted with the shuffled complex evolution (SCE) algorithm using daily observed streamflow in SWAT by adding EXT (Duan et al., 1992). The parameters were calibrated using monthly streamflow, surface runoff, and daily streamflow and baseflow from 2004 to

Table 4. Sensitive parameters chosen for autocalibration and the determined optimal values in SWAT model with adding EXT.

Parameter	Description	I_{met} [a]	Lower Bound	Upper Bound	Optimal Value
CN2	Initial SCS runoff curve number for moisture condition II	3	-25	25	-20
ALPH_BF	Baseflow alpha factor (days)	1	0	1	0.05
REVAPMN	Threshold depth of water in the shallow aquifer for revap to occur (mm)	2	-100	100	50
SFTMP	Snowfall temperature (°C)	1	0	5	1
SMTMP	Snowmelt base temperature (°C)	3	-25	25	20
SMFMX	Maximum melt rate for snow during years (mm $°C^{-1}$ d^{-1})	1	0	10	4.5
SMFMN	Minimum melt rate for snow during years (mm $°C^{-1}$ d^{-1})	1	0	10	0.5
TIMP	Snowpack temperature lag factor	1	0	1	0.9
ESCO	Soil evaporation compensation factor	1	0	1	0.75
CANMX	Maximum canopy storage (mm H_2O)	1	0	10	6
SOL_AWC	Available water capacity of the soil layer (mm H_2O mm^{-1} soil)	3	-25	25	3
SURLAG	Surface runoff lag coefficient	1	0	10	2
GW_DELAY	Groundwater delay (days)	2	-10	10	-10
CH_N2	Manning's "n" value for the tributary channels	1	0	1	0.4

[a] I_{met} means variation methods are available in autocalibration: 1 = replacement of initial parameter by value, 2 = adding value to initial parameter, and 3 = multiplying initial parameter by value.

2006 and validated from 2007 to 2008. PET (estimated by the pan evaporation equation during 1997 to 2001) was used as an approximate benchmark to compare modeled ET and PET.

The quality of the model calibration and validation was assessed by calculating the relative error (R_e), the Nash-Sutcliffe coefficient (E_{ns}; Nash and Sutcliffe, 1970), and the coefficient of determination (R^2).

Limitation of the Approach

For simplification, we assumed that the EXT was a constant that was calculated from the water balance equation. However, the estimation of EXT was very approximate because the simulated PET and the lack of data for precipitation in the mountainous area brought uncertainty into the water balance equation. Moreover, the EXT actually varied year by year (table 1), and it might vary month by month, or even day by day. Hence, the EXT added at the assumed point as a constant discharge in SWAT should be treated with caution if the dynamics of EXT are significant.

Results

Model Performance

The SWAT model was first set up to create the streamflow directly without taking the EXT into account. Consequently, no matter how the parameters were adjusted, the SWAT model always underestimated the streamflow in the Shibetsu watershed. However, after calibration (the parameters and values were shown in table 4), the streamflow can yield a high value of R^2 (0.9) at the monthly step (table 5). The high value of R^2 but low value of R_e and E_{ns} showed a good fit for the response of streamflow to precipitation but a bad fit for the magnitude of streamflow, which confirmed the existence of the EXT and highlighted the limitation of the SWAT model to simulate the EXT. The EXT was then added as a point-source discharge, and the SWAT model was run with a daily time step.

The monthly simulated surface runoff and streamflow were compared with monthly observed data, and the coefficients (R_e, E_{ns}, and R^2) are summarized in table 5. The R_e and E_{ns} values were much improved compared with the simula-

Table 5. Statistical indices applied to measured versus simulated monthly discharge for the calibration and validation periods, with and without the EXT.

Time Period	Observation	R_e (%)	E_{ns}	R^2
Added EXT as point-source discharge				
Calibration (2004-2006)	Surface runoff	-5.50	0.82	0.82
	Streamflow	2.10	0.89	0.89
Validation (2007-2008)	Surface runoff	30.80	0.54	0.68
	Streamflow	2.90	0.81	0.78
Without adding EXT				
2004-2006	Streamflow	-47.9	0.23	0.9
2007-2008	Streamflow	-51.2	-0.39	0.61

tion without adding EXT, and the values were also very acceptable compared with the previous SWAT studies summarized by Gassman et al. (2007).

The measured and simulated daily streamflows with EXT are shown in figure 3. A visual comparison revealed that the results of calibration and validation at the Shibetsu watershed represented the fluctuations in streamflow relatively well, and the streamflow responded well to rainfall events or snowmelt. However, some daily peaks were overestimated. The R^2 values were around 0.65 during both the calibration and validation periods. Compared with the daily R^2 values of previous SWAT simulations (Gassman et al., 2007), the results showed relatively high reproducibility. Although the E_{ns} values were only 0.58 and 0.51 during calibration and validation, respectively, the simulation met the criteria values according to the model evaluation guidelines ($E_{ns} > 0.5$; Moriasi et al., 2007). In addition, the R_e was also less than 25%. These results indicated that the SWAT model performance for the daily streamflow was successful. However, the simulated streamflow during summer rainfall events was very high (fig. 3, table 6). As listed in table 6, the difference between measured and simulated streamflow during August and September was much larger than for other months, especially for September (37.14 mm). The simulated annual streamflow was 1063.86 mm, which was 78.94 mm higher than the observed streamflow during the simulated period of 2004-2008. Specifically, the difference between simulated and observed annual streamflow was smallest in 2004 (5.42 mm) and largest in the dry year 2008 (224.55 mm).

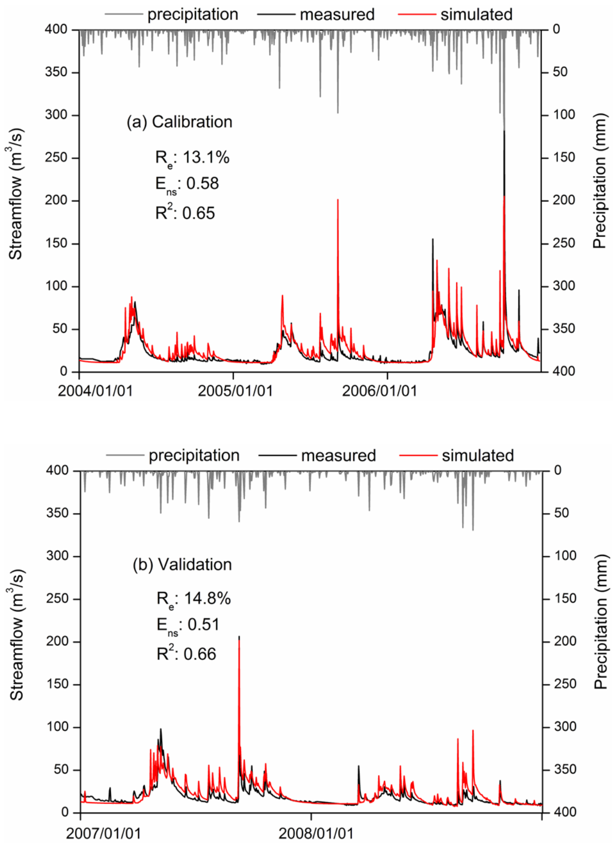

Figure 3. Modeling daily streamflow: (a) calibration period (2004-2006), and (b) validation period (2007-2008).

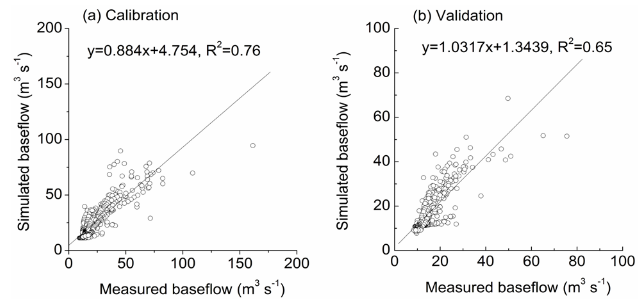

Figure 4. Relationships between measured and simulated daily baseflow: (a) calibration period (2004-2006), and (b) validation period (2007-2008) (baseflow is the streamflow during days of no rainfall).

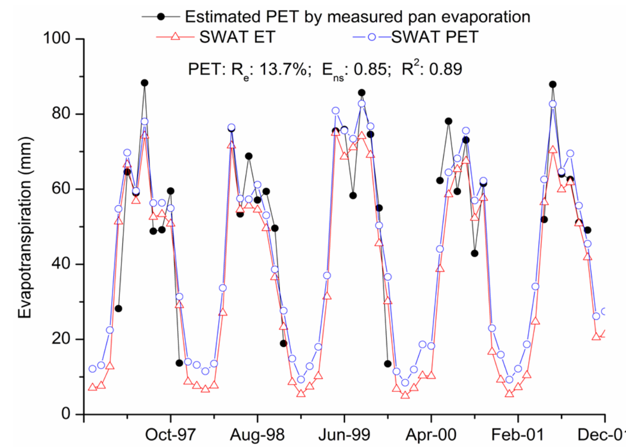

Figure 5. Comparison of measured and simulated monthly evapotranspiration during 1997-2001.

As the streamflow included surface runoff and baseflow (including EXT), calibration and validation of streamflow did not mean that the EXT was calculated and validated. Therefore, we ruled out the streamflow during rainfall events (including surface runoff) and compared the streamflow during baseflow only. Figure 4 shows the high value of R^2 between measured and simulated baseflow in both the calibration and validation periods.

To confirm the model simulation, the PET estimated by observed pan evaporation during 1997-2001 was compared with simulated PET and ET. Figure 5 shows good agreement in seasonal variability between simulated and observed PET (R^2 = 0.89), which was high in summer and low in winter. However, the simulated PET was lower than pan evaporation estimated PET, especially during summer.

Components of River Discharge

The calibration and validation showed that the SWAT model application in the Shibetsu watershed with the EXT was satisfactory. In order to calculate the EXT, the application of the SWAT model was repeated using the calibrated model but without adding the EXT as the assumed point-source discharge. The EXT was then calculated by the difference between the observed streamflow and the SWAT-simulated streamflow. Figure 6 shows the components of river discharge, including observed streamflow, SWAT-simulated streamflow, baseflow (including EXT), surface runoff, and EXT (calculated by SWAT simulation). Surface runoff and baseflow had similar trends with streamflow, which showed peaks during the snowmelt and rainfall seasons. However, the EXT only showed peaks during snowmelt (May). During rainfall seasons, the EXT usually had the opposite trend with streamflow, and the biggest decrease was often shown in September, which was likely related to the overestimated streamflow during rainfall events.

Table 7 shows that baseflow was the dominant river discharge, accounting for 71% on average during the study period, and EXT was another important component of discharge, accounting for 47% of streamflow and 66% (data not shown) of baseflow. The calculated EXT by SWAT simulation was compared with the estimated EXT by the water balance equation (table 7). The EXT estimated by the water balance equation was larger than that calculated by SWAT. The difference suggested that the supposition that the soil water storage change was negligible in the water balance equation might

Table 6. Monthly measured and simulated streamflow (mm) and difference from 2004 to 2008 (mm).

	Jan.	Feb.	March	April	May.	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Measured	55.58	49.54	53.98	107.59	184.90	91.02	66.08	64.97	88.70	97.81	68.83	55.92	984.92
Simulated	49.70	44.73	49.98	122.51	168.98	97.86	78.18	86.87	125.84	105.80	77.17	56.24	1063.86
Difference	5.88	4.81	4.00	-14.92	15.92	-6.84	-12.10	-21.90	-37.14	-7.99	-8.34	-0.32	-78.94

Table 7. Components of river discharge and their annual discharges (mm) during 2004-2008.

	2004	2005	2006	2007	2008	% of Q_{obs} (average)
Q_{obs}	967.34	1102.75	1642.43	1123.21	698.95	--
Q_{SWAT}	406.70	666.34	1027.24	558.63	343.21	--
Surface runoff	184.80	402.27	566.31	299.05	186.88	29
Baseflow (including EXT)	782.54	700.48	1076.12	824.16	512.06	71
EXT = Q_{obs} - Q_{SWAT}	560.64	436.41	615.19	564.58	355.74	47
EXT (water balance equation)[a]	615.08	659.02	860.60	699.17	525.92	63
Difference[b]	54.44	222.61	245.41	134.59	170.18	--
Precipitation	931	975	1329	1038	751	--

[a] EXT was calculated from the water balance equation in table 1.
[b] Difference in the EXT values estimated by SWAT and by the water balance equation.

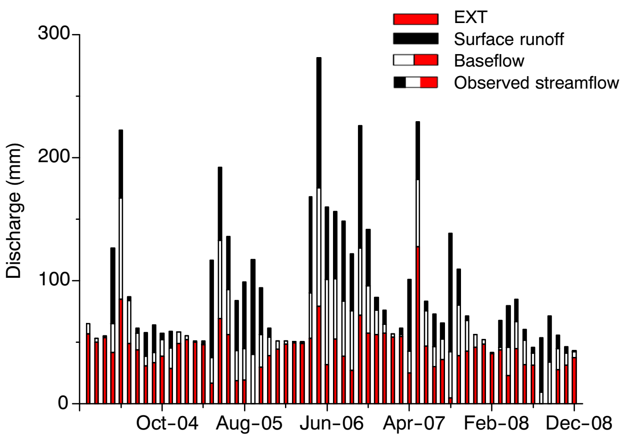

Figure 6. Monthly observed streamflow at the outlet of Shibetsu watershed and SWAT-simulated external contribution (EXT), baseflow, and surface runoff during 2004-2008.

cause uncertainty in estimating the water components in the Shibetsu watershed. The larger EXT estimated by the water balance equation might also be attributed to the lack of precipitation data in the mountainous area, where the precipitation could be higher. In addition, the SWAT EXT showed a positive correlation with precipitation ($y = 1.6067x + 191$, $R^2 = 0.67$, $p < 0.01$), indicating that 67% of the variation for the EXT could be explained by precipitation. However, the difference also indicated that the assumed EXT input into SWAT might cause uncertainty for the EXT estimation. We calculated the assumed EXT based on the average value of annual water balance from 1980 to 2008, but the average value (504.324 mm) was lower than the values from 2004 to 2008 (table 1). Therefore, the lower input of EXT might lead to a higher value of Q_{SWAT} and a lower value of EXT (Q_{obs} - Q_{SWAT}).

Discussion

The SWAT model simulated the streamflow by adding the EXT as an assumed point-source discharge in the Shibetsu watershed, resulting in an approach to calculate the EXT indirectly and to understand the river discharge components. However, the results must be placed in the context of the setting that was modeled, the assumptions needed for the study, and the model's limitations before relying on the simulation of the EXT in the Shibetsu watershed. In this study, two uncertainties need to be addressed during the SWAT calibration and validation processes: one is from SWAT itself, and the other uncertainty is the assumed discharge (estimated by the EXT from the water balance equation).

Study Limitations

Weather driver uncertainty: The SWAT results showed that the model had difficulty in modeling the peak daily streamflow during rainfall events. Problems can be attributed to uncertainty in the input climate data, particularly in the spatial and temporal coverage of precipitation and temperature. The five weather stations used for this study were all located outside the mountainous area. However, the mountainous area, with higher elevations, might have significantly different weather conditions from the other areas, and as 29% of the watershed, the mountainous area might enhance the impact of weather on streamflow in the watershed. In this study, although we adjusted the temperature lapse rate and precipitation lapse rate in the mountainous area, the result showed that model simulation was better during the snowmelt season than during rainfall events (fig. 3, table 6). This might be attributed to the precipitation lapse rate, as we used the observed precipitation from five stations that were located in agricultural areas to predict the precipitation in forested areas. Sawano et al. (2005) stated that the precipitation in agricultural and forested areas could be different in Japan. Thus, more accurate weather data for mountainous areas might be necessary to obtain more accurate daily streamflow peaks.

Snowmelt process: We observed overestimated streamflow during heavy rainfall events in snowmelt seasons, for example, a 68 mm rainfall event on 21 April 2005, a 48 mm rainfall event on 21 April 2006, and a 98 mm rainfall event on 29 and 30 May 2006. Stratton et al. (2009) suggested that the rainfall on snow (ROS) events produced the error. Rainfall during snowmelt is very common in the Shibetsu watershed. Adequate modeling of ROS events requires consideration of the transience of freezing levels as well as the distribution of snow water throughout a basin (McCabe et al., 2007). In addition, the temperate index snowmelt methods in SWAT do not account for the energy added to the snowpack by rainfall to cause enhanced snowmelt. Marks et al. (1998) showed that enhanced turbulent energy exchanges during ROS events are more significant than the energy added to the snowpack by rainfall.

Vegetation: SWAT overestimated the streamflow during the summer rainfall seasons, which can be attributed to the vegetation parameterization effect. For simplification, we considered the forest vegetation as one category (Japanese larch). However, the forest vegetation may include fir, maple, and other species. Each plant has distinct canopy characteristics, which affect the canopy storage of precipitation and consequently have an influence on the surface runoff (peak time and flux). Stratton et al. (2009) suggested that the vegetation at the peak of the growing season covered 72% of the land, and the canopy could intercept up to 8.62 mm of water from precipitation. Our vegetation parameterization was responsive to reducing the loss of precipitation from the forest canopy. In addition, the vegetation also affects the ET, since the ET processes include evaporation from the soil and transpiration by plants. Our simplification of the vegetation was likely to decrease the leaf area index (LAI), which led to underestimating the ET in summer (fig. 5).

Soil attributes: The major components of the water balance of the SWAT model are ET, soil water, and water yield. Ye et al. (2010) suggested that discrepancies in soil texture between two soil data sets with two different spatial resolutions have the greatest sensitivity in soil water and affect the partitioning between surface runoff and subsurface runoff. The SWAT model performed satisfactorily in estimating the volume and seasonal patterns of the streamflow. However, the estimation of surface runoff was difficult during validation (table 5) in this study. The discrepancy could be attributed to the lack of fine-resolution data and the reliability of the soil database. For example, the parameter of the soil available water content (SOL_AWC) in this study was calculated from the difference between field capacity (FC) and wilting point (WP) water contents. The FC and WP were obtained by pedotransfer functions (Saxton and Rawls, 2006) using sand and clay content, organic matter, salinity, and gravel. The calculation was a very rough estimation. Consequently, the SOL_AWC might produce errors that affected the soil moisture estimation as well as surface runoff simulation. When additional *in situ* field measurements of soil hydraulic properties are available, the streamflow, especially surface runoff, can be further refined.

Assumed EXT: As stated above, the estimation of EXT was rough. If we input accurate data for precipitation, ET, and streamflow into the water balance equation, the assumed EXT would improve the model simulation for streamflow. In addition, we assumed that the EXT was a constant, which also caused uncertainty. In our study, we found that the annual EXT might have a significant relationship with annual precipitation (table 7). Therefore, the annual EXT estimated from the water balance equation instead of the constant EXT should be input into the model to improve the simulation in future work.

Conclusions

The SWAT model has limitations if applied directly in a non-conservative watershed, in which the water balance is usually substantially underestimated. In this study, we added the EXT as a point-source discharge in SWAT to simulate the outlet streamflow and to evaluate the capability of SWAT applied in the Shibetsu watershed. Naturally this simulation is affected by all the errors that arise, e.g., the model's ability to simulate the hydrological processes of the study area, the accuracy and representativeness of the input data, and the assumed EXT added in SWAT as well. We used the components of the water balance equation, such as ET, surface runoff, and baseflow, as the benchmark to evaluate the ability of SWAT, except for comparison of streamflow. Results showed that the model simulation was robust at the point of simulation of hydrological processes in the Shibetsu watershed. Therefore, the EXT was examined as the difference between observed streamflow and simulated streamflow without adding EXT as a point-source discharge. The results showed that 47% of the streamflow was from the EXT, which may affect the water cycle and water quality in the Shibetsu watershed. The water source, such as the groundwater from Lake Mashu, might be part of the EXT. Further confirmation of the EXT should be undertaken by examining the water source of the EXT estimated in this study in terms of the geology in this area by using, for example, isotopic technology.

SWAT is a widely used hydrological model that is also linked with the simulation of water quality. Many applications show that SWAT can accurately simulate the water produced at a surface watershed. Although SWAT cannot yet express the EXT process, the approach of estimating the EXT from the difference between the observed streamflow and SWAT-simulated streamflow provides a way to estimate the EXT indirectly. The EXT added as assumed discharge makes the SWAT model easier to calibrate and validate by comparing the results with observed data. However, the EXT module should be included in the SWAT model in the future to fully describe both the process and function of the groundwater inflow. In addition, we simplified the EXT as a constant discharge added in SWAT in this study; this should be done cautiously when the actual EXT in a non-conservative watershed is dynamic.

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