Assessment of Watershed Soundness by Water Balance Using SWAT Model for Han River Basin, South Korea

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With increasing concerns surrounding the global climate change, there has been growing interests in the potential impacts to groundwater. It is expected that the predicted global changes in temperature and precipitation will alter the regional climates and water resources systems.

Therefore, the accurate understanding of hydrologic processes occurring in basin is important to formulate the water resources policies, planning and management decisions in the region.

We need to simulate the components of hydrologic cycle to determine the impacts of land use changes, groundwater use, and dam operation of river basin on water resources policies, planning and management.

The purpose of this study is to investigate the impacts of surface water and groundwater interaction on water balance and groundwater recharge for watershed soundness assessment of Han River basin (34,148 km²) in South Korea by SWAT modeling.
5 Major River basins of South Korea

- 5 Major river basins in our country (Han, Geum, Yeongsan, Seomjin, and Nakdong)
- The global warming is now warning the management of streamflow (intensify drought and flood)
- Need to evaluate the availability water resource by water balance analysis
- From the evaluation, find out some insight and prepare proper direction for water management system
At present, we have **20 multipurpose dams and 19 multifunction weirs** in South Korea.

They have been successfully managed by both Korea Water Resources Corporation (K-water) and Korea Hydro & Nuclear Power Co. Ltd. (KHNP) to fulfill water demands, flood control and hydropower generation.

Korea needs fundamental countermeasures to mitigate damages from repetitive floods and droughts caused by climate change.
Model Input

<table>
<thead>
<tr>
<th>Observed Data</th>
<th>GIS Data</th>
<th>Multipurpose Dam Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather data (1984-2014)</td>
<td>DEM, Soil, Land use</td>
<td>4 multipurpose water supply dams (1984-2014)</td>
</tr>
<tr>
<td>Evapotranspiration (2009-2013)</td>
<td></td>
<td>Dam inflow, storage, release</td>
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<tr>
<td>Soil moisture (2009-2013)</td>
<td></td>
<td>3 multifunction weirs (2012-2014)</td>
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<tr>
<td>Groundwater level (2009-2013)</td>
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<td>Dam inflow, storage, release</td>
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</table>

Model Process Dynamics

SWAT Model

<table>
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<th>Model run (1984-2014)</th>
<th>Surface Processes</th>
</tr>
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<tbody>
<tr>
<td>Warm-up (1984)</td>
<td>Vertical water budget: infiltration, evapotranspiration</td>
</tr>
<tr>
<td>Calibration (2005-2009)</td>
<td>Horizontal water transfer: surface runoff</td>
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<tr>
<td>and validation (2010-2014)</td>
<td></td>
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<tr>
<td>Dam &amp; weir inflow</td>
<td></td>
</tr>
<tr>
<td>Dam &amp; weir storage</td>
<td></td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td></td>
</tr>
<tr>
<td>Soil moisture</td>
<td></td>
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<td>Groundwater level variation</td>
<td></td>
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<tr>
<td>Dam operation (2005-2014)</td>
<td></td>
</tr>
</tbody>
</table>

Soil Water Dynamics

| Vertical water budget: percolation, soil water storage, |
| Horizontal water transfer: lateral flow               |

Groundwater Dynamics

| Vertical water budget: groundwater revap, groundwater recharge, |
| Horizontal water transfer: return flow                  |

Model Results

Analysis of Water Balance

| Vertical water budget and horizontal water transfers |
| Surface-groundwater exchange fluxes                  |

Watershed Soundness Assessment

| Normalized metric value → sub-index |
| Watershed health index               |
The largest river basin in South Korea (Han, Geum, Yeongsan, Seomjin, Nakdong)

Han River basin (34,148 km²)
- Average precipitation 1254 mm
- Average temperature 11.5°C
**SWAT model** (Soil and Water Assessment Tool)

### Water balance

\[
SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})
\]

- \(SW_t\) = Final soil water content (mm)
- \(SW_0\) = Initial soil water content on day \(i\) (mm)
- \(R_{day}\) = Amount of precipitation on day \(i\) (mm)
- \(Q_{surf}\) = Amount of surface runoff on day \(i\) (mm)
- \(E_a\) = Amount of evapotranspiration on day \(i\) (mm)
- \(W_{seep}\) = Amount of water entering the vadose zone from the soil profile on day \(i\) (mm)
- \(Q_{gw}\) = Amount of return flow on day \(i\) (mm)

### Reservoir

\[
V = V_{stored} + V_{flowin} - V_{flowout} + V_{pcp} - V_{evap} - V_{seep}
\]

- \(V\) = volume of water in the impoundment at the end of the day (m\(^3\)H\(_2\)O)
- \(V_{stored}\) = volume of water stored in the water body at the beginning of the day (m\(^3\) H\(_2\)O)
- \(V_{flowin}\) = volume of water entering the water body during the day (m\(^3\) H\(_2\)O)
- \(V_{flowout}\) = volume of water flowing out of the water body during the day (m\(^3\) H\(_2\)O)
- \(V_{pcp}\) = volume of precipitation falling on the water body during the day (m\(^3\) H\(_2\)O)
- \(V_{evap}\) = volume of water removed from the water body by evaporation during the day (m\(^3\) H\(_2\)O)
- \(V_{seep}\) = volume of water lost from the water body by seepage (m\(^3\) H\(_2\)O)
Data for SWAT model evaluation

GIS data

Elevation: 0 - 1650m  
(SRTM 90m grid size)

Soil: Loam (24%) and sandy loam (58%)

Land cover (2008): Forest (73%) and paddy rice (6%)
4 Multipurpose dam data (area-level and storage-level relationship curve)

**Soyang dam (SYD)**
- Total storage: 2.9 billion m³
- Sub-basin area: 2,694 km²
- (the largest in South Korea)

**Hoengseong (HSD)**
- Total storage: 87 million m³
- Sub-basin area: 209 km²

**Chungju dam (CJD)**
- Total storage: 2.8 billion m³
- Sub-basin area: 6,662 km²
- (the second largest in South Korea)

**Paldang dam (PDD)**
- Total storage: 244 million m³
- Sub-basin area: 23,539 km²
Data for SWAT model evaluation

3 Multifunction weir data (area-level and storage-level relationship curve)

- Ipo weir (IPW)
  - Total storage: 17 million m³

- Yeoju weir (YJW)
  - Total storage: 13 million m³

- Kangcheon weir (KCW)
  - Total storage: 11 million m³

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**Watershed outlet**
Data for SWAT model evaluation

4 Multipurpose dam data (release and storage: 1984-2014)

- **Soyang dam (SYD)**
  - ![Graph showing precipitation, release, and storage for Soyang dam from 1984 to 2014.](image)
  - Key points:
    - Volume of flood water level: $2,500 \times 10^3\text{m}^3$
    - Volume of full water level: $2,504 \times 10^3\text{m}^3$

- **Hoengseong (HSD)**
  - ![Graph showing precipitation, release, and storage for Hoengseong dam from 2000 to 2012.](image)
  - Key points:
    - Volume of flood water level: $87 \times 10^3\text{m}^3$
    - Volume of full water level: $79 \times 10^3\text{m}^3$

- **Chungju dam (CJD)**
  - ![Graph showing precipitation, release, and storage for Chungju dam from 1985 to 2012.](image)
  - Key points:
    - Volume of flood water level: $2,750 \times 10^3\text{m}^3$
    - Volume of full water level: $2,252 \times 10^3\text{m}^3$

- **Paldang dam (PDD)**
  - ![Graph showing precipitation, release, and storage for Paldang dam from 1984 to 2014.](image)
  - Key points:
    - Volume of flood water level: $244 \times 10^3\text{m}^3$
    - Volume of full water level: $226 \times 10^3\text{m}^3$
Data for SWAT model evaluation

3 Multifunction weir data (release and storage: 2012-2014)

Ipo weir (IPW)

Yeoju weir (YJW)

Kangcheon weir (KCW)
Model calibration and validation

Observed vs. simulated streamflow results of model calibration and validation

Calibration: 5 years (2005-2009) / Validation: 5 years (2010-2014)

- **SYD**: Calibration period R²: 0.90, NSE: 0.78, PBIAS(%): 12
- **HSD**: Calibration period R²: 0.83, NSE: 0.59, PBIAS(%): 14
- **CJD**: Calibration period R²: 0.78, NSE: 0.61, PBIAS(%): 9
- **PDD**: Calibration period R²: 0.90, NSE: 0.80, PBIAS(%): 5
Model calibration and validation

Observed vs. simulated streamflow results of model calibration and validation

✓ Calibration: 2 years (2012-2013) / Validation: 1 year (2014)
Model calibration and validation

Fitted results of 4 multipurpose dams storage

- **SYD**
  - Calibration period: $R^2: 0.95$, PBIAS (%): 13
  - Validation period: $R^2: 0.95$, PBIAS (%): 13

- **HSD**
  - Calibration period: $R^2: 0.75$, PBIAS (%): 14
  - Validation period: $R^2: 0.75$, PBIAS (%): 14

- **CJD**
  - Calibration period: $R^2: 0.86$, PBIAS (%): 17
  - Validation period: $R^2: 0.86$, PBIAS (%): 17

- **IPW**, **SM**, **PDD**, **KCW**, **YJW**
  - Calibration period: $R^2: 0.42$, PBIAS (%): 1
  - Validation period: $R^2: 0.42$, PBIAS (%): 1
Model calibration and validation

Fitted results of 3 multifunction weirs storage

- **Calibration period**
  - **IPW**: $R^2: 0.63 / \text{PBIAS} (\%): 8$
  - **YJW**: $R^2: 0.65 / \text{PBIAS} (\%): 7$
  - **KCW**: $R^2: 0.71 / \text{PBIAS} (\%): 6$

[Map with watershed and outlet points]
Model calibration and validation

Observed vs. simulated ET & SM results of model calibration and validation

- **Calibration**: 3 years (2009-2011) / **Validation**: 2 years (2012-2013)

![Map of Watershed with Stations and SM indicator](image)

- **SM**: Soil Moisture
- **Evapotranspiration (mm)**: Graph showing observed vs. simulated values with R²: 0.77, NSE: 0.55, PBIAS(%): 20
- **Soil Moisture (%)**: Graph showing observed vs. simulated values with R²: 0.80
- **Evapotranspiration (mm)**: Graph showing observed vs. simulated values with R²: 0.72, NSE: 0.53, PBIAS(%): 18
- **Evapotranspiration (mm)**: Graph showing observed vs. simulated values with R²: 0.78

- **Watershed outlet**

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Model calibration and validation

Observed vs. simulated groundwater level variation results of model calibration and validation

Calibration: 3 years (2009-2011) / Validation: 2 years (2012-2013)
Water balance analysis

River basin water balance (water balance ratios based on precipitation)

30 years (1985-2014) simulated by SWAT

<table>
<thead>
<tr>
<th>Period</th>
<th>Total</th>
<th>Surface Processes</th>
<th>Soil Water Dynamics</th>
<th>Groundwater Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P (mm)</td>
<td>TQ (mm)</td>
<td>INFILT (mm)</td>
<td>ET (mm)</td>
</tr>
<tr>
<td>Rainy Season (Jun-Sept)</td>
<td>1004.5</td>
<td>644.0 (66%)</td>
<td>577.9</td>
<td>249.8 (25%)</td>
</tr>
<tr>
<td>Dry season (Oct-May)</td>
<td>387.6</td>
<td>227.0 (59%)</td>
<td>159.6</td>
<td>208.2 (54%)</td>
</tr>
<tr>
<td>Annual</td>
<td>1392.1</td>
<td>909.2 (65%)</td>
<td>737.5</td>
<td>458.0 (33%)</td>
</tr>
</tbody>
</table>

Total Runoff (TQ) 909.2 (65.3%)

Evapotranspiration (ET) 458.0 (32.9%)

Precipitation (P) 1392.1 (100%)

Lateral flow (LQ) 360.4 (25.9%)

Return flow (RQ) 321.5 (23.1%)

Reevaporation (REVAP) 16.7 (1.2%)

Percolation (PERCOL) 360.4 (25.9%)

Flow out of watershed

Groundwater recharge (GR) 22.2 (1.6%)
Water balance analysis

Daily water balance (between surface water and groundwater)

Flood year (2011)

- ET: 23%
- TQ: 75%
- INFILT: 60%
- PERCOL: 31%
- P: 1920 mm

Surface Processes
- SQ: 339 mm
- ET: 439 mm

Soil Water Dynamics
- LQ: 536 mm

Groundwater Dynamics
- RQ: 540 mm

Drought year (2014)

- ET: 56%
- TQ: 44%
- INFILT: 38%
- PERCOL: 15%
- P: 791 mm

Surface Processes
- SQ: 71 mm
- ET: 441 mm

Soil Water Dynamics
- LQ: 166 mm

Groundwater Dynamics
- RQ: 103 mm
Impact of surface-groundwater exchange fluxes

Monthly average discharge (surface runoff, lateral flow, and return flow)

- 30 years (1985-2014) simulated by SWAT

Higher discharges

Surface runoff

- Average surface runoff
- Min. surface runoff
- Max. surface runoff
- 25 quantile
- 75 quantile

Lateral flow

- Average lateral flow
- Max. lateral flow
- Min. lateral flow
- 25 quantile
- 75 quantile

Return flow

- Average return flow
- Max. return flow
- Min. return flow
- 25 quantile
- 75 quantile
Impact of surface-groundwater exchange fluxes

Monthly average exchange fluxes (between surface water and groundwater) and groundwater recharge

✓ 30 years (1985-2014) simulated by SWAT

Exchange fluxes (between groundwater and surface water)

Groundwater recharge

(a) February to August
(b) September to January
Comparison of the water balance components


Watershed Soundness Assessment

<table>
<thead>
<tr>
<th>Category</th>
<th>Precipitation (mm)</th>
<th>Total Q (mm)</th>
<th>Infiltration (mm)</th>
<th>ET (mm)</th>
<th>Surface runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation (mm)</td>
<td>(a) 30yrs</td>
<td>(a)</td>
<td>(a)</td>
<td></td>
<td>(a)</td>
</tr>
<tr>
<td>(b) 2011 (flood)</td>
<td></td>
<td>(b)</td>
<td></td>
<td></td>
<td>(b)</td>
</tr>
<tr>
<td>(c) 2014 (drought)</td>
<td></td>
<td>(c)</td>
<td></td>
<td></td>
<td>(c)</td>
</tr>
</tbody>
</table>

Surface Processes

- ET (mm)
- SW storage (mm)
- Revap (mm)
- GW recharge (mm)
- Return Q (mm)
Watershed soundness index (hydrology)

✓ 30 years (1985-2014)

Normalized sub-index

<table>
<thead>
<tr>
<th>Sub-index</th>
<th>Simulated value for watershed x</th>
<th>Max. value for all watersheds</th>
<th>Total number of normalized values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface Processes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Water Dynamics</td>
<td>(Normalized value 1 + Normalized value 2 + ... + Normalized value x)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groundwater Dynamics</td>
<td>(Sub-index 1 + Sub-index 2 + ... + Sub-index x)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Watershed soundness index

- Standard watershed 100902
  - Total: 0.76
  - Surface Processes: 0.43
  - Soil Water Dynamics: 0.84
  - Groundwater Dynamics: 0.09
  - Watershed soundness: 0.29

- Standard watershed 101306
  - Total: 0.98
  - Surface Processes: 0.99
  - Soil Water Dynamics: 0.58
  - Groundwater Dynamics: 0.72
  - Watershed soundness: 0.96

Ref.) EPA 2012, Identifying and Protecting Healthy Watersheds
In this study, the surface water and groundwater interaction modeling of Han River basin in South Korea was performed using SWAT model.

- The SWAT was calibrated using 4 measured dam and 3 weir operation data (storage and inflow) and with spatial hydrologic component data (evapotranspiration and soil moisture).
- The SWAT model was used in the analysis of the water balance by vertical water budget (INFILT, ET, PERCOL, SW, REVAP and GR) and the horizontal water transfers (SQ, LQ and RQ).

During dry season (Oct. to May), the evapotranspiration and return flow was 29% and 10% higher compared to those of wet season. So, they should be treated as important factors for the whole hydrological cycle.

The period of (a) February to August was characterized by net inflow of infiltration into the groundwater. For the (b) September to January period, the groundwater flow into the river of the basin showed net outflow. The whole period was nearly balanced by the net flux. The groundwater recharge was found as an important factor to show the same pattern of exchange fluxes during the hydrological year.

The results of this research is planned to investigate the impact of climate and land use change scenarios on water resources and to assess the soundness and vulnerability of watershed regions.
Thank you

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