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The use of HYDRUS-1D for groundwater recharge estimation in boreal environments

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**General features of boreal climate with regard to groundwater recharge processes**

1. Total precipitation ($P$) more then potential evapotranspiration ($ET^0$)
   
   **Dry index** $ET^0/<P < 1$

2. Long winter season with accumulated snow precipitation

3. Short and rare winter thaws

4. Soil freezing and melting
   
   - Soil freezing depth: $> 0.1 - 0.5$ m
   - Snow evaporation and sublimation:
     - $31\%$
     - $69\%$

5. Short and intensive snow melting period and flood

**Surface water balance model SurfBal**

$V^i_p = P^i \pm \Delta V^i_S - \Delta V^i_L - S^i - E^i_S - E^i_L$

**Canopy interception and evaporation – bucket model**

$\Delta V^i_L = V^i_L - V^i_{L}^{\tau_1}$

$P^i = N^i \left[ 1 - \exp \left( \frac{P^i}{N^i} \right) \right]$

**Penman-Monteith or Priestley-Taylor methods**

$ET^0 = ET^0 - (E_S + E_P) - E_L$

Potential transpiration:

$TR^0 = (1 - \beta) ET^0$

$S$:

- Excess surface runoff $S^i(t)$
- Soil evaporation and root water uptake $E_S^i(t)$, $TR^0(t)$
- Potential infiltration $v_p^i(t)$

**Upper boundary conditions**

- Soil freezing and melting
  - $95 - 98%$
  - $\varepsilon$ - retardation factor

**Surface runoff – curve number model (USDA)**

$S = \left\{ \begin{array}{ll}
\frac{P_i - a_{min}}{a_{max}} & \text{при } P^i \geq a_{min} \\
0, & \text{при } 0 \leq P^i < a_{min}
\end{array} \right.$

$CN = \frac{1000}{V_{max} + 10}$

For frozen soil: $CN = 95 - 98$

**Snow melt:**

$T_m > 0$  $H_s < 20$ cm

$T_m = \int \left( T(t) \exp \left( -\varepsilon(t - t) \right) \right) dt$
Snow accumulation and melting model
(modified model of Kuchment and Gelfan, 1996)

\[ \rho_s = f(z, t) \]

Snow package: 3-phase system
\[ H_s \]
water: \( \theta \), ice: \( \rho \), void space: \( \rho_s = 1.0 \text{ g/cm}^3 \), \( \rho_i = 0.917 \text{ g/cm}^3 \)

\[ \rho_s = \frac{\rho I + \rho_w \theta}{H_s} \]

Snow dynamic and melting (L) subject to snow density \( \rho_s \)

\[ \frac{dH_s}{dt} = \left[ \rho \left( L + E_2 \right) \right] \chi^{E_1} - V \]

Rate of refreezing water (\( T < 0 \))
\[ S = K_s \left[ \theta \right] \]
\[ K_s = 4.5 \text{ mm/day} \]

Snowpack self-compression rate:
\[ \chi \approx 0.233 \text{ g/cm}^3 \text{ day}^{-1} \]
\[ \xi \approx 0.08 \text{ deg}^{-1} \]
\[ \xi \approx 16 \text{ cm}^3/\text{g} \]

Evaporation and sublimation:
\[ \left( \chi \right) \left[ \theta \right] \left( \rho \right) \approx 4.5 \text{ mm/day} \]

Rate of melted water release to soil:
\[ V = \left\{ \begin{array}{ll}
K_s \theta, & \theta \geq \theta_{\text{max}} \\
0, & \theta < \theta_{\text{max}}
\end{array} \right. \]
\[ \theta_{\text{max}} = 0.05 \text{ cm} \]
\[ K_s = 400 \text{ m/day} \]

**Main principles of regional-scale estimation of mean annual GW recharge**
(Grinevskii, Pozdnyakov, 2010)

I. Division of the investigation area into districts with the same typical conditions of groundwater recharge (meteorological, landscape and hydrogeological).

II. Model’s parameterization for typical GWR conditions

III. GWR simulation (surface water balance and unsaturated flow) for each type of conditions based on long-term meteorological data and estimation the mean annual GWR values and their seasonal variations as a function of GW level depth

IV. Verification of GWR values by the comparison of simulated river runoff with the observed data on stream gage stations

V. The final result of estimation is the regional map of mean annual GW recharge.

Such investigations for the south-western part of Moscow Artesian basin (total area of 49 600 km²) are presented.

**Types of groundwater recharge conditions**

The regional scale heterogeneity of GWR caused by the **major differences** of natural conditions called as typical conditions of groundwater recharge.
Meteorological conditions of the region (1960-2010 y.)
Mean annual precipitation 600 - 700 mm; air temperature 4.6 - 5.0 °C.
Mean annual potential evapotranspiration 550 - 600 mm; Dry index (ET0/P) = 0.85-0.95.

Areal distribution of precipitation and river runoff (mm/year) and representative weather stations for local river basins.

Example of GWR typical conditions zoning for Jizdra river basin (area 7226 km²)
Surface type and vegetation
Types of vadose zone texture

Surface water balance model parameterization (SurfBal)
Monthly variations of LAI for different types of vegetation (European part of Russia)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Field</th>
<th>Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leaf area index (LAI)</td>
<td>0 - 3</td>
<td>2 - 8</td>
</tr>
<tr>
<td>Vegetation period, days</td>
<td>123 - 282</td>
<td>123 - 282</td>
</tr>
<tr>
<td>Snow melting rate, mm/day degree</td>
<td>4 - 6</td>
<td>1.5 - 3.5</td>
</tr>
<tr>
<td>Snow melting retardation, days</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

Annual variations of average snow melting rate (simulation results)

Snow model calibration
Simulated (dots) and observed (lines) snow depth and its cumulative probability

Study snow depth CDF for 25 years of simulation
Simulation
Observations
Surface water balance model parameterization (SurfBal)

CN values for different types of soil and vegetation (USDA)

\[ C_N = \frac{1}{F} \sum_{i} C_N f_i \]

Surface runoff:

\[ S_{\text{calc}} = \frac{1}{F} \sum_{i} S_i (C_N) f_i \]

\[ S_{\text{calc}} - S_{\text{obs}} \rightarrow 0 \]

- \( F \) - catchment area;
- \( f \) - landscape area;
- \( n \) - number of landscape types

Vegetation and soil type:

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Sandy</th>
<th>Loamy</th>
<th>Clayey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>70</td>
<td>88</td>
<td>94</td>
</tr>
<tr>
<td>Forest</td>
<td>40</td>
<td>83</td>
<td>91</td>
</tr>
</tbody>
</table>

Example of the relationship between surface runoff and effective precipitation for Vytebet river (1960-2003)

Parameterization of the unsaturated flow model (HYDRUS-1D)

Vadose zone structure

Regional schematization of the vadose zone structure

\[ \Phi(h) = \frac{1}{1 + (h/h_p)} \]

- \( h_p \) - saturated hydraulic conductivity

Average Van Genuchten WRC parameters for main soil textures and layers (A,B,C)

\[ \tau \approx -3 \text{ m}; \ h_{wp} \approx -153 \text{ m}; \]

 triturated loam

Grass: \( \tau = 4 \)

Tree: \( \tau = 2 \)

Differences in WRC curves due to landscape-vegetation type (for upper soil)

Parameterization of the root water uptake model

S-shape model (van Genuchten, 1987)

\[ \phi(h) \]

Vegetation parameters for root water uptake model (Grinevskii, 2011)

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Soil</th>
<th>( h_{wp} ) (m)</th>
<th>( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree</td>
<td>Loam</td>
<td>-37.3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Loamy sand</td>
<td>-33.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>-15.0</td>
<td></td>
</tr>
<tr>
<td>Grass</td>
<td>Loam</td>
<td>-45.5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Loamy sand</td>
<td>-31.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sand</td>
<td>-24.0</td>
<td></td>
</tr>
</tbody>
</table>
**Root distribution** \( b(z) \)

**Trees (bar system):**

\[ b(z) = \eta^2; \ \eta = 0.01^{\text{mm}} \]

(Hale, Grigel, 1987)

**Grass (fibrous system):**

\[
\begin{align*}
& b(z) = \left. \frac{2.0833}{m_z} \left( 1 - \frac{z}{m_z} \right) \right|_{0.2 < z < m_z}, \\
& 0, \ \text{when } z > m_z \\
\end{align*}
\]

(Hoffman, van Genuchten, 1983)

**Results of simulation**

Map of mean annual GW recharge for southwestern part of MAB (area 49,600 km\(^2\))

- **Total GW recharge**: 8,811,200 m\(^3\)/day
- **Discharge to the river**: 8,427,820 m\(^3\)/day (95%)
- **Evapotranspiration discharge**: 383,400 m\(^3\)/day (5%)

**Soil type**

- **Trees**
  - Grass: 0.5
  - Loamy sand: 0.3
  - Loam: 0.15

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<tr>
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<tr>
<td>Sand</td>
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<td>2.0</td>
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<tr>
<td>Loamy sand</td>
<td>0.3</td>
<td>1.5</td>
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<tr>
<td>Loam</td>
<td>0.15</td>
<td>1.0</td>
</tr>
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**Results and discussion**

- **Surface runoff**, mm
- **Potential infiltration**, mm
- **Transpiration**, mm
- **Total evaporation**, mm
- **Recharge**, mm

- **Mean annual GW recharge** (for GW level depth > 5 m)
  - **GWR**: from 15 to 145 mm/year

- **Relationship between GWR and groundwater level depth**

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<tr>
<td>Sandy</td>
<td>0.7-1.0</td>
<td>0.1-0.6</td>
</tr>
<tr>
<td>Loamy</td>
<td>1.7-3.0</td>
<td>1.2</td>
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\[ Z^0 \]

- **Surface runoff**, mm
- **Potential infiltration**, mm
- **Transpiration**, mm
- **Total evaporation**, mm
- **Recharge**, mm

- **Mean annual GW recharge** (for GW level depth > 5 m)
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\[ Z^0 \]

\[ Z^0 \]

\[ Z^0 \]
Conclusions:

- Principal differences of GW recharge due to landscape conditions in boreal environment form during short snow melting period

- Main model parameters, which firstly need for calibration based on observation data, are:
  - snow melting model parameters;
  - surface runoff model parameters.