Towards an Improvement of the Water Balance on Steep Slopes - Development of a Correction Algorithm of the Runoff Curve Number for Slope Angles up to 100%

Para um aperfeiçoamento do balanço hídrico em encostas íngremes – Desenvolvimento de um Algoritmo de Correção da “Curva-Número” para declividades até 100%

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Motivation

Reliable estimations of stream flow, soil erosion or nutrients critical for model-based scenario evaluations

The crucial processes should be represented adequately for the conditions of the research region

SWAT-based study on diffuse matter inputs in the Three Gorges Region, China, with very steep slopes (average slope: 40%)

Critical question for representation of processes in SWAT: **How do HRUs in SWAT behave with slope?**
Experimental Design
A estrutura do projeto experimental

- **Experimental design:**
  - SWAT model with only one subbasin containing one HRU
  - different vegetation types
  - different soil types with uniform soil depth
  - two years run (1 year warmup)
  - climate data from Xiangxi catchment (China): 1116 mm/a

**Parametrization:**

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Agricultural Land</th>
<th>Fallow Land</th>
<th>Forest</th>
<th>Rangeland</th>
</tr>
</thead>
<tbody>
<tr>
<td>CN2</td>
<td>77</td>
<td>86</td>
<td>55</td>
<td>61</td>
</tr>
<tr>
<td>USLE_C</td>
<td>0.200</td>
<td>1.000</td>
<td>0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>Soil</td>
<td>Brown</td>
<td>Limestone</td>
<td>Yellow Brown</td>
<td>Yellow</td>
</tr>
<tr>
<td>SOL_AWC</td>
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<td>0.15</td>
<td>0.15</td>
<td>0.14</td>
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<tr>
<td>SOL_BD</td>
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<td>1.20</td>
<td>1.43</td>
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<td>SOL_K</td>
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<tr>
<td>USLE_K</td>
<td>0.43</td>
<td>0.34</td>
<td>0.39</td>
<td>0.30</td>
</tr>
</tbody>
</table>

- HRU slope is varied > Annual output from output.hru
Relation between Slope and Slope Length
Relação entre declividade e comprimento da encosta
SED_YLD - Sediment Yield – Produção de sedimentos

**Agricultural Land**

- **Sediment Yield (t/ha/a)** vs **Slope (m/m)**

**Fallow Land**

- **Sediment Yield (t/ha/a)** vs **Slope (m/m)**

**Evergreen Forest**

- **Sediment Yield (t/ha/a)** vs **Slope (m/m)**

**Rangeland**

- **Sediment Yield (t/ha/a)** vs **Slope (m/m)**

**Legend**:
- Brown Soil
- Limestone Soil
- Yellow Brown Soil
- Yellow Soil
How does surface runoff behave with slope?  
Como o escoamento superficial se comporta em relação à declividade?

- Surface runoff:
  Increases with increasing slope angle  
e.g. El Kateb et al., 2013

Many other studies also confirm this relation, e.g. Chaplot & Bissonnais, 2003  
Haggard et al., 2002  
Barros et al., 1999
How does surface runoff behave with slope? Como o escoamento superficial se comporta em relação à declividade?

- According to Huang et al. (2006) surface runoff increases with slope due to:

1. a reduction of the initial abstraction (Huang, 1995; Fox et al., 1997; Chaplot & Bissonnais, 2003)

2. a decrease in infiltration

3. a reduction of the recession time of overland flow (Evett & Dutt, 1985)
Correction Algorithms for CN
Algoritmos de correção para CN

- Williams (1995):

\[
CN_{2s} = \frac{(CN_3 - CN_2)}{3} \cdot [1 - 2 \cdot \exp(-13.86 \cdot \text{slp})] + CN_2
\]

- Huang et al. (2006):

\[
CN_{2s} = CN_2 \frac{322.79 + 15.63 \cdot \text{slp}}{\text{slp} + 323.52}
\]
Slope Correction – Correção de declividade – Williams, 1995

Agricultural Land

- Brown Soil
- Limestone Soil
- Yellow Brown Soil
- Yellow Soil

Fallow Land

- Brown Soil
- Limestone Soil
- Yellow Brown Soil
- Yellow Soil

Evergreen Forest

- Brown Soil
- Limestone Soil
- Yellow Brown Soil
- Yellow Soil

Rangeland

- Brown Soil
- Limestone Soil
- Yellow Brown Soil
- Yellow Soil
Slope Correction – Correção de declividade – Huang et al., 2006

Agricultural Land

Fallow Land

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Rangeland

- Brown Soil
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- Yellow Soil
Data analysis of different studies, e.g.:

- Haggard et al., 2005
- Huang et al., 2006
- El Kateb et al., 2013

- Data analysis from these studies suggests a linear increase of surface runoff with slope by 1.5% of the annual precipitation sum per 10% slope increment on agricultural land

- With this, for the test dataset (1116 mm/a), the surface runoff increase per 10% slope increment was defined as 16.7 mm

- The curve numbers to meet the desired increase rate were determined with an iterative approach using the single-HRU models
Ideal curve number values for the Slope Correction Algorithm
Valores ideais da CN para o Algoritmo de Correção da Declividade

\[ y = 10.9x + 76.8 \]

\[ y = 6.7x + 85.7 \]

\[ y = 31.9x + 54.3 \]

\[ y = 22.1x + 61.2 \]
Development of a CN correction algorithm for slopes up to 100% Desenvolvimento de algoritmo de correção da CN para declividades até 100%

- To adjust the rate of CN correction for different land uses, the initial CN was used
- With the adjustment of the correction function, also the lower surface runoff increase rates for forest and shrubland could be implemented
- With this the CN correction equation can be written as:

\[ CN_{korr} = a \cdot slp + CN2 \cdot (1 - 0.05 \cdot a) \]

with

\[ a = 158 \cdot \exp(-0.035 \cdot CN2) \]
New CN Slope Correction Algorithm – Novo Algoritmo de Correção da Declividade da CN

Agricultural Land

Fallow Land

Evergreen Forest

Rangeland

Surface Runoff [mm]

Surface Runoff [mm]

Surface Runoff [mm]

Surface Runoff [mm]

Slope [m/m]

Slope [m/m]

Slope [m/m]

Slope [m/m]

- Brown Soil
- Limestone Soil
- Yellow Brown Soil
- Yellow Soil
Test of the New CN Correction Algorithm
Teste do Novo Algoritmo de Correção da CN

- Steep-sloping watershed in the northwest of South Korea
- Area: 7.8 km²
- Mainly forested (~70%)
- Annual Precipitation: 1210 mm

Diagram showing slope distribution and area by slope range:

Source: Joh et al., 2011
Test of the New CN Correction Algorithm
Teste do Novo Algoritmo de Correção da CN

Method:

- Implementation of the different slope correction algorithms in the source code of SWAT
- Separate calibration of streamflow for every slope correction algorithm
- No calibration of the curve number (CN2)

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>unmodified</th>
<th>Williams, 1995</th>
<th>Huang et al., 2006</th>
<th>New Algorithm</th>
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</thead>
<tbody>
<tr>
<td>( R^2 )</td>
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<td>0.936</td>
<td>0.935</td>
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<tr>
<td>NSE</td>
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<tr>
<td>RSR</td>
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<tr>
<td>PBIAS</td>
<td>16.28</td>
<td>22.85</td>
<td>19.66</td>
<td>11.18</td>
</tr>
</tbody>
</table>
Test of the New CN Correction Algorithm
Teste do Novo Algoritmo de Correção da CN

- Event-based validation:
  Application of a baseflow filter (Arnold & Allen, 1999)

<table>
<thead>
<tr>
<th>RMSE</th>
<th>Event #1</th>
<th>Event #2</th>
<th>Event #3</th>
<th>Event #4</th>
<th>Event #5</th>
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<tbody>
<tr>
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<td>0.1990</td>
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<td>Huang et al., 2006</td>
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<td>0.1978</td>
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<td>0.1452</td>
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<td>New Algorithm</td>
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<td>0.1184</td>
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<td>0.1082</td>
<td>0.6120</td>
</tr>
</tbody>
</table>
Conclusion
Conclusão

- A new approach for the correction of the curve number for slopes up to 100% was developed

- The newly developed slope correction for the curve number yields solid results for a steep-sloping Korean watershed

- Additional tests of the algorithm in other mountainous catchments towards its general applicability necessary

- Further improvement and validation of the algorithm can be supported by field experiments

- The water balance on steep slopes in SWAT behaves not always plausibly

- The development of this algorithm is a step towards better representation of landscape processes in SWAT
Thank you for your attention!

Muito obrigado por sua atenção!

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