Model for Water Availability in Semi-Arid Environments (WASA)

Estimation of transmission losses by infiltration at rivers in the semi-arid Federal State of Ceará (Brazil)

Vertiefungsarbeit

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1 Introduction

The hydrological model WASA (Model of Water Availability in Semi-Arid Environments) has been developed as a deterministic, spatially distributed model, consisting of conceptual, process-based approaches, to quantify water availability in large semi-arid regions. Water availability can be calculated with a daily resolution and on different spatial levels.

The model has been applied by Güntner (2002) to the study area "Federal State of Ceará", a 150,000 square-kilometre large region in the semi-arid north-eastern part of Brazil. The mean annual precipitation of 850 mm occurs generally during a rainy season of five months (Güntner: XVII). As precipitation in semi-arid tropical areas is mainly of convective type and rainfall events characterized by short duration, high intensities, large spatial and temporal heterogeneity, river channel runoff is correspondingly variable. In the study area, river flow occurs only periodically during the rainy season. Besides this seasonal variation of river flow, the intermittency is also due to the lack of important groundwater reservoirs which could provide base flow and avoid influent conditions of rivers (Güntner: 6).

In WASA spatial units are connected by a dendritic river network and the routing process of river runoff through each of these units is approximated by a daily response function.

Up to now, the routing process in WASA considers only transmission losses by evaporation from the surface of the river network. Transmission losses by infiltration are not taken into consideration in routing processes yet, although the volume of these supplementary losses under the aforementioned conditions seems to be important and affects several hydrological processes as runoff volume and peak discharge, groundwater recharge etc..

In this study an attempt to consider transmission losses by infiltration and implement a corresponding approach in the river routing process of WASA has been undertaken and will be described in the following chapters in detail.

2 Transmission losses

"When flow occurs in normally dry stream channels, the volume of flow is reduced at downstream points by evaporation and infiltration to the bed, the banks, and possibly the flood plain. This flow reduction is termed transmission losses. Quantification of transmission losses yields useful information not only on surface runoff volumes, but also on ground water recharge in some regions." (Walters: 129)

The two dominant processes forming transmission losses are infiltration and evaporation. Transmission losses by evaporation are actually considered in the WASA model, subtracting in each sub-basin transmission losses from the river runoff volume. These evaporation losses are computed by multiplying the potential evaporation rate with the evaporating water surface, which can be derived from channel length and mean channel width in the sub basin.

This study focuses on infiltration losses, which means the loss of water by infiltration into the riverbank and bed of the river. This water either finds its way into the underlying groundwater aquifer or returns later as flow into the river. The rate at which it is lost from the river depends on multiple factors which will be discussed in the following subchapter in depth.
In particular under arid or semi-arid conditions, where the adjacent groundwater level is extremely low and most of the time beneath the water level of the river, rates of transmission losses are considerable. For instance, Boroto/Görgens (2003) mentioned within the scope of a case study at the Limpopo River in semi-arid Southern Africa, that transmission losses of the order of 30 percent of the water balance occurred along the river, caused by recharge of storage volume, evaporation and evapotranspiration.

2.1 Factors affecting transmission losses

In order to develop some comprehension of the magnitudes of transmission losses, it is essential to understand the factors that affect these losses. All river channels are subject to some losses at some times, regardless of soils, geology, or geometry. Transmission losses are not a constant for a given channel, either in absolute quantities or by percentages, but depend from adjacent conditions.

Three major categories of flood-water storage in valleys that may contribute to transmission losses are as follows (Sharp/Saxton: 123):

1. Storage beneath the channel bottom in streams with ground water at depth below the channel bottom.
2. Bank storage – that water entering, more or less horizontally, the banks of the channel as the stream stage rises.
3. Storage in valley alluvium away from the channel when over bank flow occurs.

"Among the more important factors affecting channel losses are: size and sequence of floods; geology and soils of the valley; the gradient, depth, size, continuity, meander, and number of channels; riparian and phreatophytic vegetation along the channels and in the valleys; soil-frost conditions; depth to the water table; soil-moisture content; gross and gravitational pore space in the soil; man-made structures and alterations; antecedent and current rainfall; and the content and nature of sediment in the stream flow." (Sharp/Saxton: 123)

The most important factors having a general influence on transmission losses are described below (Sharp/Saxton: 124/25):

- As transmission losses are strongly related to runoff volume and velocity, large floods are normally associated with greater absolute channel losses unless such floods occur under saturated conditions.
- River channel geometry can also affect transmission losses, as valleys with a deeply incised channel with steep gradient will normally have lower transmission losses than a similar valley with a very small channel that cannot carry the flood flow, and braided-channel systems will induce more losses than a single-stem channel.
- Vegetation along the channels may increase the rate of transmission losses by reducing velocities of flow and direct water consumption.
- Man-made structures and alterations, as ponds, check dams, reservoirs or bridges, may also affect valley transmission losses.
- The depth to water table affects the available storage capacity of the valley alluvium and influences consequently transmission losses.
- The infiltration rate depends strongly on the soil characteristics of the river bed and banks. A gravelly, sandy channel and valley may have much higher intake rates per day than finer soils, such as silts and
loams or even less for clays.

- Total pore space of channel and valley soils is another important factor in transmission losses. The sizes, shapes, and continuities of these pore spaces determine the total, field, wilting point, air-dry, and over-dry water-holding capacities of soils. These several capacities, in turn, control the available storage volume that is available to valley soils to store flood waters.

- The evaporation process also affects transmission losses. To date, evaporation loss associated with transmission losses has not been studied in detail; even though it has been identified as a dominant process by which water is lost.

Despite the fact that transmission losses can be affected by many of these factors, only few of the above-mentioned factors have successfully been used as parameters in estimating transmission losses in previous studies (as e.g. the Lane-approach). The most common factors, considered in estimating procedures, are runoff volume and velocity, river channel geometry and soil characteristics of bed material.

### 2.2 Methods of estimating transmission losses

Many investigations have been undertaken in the past to better understand and attempt to quantify transmission losses in rivers and streams. However, most of these studies focused on transmission losses associated with ephemeral streams as the ratio of transmission losses to runoff volume under semi-arid conditions seems to be particular high because the mentioned influencing factors (see 2.1) are correspondingly favourable.

The following list gives an overview of types of methods which have been applied so far and which differ in their complexity (Vivarelli/Perera: 3):

- Simple regression equations
- Simplified differential equations
- Combined use of differential equations and regression
- Stream flow routing (kinematic wave / Muskingham procedure / St Venant approach)
- Hydrologic budget

“In general, the simplified procedures require less information about the physical features of the channels but are less general in application. The complex procedures may be more physically based, but require correspondingly more data, and more complex computations” (Lane, 1980).

The most appropriate approach to use often depends heavily on the circumstances related to the individual study. Most of the studies conducted in the past related to transmission losses were based on empirical analysis of flow data, and therefore these methods cannot provide useful long term estimates of transmission losses.

Of all the mentioned approaches the combined use of differential and regression equations, as done by Lane et al. (1980), offer the most promise and seem more realistic as they consider the physical processes related to transmission losses to study the generic form of the equations and then use regression to develop site specific prediction equations (Vivarelli/Perera: 4).
3 Estimating procedure after LANE et al. (1983)

The here described approach after LANE et al. (1983) to estimate transmission losses is based on a combined use of differential and regression equations as mentioned in subchapter 2.2 and has been selected within the scope of the hydrological model WASA as corresponding estimating procedure.

Up to now, this approach represents one of the most frequent procedures used to calculate transmission losses in hydrological modelling within the scope of river routing routines and served as basis for many similar estimating procedures adapted by various authors (e.g. Sharma/Murphy, 1994; Osterkamp et al., 1994; Rao/Maurer, 1996). Among others, it has been implemented in the SWAT and SWIM hydrological model as procedure to estimate transmission losses by infiltration.

This chapter will first give an introduction to the general assumptions of the LANE-approach (3.1), and gives an overview of the main equations, their relationship and parameters which are required for the estimation of transmission losses (3.2). Different possibilities of application will be shortly mentioned (3.3) and general assumptions and limitations of this estimating approach (3.4) will be nominated. Then, the derivation of procedures for estimating transmission losses (3.5) will be described step by step to fully understand the estimating procedure with all its equations and parameters where it is based on. Finally, the integration of the suggested transmission-losses-estimating procedure (3.6) in the WASA model and the subroutine in its FORTRAN-code structure (3.7) will be presented.

3.1 Introduction

Lane et al. (1983) developed a procedure to estimate transmission losses for stream channels of arbitrary length and width. This was achieved by linking a two-parameter linear regression equation (see 3.2/B) that relates outflow volume of a channel reach to inflow volume with a simplified two-parameter differential equation (see 3.2/A) that describes the transmission loss rate as a function of length and width of the wetted channel. This differential equation also assumes the volume of losses in the reach is proportional to the volume of upstream inflow and a constant or steady-state loss rate. Transmission loss rates were also assumed to vary directly with the surface area of the river bed and bank wetted by passing flood wave through a channel reach.

This model was used in several subsequent studies including LANE (1985, 1990), but was limited to stream flow in ephemeral stream channels with infiltrating losses. Although, the model was unable to fully describe the dynamic nature of transmission losses, it requires a minimum amount of observed data, considers lateral inflow, if corresponding data is available, and can be used to estimate transmission loss in ungaged catchments.

“Despite some scatter, the results [of the Lane-approach] were generally consistent” (Vivarelli/Perera: 5).

“Parameters of the transmission-loss model are determined, by calibration, using measured inflow and outflow volumes from gaged ephemeral stream channel segments. Data from 127 hydrographs on 10 channel reaches in Arizona, Kansas, Nebraska, and Texas are used to develop parameter estimation equations and tables of parameter values for the transmission-loss model.” (Lane, 1990: 1)
3.2 Overview of the model (after Lane, 1990)

In equation form:

(A) \[ \frac{dQ(x,w)}{dx} = - w^c - w^k Q(x,w) \]  
\textit{(two-parameter differential equation)}

where: \( Q(x,w) \) ist the volume of flow in a channel segment of length \( x \) and mean width \( w \). \( c \) and \( k \) are parameters.

(B) \[ Q(x,w) = a(x,w) + b(x,w)^Q_{in} \]  
\textit{(linear regression equation)}

where: \( Q(x,w) \geq 0 \) is the outflow volume, \( Q_{in} \) is the upstream inflow volume in the same units, and \( a(x,w), b(x,w) \) are functions described below. Notice that in the absence of lateral inflow, the upstream inflow \( Q_{in} \) must be larger than \(-a(x,w)/b(x,w)\) or all the inflow is lost in the channel segment and \( Q(x,w) = 0 \).

To calculate the volume of transmission losses in a channel segment rather than the volume of outflow, the volume of transmission losses is computed as the upstream volume minus the outflow volume.

In equation form:

(C) \[ t_{loss}(x,w) = Q_{in} - (a(x,w) + b(x,w)^Q_{in}) \]

where \( t_{loss}(x,w) \) is the volume of transmission losses in the segment in the same units as \( Q(x,w) \).

The relationship between the functions and the parameters \( c \) and \( k \) are:

(D) \[ a(x,w) = (a / (1 - b))^{(1 - b(x,w))} \]

(E) \[ b(x,w) = \exp (-k^x^w) \]

and

(F) \[ c = -k^a / (1 - b) \]

Values of \( a, k, \) and \( b \) have been related to the effective, steady-state hydraulic conductivity \( K \) (in/h), the mean duration of inflow to the reach \( D \) (h), and the mean volume of inflow to the reach \( Q \) (acre-feet) in English units as:

(G) \[ a = -0.00465 K*D \]

(H) \[ k = -1.09 \log_{e} (1 - 0.00545 K*D / V) \]

and

(I) \[ b = \exp (-k) \]
The effective saturated conductivity, $K$, represents the steady-state conductivity of the channel bed material under field conditions of entrapped air and sediment laden flow. Therefore, it can be an order of magnitude less than conductivity estimates made with infiltrometers and clear water. Values of the effective conductivity were derived by taking the total losses from an event divided by the length and width of the segment and by the duration of flow. These estimates were averaged over all flow events for a channel segment to derive an estimate of the mean effective hydraulic conductivity. Values of $K$ for different bed material classes were tabulated by Lane (1983) and are listed in 3.5/Fig.1.

The detailed derivation of equation A to I will be also discussed there.

### 3.3 Use of the estimating procedure with and without observed data

The Lane-procedure to estimate the volume of runoff for ephemeral streams can be used with or without observed inflow-outflow data.

If available, observed inflow-outflow data can be used to derive regression equations for the particular channel reach. Procedures based on the derived regression equations enable a user to determine prediction equations for similar channels of arbitrary length and width.

Also presented are procedures for estimating parameters of the prediction equations in the absence of observed inflow-outflow data. These procedures are based on characteristics of the bed and bank material (see 3.5/Fig.1).

Lane proposes the following possible applications of the estimating procedure:

- No lateral inflow or out-of-bank flow (with or without observed inflow-outflow data)
- Uniform lateral inflow
- Approximations for out-of-bank flow
- Transmission losses limited by available storage

In this case study, the first approach with no lateral inflow and without inflow-outflow data has been applied in the WASA model as no inflow-outflow data and no further flow characteristics are available. The derivation of procedures and its detailed application will be described in subchapter 3.5.

### 3.4 Assumptions and limitations

Before the application of the estimating procedure after Lane the following assumptions and limitations of this approach have to be taken in consideration.

The methods described above are based on the following assumptions:

1. Water is lost in the channel; no streams gain water.
2. Infiltration characteristics and other channel properties are uniform with distance and width.
3. Sediment concentration, temperature, and antecedent flow affect transmission losses, but the equations represent average conditions.
4. The channel reach is short enough that an average width and an average duration represent the width and
duration of flow for the entire channel reach.

5. Once a threshold volume has been satisfied, outflow volumes are linear with inflow volumes.

The main limitations of the procedures are:

1. Hydrographs are not specifically routed along the stream channel; predictions are made for volume discharge.

2. Analyses on which the procedures are based represent average conditions or overall trends.

3. Influences of antecedent flow and sediment concentration in the stream flow have not been quantified.

4. Estimates of effective hydraulic conductivity in the streambed are empirically based and represent average rates.

5. Procedures for out-of-bank flow are based on the assumption of a weighted average for the effective hydraulic conductivity.

3.5 Derivation of procedures for estimating transmission losses (after Lane, 1983)

When observed inflow-outflow data for a channel of an ephemeral stream with no lateral inflow are plotted on rectangular coordinate paper, the result is often no outflow for small inflow events, with outflow increasing as inflow increases. When data are fitted with a straight-line relationship, the intercept on the x-axis represents an initial abstraction.

Graphs of this type suggest equations of the form:

\[
Q(x, w) = 0 \\
Q(x, w) = a(x, w) + b(x, w)Q_{in} \quad \text{if} \quad Q_{in} \leq Q_0(x, w) \\
Q_{in} > Q_0(x, w)
\]

By setting \(Q(x, w)=0\) and solving for \(Q_{in}\), the threshold volume, the volume of losses that occur before outflow begins, is:

\[
Q_{in}(x, w, c) = \frac{-a(x, w)}{b(x, w)}
\]

Differential equation for changes in volume: Linkage with the regression model

Differential equations (A) can be used to approximate the influence of transmission losses on runoff volumes \(Q(x, w, c)\). Because the solutions of these equations can be expressed in the same form as the regression equations, least-squares analysis can be used to estimate parameters in the transmission loss equations.

Unit channel

The rate of change in volume, \(Q\) (as a function of arbitrary distance), with changing inflow volume, \(Q_{in}\), can be approximated as:

\[
\frac{dQ}{dx} = -c - kQ(x).
\]

(see also eq. A)

Substituting the initial condition and defining \(Q_{in}=Q(x=0)\), the solution of equation (3) is:
(4) \[ Q(x) = -\frac{c}{k} (1 - e^{-kx}) + Q_m e^{-kx}. \]

For a unit channel, equation (4) becomes:

(5) \[ Q = -\frac{c}{k} (1 - e^{-k}) + Q_m e^{-k}, \]

which corresponds to the regression equation:

(6) \[ Q = a + b Q_m. \] (see also eq. B)

Equating equations (5) and (6), it follows that:

(7) \[ b = e^{-k} \] (see also eq. I)

and

(8) \[ a = -\frac{c}{k} (1 - e^{-k}) = -\frac{c}{k} (1 - b) \]

are the linkage equations. Equation (8) can be solved for \( c \) as:

(9) \[ c = -k \frac{a}{1 - b}. \] (see also eq. F)

**Channel of arbitrary length and width**

For a channel of width \( w \) and length \( x \):

(10) \[ \frac{dQ}{dx} = -wc - wk Q(x, w), \]

where \( c = -k \frac{a}{1 - b} \), so that the differential equation is:

(11) \[ \frac{dQ}{dx} = wk \frac{a}{1 - b} - wk Q(x, w). \]

Defining \( Q_m \) as \( Q(x=0) \) and substituting this initial condition, the solution is:

(12) \[ Q(x, w) = \frac{a}{1 - b} (1 - e^{-kw}) + Q_m e^{-kw}. \]

From the linkage

(13) \[ b(x, w) = e^{-kw} \] (see also eq. E)

and

(14) \[ a(x, w) = \frac{a}{1 - b} (1 - b(x, w)) = \frac{a}{1 - b} (1 - e^{-kw}), \] (see also eq. D)

where \( a \) and \( b \) are unit channel parameters and \( k \) is the decay factor.
Estimating transmission losses when no observed data are available

So that parameters of the prediction equations could be related to hydrograph characteristics and to effective hydraulic conductivity, it was necessary to analyze selected data (see subchapter 3.1). These data were subjected to linear regression analysis to estimate the parameters \( a(x,w), b(x,w), Q_{in}(x,w) \) and \( k^x*w \).

Estimating transmission losses when observed inflow-outflow data are not available requires a technique for using effective hydraulic conductivity to develop parameters for the regression analysis.

Estimating effective hydraulic conductivity

The total volume of losses for a channel reach is \( KD \), where \( K \) is the effective hydraulic conductivity and \( D \) is the duration of flow. Also, the total losses are \( Q_{in}-Q(x,w) \), so that:

\[
KD = 0.0275(Q_{in} - Q(x,w)),
\]

where 0.0275 converts acre-feet per foot-mile-hour to inches per hour. Or, solving for \( K \),

\[
K = \frac{0.0275(Q_{in} - Q(x,w))}{D}.
\]

But

\[
Q_{in} - Q(x,w) = -a(x,w) + (1 - b(x,w))Q_{in},
\]

so that

\[
K = \frac{0.0275}{D} (-a(x,w) + (1 - b(x,w))Q_{in})
\]

is an expression for effective hydraulic conductivity. If mean values for \( D \) and \( Q_{in} \) are used, then equation (18) estimates the mean value of the effective hydraulic conductivity.

Effective hydraulic conductivity vs. model parameters

For a unit channel, outflow is the difference between inflow and transmission losses:

\[
Q = Q_{in} - KD.
\]

Because \( Q = a + bQ_{in} \),

\[
-a + (1 - b)Q_{in} = KD,
\]

But because \( a \) and \( (1-b)Q_{in} \) are in acre-feet and \( KD \), the product of conductivity and duration is in inches, the dimensionally correct equation is

\[
-a + (1 - b)Q_{in} = 0.0101KD,
\]

where 0.0101 converts inches over a unit channel to acre-feet. Because this equation is in two unknowns (\( a \) and \( b \)), an additional relationship, the total losses are partitioned between the two terms in the equation.

That is, let:

\[
a = -\alpha(0.0101KD)
\]

and
\[(1 - b) = (1 - \alpha)(0.0101 \frac{KD}{Q_{in}}).\]

Solving for \(b\),

\[b = 1 - (1 - \alpha)(0.0101 \frac{KD}{Q_{in}}),\]

where \(0 \leq \alpha \leq 1\) is a weighting factor. Solve for \(k\) by substituting \(b = e^{-k}\) and taking the negative natural log of both sides, i.e.,

\[k = -\ln(1 - (1 - \alpha)(0.0101 \frac{KD}{Q_{in}})).\]

The selected data were analyzed to determine \(\alpha\) by least-square fitting.

From this data analysis followed:

(19) \(a = -0.00465KD\) (see also G)

and

(20) \(k = -1.09 \ln(1 - 0.00545 \frac{KD}{Q_{in}})\), (see also H)

where for each channel reach, mean values were used for \(K, D,\) and \(Q_{in}\). These data, complemented by auxiliary data compiled in a report by Wilson et al. (1980), were used to calculate the values of \(K\) shown in the following table.

<table>
<thead>
<tr>
<th>Bed material group</th>
<th>Bed material characteristics</th>
<th>Effective hydraulic conductivity ((K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>very high loss rate, very clean gravel and large sand</td>
<td>&gt; 127 mm/h (&gt; 5 inch/h)</td>
</tr>
<tr>
<td>2</td>
<td>high loss rate, clean sand and gravel, field conditions</td>
<td>51-127 mm/h (2-5 inch/h)</td>
</tr>
<tr>
<td>3</td>
<td>moderately high loss rate, sand and gravel mixture with low silt-clay content</td>
<td>25-76 mm/h (1-3 inch/h)</td>
</tr>
<tr>
<td>4</td>
<td>moderate loss rate, sand and gravel mixture with high silt-clay content</td>
<td>6-25 mm/h (0.25-1 inch/h)</td>
</tr>
<tr>
<td>5</td>
<td>insignificant to low loss rate, consolidated bed material; high silt-clay content</td>
<td>0.025-2.5 mm/h (0.001-0.1 inch/h)</td>
</tr>
</tbody>
</table>

### 3.6 Integration of estimating procedure in WASA

As the WASA model does not give any detailed information about flow characteristics, physical features of the channel reach and valley as river channel geometry or discrete lateral inflow, besides the computed river discharge per day and sub basin \(Q_{in}\) (variable in WASA: \(qout\)), the application of the aforementioned estimating procedure will be illustrated for conditions without observed data, without lateral inflow and regular flow within the channel banks as discussed in subchapter 3.5.

Therefore procedures to generate or estimate necessary parameters for the application of the discussed transmission-
losses-estimating procedure will be illustrated in the following paragraph and integrated in an overview of the complete computation process.

The here presented steps are in strong relationship to the explanations in 3.2 and 3.5 which can serve for better orientation and further information.

The here mentioned estimating procedure will be integrated in the river network routing response function, calculating routing for each sub-basin of the examined area. For further information and comments on the applied procedures see also 3.7.

The first command of the transmission loss subroutine checks if there is any inflow $Q_{in}(q_{out})$ to the regarded sub-basin, in the regarded time step, and for daily calculation, from the upstream basin. In case of inflow, the mean channel width and length have to be estimated by using the following relationships:

Channel width: $\log w = \log Q_{in} * 0.494 + 1.031$ \textit{(after Leopold, 1994)}

Channel length (estimated as diameter of (circular) catchment area multiplied by sinuosity factor of meandering stream (=1.5)):

$$x = ((\text{area} / 3.147)^{0.5}) \times 1000 \times 1.5$$

Adjacent, these three parameters have to be transformed from metric into English units (acre-feet) for further computation.

As river network routing can only be computed in daily time steps and more detailed information cannot be derived, the duration of inflow $D(S)$ has to be set generally to 24 hours. Besides, as sets of inflow-outflow data are not available, an estimate of effective hydraulic conductivity is needed to predict transmission losses. Effective hydraulic conductivity, $K(K1)$, is the infiltration rate averaged over the total area wetted by the flow and over the total duration of flow.

$K$ can be derived from the relationship of bed material characteristics and effective hydraulic conductivity, formulated by Lane (1983). In a first attempt, the effective hydraulic conductivity is set to 1.0 inch per hour, which corresponds to a moderately high loss rate and sandy-gravely bed material characteristics (see also: 3.5 – Tab. 1, Lane, 1983).

With the generation of these parameters the calculation of transmission losses can be executed as described in 3.2 and 3.5.

First the regression intercept for unit channel $a(a1)$ in acre-feet, the regression slope $b(b1)$ for unit channel and the decay factor $k$ in (foot-miles)$^{-1}$ can be calculated using equation (G), (H) & (I).

For a given channel reach of the determined length $x$ and width $w$, the specific regression intercept $a(x,w)$ $(a2)$ and regression slope $b(x,w)$ $(b2)$ can be calculated using equation (D) & (E).
Finally, the transmission losses TL(x,w) \((tloss)\) and the corresponding outflow volume \((qout)\) at the outlet of the regarded sub-basin have to be determined using equation (B) or/and (C), where inflow, regression intercept and regression slope have to be considered; total transmission losses by evaporation and infiltration are summed up \((qloss)\) and negative outflow at the outlet as result of equation (B) has to be excluded by an adequate procedure.

As this estimating procedure is based on English units, the achieved final results of outflow volume and transmission losses have to be retransformed after all into metric units so that they can be used for further computation in the river network routing response function in the WASA model. The following tables (Tab. 2 & 3) give an overview of all conversions between English and metric units, and its corresponding conversion factors, carried out and of all variables with its units and its definitions, used in this subroutine.

### Tab. 2 Overview of conversion factors for British and metric units

<table>
<thead>
<tr>
<th>From (unit)</th>
<th>To (unit)</th>
<th>Conversion factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meter (m)</td>
<td>Feet</td>
<td>3.2808339</td>
</tr>
<tr>
<td>Meter</td>
<td>Miles</td>
<td>0.00062137</td>
</tr>
<tr>
<td>Cubic meter</td>
<td>Acre-feet</td>
<td>0.00080997</td>
</tr>
<tr>
<td>Millimeter</td>
<td>Inch</td>
<td>0.0394</td>
</tr>
<tr>
<td>Acre-feet</td>
<td>Cubic meter</td>
<td>1234.61451141</td>
</tr>
</tbody>
</table>

### Tab. 3 Overview of variables and definitions of the transmission loss-subroutine

#### Incoming variables

<table>
<thead>
<tr>
<th>name</th>
<th>units</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>qout</td>
<td>m/s</td>
<td>inflow from upstream sub basin</td>
</tr>
<tr>
<td>qloss</td>
<td>m³</td>
<td>total river channel losses in sub basin</td>
</tr>
</tbody>
</table>

#### Outgoing variables

<table>
<thead>
<tr>
<th>name</th>
<th>units</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>tloss</td>
<td>m³</td>
<td>transmission losses by infiltration in sub basin</td>
</tr>
<tr>
<td>qloss</td>
<td>m³</td>
<td>total river channel losses (including transmission losses by infiltration)</td>
</tr>
<tr>
<td>qout</td>
<td>m³/s</td>
<td>outflow at the outlet of the sub basin</td>
</tr>
</tbody>
</table>

#### Local variables and definitions

<table>
<thead>
<tr>
<th>name</th>
<th>units</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1</td>
<td>mm/h</td>
<td>effective hydraulic conductivity (see table!)</td>
</tr>
<tr>
<td>K2</td>
<td>(inch/h)</td>
<td>effective hydraulic conductivity</td>
</tr>
<tr>
<td>S</td>
<td>h</td>
<td>duration of inflow</td>
</tr>
<tr>
<td>w</td>
<td>m (feet)</td>
<td>average width of river channel in sub basin</td>
</tr>
<tr>
<td>x</td>
<td>m (miles)</td>
<td>average length of river stretch in sub basin</td>
</tr>
<tr>
<td>V</td>
<td>m³ (acre-feet)</td>
<td>inflow volume from upstream sub basin</td>
</tr>
<tr>
<td>a1</td>
<td>(acre-feet)</td>
<td>regression intercept for unit channel</td>
</tr>
<tr>
<td>a2</td>
<td>(acre-feet)</td>
<td>regression intercept for a channel reach of length x and width w</td>
</tr>
<tr>
<td>b1</td>
<td>none</td>
<td>regression slope for unit channel</td>
</tr>
<tr>
<td>b2</td>
<td>none</td>
<td>regression slope for a channel reach of length x and width w</td>
</tr>
<tr>
<td>k</td>
<td>(foot-miles)⁻¹</td>
<td>decay factor for unit channel</td>
</tr>
</tbody>
</table>
3.7 Subroutine: transmission losses by infiltration

c Declaration of variables for transmission losses by infiltration in rivers

c w: width of channel [feet]
c x: length of channel [miles]
c V: inflow from upstream sub basin

c a1: regression intercept for unit channel
c a2: regression intercept for channel of width w and length x

c b1: regression slope for unit channel
c b2: regression slope for channel of width w and length x

c k: decay factor for unit channel

c K2: effective hydraulic conductivity (converted to inch per hour)

    real  w, x, xx, V, a1, a2, b1, b2, k, K2, tloss

c S: flow duration [hours]
c K1: effective hydraulic conductivity [mm per hour]

    real  S, K1

...

c Transmission losses by infiltration in rivers

c (after LANE, 1983)

    if (ih .eq. 1) then
    c calculation only if discharge from upstream sub basin [m**3/s]

    c (otherwise transmission losses cannot occur!)

    if (qout(d+ih-1,upstream) .gt. 0.) then

    c first approach: effective hydraulic conductivity (K1) is set to

    c 21.4 mm/h (moderately high loss rate, see LANE)

    c & duration of inflow (S) is set to 24 hours

        K1=21.4
        S=24.0

    c length of river stretch (x) in sub basin estimated as diameter of

    c (circular) catchment area multiplied by

    c sinuosity factor of meandering stream (=1.5) [miles]

    c conversion: meter to miles / factor: 0.00062

        x=2.*(area(upstream)/3.147)**0.5*1000.*1.5*0.00062

    c river width (w) for given discharge (estimated according to global

    c relationship given by Leopold, 1994 (Fig 8.10) [m]

    c conversion: m to feet / factor: 3.281
\[ w = 10.0^{(\log_{10}(qout(d+ih-1,upstream)) \times 0.494 + 1.031)} \times 3.281 \]

- **Inflow volume** \( V \) from upstream sub basin [acre-feet]
- **Conversion:** m\(^3\)/s to acre-feet / factor: \((3600 \times S) \times 0.00081\)
  \[ V = qout(d+ih-1,upstream) \times 0.00081 \times (3600 \times S) \]

- **Effective hydraulic conductivity** [inch/hr]
  - **Conversion:** mm/hr to inch/hr / factor: 0.0394
  \[ K2 = 0.0394 \times K1 \]

- **Regression intercept for unit channel** (length: 1 mile / width: 1 foot) [acre-feet]
  - (see also: equation (G))
    \[ a1 = -0.00465 \times K2 \times S \]
    \[ xx = \left(1.0 - 0.00545 \times (K2 \times S / V)\right) \]
  - Calculation only if value of \( xx \) positive (\( \to \) log!)
    - if \( xx \geq 0.0 \) then

- **Decay factor for unit channel** [foot-miles**-1]
  - (see also: equation (H))
    \[ k = -1.09 \times \log(1.0 - 0.00545 \times (K2 \times S / V)) \]
  - Regression slope for unit channel
    \[ b1 = \exp(-k) \]
  - Regression slope for a channel reach of length \( x \) and width \( w \)
    - (see also: equation (E))
    \[ b2 = \exp(-k \times w \times x) \]
  - Regression intercept for a channel reach of length \( x \) and width \( w \) [acre-feet]
    - if \((1-b1)\) less than 0.01: \( a2 \) would move towards negative infinity
      - if \((1-b1) \geq 0.01\) then
        \[ a2 = (a1 / (1-b1)) \times (1-b2) \]
      - else
        \[ a2 = (a1 / 0.01) \times (1-b2) \]

- **Transmission losses in regarded sub basin** [m\(^3\)]
  - (see also: equation (C))
  - **Conversion:** acre-feet to m\(^3\) / factor: 1234.6
    \[ tloss = (V-(a2+b2 \times V)) \times 1234.6 \]
  - **Total amount of transmission losses (by infiltration and evaporation)** [m\(^3\)]
    \[ qloss(d,upstream) = qloss(d,upstream) + tloss \]

- **Discharge from regarded sub basin to downstream sub basin** [m\(^3\)/s]
  - (see also: equation (B))
4 Model Applications

4.1 Application methods, area and time-scale

Finally, the modified hydrological model WASA, extended by the already in detail described subroutine for additional transmission losses by infiltration, has been applied to the aforementioned semi-arid north-eastern part of Brazil, the Federal State of Ceará (see chapter 1).

This study focuses mainly on the results for runoff discharge and transmission losses of the whole state as a large spatial unit and on the other hand, of two particular sub basins along the Jaguaribe River: the Oros Reservoir and the estuary of the Jaguaribe River.

Therefore, as illustrated in figure 1a & 1b, showing the entire study area and the particular areas of interest, simulation results have been evaluated, considering all costal sub basins (yellow & red) which represent global discharge of the entire State of Ceará to the Atlantic Ocean, sub basin n°67 (red) which represents river discharge of the Jaguaribe River at the estuary and sub basin n°91 (blue) which represents river discharge at the Oros Reservoir.

The simulation of river discharge and transmission losses has been carried out for a period of 11 years (from 01.01.1980 to 31.12.1990) and for a number of 137 sub basins, representing the entire State of Ceará. Subroutines, representing reservoirs within the scope of the routing routine, were not considered and time resolution had to be limited to daily time steps.

The following analysis will give an overview of the achieved results by the application of the modified WASA-model and will analyze the influence of the integrated transmission loss-subroutine on river discharge. Therefore the simulation results will be compared with the original ones which were neglecting these additional losses when river flow occurs.
4.2 River runoff discharge and transmission losses

4.2.1 Yearly river discharge with and without transmission losses

In a first attempt, which serves as a reference simulation, besides the already mentioned limited time resolution, the effective hydraulic conductivity has been set to 21.5 mm/h (=1 inch/h) for the entire simulation area (see 3.6). Figure 2 shows the results of yearly river discharge which were achieved for the whole time period and simulation area, considering three cases of the river routing routine: without transmission at all (by infiltration & evaporation), without transmission losses by infiltration and its consideration as effected and described in this study. Figure 3 and 4 show analogous results at the estuary of the Jaguaribe River and at the Oros Reservoir.
4.2.2 Relative yearly reduction of river discharge by transmission losses

As figure 5 indicates, the consideration of transmission losses by infiltration, under the aforementioned conditions (as e.g. effective hydraulic conductivity of 21.5 mm/h), would lead to a reduction of yearly river volume discharge between around 29.5 and 51.0 percent, depending on the specific year and a mean loss rate of 40.8 percent for the entire State of Ceará.

The annual variability of relative river flow reduction is due to the different yearly amount of total river discharge. The implemented transmission loss routine reduces smaller volumes (e.g. 1983 – Ceará) of river discharge by a higher percentage than larger volumes (e.g. 1985 – Ceará).
Fig. 5 Relative yearly reduction [%] of river discharge by transmission losses

4.2.3 Monthly river discharge with and without transmission losses

Figure 6, 7 & 8 illustrate monthly river volume discharge with and without considering transmission losses by infiltration for the same areas as above and assuming similar conditions, but only for the year of 1985.

Fig. 6 Monthly river discharge [m$^3$] with and without transmission losses (Federal State of Ceará)

Fig. 7 Monthly river discharge [m$^3$] with and without transmission losses (Estuary of Jaguaribe River)
4.2.4 Relative monthly reduction of river discharge by transmission losses

The comparison of the simulated river discharge with transmission losses and discharge without transmission losses shows in figure 9, that the monthly losses vary between around 24.9 and 99.5 percent at the State of Ceará and even up to 100 percent in some years at the estuary and at the regarded reservoir of Jaguaribe River. In particular when river discharge volume is low (as from June to November), transmission losses are considerably high; on the other hand for high discharge volume (from February to May), transmission losses are correspondingly low.

4.2.5 Relative share of transmission losses by evaporation

Under these conditions the share of transmission losses by evaporation would be for the whole simulation area and at every time-step between only 1.9 and 3.9 percent (and up to 5.4 percent at the reservoir) of the total transmission losses, as shows figure 10.
In summary, the consideration of transmission losses by infiltration on the basis of the mentioned reference simulation leads generally to a decrease of river discharge and rising total transmission losses at every (yearly and monthly) timescale and for all in this study regarded areas. Further analyses of the simulation results and the corresponding transmission loss-subroutine indicate that small values of river discharge were reduced by a higher percentage than large volumes of river discharge. Under the aforementioned conditions, the share of transmission losses by infiltration is considerably higher than that of transmission losses by evaporation.

4.3 Sensitivity analysis

In the following, several model applications are carried out to evaluate the sensitivity of the transmission loss-subroutine, or generally spoken of the modified WASA model, to several parameters, as there are effective hydraulic conductivity and river channel length and width, on results of river volume discharge. The first attempt of model application and its parameter settings serve again as reference simulation (see 4.2) and basis for several sensitivity analyses. However, this reference is not based on any field observation or calibration, but the parameter settings are based on available physical information (as e.g. bed material characteristics) and arbitrary definitions which should be further evaluated. In comparison to the reference simulation, for each analyzed parameter two simulations with an increased and a decreased parameter value have been effected.

4.3.1 Model sensitivity to effective hydraulic conductivity

First, the model sensitivity to effective hydraulic conductivity K has been examined for a yearly and monthly timescale; therefore simulations of river discharge volume were realized using three different values of conductivity. Besides the reference simulation with an effective hydraulic conductivity of 21.4 mm/h, corresponding to a “moderately high loss rate” and bed material consisting of “sand and gravel mixture with low silt-clay content” (see 3.5/Tab.1), further simulations changing the value of conductivity by the factor 0.1 and 10.0 were effected. Therefore the lower value would correspond to an “insignificant to low loss rate” and bed material consisting of “consolidated bed material and/or high silt-clay content”, and the higher value correspond to conditions which
represent a “very high loss rate” and “very clean gravel and large sand” as bed material.

4.3.1.1 Yearly river discharge for different values of conductivity

The following three figures (11, 12 & 13) illustrate the achieved results of simulated yearly river discharge, considering transmission losses by infiltration, for the already described areas (State of Ceará, Jaguaribe River, Oros Reservoir) and period of time (1980 to 1990).

**Fig. 11** Yearly river discharge [m$^3$] for different values of conductivity (Federal State of Ceará)

**Fig. 12** Yearly river discharge [m$^3$] for different values of conductivity (Estuary of Jaguaribe River)

**Fig. 13** Yearly river discharge [m$^3$] for different values of conductivity (Oros Reservoir)
4.3.1.2 Relative yearly reduction of river discharge by transmission losses for different values of conductivity

For each simulation of discharge volume, the relative losses of river discharge compared to a model run without considering transmission losses has been evaluated and is presented in figure 14, 15 & 16.

As it can be observed, compared to the reference simulation with a medium value of effective hydraulic conductivity (21.4 mm/h) and transmission losses of 40.8 percent on average, the simulation, changing the value of conductivity by the factor 10.0, achieves considerable high average losses of 91.4 percent (Ceará) of the total amount of river discharge for each of the three simulations carried out.

Correspondingly low (6.9 percent at State of Ceará) are transmission losses, when decreasing the value of effective hydraulic conductivity by the factor 0.1.

This model analysis illustrates the high sensitivity of the transmission loss-subroutine on simulation results of river discharge volume, when changing the internal parameter of effective hydraulic conductivity $K$.

**Fig. 14** Relative yearly reduction [%] of river discharge by transmission losses for different values of conductivity (Federal State of Ceará)

**Fig. 15** Relative yearly reduction [%] of river discharge by transmission losses for different values of conductivity (Estuary of Jaguaribe River)
4.3.1.3 Relative yearly reduction of river discharge by transmission losses for a higher value of conductivity

Figure 17 & 18 show results of the same sensitivity analysis, but compare the simulated transmission losses, assuming a higher effective hydraulic conductivity (figure 17) and a lower effective hydraulic conductivity (figure 18) of aforementioned values, to the transmission losses of the reference simulation. As figure 17 indicates, an increase of the value of effective hydraulic conductivity by the factor 10.0 leads to an increase of transmission losses between about 81.2 and 95.5 percent (average value of 86.1 percent) compared to the reference simulation for the entire State of Ceará. The exceptionally high losses at the Oros Reservoir (average losses of 99.1 percent) are caused by continuous small river discharge volumes which are more consequently eliminated by the transmission loss-subroutine of the WASA-model.

4.3.1.4 Relative yearly rise of river discharge by transmission losses for a lower value of conductivity

Correspondingly, for a reduction of the value of effective hydraulic conductivity by the factor 0.1, transmission losses decrease and a significant increase of river discharge compared to the reference simulation can be observed.
As illustrated in figure 18, the relative rise of river discharge amounts to an average value of 62.0 percent and a range from 36.3 to 148.4 percent at the State of Ceará, and at the estuary or at the reservoir even up to 232.2 (average value of 100.6 percent) or 189.5 percent (average value of 88.9 percent), when the specific original river discharge is particularly low (as in 1983 and 1990!).

![Fig. 18 Relative yearly rise [%] of river discharge by transmission losses for a lower value of conductivity](image)

**Fig. 18** Relative yearly rise [%] of river discharge by transmission losses for a lower value of conductivity

### 4.3.1.5 Monthly river discharge for different values of conductivity

The following figures 19, 20 & 21 illustrate the achieved results of the same sensitivity analysis and of the same areas (State of Ceará, Jaguaribe River, Oros Reservoir), but at a monthly timescale and only for the year of 1985.

The simulated monthly river discharge differs correspondingly to the changes in value of effective hydraulic conductivity as already described for the yearly timescale.

![Fig.19 Monthly river discharge [m³] for different values of conductivity (Federal State of Ceará)](image)

**Fig.19** Monthly river discharge [m³] for different values of conductivity (Federal State of Ceará)
4.3.1.6 Relative monthly reduction of river discharge by transmission losses for different values of conductivity

These simulation results of monthly river discharge can be further analyzed, regarding the achieved transmission losses in comparison to the original river discharge without any transmission losses by infiltration to determine the relative monthly losses for different values of effective hydraulic conductivity.

Figure 22, 23 & 24 confirm the results of the corresponding analysis at a yearly timescale, as the simulated transmission losses for different values of effective hydraulic conductivity and monthly resolution are in the same range of value as for yearly resolution (see figure 14, 15 & 16). Besides, the monthly values of transmission losses prove the already mentioned tendency of the transmission loss-subroutine to reduce river discharge by a higher percentage when the absolute discharge volume is particularly low.
In summary, the analysis of model sensitivity to effective hydraulic conductivity shows a high sensitivity of conductivity on river discharge.

At the yearly and monthly timescale, compared to the reference simulation, an increase in effective hydraulic
conductivity leads to a considerable decrease of river discharge and corresponding rise of total transmission losses, a
decrease in conductivity raises correspondingly the value of river discharge and reduces the amount of transmission
losses.
Especially when river discharge is particularly low, the transmission loss routine shows high sensitivity to changes
of conductivity, as the modification of effective hydraulic conductivity leads to considerably high changes of
discharge volume.
In general, the relative changes of river discharge caused by transmission losses are considerably higher, when the
original discharge volume is of lower value. Consequently, small river discharge volumes are easily eliminated by
the transmission loss routine.
Further, when increasing or decreasing the value of effective hydraulic conductivity (as done in this study by the
factor 10.0), the range of transmission loss values and the influence of river discharge volume on the amount of
transmission losses decline, compared to the reference simulation (see Fig. 13, 14 & 15), and leads to a more
homogenous transmission loss generation at a yearly timescale.

4.3.2 Model sensitivity to river width/length
A second model sensitivity analysis examines the influence of changes in width and length of the regarded river
channel on simulated results of river discharge.
The first mentioned model simulation and its original parameter settings serve again as a reference simulation for
the here effected further sensitivity analysis.
As river width and length influence the simulated river discharge volume to the same extent (see sub chapter 3.7:
length x and with w are factors of the product, forming the exponent of an operation to compute the slope of the
effected regression analysis \[b2=\text{e}^{k \cdot w \cdot x}\]), the following illustrations are valid for a change in value of river width as
well as for the same change in value of river length. Within the scope of the sensitivity analysis of the transmission
loss-subroutine, the value of river width/length has been changed by 20 percent.

4.3.2.1 Yearly river discharge for different values of river width/length
The following figures 25, 26 & 27 illustrate the changes of simulated yearly river discharge for the same case
studies as above (State of Ceará, Jaguaribe River, Oros Reservoir), when river width/length increases and/or
decreases by a value of 20 percent. The observed results of yearly resolution indicate a weaker sensitivity of the
transmission loss-subroutine to changes in river width/length as the values of river discharge volume do not change
evermously.
4.3.2.2 Relative yearly reduction of river discharge by transmission losses for different values of river width/length

The fact of smaller changes in river discharge can be confirmed by the illustrations of figure 28, 29 & 30, showing the results of relative yearly transmission losses for a simulation with a by 20 percent higher and lower value of river width/length, which vary in a range of mainly around 10 to 15 percent.
4.3.2.3 Monthly river discharge for different values of river width/length

The following figures 31, 32 & 33 illustrate the achieved results of the same sensitivity analysis and the same areas (State of Ceará, Jaguaribe River, Oros Reservoir), but at a monthly timescale and only for the year of 1985.
The simulated monthly river discharge differs correspondingly to the changes in value of river width/length as already described before. As previously observed for yearly discharge, compared to the reference simulation without changes in river width/length, the results of monthly river discharge show again only weak variation.

**Fig.31** Monthly river discharge [m$^3$] for different values of river width/length (Federal State of Ceará)

**Fig.32** Monthly river discharge [m$^3$] for different values of river width/length (Estuary of Jaguaribe River)

**Fig.33** Monthly river discharge [m$^3$] for different values of river width/length (Oros Reservoir)
4.3.2.4 Relative monthly reduction of river discharge by transmission losses for different values of river width/length

The fact of smaller changes in river discharge can be confirmed again by the illustrations of figure 34, 35 & 36, showing the results of relative monthly transmission losses for a simulation with a by 20 percent higher and lower value of river width/length, which vary in a range of mainly around 10 to 15 percent.

Fig.34 Relative monthly reduction [%] of river discharge by transmission losses for different values of river width/length (Federal State of Ceará)

Fig.35 Relative monthly reduction [%] of river discharge by transmission losses for different values of river width/length (Estuary of Jaguaribe River)
4.3.2.5 Relative yearly change of river discharge by transmission losses for a lower value of river width/length

Finally the simulation results of yearly river discharge, assuming a lower river width/length (figure 37) and a higher river width/length (figure 38), are compared to transmission losses of the reference simulation.

As figure 37 indicates, a decrease of the value of river width/length by 20 percent leads to a mean increase of river discharge in the State of Ceará of about 9.4 percent and correspondingly to a decrease of transmission losses. Its value varies between 6.0 and 14.9 percent. At the estuary of Jaguaribe River (12.1 percent) and at the Oros Reservoir (11.4 percent) the mean annual rise of discharge, caused by a decrease of river width/length, is even higher.

The annual and spatial variation of relative changes of river discharge is due to different annual and regional discharge volumes. As already mentioned in section 4.3.1 for effective hydraulic conductivity, river width/length is also more sensitive when discharge volumes are of small values. Therefore, higher changes of river discharge by decreasing river width/length are achieved, when total discharge volume is particular low (e.g. 1983) and only small flow reductions occur, when total discharge is correspondingly high (e.g. 1985).
4.3.2.6 Relative yearly change of river discharge by transmission losses for a higher value of river width/length

In contrast, the rise of river width/length by 20 percent produces higher transmission losses as river water can infiltrate into the river bed over a longer distance or larger hydraulic cross-section. The simulation of the case study for the entire State of Ceará computes a mean decrease of river discharge from 1980 to 1990 of 8.1 percent.
At the estuary a shorter river width/length leads to a mean increase of discharge of 12.1 percent, at the Oros Reservoir the same reduction reduces discharge by a mean value of 11.4 percent.
The annual variability of the relative changes of river discharge by transmission losses is again caused by different spatial and temporal discharge volumes, which influence loss rates as described before.

![Graph showing relative yearly change of river discharge by transmission losses for a higher value of river width/length.]

In summary, the sensitivity analysis, examining the influence of river width/length on river discharge volume, illustrates lower model sensitivity to river channel geometry than to conductivity. At monthly and yearly timescale, river discharge changes by a lower percentage, when channel geometry (width/length) varies.
The rise of river width/length increases the amount of transmission losses and leads to a decline of mean river discharge, because the infiltration surface of the river rises. Correspondingly, a lower value of river width/length reduces transmission losses, caused by a decrease of infiltration surface, and increases the amount of river discharge.
As, within the scope of the transmission loss-subroutine, a direct link between effective hydraulic conductivity and river width/length exists (see subchapter 3.7), the sensitivity of river width/length on river discharge is also highly dependent on original discharge volumes. Correspondingly to effective hydraulic conductivity, a variation of river width/length changes river discharge by a higher percentage, when original discharge is of low quantity and by a smaller value, when original discharge is of high quantity.
5 Conclusions and Perspectives

5.1 General Discussion and Conclusions

5.1.1 Approach – Modelling concept
In this study, a first attempt to consider transmission losses by infiltration within the scope of the hydrological model WASA has been undertaken and a corresponding transmission loss subroutine could be implemented into the already existing river routing routine.

It has to be taken in consideration that the discussed approach had to be implemented at a large regional scale, but that it could not base on empirically data or field observation concerning infiltration losses in the Ceará region and that only little information about physical features has been available.

5.1.2 Factors of model uncertainty
Therefore the transmission loss subroutine had to be mainly based on general information about simulated incoming discharge volume, expected bed material and river channel geometry to enable the implemented subroutine to compute transmission losses at the scale of sub basins.

At this transmission loss approach, further simplifying assumptions had to be made, as no corresponding information could be derived.

The duration of river flow, when river discharge occurs, had to be generally set to 24 hours, as a higher than daily resolution could not be generated by the model. Further, necessary information about river channel geometry could not be derived directly, but had to be generated, using a global relationship (after Leopold) which bases on river discharge volume to generate a corresponding value of river width for each sub basin, and an equation which estimates river length, using information about the diameter of the regarded sub basin area.

Besides, the effective hydraulic conductivity had to be set to a medium value for the entire simulation area, without considering spatial heterogeneities and without having further empirical information about river bed material and characteristics.

Further, in the here presented approach, neither supplementary potential alluvium storage capacities, which could considerable reduce river discharge in plain areas, nor the complete lack of any storage volume in some areas, which would lead to higher run off volume, have been considered, but had to be represented by a mean threshold volume for each occurring river discharge volume, representing a initial loss rate at the beginning of each river run off.

5.1.3 Results and reliability of simulation
Despite this simplifying assumptions, which were made within the scope of the implementation of the transmission loss routine, some reliable results could be achieved, which show at least a consistent tendency for simulated processes of the formulated subroutine.

As discussed in chapter 4, the application of the transmission loss subroutine shows at every time scale a considerable additional reduction of river discharge volume by infiltrating transmission losses. It eliminates in particular small run off volumes which occurred up to now in every simulation but which could not be confirmed by field observation and measurements.
At the same time, the implementation of the transmission loss subroutine reduces the share of transmission losses by evaporation along river channels to a realistic value of around 5 percent of the total amount of transmission losses under reference conditions.

Nevertheless, the mean reduction of river discharge within the scope of the mentioned reference simulations achieves results, which are considerably too high and do not correspond to site-specific run-off characteristics. To explain this fact, several assumptions and parameters implemented in the actual version of the transmission loss subroutine could be questioned.

First, the parameter of effective hydraulic conductivity has been generally set to a mean value, representing mean bed material and infiltration characteristics. But nor this parameter setting considers spatial heterogeneities of bed material, neither it shows any linkage to soil characteristics as the saturated conductivity of bordering soils in the regarded study area of Ceará.

The spatial availability (or no-availability) of alluvium storage volume and its dynamic behaviour is an additional factor which is influencing the generation of transmission losses, but it is not sufficiently represented in the actual version of the transmission loss subroutine. As in large parts of the study area such storage volume do not occur because the soil layer is correspondingly thin, the assumption of a constant threshold at the beginning of river run off and a following steady-state loss rate can not be maintained anymore. These circumstances could partly explain the too high results of simulated river discharge.

Further, as already mentioned, the global assumption to derive channel geometry can not be screened on their influence on river discharge and transmission losses, but it can be supposed, that its generated values are quite uncertain.

Still, it has to be taken in consideration, when regarding the sensitivity analysis, which has been effected within the scope of this study, that the influence of effective hydraulic conductivity, compared to channel geometry, is of higher importance, concerning the generation of river discharge and transmission losses and should therefore be optimized first.

5.2 Perspectives

5.2.1 Adjustment of model to specific characteristics

As discussed in subchapter 5.1, the simulated results of river discharge and transmission losses show a consistent tendency but seem to be of too high values, combined with high uncertainty of several subroutine parameters and simplifying model assumptions.

The comparison of the effective hydraulic conductivity, used at the reference simulation, and the saturated conductivity of alluvium soils in the State of Ceará indicates that the conductivity of corresponding soils is more than one dimension higher than the parameter setting for the effective hydraulic conductivity of river bed material in the modelling approach. Even if soil and effective hydraulic conductivity can not be compared directly, it can be assumed that the mean value of effective hydraulic conductivity (set to 21.4 mm/h at the reference simulation), supposing mean infiltration conditions, could be even set to a higher value, representing mean conditions. But as higher effective hydraulic conductivity would lead to even higher values of the already overestimated river discharge, other limiting factors should be taken in consideration to optimize the simulated river discharge and
transmission losses.

As mentioned before, in a further modelling attempt, in particular the available or limited capacity of storage alluvium should be considered, assuming that the spatial lack of such storage volumes would lead to a linear river discharge response without any transmission losses.

The integration of a corresponding storage model with spatial and temporal resolution could replace the existing assumption of an initial threshold volume and lead to changes in river discharge and transmission losses with higher spatial resolution.

In particular, the dynamic behaviour of such alluvium storage volume should be taken in consideration, as dry (empty) alluvium could first serve as storage volume and reduce river discharge considerably, and after its fill-up it would lead to an increase of transmission losses and linear river discharge, as long as water persist in the storage alluvium.

Therefore, the existing transmission loss subroutine would have to be connected to existing soil data, as it is already used in the WASA-model (soil.dat) and further information about storage dynamics would have to be derived.

Finally, the simulated values of river channel geometry are highly questionable as they are based on global relationships using discharge volumes and sub basin diameters to generate information about river channel geometry. Although, the influence of river geometry (width and length) is of lower importance within the scope of river discharge and transmission loss simulation, as presented in this study; in a further attempt, this information should be derived directly form measurements or adequate maps. Especially, the high variability of river width in the here presented subroutine should be replaced by a more consistent procedure which limits the variation and improves correspondingly the achieved results.

Nevertheless it has to be considered, that the simulation of transmission losses at a large regional scale has always to apply simplifying assumptions and can not consider all occurring heterogeneities of each model parameter, but has to be reduced to the most important factors which allow achieving consistent simulation results for the entire study area that represent medium values of transmission losses.
6 References

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