

Dear Referees, dear Editor,

We would like to thank you for your feedback and final suggestions of improvement for our work. All the propositions of modifications presented hereafter, and based on the Referee #3 comments, will be added to the precedent version of our manuscript.

C1: The description of the HydroBudget area is still too vague. I could not rebuild the model with a scripting language if I wanted to from the description and the schematic figure alone. So, I urge the authors to also include (can be done in an appendix) the equations behind every reservoir's states and fluxes, particularly how the fluxes depend on the states. These may be time-explicit difference equations if these are being used, but they should be in to understand what is going on.

A1: We would like to thank the Referee for pointing out that the HydroBudget description needed to be more precise. As suggested, we will include the equations in Appendix A.1, as shown at the end of this document (these equations are also found in the HydroBudget User Guide – Dubois et al., 2021).

L137-144 will be rephrased into: “HydroBudget (HB) is a spatially-distributed GWR model that computes a superficial water budget on grid cells of regional-scale watersheds with outputs aggregated into monthly time steps. The model uses commonly available meteorological data (daily precipitation and temperature, spatialized if possible) and spatially-distributed data (pedology, land cover, and slopes). It is based on simplified process representations and is driven by eight parameters that need to be calibrated. These parameters are uniform over the grid and held constant through time (**Erreur ! Source du renvoi introuvable.**). Coded in R, HB uses a conceptual lumped reservoir to compute the soil water budget on a daily time step (Appendix A.1). For each grid cell and each time step, precipitation is divided between runoff (R), evapotranspiration (ET), and infiltration that could reach the saturated zone (potential GWR), with a monthly time step (Erreur ! Source du renvoi introuvable.; Dubois et al., 2021).”

C2: I assume that if the authors state (line 141) that “these parameters are held “constant” for all grids” they mean that they are “uniform” over the grid (the same value everywhere)? Please restate!

A2: We agree that this sentence was not clear. It was rephrased L141-142 in the modified paragraph presented in A1: “These parameters are uniform over the grid and held constant through time (Table 2).”

As well, it appears as a footnote in Table 2.

C3: It is not clear how the cell-specific land properties “pedology, land cover and slopes” come in to make it a distributed model. Are these properties only used in the CN method to calculate the discharge proportion? This would also become much clearer if we can see the equations and the equations denote which parameters are uniform and which location-dependent. Also, is the maximum storage capacity of the soil dependent on pedology or uniform across the grid as well?

A3: We understand that the information about HydroBudget parameters was not precise enough and we thank the Referee for pointing it out. The Referee is correct, the spatialized pedology, land cover, and slopes are only used in the RCN computation. We followed the Referee's suggestion and highlighted the calibration parameters that are uniform over the grid and held constant in time in the new Appendix A1, and these include the sw_m parameter (maximum storage capacity).

To clarify this point, L149-150 have been rephrased as follows: "Runoff is calculated using the runoff curve number (RCN) method (USDA-NRCS, 2004; 2007) on a cell-by-cell basis (two parameters, t_{API} and f_{runoff}), similar to what is done in the SWAT model (Arnold et al., 2012; Neitsch et al., 2002). The RCN is attributed per cell based on its pedology, land cover, and slope following the USDA-NRCS method adapted for the Quebec environment (Dubois et al., 2021; Monfet, 1979)."

C4: *The calibration strategy is still not clear. Do you calibrate a separate set of parameters (8 in total) per sub-catchment (grouped discharge stations) or identify single sets for the entire catchments using a weighted criterion from sub-criteria of the different grouped stations? An equation of the criterion could help clarify this.*

A4: We think that it is a very good idea to be more precise about the calibration strategy, by adding more information about the equations of the objective functions and the regionalized parameters. We thank the Referee for suggesting it. To do so, L178-204 have been modified as follows:

"The model was simultaneously calibrated for all the gauging stations using the automatic calibration procedure of the R package *caRamel* (Monteil et al., 2020) to obtain a regionalized set of parameters. Up to 5 000 model calls were used, with several successive optimizations to confirm the reproducibility of the results, as recommended by Monteil et al. (2020). Model performance was assessed using the Kling–Gupta Efficiency (KGE) calculated with total monthly measured and simulated total flow ($KGE_{q_{tot}}$), as well as monthly baseflow and monthly potential GWR ($KGE_{q_{base}}$). The KGE is preferred here over the Nash–Sutcliff Efficiency because it better represents the low flow periods (Gupta et al., 2009). Each river flow time series was divided into a calibration period (first two thirds) and a validation period (last third), therefore allowing the objective functions to be computed per period.

The *caRamel* algorithm (Monteil et al., 2020), a combination of the multi-objective evolutionary annealing simplex algorithm (MEAS; Efstratiadis and Koutsoyiannis, 2008) and the non-dominated sorting genetic algorithm II (ϵ -NSGA-II; Reed and Deviredy, 2004), automatically calibrated the eight HB parameters to maximize $KGE_{q_{tot}}$ and $KGE_{q_{base}}$ values. The algorithm produces an ensemble of parameter sets (called *generation*) to run the model, downscales the generation to the parameter sets that optimize the objective functions, and creates a new set of parameters that produces better results. To produce new generations and ensure that the optimization tends toward a global maximum, the algorithm samples the parameter sets that individually maximizes the two objective functions, $KGE_{q_{tot}}$ and $KGE_{q_{base}}$, samples the parameter sets that maximizes the minimum values of the two objective functions, and increases the variance of each parameter

The eight HB parameters were optimized for each gauging station, grouped by river watershed to save computational time (from 51 individual optimizations to eight grouped optimizations producing eight set of calibrated parameters) such as:

$$(KGE_{qtot})_{ws} = \frac{1}{N_{ws}} \sum_{station=1}^{N_{ws}} (KGE_{qtot})_{station} \quad (1)$$

$$(KGE_{qbase})_{ws} = \frac{1}{N_{ws}} \sum_{station=1}^{N_{ws}} (KGE_{qbase})_{station} \quad (2)$$

With:

$(KGE_{qtot})_{ws}$ the KGE_{qtot} obtained over a river watershed (group of gauging stations)

$(KGE_{qtot})_{station}$ the KGE_{qtot} obtained for a gauging station

N_{ws} the number of gauging stations per watershed

$(KGE_{qbase})_{ws}$ the KGE_{qbase} obtained over a river watershed (group of gauging stations)

$(KGE_{qbase})_{station}$ the KGE_{qbase} obtained for a gauging station

Finally, the set of parameters that allowed reaching the best compromise was chosen by identifying the highest mean KGE value (KGE_{mean}):

$$KGE_{mean} = 0.4 \times (KGE_{qtot})_{ws} + 0.6 \times (KGE_{qbase})_{ws} \quad (3)$$

The weights attributed to each objective function in KGE_{mean} were arbitrarily chosen to select the calibrated parameter set that maximizes the reproduction quality of the baseflows, considered to be the proxy for GWR (KGE_{qbase}), without losing the benefits of the multi-objective optimization (Supplementary **Erreur ! Source du renvoi introuvable.**).

The eight sets of eight calibration parameters were regionalized (uniform calibration parameters over the grid), using the normalized density of stations per group (number of stations per km²) as weights. The grid-wise uniform calibration parameters used for the simulation were obtained:

$$x_{regionalized} = \frac{\sum_{ws=1}^8 \frac{N_{ws}}{area_{ws}} \times x_{ws}}{\sum_{ws=1}^8 \frac{N_{ws}}{area_{ws}}} \quad (4)$$

With:

$x_{regionalized}$ one of the eight calibration parameters regionalized

x_{ws} one of the eight calibration parameters optimized for the gauging stations of a river watershed

$area_{ws}$ the area of the watershed (km²)

Finally, the 100 best compromises of each group of gauging stations were used to produce the 100 best regionalized parameter sets and the HB model was run with these parameters, estimating uncertainty from the standard deviation.”

C5: It is not clear how the calibrated parameters are “averaged” or “regionalized” and downscaled. What is the use of that if all grids get the same parameter values? Or is it downscaling in time? Please extent on this and use equations if this is possible.

A5: We understand the Referee’s concern, and we believe that the modified L178-204 presented in our previous answer resolves that question.

C6: If the code of HydroBudget is open source, then I would urge the authors to place it somewhere where it can be downloaded directly, such as on GitHub.

A6: We agree with the Referee that the code needs to be available for direct download. It will be deposited on a Dataverse linked to UQAM (<https://dataverse.scholarsportal.info/dataverse/sp?q=>). The code will be available to download with an application example on the smallest river watershed of our study area and an updated version of the User Guide.

The precise Internet address and the DOI of the documents will be available soon and the information will be added in the section 8 Code availability of the next version of the paper.

Appendix A.1: Equations used in the HydroBudget model (adapted from Dubois et al., 2021 – the eight calibration parameters, uniform over the grid and constant through time, are identified with bold characters)

Degree-days snowmelt model

Determining if the temperatures generates snowfall

$$\text{If } T_t \leq 0 \quad \text{Then } snowfall_t = P_{TOTt} \quad (\text{A.1.1})$$

$$\text{Else } snowfall_t = 0 \quad (\text{A.1.2})$$

Determining if the temperature generates snowmelt, calculating snowmelt and VI.

$$\text{If } T_t \leq T_M \quad \text{Then } snowpack_t = snowpack_{t-1} + snowfall_t \quad (\text{A.1.3})$$

$$\text{Else } snowmelt_t = C_M \times (T_t - T_M) \times snowpack_{t-1} \quad (\text{A.1.4})$$

$$\text{And } snowpack_t = snowpack_{t-1} - snowmelt_t \quad (\text{A.1.5})$$

$$\text{If } T_t > 0 \quad \text{Then } VI_t = P_{TOTt} + snowmelt_t \quad (\text{A.1.6})$$

$$\text{Else } VI_t = snowmelt_t \quad (\text{A.1.7})$$

With:

t = the current daily time step

snowpack_{t-1} = the snowpack in snow water equivalent at the previous time step (mm)

T_t = the air temperature (°C)

snowfall_t = the snowfall in snow water equivalent (mm)

snowmelt_t = the liquid water produced by snowmelt (mm)

P_{TOTt} = the total precipitation (mm)

C_M = the melting coefficient (mm.°C⁻¹.d⁻¹)

T_M = the melting temperature (°C)

VI_t = vertical inflow (mm)

snowpack_t = the snowpack in snow water equivalent (mm)

Runoff Computation

Computing the antecedent soil conditions

$$API_t = \sum_{t=t-t_{API}}^t VI_t \quad (A.1.8)$$

Computing the values of RCN for dry and humid soil conditions based on equations from Monfet (1979)

$$RCN_{dry} = 0.00865 \times f_{runoff} \times RCN^2 + 0.0145 \times f_{runoff} \times RCN + 7.39846 \quad (A.1.9)$$

$$RCN_{wet} = -0.00563 \times f_{runoff} \times RCN^2 + 1.45535 \times f_{runoff} \times RCN + 10.82878 \quad (A.1.10)$$

Adjusting the RCN value based on the antecedent soil conditions

If $July\ 1^{st} \leq t < September\ 1^{st}$

$$\begin{aligned} &\text{If } API_t < 50 \\ &\quad \text{Then } RCN_t = RCN_{dry} \end{aligned} \quad (A.1.11)$$

$$\begin{aligned} &\text{If } API_t > 80 \\ &\quad \text{Then } RCN_t = RCN_{wet} \end{aligned} \quad (A.1.12)$$

$$\text{Else } RCN_t = f_{runoff} \times RCN \quad (A.1.13)$$

If $June\ 1^{st} \leq t < July\ 1^{st}$ or $September\ 1^{st} \leq t < October\ 10^{th}$

$$\begin{aligned} &\text{If } API_t < 18.5 \\ &\quad \text{Then } RCN_t = RCN_{dry} \end{aligned} \quad (A.1.14)$$

$$\begin{aligned} &\text{If } API_t > 37 \\ &\quad \text{Then } RCN_t = RCN_{wet} \end{aligned} \quad (A.1.15)$$

$$\text{Else } RCN_t = f_{runoff} \times RCN \quad (A.1.16)$$

If $October\ 10^{th} \leq t < June\ 1^{st}$

$$\begin{aligned} &\text{If } API_t < 11 \\ &\quad \text{Then } RCN_t = RCN_{dry} \end{aligned} \quad (A.1.17)$$

$$\begin{aligned} &\text{If } API_t > 22 \\ &\quad \text{Then } RCN_t = RCN_{wet} \end{aligned} \quad (A.1.18)$$

$$\text{Else } RCN_t = f_{runoff} \times RCN \quad (A.1.19)$$

Computing runoff (with condition on the soil frost)

$$\text{If } \frac{1}{F_T} \sum_{t=t-F_T}^t T_t > TT_F$$

$$\text{Then } R_t = \frac{[VI_t - 0.2 \times (1000/RCN_t - 10)]^2}{VI_t - 0.8 \times (1000/RCN_t - 10)} \quad (A.1.20)$$

$$\text{Else } R_t = VI_t \quad (A.1.21)$$

With:

API_t = the antecedent precipitation index (mm)

t_{API} = the antecedent precipitation index time (d)

RCN = the computed value of runoff curve number for the considered pixel (-)

f_{runoff} = runoff factor (-)

RCN_{dry} = the corrected value of runoff curve number for dry soil conditions (for the Quebec environment) (-)

RCN_{wet} = the corrected value of runoff curve number for humid soil conditions (for the Quebec environment) (-)

RCN_t = the considered value of runoff curve number for the time step (-)

F_T = the freezing time (d)

TT_F = the threshold temperature for soil frost (°C)

R_t = runoff (mm)

Lumped soil reservoir

Computing infiltration as runoff excess

$$Inf_t = VI_t - R_t \quad (A.1.22)$$

Computing saturation excess

$$\text{If } (sw_m - sw'_{t-1}) \geq Inf_t \quad (A.1.23)$$

$$\text{Then } Excess R_t = 0$$

$$\text{Else } Excess R_t = Inf - (sw_m - sw'_{t-1}) \quad (A.1.24)$$

$$Total R_t = R_t + Excess R_t \quad (A.1.25)$$

Computing the AET based on the soil water content

$$\text{If } sw_{t-1}' + Inf_t - Excess R_t \geq PET_t \quad (A.1.26)$$

$$\text{Then } AET_t = PET_t$$

$$sw_t = sw_{t-1}' + Inf_t - Excess R_t - AET_t \quad (A.1.27)$$

$$\text{Else } AET_t = sw_t + Inf_t - Excess R_t \quad (A.1.28)$$

$$sw_t = 0 \quad (A.1.29)$$

Computing the potential GWR based on the soil water content after the AET computation

If $sw_t > 0$

$$\text{Then } GWR_t = sw_t \times f_{inf} \quad (A.1.30)$$

$$sw_t' = sw_t - GWR_t \quad (A.1.31)$$

$$\text{Else } GWR_t = 0 \quad (A.1.32)$$

$$sw_t' = 0 \quad (A.1.33)$$

With:

Inf_t = infiltration to the soil reservoir (mm)

sw_m = maximum soil water content in the soil reservoir (mm)

sw_{t-1}' = soil water content at the end of the previous time step (mm)

Excess R_t = saturation excess produced by the soil reservoir (mm)

Total R_t = total runoff (mm)

PET_t = potential evapotranspiration (mm)

AET_t = actual evapotranspiration (mm)

sw_t = soil water content after the AET computation (mm)

GWR_t = potential GWR (mm)

f_{inf} = infiltration factor (d^{-1})

sw_t' = soil water content after the AET and GWR computation (mm)

Model output per grid cell

$$R_m = \sum_{t=1}^n Total R_t \quad (A.1.34)$$

$$AET_m = \sum_{t=1}^n AET_t \quad (A.1.35)$$

$$GWR_m = \sum_{t=1}^n GWR_t \quad (A.1.36)$$

With:

R_m = simulated monthly total runoff (mm)

n = number of days in the considered month

AET_m = simulated monthly AET (mm)

GWR_m = simulated monthly potential GWR (mm)