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HMETS—A Simple and Efficient Hydrology Model for Teaching Hydrological Modelling, Flow Forecasting and Climate Change Impacts*

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Hydrological models are commonly used to forecast streamflow and for climate change impact studies. There is a wide range of hydrology models using lumped conceptual approaches all the way to more physically based distributed algorithms. Most of these models come with a steep learning curve before they can be used efficiently by the end user, and they can be tricky to calibrate appropriately. Only a small number of hydrology models can be considered easy to set up and use, and even fewer provide their source code for easy modification to be tailored to individual needs. These drawbacks make it difficult to use these models in educational applications. The goal of this paper is to introduce a very simple, yet efficient, lumped-conceptual hydrological model designed to address the above problems. The MATLAB-based HMETS hydrological model is simple and can be easily and quickly set up on a new watershed, including automatic calibration using state of the art optimization algorithms. Despite its simplicity, the model has proved to perform well against two other lumped-conceptual hydrological models over 320 watersheds. HMETS obtained a median Nash-Sutcliffe Efficiency of 0.72 in validation, compared to 0.64 for MOHYSE (similar structure) and 0.77 for HSAMI (more complex structure). The model's source code is freely available and includes an optional simplified user interface. A climate change impacts simulation tool using the constant scaling downscaling method is also incorporated to the interface. HMETS has been tested in the Construction Engineering Final-Year Project for a group of 60 undergraduate students.

Keywords: teaching hydrological modelling; rainfall-runoff model; lumped model; conceptual model; climate change impact studies

1. Introduction

Rainfall-runoff models have been widely used to predict streamflow for a long time and are used in many applications like streamflow forecasting, agriculture, risk management, flood control and reservoir operations. With the easy access to computers, a broad variety of hydrological models with varying degrees of complexity were developed over the past 40 years and used all over the world [1]. However, there are drawbacks to the use of many of these models, especially in an education context. The first problem is that the source code of most models has not been made available to the public, thus limiting the ability to tweak the model to local particularities. Another problem is that most models can be complicated to use, even if their structure is relatively simple. It may take months and even years to master the most complex models. Unfortunately, this is a serious drawback for educational applications. For instance, more complex models such as HEC-HMS, while free, are not easily adjustable, whereas other such as HBV [2] requires coding capabilities that not all students possess.

The main goal of the proposed model is to provide students, engineers, researchers, and water resources systems operators with a tool that provides good modelling performance in a very simple open-source package that can easily be mastered and modified. To reach this goal, it should be possible for an experienced hydrologist to set up and calibrate the model over a new watershed in half a day or less. Students, if correctly guided, can be up and running within a day as our experiment (detailed in Section 5) showed. The equations simulating the water cycle main processes have to be simplified enough so the user can understand the model structure with minimal effort. Despite the

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simple structure, the model also needs to provide good streamflow simulation. For streamflow prediction at watershed outlets, lumped models have been shown to be just as good as their more complex distributed counterparts in several inter-comparison studies [3, 4]. Accordingly, a lumped conceptual modelling approach was used to develop HMETS. HMETS was given a graphical interface to guide the users throughout the model setup and automatic calibration process. With the ever-increasing need to perform climate change impact studies [5–7] a routine serving this purpose was developed in the code and interface.

HMETS has also been tested among a group of 60 undergraduate students in their Construction Engineering Final-Year Projects (FYP). The goal of this paper is to show that HMETS has achieved its previously described goals and that it is ready to be used to teach hydrological modelling to civil engineering students.

2. Material and methods

The Hydrological Model of École de technologie supérieure (HMETS) is a lumped-conceptual model using two connected reservoirs for the vadose and saturated zones. The model simulates the basic hydrological processes of evapotranspiration, infiltration, snow accumulation, melting and refreezing processes as well as the flow routing to the watershed outlet as illustrated in Fig. 1.

2.1 Input data

HMETS only requires precipitation (liquid and solid) as well as minimum and maximum temperatures, all at the daily time step. Precipitation and temperature data must be averaged at the watershed scale. Daily observed streamflow must also be provided for model calibration.

2.2 Model parameters

HMETS has up to 21 parameters that can be optimized during calibration, which is detailed in Table 1. Several of these parameters can be fixed if a more parsimonious, less sensitive to equifinality model is needed.

2.3 Snow accumulation and snowmelt model

The snowmelt model is based on the work of Vehviläinen [8]. It is a degree-day model that allows for melting and refreezing process within the snowpack. Ten parameters are used to describe the snowmelt and snow accumulation processes. The model works in three steps: the overnight

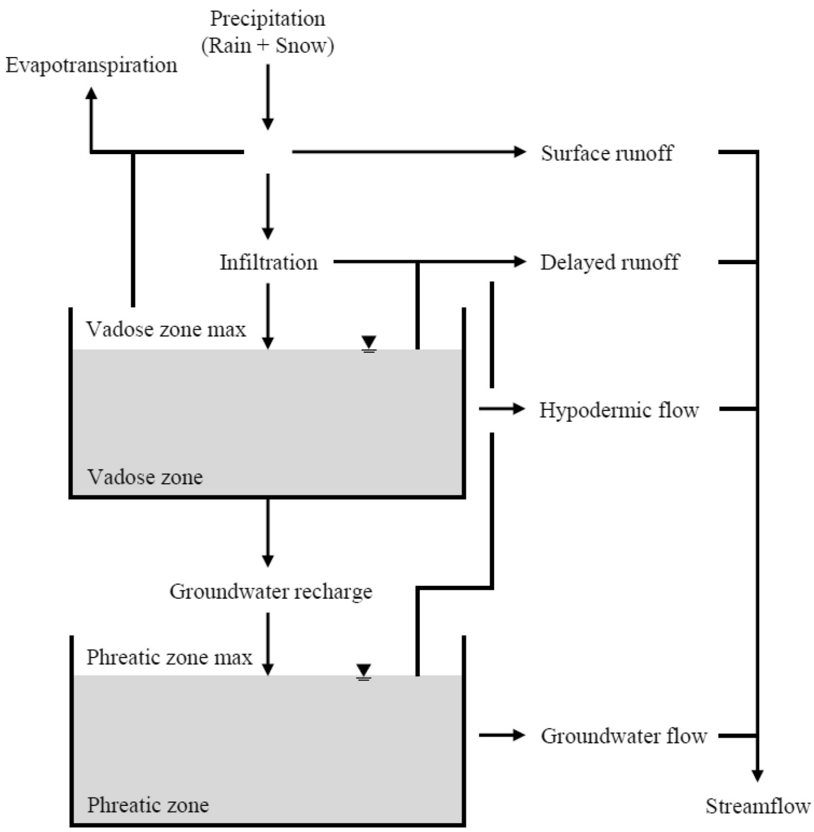

Fig. 1. HMETS representation of hydrological processes.

Table 1. List of the HMETS model's 21 parameters

Snowmelt model parameters (10 parameters):
ddf_{min} : Minimum degree-day-factor in mm/°C/day
ddf_{plus} : Maximum degree-day-factor in mm/°C/day (ddf_{min} + ddf_{plus} = ddf_{max})
T_{bm} : Base melting temperature in °C
K_{cum} : Empirical parameter for the calculation of the degree-day-factor in mm^{-1}
fc_{min} : Minimum fraction for the snowpack water retention capacity
fc_{plus} : Maximum fraction of the snowpack water retention capacity (fc_{min} + fc_{plus} = fc_{max})
C_{cum} : Parameter for the calculation of water retention capacity in mm^{-1}
T_{bf} : Base refreezing temperature in °C
K_f : Degree-day factor for refreezing in mm/°C/day
Fe : Empirical exponent for the freezing equation

Real evapotranspiration (1 parameter):
ET_{eff} : Fraction of the potential evapotranspiration

Subsurface (6 parameters):
c_r : Fraction of the water for surface and delayed runoff
c_{vp} : Fraction of the water for groundwater recharge
c_v : Fraction of the water for hypodermic flow
c_p : Fraction of the water for groundwater flow
LV_{max} : Maximum level of the vadose zone in mm
LP_{max} : Maximum level of the phreatic zone in mm

Unit hydrograph parameters (4 parameters):
α_1: Shape parameter α for the gamma distribution used on the surface unit hydrograph
β_1: Rate parameter β for the gamma distribution used on the surface unit hydrograph
α_2: Shape parameter α for the gamma distribution used on the delayed unit hydrograph
β_2: Rate parameter β for the gamma distribution used on the delayed unit hydrograph

refreezing process, snowmelt and snowpack water retention capacity.

The overnight refreezing process is based on three parameters: K_f, T_{bf} and Fe. Freezing of liquid water in the snowpack will only be effective if the mean diurnal temperature T_{dt} (equation (1)) is below the freezing temperature threshold T_{bf}. In this case, the potential amount of overnight refreezing (POR) is given by the equation (2). The actual amount of refreezing cannot exceed the amount of liquid water present in the snowpack.

$$T_{dt} = (T_{mean\ t} + T_{min\ t})/2 \tag{1}$$

$$POR_t = K_f(T_{bf} - T_{dt})^{Fe} \tag{2}$$

For the snowmelt, the model uses a variable degree day factor that depends on cumulative snowmelt (CSM). This is done to simulate the impact of the aging of the snowpack and its drop in surface albedo. The actual degree day factor ddf will vary between a minimum value ddf_{min} all the way to a maximal potential value ddf_{max} as a function of cumulative snowmelt. This is computed as:

$$ddf_t = ddf_{min} \cdot (1 + K_{cum} \cdot CSM_t) \tag{3}$$

The state variable CSM is the cumulative amount of snowmelt in mm. The potential daily snowmelt (PSM) is then calculated as follows:

$$PSM_t = \max(0, ddf_t \cdot (T_{mean\ t} - T_{bm})) \tag{4}$$

Snowmelt will only occur if the mean temperature is above ddf.

The snowpack water retention capacity varies from a maximum to a minimum as a function of the snowpack aging represented by cumulative snowmelt. The water retention fraction (WRF) is calculated as follows:

$$WRF_t = \max(fc_{min}, fc_{max} \cdot (1 - C_{cum} \cdot CSM_t)) \tag{5}$$

The water in the snowpack is supplied from snowmelt and liquid precipitation. If the amount of water in the snowpack is higher than the water retention of the snowpack, the remaining is added to the water available for runoff (WAR).

2.4 Potential and real evapotranspiration

The routine that calculates potential evapotranspiration follows the work of Oudin et al. [9]. From their analysis, they suggested the following formulation:

$$\begin{aligned} &\text{if}(T+5) > 0,\ PET = \frac{Rad}{\lambda\rho} \cdot \frac{(T+5)}{100} \\ &\text{otherwise},\quad PET = 0 \end{aligned} \tag{6}$$

Where PET is the potential evapotranspiration in mm/day, Rad is the extraterrestrial radiation in MJ/m^2/day, λ is the latent heat flux (equal to 2.26 MJ/kg) and ρ is the average water density (1000 kg/m^3). To get the averaged potential evapotranspiration, the temperature (T) is entered as the daily mean temperature.

The extraterrestrial radiation depends only on the day and latitude. It makes use of the routines from the Woods Hole Science Center [10] "Air_Sea" toolbox.

The real evapotranspiration (RET) is then computed as a function of potential evapotranspiration (PET) using a single free parameter:

$$RET_t = ET_{eff} \cdot PET_t \tag{7}$$

Water returning to the atmosphere as evapotranspiration is taken from the vadose zone if there is not enough water from the runoff component.

2.5 Vertical water balance

The vertical water balance takes into consideration all the exchanges made between the surface, vadose and saturated zones.

First, a fraction of the water available for runoff (c_r) will be directed to surface runoff ($H_{t,1}$) depending on the vadose zone reservoir water level (LV_t):

$$H_{t,1} = c_r \cdot \left(\frac{LV_{t-1}}{LV_{max}}\right) \cdot WAR_t \tag{8}$$

The amount of water that will infiltrate the vadose zone reservoir (I) depends of the remaining water available for runoff once the real evapotranspiration has been computed and taken out:

$$I_t = WAR_t - H_{t,1} - RET_t \tag{9}$$

If there is not enough water available for runoff, the remainder of the real evapotranspiration is taken from the vadose zone and there is no infiltration for this given time step. Evapotranspiration from the vadose is limited by the amount of water present in the reservoir. A portion of the infiltration which depends on the vadose reservoir level is sent to the delayed runoff component ($H_{t,2}$). The vadose zone also provides the water for the hypodermic flow component ($H_{t,3}$). Finally, there will be some exchange from the vadose zone to the saturated zone (GR_t). These processes are calculated as follows:

$$H_{t,2} = c_r \cdot I_t \left(\frac{LV_{t-1}}{LV_{max}}\right)^2 \tag{10}$$

$$H_{t,3} = c_v \cdot LV_{t-1} \tag{11}$$

$$GR_t = c_{vp} \cdot LV_{t-1} \tag{12}$$

Subsequently, the water level in the vadose zone is updated following equation (13). If the vadose zone reservoir fills up, the overflow will be added to the delayed runoff component as shown in equation (14).

$$LV_t = LV_{t-1} + I_t - RET_t - H_{t,2} - H_{t,3} - GR_t \tag{13}$$

$$H_{t,2} = H_{t,2} + LV_t - LV_{max} \tag{14}$$

The saturated zone is represented by a linear reservoir releasing groundwater flow ($H_{t,4}$). Mass balance for the linear reservoir is computed with equations (15) to (17). If the reservoir level exceeds its maximum, the exceeding part is also sent to the delayed runoff component.

$$H_{t,4} = c_p \cdot LP_{t-1} \tag{15}$$

$$LP_t = LP_{t-1} + q_t - H_{t,4} \tag{16}$$

$$H_{t,2} = H_{t,2} + LP_t - LP_{max} \tag{17}$$

2.6 Horizontal transport

Outlet streamflow is calculated based on the four components of the horizontal transfer. For surface and delayed runoff, two unit hydrographs (UH) are used to transfer water at the outlet. The unit hydrograph shapes are based on a two-parameter gamma distribution density function (*gampdf*) with shape parameter α and rate parameter β with x in days.

$$gampdf = \frac{\beta^\alpha}{\Gamma(\alpha)} \cdot x^{\alpha-1} \cdot \exp^{-\beta x} \tag{18}$$

Both unit hydrographs are then computed and converted to m^3/s/mm as follows:

$$UH = gampdf \cdot 0.001 \cdot A \cdot 100000/(3600 \cdot 24) \tag{19}$$

Where A is the watershed area in km^2. The streamflow for the surface runoff ($H_{t,1}$) and the delayed runoff ($H_{t,2}$) are then computed using their respective unit hydrograph following:

$$Q_t = \sum_{i=1}^{n} UH_i \cdot H_{t-i+1} \tag{20}$$

Where n is the length (in days) of the unit hydrograph. The hypodermic flow ($H_{t,3}$) and the base flow ($H_{t,4}$), components are converted from mm to m^3/s:

$$Q_t = H_t \cdot 0.001 \cdot A \cdot 100000/(3600 \cdot 24) \tag{21}$$

Finally, modelled streamflow is computed by summing up all four horizontal flow components together:

$$Q_{m,t} = \sum_{i=1}^{4} Q_{t,i} \tag{22}$$

3. HMETS source code and graphical user interface

The entire HMETS MATLAB main file uses a mere 150 lines of code. Mastering the model is relatively easy, as is any modification to its main components (e.g. switching the snowmelt model). There are additional files for pre-processing inputs, calibration and post-processing outputs, but all of the hydrological components fit within the main file. Inputs to the model are provided via a Microsoft Excel spreadsheet available with the model. There are three main functions to the interface: (1) calibration and validation of a watershed, (2) simulation of streamflow using a chosen parameter set and (3) climate change simulation. A user's guide is available to help the user throughout the process.

3.1 Calibration and validation

Automatic calibration of the model parameters can be made using one of the two optimization methods available through the source code or within the interface. The choice of optimization algorithm was based on the work of Arsenault et al. [11]. In their study of 10 different optimization methods, the Dynamically dimensioned search (DDS) algorithm [12] was among the very best for HMETS, while providing the fastest convergence time. The Shuffled Complex Evolution—University of Arizona (SCE-UA) [13] was also added because this method has been a widely-used method in hydrological model calibration over the past 20 years. Default parameters and number of evaluations for all methods are pre-established, but can easily be modified if necessary.

Five different objective functions are available: the Nash-Sutcliffe efficiency criteria (NSE) [14], the normalized root-mean-square-error (NRMSE), the natural logarithm of the NSE, the natural logarithm of the NRMSE and the bias. Additional objective functions can easily be added to the code.

The interface offers the traditional split-sample calibration/validation method. Various graphs representing streamflow, meteorological data and internal variables (e.g.: evapotranspiration and snow cover) can easily be plotted. Fig. 2 shows typical graphs from the interface.

3.2 Simulation of streamflow

A simulation of streamflow can be performed on a given watershed by using any existing parameter set, either obtained through calibration or based on user experience. Students can use this feature to perform sensitivity analyses of the parameters and determine which ones generate the most uncertainty. This proved to be a valuable tool during the Construction Engineering final-year project as discussed in section 5.

3.3 Climate change tool

A climate change impact study module is also provided with the code. It is based on the simple constant scaling downscaling method [15], also called the "delta change" method. It is a simple method that only requires monthly perturbation values (ΔT and $\Delta P/P$) between the future and reference period climates. Perturbation values are easily obtained from climate model outputs and data centers. This method has been used in dozens of studies [6, 16, 17].

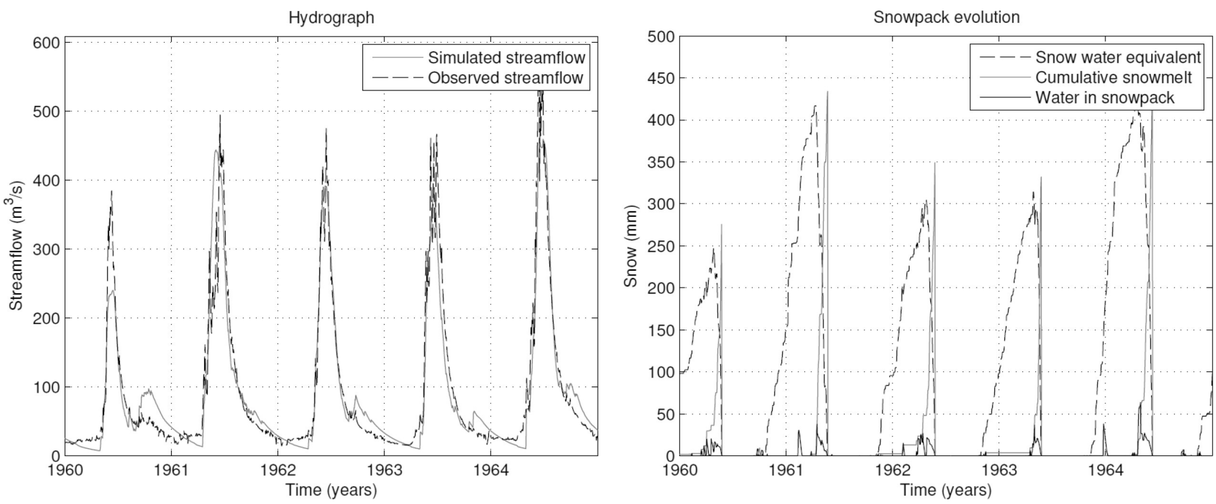

Fig. 2. Typical graphs provided by the graphical interface.

4. Evaluation of HMETS performance

Before handing the model to students, the HMETS model's performance was compared against that of two other lumped-conceptual hydrological models of different complexities with all having the ability to simulate the evolution of a snow cover. The two models are MOHYSE and HSAMI.

MOHYSE is a ten-parameter model that was developed [18] for teaching hydrological modelling to earth systems science graduate students. HSAMI is a 23-parameter model which has been used for nearly 30 years by Hydro-Québec for the daily forecasting of streamflow over 100 Quebec watersheds. Since HSAMI is Hydro-Québec's key inflow forecasting model, its performance has been thoroughly evaluated against that of much more complex and distributed models, and was consistently found to be the top performer on average. More details about the model and its use in climate change impact studies can be found in a number of studies [6, 7, 9, 19, 20].

In order to quantify their relative performance, all three models were calibrated 30 times on 320 watersheds of the Model Parameters Estimation Experiment (MOPEX) database [21]. These watersheds cover many climate zones over most of the continental United States. The models were calibrated using the Nash-Sutcliffe efficiency (NSE) on the first 10-year period and validated on the following 10 years. The DDS optimization method with 10 000 model evaluations was used to perform the calibration of all models. The NSE is calculated with the equation (23) where Q_o is the observed streamflow and Q_m the modelled streamflow.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \bar{Q}_o)^2} \tag{23}$$

The NSE criteria can range from $-\infty$ to 1 with 1 being a perfect match between both the observed and simulated streamflow, with 0 corresponding to an estimator as good as the mean of observed data. Results obtained with the NSE in calibration and validation are shown in Table 2.

In order to find out which lumped model performs the best, a two-way layout Friedman nonparametric test was computed. This test allowed determining if the differences between the hydrological models performance are statistically significant or not.

Figure 3 presents the results of the inter-comparison study. On the left-hand side panels of Fig. 3, a comparison of the NSE performance of each hydrological model over the calibration and validation periods is presented using the median of the 30 calibrations. In other words, a single NSE value (the median) was used for each of the 320 watersheds to construct the box plots. The results obtained with a multiple comparison test are shown on the right-hand side panels. The distribution of HMETS performance is illustrated with the dashed line (95% confidence level). The difference in the NSE scores between models is not statistically significant when the confidence intervals overlap. In this case, the difference in performance is significant for all models.

Results suggest that HMETS performance was significantly better than MOHYSE, despite being very comparable in terms of complexity, or lack of. Also, the median value of NSE of the 320 watersheds was 0.72 for HMETS over the validation period and 0.64 for MOHYSE. Hydro-Quebec's HSAMI model performed better than HMETS with a median value of NSE in validation of 0.77. This is not surprising since it is a much more complex model with a long history of improvements. Altogether, the inter-comparison study showed that HMETS performs significantly better than a model of similar complexity, while getting 93% of the performance of a much more complex model that has been used operationally for nearly 30 years.

It is important to restate that HMETS does not aim to be the best model, but to be the easiest to learn to use, to apply and to learn from on study cases for engineering students. It is not expected that HMETS will replace any operational model but it could provide a very good option for a preliminary design when quick results are needed or to test the impact of changing algorithms within a hydrological model. For example, different snowmelt modules could easily be implemented within HMETS, something that would be quite difficult to do with most models. Also, HMETS could easily be added

Table 2. Results of the NSE for the calibration period and validation period on the 320 selected watersheds of the MOPEX database.

Calibration			
	HMETS	**HSAMI**	**MOHYSE**
Median	0.78	0.82	0.67
Mean	0.74	0.80	0.66
Variance	0.03	0.01	0.01
% < 0.7	23.13%	9.69%	61.88%
% < 0.5	3.13%	0.32%	8.75%
Validation			
	HMETS	**HSAMI**	**MOHYSE**
Median	0.72	0.76	0.64
Mean	0.71	0.75	0.63
Variance	0.01	0.01	0.01
% < 0.7	42.81%	23.75%	75.00%
% < 0.5	3.44%	0.32%	13.75%

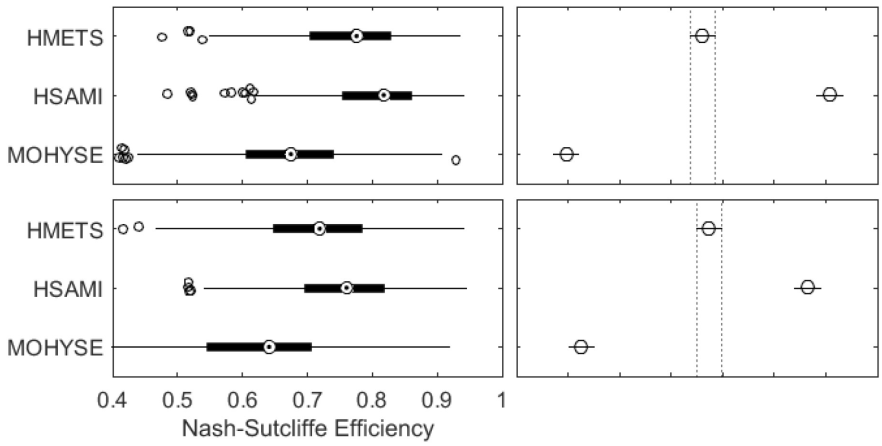

Fig. 3. Box plots (left) and multiple comparison test (right) on the NSE median values for the calibration period (top) and validation period (bottom) on 320 selected watersheds of the MOPEX database. To facilitate comprehension, the abscissa values of the multiple comparison tests were removed because they represent NSE score ranks and provide no useful information. The test results that the intermodal differences in efficiency are all statistically significant.

to a multi-model ensemble streamflow prediction system (ESP) with minimal work. Keeping the above in mind, HMETS is the result of aiming for an optimal performance to complexity ratio in hydrological modelling while maintaining the simplest graphical interface possible.

5. Application during the final-year project in construction engineering

The HMETS model was used in the final-year project (FYP) of a group of undergraduate students in Construction Engineering at the École de technologie supérieure (ETS) in Montreal (Canada). This section describes the context in which HMETS was used as an instrumental tool in developing modelling expertise and capabilities for future engineers.

5.1 General description and objectives of the final-year project

Since the year 2010, FYPs in Construction Engineering at ETS are team projects that integrate multiple fields of engineering and simulate the engineer's future practice. Each FYP extends over an entire semester and is coordinated and supervised by a group of professors who define the project. Participating students are grouped into teams, each of which has to include one "specialist" per field that is covered by the FYP. Every team acts as a contracting firm and professors may alternately act as technical supervisors ("bosses") or clients.

In the fall 2014 semester, a group of 60 undergraduate students took part in a design-build project that involved planning and designing the demolition of an existing road bridge crossing the Des Anglais River (in Quebec, Canada) and the construction of a new bridge. The project also included the construction of approach fills, the reconstruction and rehabilitation of adjacent roadways and their connection to existing roadways. The entire planning and design processes had to comply with applicable standards and state of the art. Five different fields of construction engineering were involved in that project: hydraulics and hydrology, bridge structure engineering, project management, road engineering as well as geotechnical and foundation engineering. Participating students were therefore grouped into 12 teams of 5 members (one expert per field in each team).

5.2 Hydraulics and hydrology in the final-year project and the use of HMETS

The drainage area of the river basin under study at the construction site is greater than 25 square kilometers and the road supported by the bridge is a national class road. Therefore, according to Transports Québec [22] a 50-year return period flood discharge had to be taken into account in the bridge design process. The project description that was provided to the students included an additional constraint that they had to fulfill: a three meters minimum height had to be left between the water level reached by the design flood and the bridge superstructure, for river ice jam considerations. As specified in Transports Québec [23], the bridge design process also had to take into account the flood potential from the river obstruction (number of piers, pier dimensions). Twelve (12) students (one per team) worked on this part of the FYP.

Three main objectives were pursued through the students' work:

- Conceive the solution approach to ultimately obtain the design water level: identify the required data; define the entire chain of engineering tools (which include standards, guides, and computerized tools, for instance) to be used.
- Cope with the use of a new engineering tool (in the present case the HMETS hydrological model), as they will most likely be faced with this type of challenge in their careers as engineers.
- Acknowledge the different sources of uncertainty involved in the computation of the design water level.

The data that were initially provided to the students were a 21-year daily streamflow time series for the Des Anglais river basin at the bridge construction site (1978–1998), as well as 44 years of daily precipitation and minimum and maximum temperature data (1968–2010) (spatial average over the entire river basin).

The solution approach that allows the computation of the design water level is shown in Fig. 4. The left chain identifies the engineering tools while the right chain is the modelling chain (models, input data and output data). Once the students had reached the point where they needed to select a hydrological model, HMETS was recommended.

5.3 Hydrological modelling with HMETS

The HMETS model was used in this FYP to extend the maximum annual discharge time series from 21 to 44 years through simulation and hence obtain a larger sample of values before proceeding to the frequency analysis step (Fig. 4). The river basin characteristics that are required to run HMETS are the area of the basin and the coordinates of its centroid. This information was not initially provided to the students so they either had to generate it/find it or come to their technical supervisor to obtain it. The study basin area is 658 square kilometers, and the latitude and longitude of its centroid are respectively 45.08°N and 73.72°W. As shown in Fig. 4, the HMETS model was first calibrated using the available hydrometric and meteorological observations for the 1978–1998 time period. At this point, the hydraulics and hydrology specialists had to question themselves as to how they should proceed: (1) use a classical type of approach and split the available data into a calibration period and a validation period, or (2) use the entire period to calibrate the model and let it "learn" from the longest available data. They all opted for the second alternative considering that a single value per year (the maximum annual discharge) is then extracted from the simulation step before going to the frequency analysis step (Fig. 4). Among the objective functions available in HMETS, the NSE option was generally selected by the students since it assigns greater weight to the higher streamflow values (which include the maximum annual stream-

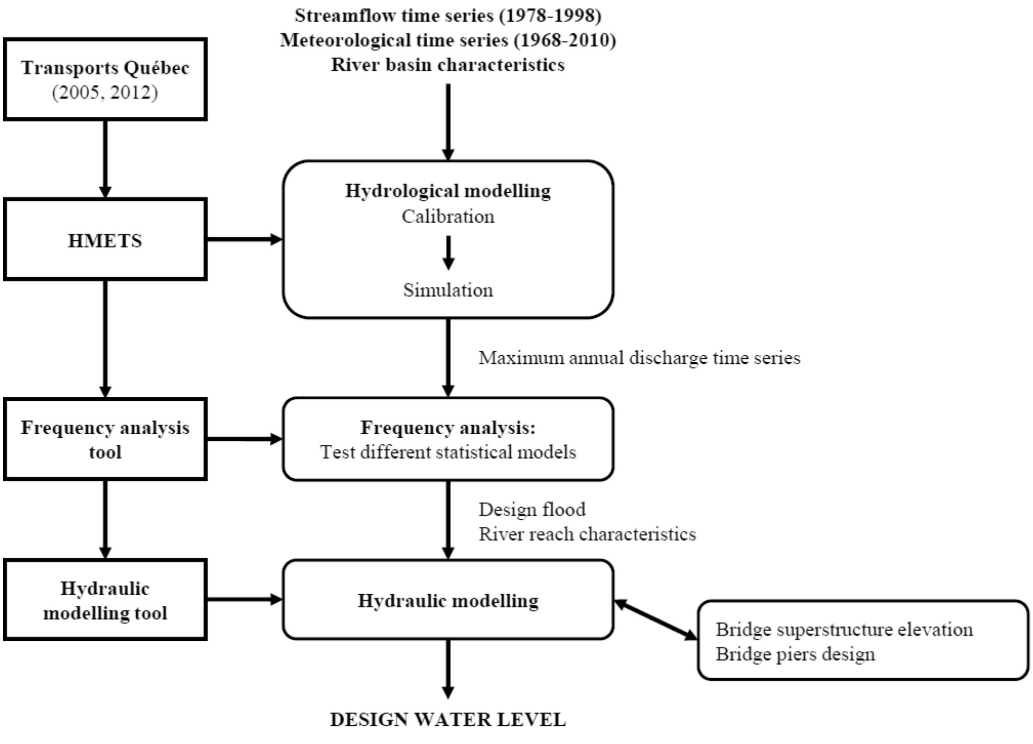

Fig. 4. Solution approach for the computation of the design water level. Left chain: engineering tools. Right chain: modelling process. Input/output data are indicated at the beginning and end, and in between the steps of the modelling chain. For the hydraulic modelling step, an interaction with bridge engineering was required.

flow). Most of teams (8/12) naturally ran multiple calibrations and realized this modified the hydrological modelling results, and acknowledged the impact of the different calibrations on the differences between the observed and simulated streamflow. Following the calibration, it was expected from the students to provide a thorough discussion on their methodology and the results obtained before performing the frequency analysis.

The students were thus able to learn the basics of the model, apply a calibration algorithm to minimize an objective function and extract the necessary data. However, one of the strongest points of the HMETS model is that it also allowed students to go beyond the scope of the project. For example, some groups attempted to determine the impacts of climate change for given greenhouse gas emissions scenarios and then estimate the impacts on the water levels. It served as a powerful lesson to always use all available information. Students had the preconceived notion that climate change would pose a greater risk to their bridge. However, they found that the higher temperatures would delay the snow accumulation and jump-start the melt, effectively lowering the peak floods for this particular watershed. Uncertainty analyses at each step allow defining a confidence interval around the final design, which was the main goal behind the HMETS model.

6. Conclusion

While there is a large number of hydrological models available to the scientific and user community, there is lack of simple yet efficient open-source models. HMETS aims at filling this gap with a simple model structure that is easy to master and modify. HMETS is a simple, yet efficient and versatile hydrological model for teaching civil engineering students.

In an inter-comparison study, HMETS performed significantly better than MOHYSE, another lumped-conceptual model, despite a similar level of complexity. A median NSE value over 320 watersheds of 0.72 over the validation period was obtained for HMETS compared to 0.64 for MOHYSE. It did not quite perform to the level of HSAMI (median NSE value of 0.77), the most complex model used in this study, but its performance was close (93%) despite a much simpler structure.

By providing its source code, it is hoped that HMETS may be useful to academic applications, the water resources community and that it evolves to better fit specific needs of end users. HMETS demonstrated its potential by having been used successfully in a Construction Engineering FYP by a group of 60 undergraduate students. Finally, a distributed version of the model, having the same goal of simplicity, is currently under development.

Website URL

The HMETS source code, graphical interface and user-guide can be found on the MathWorks website under the User Community/File Exchange tab and then searching for HMETS.

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References

1. V. P. Singh and D. A. Woolhiser, Mathematical modeling of watershed Hydrology, *Journal of Hydrologic Engineering*, **7**(4), 2002, pp. 270–292.
2. A. Aghakouchak and E. Habib, Application of a Conceptual Hydrologic Model in Teaching Hydrologic Processes, *International Journal of Engineering Education*, **26**(4), 2010, pp. 963–973.
3. M. B. Smith, V. Koren, Z. Zhang, Y. Zhang, S. M. Reed, Z. Cui and E. Anderson, Results of the DMIP 2 Oklahoma experiments, *Journal of Hydrology*, 418–419, 2012, pp. 17–48.
4. S. Reed, V. Koren, M. Smith, Z. Zhang, F. Moreda, D.-J. Seo and DMIP Participants, Overall distributed model intercomparison project results, *Journal of Hydrology*, **298**(1–4), 2004, pp. 27–60.
5. M. A. Boucher and R. Leconte, Changements climatiques et production hydroélectrique canadienne: où en sommes-nous? *Canadian Water Resources Journal*, **38**(3), 2013, pp. 196–209.
6. M. Minville, F. Brissette and R. Leconte, Uncertainty of the impact of climate change on the hydrology of a nordic watershed, *Journal of Hydrology*, **358**(1), 2008, pp. 70–83.
7. A. Mareuil, R. Leconte, F. Brissette and M. Minville, Impacts of climate change on the frequency and severity of floods in the Châteauguay River basin, Canada, *Canadian Journal of Civil Engineering*, **34**(9), 2007, pp. 1048–1060.
8. B. Vehviläinen, Snow Cover Models in Operational Watershed Forecasting. PhD Thesis, National Board of Waters and the Environment, Helsinki, 1992.
9. L. Oudin, F. Hervieu, C. Michel, C. Perrin, V. Andreassian, F. Anctil and C. Loumagne, Which potential evapotranspiration input for a lumped rainfall-runoff model? Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall-runoff modeling, *Journal of Hydrology*, **303**, 2005, pp. 290–306.
10. Woods Hole Science Center. 2003. Matlab Tools for Oceanographic Analysis. http://woodshole.er.usgs.gov/operations/sea-mat/. Accessed 15 July 2014.
11. R. Arsenault, A. Poulin, P. Côté and F. P. Brissette, A comparison of stochastic optimization algorithms in hydrological model calibration, *Journal of Hydrologic Engineering*, **19**(7), 2014, pp. 1374–1384.
12. B. A. Tolson and C. A. Shoemaker, Dynamically dimensioned search algorithm for computationally efficient watershed model calibration, *Water Resources Research*, **43**(1), 2007, pp. 1–16.
13. Q. Duan, S. Sorooshian and V. Gupta, Effective and Efficient Global Optimization for Conceptual Rainfall-Runoff Models, *Water Resources Research*, **28**(4), 1993, pp. 1015–1031.
14. J. E. Nash and J. V. Sutcliffe, River flow forecasting through

conceptual models part I—A discussion of principles, *Journal of Hydrology*, **10**(3), 1970, pp. 282–290.
15. F. S. Mpelasoka and F. H. S. Chiew, Influence of Rainfall Scenario Construction Methods on Runoff Projections, *Journal of Hydrometeorology,* **10**, 2009. pp. 1168–1183.
16. R. Arsenault, J. Malo, F. Brissette, M. Minville and R. Leconte, Structural and non-structural climate change adaptation strategies for the Péribonka water resource system, Water Resources Management, **27**(7), 2013, pp. 2075–2087.
17. J. Chen, F. P. Brissette and R. Leconte, Uncertainty of downscaling method in quantifying the impact of climate change on hydrology, *Journal of Hydrology*, **401**(3), 2011, pp. 190–202.
18. V. Fortin and R. Turcotte, Le modèle hydrologique MOHYSE (bases théoriques et manuel de l'usager). Course notes for SCA7420, Department of Earth Sciences and Atmospheric, Université du Québec à Montréal, Montreal, 2007.
19. R. Arsenault and F. P. Brissette, Continuous streamflow prediction in ungauged basins: The effects of equifinality and parameter set selection on uncertainty in regionalization approaches, *Water Resources Research*, **50**(7), 2014, pp. 6135–6153.
20. R. Arsenault and F. P. Brissette, Determining the Optimal Spatial Distribution of Weather Station Networks for Hydrological Modeling Purposes Using RCM Datasets: An Experimental Approach, *Journal of Hydrometeorology*, **15**(1), 2014, pp. 517–526.
21. NOAA's National Weather Service, Model parameter Estimation Experiment (MOPEX), http://www.nws.noaa.gov/oh/mopex/. Accessed 7 August 2014.
22. Drainage, Transports Québec, http://www2.publicationsduquebec.gouv.qc.ca/transports/html/2c3.html. Accessed 8 September 2014.
23. Manuel de conception hydraulique des ponts—Procédure pour la réalisation des études hydrauliques, Transports Québec, http://www3.publicationsduquebec.gouv.qc.ca/produits/ouvrage_routier/guides/guide3.fr.html. Accessed 8 September 2014.
24. G. Di Baldassarre and A. Montanari, Uncertainty in river discharge observations: a quantitative analysis, *Hydrology and Earth System Sciences*, **13**, 2009, pp. 913–921.
25. K. Beven, A manifesto for the equifinality thesis, *Journal of Hydrology*, (320), 2006, pp. 18–36.

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