J.Natn.Sci.Foundation Sri Lanka 2022 50 (3): 577 - 587
DOI: http://dx.doi.org/10.227/jnsfsr.v50i3.10536

RESEARCH ARTICLE

Agricultural Statistics

Evaluating the potential of an open sensor network to support reservoir pre-release decision making

E Warusavitharana[1*], PKS Mahanama[1], M Cannata[2], R Ratnayake[1], BH Sudantha[1] and D Strigaro[2]
[1] *Department of Town and Country Planning, Faculty of Architecture, University of Moratuwa, Moratuwa.*
[2] *University of Applied Sciences and Arts of Southern Switzerland, Switzerland.*

Submitted: 17 May 2021; Revised: 22 December 2021; Accepted: 25 February 2022

Abstract: Still in most countries, reservoir flood warnings are threshold-based alerts issued when water levels exceed thresholds. This current practice of releasing water from reservoirs causes flash floods in downstream areas and increases the likelihood of dam failures and public outrage. Pre-release of water from reservoirs is therefore an important strategy for downstream flood mitigation. Hydrological models can simulate river flow with sufficient lead time. Thus, the resulting outputs can be effectively applied to pre-release decision making in the reservoirs. Since the beginning of computer-aided applications, many attempts have been made to establish a decision support system for reservoir flood control. However, this is hampered by manual stations, low quality data, high cost of software and data, unknown parameter values, and lack of expertise, especially in developing countries. Therefore, a total open-source solution combined with low-cost open-source hardware, free and open-source software, and open standards was seen as the only way to overcome reservoir-related flood risk. Moreover, research studies on open-source hardware, software, standards, and data are limited to a few case studies reporting real-time data on certain environmental parameters. Therefore, the application of integrated open-source technologies for reservoir flood control remains an unexplored area. In this background, a hydrological model powered by integrated open-source technology is presented in this research for reservoir pre-release decision making. The model was tested for the Deduru Oya watershed using the SWAT (Soil and Water Assessment Tool) toolkit. The calibration results appear to be satisfactory for both daily and hourly time intervals. Thus, this model helps to simulate the inflow of the reservoir and determine the level of reservoir gate opening.

Keywords: 4ONSE, Deduru Oya basin, open-source technologies, reservoir pre-release.

INTRODUCTION

A reservoir is an artificial or natural lake or pond which is used to collect and store water for versatile activities. In Sri Lanka, reservoirs are called tanks or 'wewa', which is the Sinhala word. Reservoir flood control measures can be broadly classified as structural and non-structural. Structural measures involve the mitigation of floods through physical constructions. In ancient Sri Lanka, floods associated with tanks were mainly controlled through the 'Ellanga gammana' system which is also known as the 'Cascaded tank-village' system (Figure 1). This system includes a network of small to large tanks in a micro or mesoscale catchment for storing, conveying, and utilizing water from an ephemeral rivulet (Bandara, 1995). It can be considered as one of the structural measures adopted by ancient Sri Lankans to create a buffer against seasonal flooding and to store water during droughts. However, in certain circumstances, the functioning of this system has been negatively affected by the filling of paddy lands and the availability of abandoned tanks.

Compared to structural methods, non-structural methods of flood control have been accepted in the present day as a more proven method for reducing flood risk and damages. This is mainly due to its long-term sustainability and minimal cost for operation and maintenance. Out of the different non-structural measures, the flood warning is the best measure to undertake for the areas that deserve prompt attention. Flood warnings differ from forecasts

* Corresponding author (emeshi@uom.lk; https://orcid.org/0000-0002-0352-2926)

as they are issued when an event occurs or is about to occur (WMO, 2013). In the Asian context, China and Japan have established reservoir flood control systems, taking advantage of real-time hydro-meteorological data (Takeuchi *et al*, 1998; Guo *et al*, 2004). However, like most developing countries, Sri Lanka lacks a reliable weather station network, which could offer continuous near-real-time data for decision-making. Limited weather stations, costly and offline data, unavailability of parameter values, expensive modeling software, and limited resource persons are some of the major reasons which hinder the application of hydro-meteorological data for reservoir pre-release decision making. In many countries, even in Sri Lanka, reservoir flood warnings are issued under conditions where the reservoir is already at full capacity. This creates flash floods in downstream areas due to sudden release of water at a high speed.

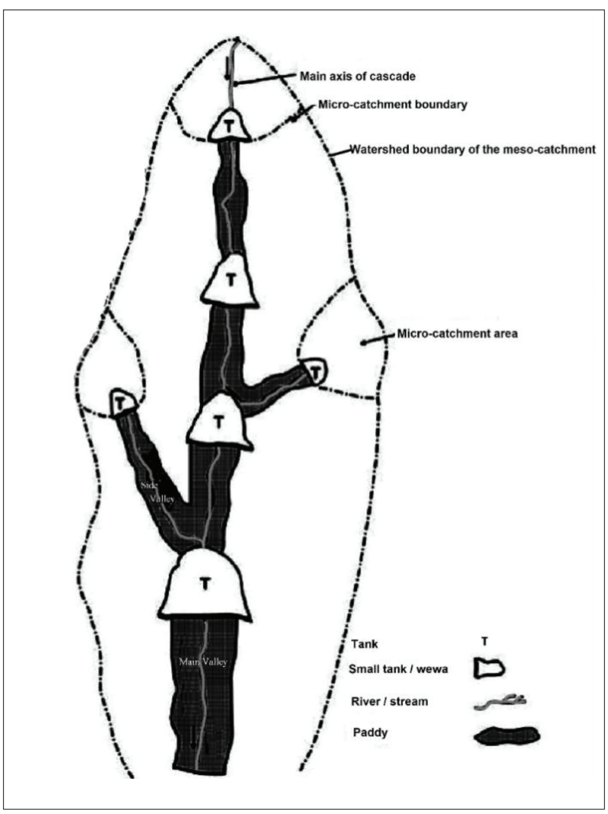

Figure 1: Schematic diagram of a tank cascade system (Panabokke *et al*., 2002)

The project 4ONSE (4 times open and non-conventional technologies for sensing the environment) was launched in this setting to introduce an open-source weather station network to support disaster warnings. IoT (internet of things) enabled technologies, open-source standards, and software have now made a significant turning point in the future of disaster warning from high-cost sophisticated devices to low-cost, open-source solutions. Evans (2011) defined the term internet of things (IoT) as a moment where more things are connected to the internet than people. Wireless connectivity and smart sensors are the two technologies that shape up the IoT network. Hence, IoT usually does the collecting of data through smart sensors and sharing them through the internet. Hart & Martinez (2015) have stated that most of the IoT-based applications and IoT-oriented research have been applied in cities and indoor environments where the relevant infrastructure facilities such as internet connectivity, accessibility, and electric power supply are available. Therefore, the most essential requirement to form a global environmental monitoring sensor network is to introduce IoT to remote environments where the IoT systems are powered by energy harvesting systems composed of sustainable energy source/s and energy storage units and wireless internet connectivity. Several of the world's most recognized companies such as IBM and HP have already started some initiatives in this respect (IBM,2010; HP, 2013; Liang & Huang, 2013).

The most cost-effective IoT applications have started to become popular after the addition of low-cost sensors, open-source hardware platforms, open-source software and standards in system development (Bitella *et al*., 2014; Sadler *et al*., 2014; Chemin *et al*., 2015; Formisano *et al*., 2015; Prescott *et al*., 2016; Rao *et al*., 2016; Saini *et al*., 2016). However, only a few cases of integration of these open-source platforms for monitoring various environmental parameters have been reported. Valenzuela *et al*. (2018) developed a turbidity data acquisition system using Arduino as open hardware and MyOpenLap free software as open-source software. Sabatini (2017) has presented an approach of step-by-step installation of an automatic weather station in remote sites. Daniele *et al*. (2016) have developed an open hardware device based on Arduino to monitor the soil water potential for irrigation activities. A similar kind of application was developed by Bitella *et al*. (2014) to monitor the soil water content integrating the soil, vegetation, and atmosphere parameters. Prescott *et al*. (2016) discussed a hydro-climatic monitoring station that observes six water quality parameters. Mesas-Carrascosa *et al*. (2015) developed an open-source hardware device to record environmental parameters and a smartphone application to analyze the data. Sadler *et al*. (2014) developed a low-cost environmental monitoring system that measures air temperature and relative humidity and automatically sends the collected data to Hydrologic Information System. Samourkasidis & Athanasiadis (2014) demonstrated an automated data archival system integrated with OGC-SOS, low-cost sensors, and Raspberry Pi as open hardware. Therefore, the integration of open-source technologies for reservoir management in river basins, remains an unexplored area, especially with regard to reservoir pre-release decision making. Therefore, the main objective of this research is to evaluate the potential of such a system for reservoir pre-release decision-making with the support of a hydrological model.

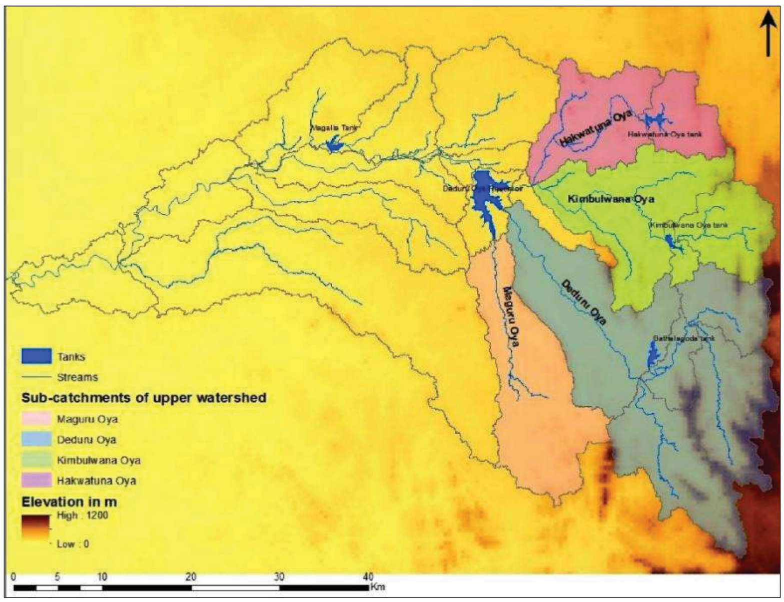

Figure 2: Hydrological network, sub-catchments & sub-basins of Deduru Oya basin

MATERIALS AND METHODS

Study site

Figure 2 shows the river basin chosen to establish the 4ONSE network, the Deduru Oya river basin. It's catchment area is about 2687 km^2 and the length of the main channel is 115 km. There are 8 major reservoirs and 2408 minor reservoirs in the basin. Among them, Deduru Oya reservoir is the largest and main reservoir in the basin. Thus, it has been selected for testing the reservoir management decision support system. Its significant geographical location is a major factor in flood control in the lower basin. The upper catchment area can be divided into four sub-catchments based on the four stream networks originating from the Central Highlands. Among them, the reservoir receives the largest amount of water from the Deduru Oya sub-catchment.

Open-source Framework

Arduino, istSOS (Instituto Scienze della Terra Sensor Observation Service) and OGC-SOS (Open Geospatial Consortium – Sensor Observation Service) are the open-source hardware, software and standards, respectively, used in system development. The istSOS allows access to all sensor observations from a centralized location based on OGC-SOS standard. The data are visualized in istSOS at a rate of 10 min It has an automatic data validation procedure to identify the quality of near-real-time data. This validation procedure assigns a code for each datum after the validation test.

All the 4ONSE stations were built on Arduino Mega 2560 open hardware platforms. In addition to the weather stations, several river gauges were built using the same Arduino Mega version, to measure the water levels of the streams. Each station is powered by 30W solar panel and 12V 35Ah rechargeable battery. The sensors of the stations, measured parameters, units, accuracy, and measuring range are shown in Table 1. Cost, WMO standards, and durability are the main factors that have been considered when selecting sensors for the stations (Cannata *et al*., 2017; Sudantha *et al*., 2018, 2019). Figures 3a and 3b shows photographs of a weather station and a river gauge developed under the 4ONSE project. Figure 4 shows the locations where the 27 weather stations and 06 river gauges are deployed. The quality of the 4ONSE data was checked using some reference stations' data at daily and 10 minutes intervals.

Table 1: Sensors of the 4ONSE stations

Sensor	Parameter	Unit	Accuracy	Measuring range
DS18B20	Temperature	Degrees Celsius (°C)	±0.5°C	-10 to 85 °C
BME280	Relative Humidity	Percentage (%)	±3%	0% - 100%
BME280	Barometric pressure	Hectopascals (hPa)	±1 hPa	300 – 1000 hPa
ZHIPU wind speed sensor	Wind speed	Meters per second (ms^{-1})	±1 m/s	0-32.4 m/s
Anemometer 485 wind direction sensor	Wind direction	Degrees	±3°	16 different directions and any angle values can be identified
6465 Davis AeroCone Rain Gauge with Mountable Base	Precipitation	Millimeters (mm)	0.2mm	N/A
BH1750 light sensor module	Light intensity	Lux (lx)	1.44 times, Sensor Out / Actual lx	(1-65535lx)
Soil moisture module	Soil moisture	Percentage (%)	±2%	0 to 22%
River gauge module MB7062 XL-MaxSonar-WR1 Ultrasonic sensor	Water Level	Meters	±0.5cm	0 - 10m

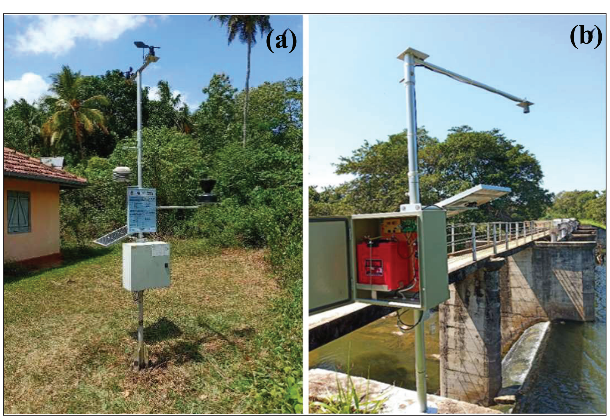

Figure 3: 4ONSE (a) weather station and (b) river gauge

In this study, the SWAT (Soil and Water Assessment Tool) open-source tool has been used to develop the hydrological model. The model calibration part has been done using the SWAT-CUP open-source tool. Figure 5 shows the complete open-source framework used to develop the hydrological model to support pre-release decision making in the reservoir.

Development of hydrological model

The SWAT model has shown its capability in regional-scale hydrological modelling for simulation of river discharge (Ghoraba, 2015; Bailey *et al*., 2016; Zhang *et al*., 2016; Rafiei *et al.,* 2017; Warusavitharana, 2020). The model was developed using QSWAT plugin version 1.9 (Dile *et al*., 2016) embedded in QGIS software. The QSWAT plugin successfully works in QGIS 2.6.1 Brighton version. The processing of input data such as DEM (Digital Elevation Model), land use, and soil was performed using QGIS Brighton version. SWAT's algorithms for infiltration, surface runoff, flow routing, impoundments, and lagging of surface runoff have been modified to allow flow simulations with a sub-daily time interval as small as one minute, and evapotranspiration, soil water contents, base flow, and lateral flow are estimated daily and distributed equally for each time step (Jeong *et al*., 2010). Therefore, using precipitation on a sub-daily basis and the other input data (relative humidity, temperature, wind speed and solar radiation) on a daily basis was sufficient.

Since SWAT is a continuous hydrological model, it requires a warm-up period of several years to stabilize the model. Since 4ONSE is a newly deployed sensor network, the required data for the model's warm-up period has been estimated through SWAT's weather generator. The required monthly statistical data to operate the weather generator has been calculated using CFSR (Climate Forecasting System Reanalysis) data. Table 2 shows the models and methods used in the SWAT weather generator to estimate the missing weather data.

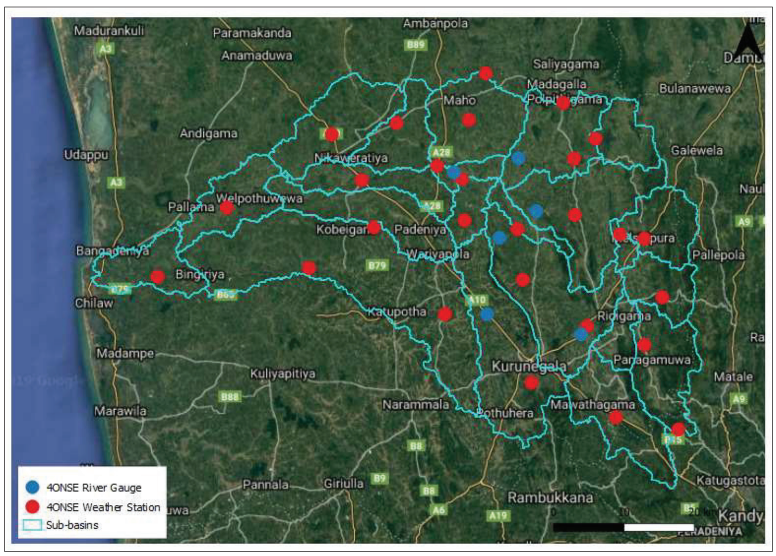

Figure 4: Locations of the 4ONSE stations in Deduru Oya basin

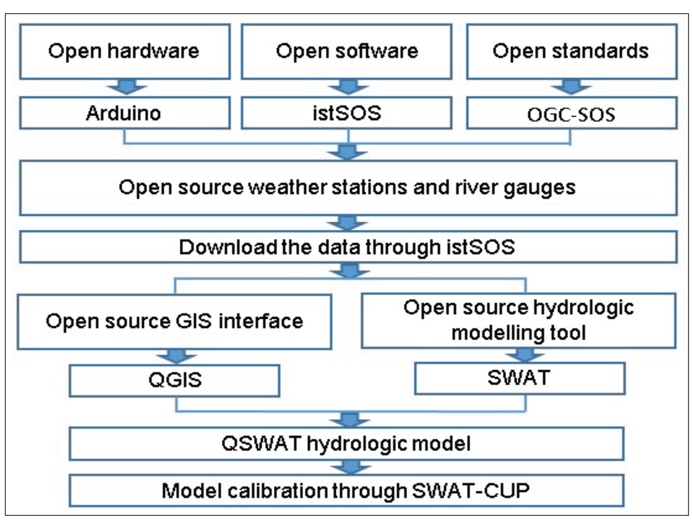

Figure 5: 4ONSE open-source framework for reservoir pre-release decision making

Table 2: Models and methods used in SWAT weather generator

Climatic variable	Model / Method
Daily precipitation	Model developed by Nicks (1974)
Sub-daily precipitation	Double exponential function
Daily maximum and minimum air temperature	Normal distribution
Daily average relative humidity	Triangular distribution
Daily solar radiation	Normal distribution
Daily mean wind speed	Modified exponential equation

Model calibration and uncertainty analysis

The model calibration and uncertainty analysis has been accomplished through the SWAT-CUP (SWAT-Calibration and Uncertainty Procedures) public domain programme. The four upper sub-catchments in the Deduru Oya basin have been separately calibrated in this study by developing four separate SWAT models. However, this research extends the results of the model associated with the Deduru Oya sub-catchment.

Primarily, the effectiveness of the model at daily time-step was checked using the default parameter values in the tool. As there was a substantial difference between the simulated flow and the observed flow, the model was regionalized first. Generally, the terms regionalization, parameterization, and calibration have similar meaning, which is adjusting the parameter values to reduce the difference between a simulated result and observed values. The parameterization / regionalization scheme of SWAT-CUP tool is as follows:

$$x\_ < parname >. < ext > \_ < hydrogrp > \_ < soltext > \_ < landuse > \_ < subbasn > \_ < slope >$$

The components in the scheme namely, $parname$, ext, $hydrogrp$, $soltext$, $landuse$, $subbasn$ and $slope$ represents the name of the parameters (as it appears in SWAT), the extension of the parameter, soil hydrologic group, land use type, sub-basin number, and the slope, respectively. As per the scheme, *x_* represents the type of change to be applied to the parameter. The type of changes represented by *x_* are as follows:

1) *V_* - replacing the existing parameter
2) *A_* - (existing parameter) + (given value)
3) *R_* - (existing parameter) × (1+ given value)

In this study, several rules have been applied when selecting the appropriate *x_* type. The usual principle in the SWAT_CUP tool to use type R_ for spatial parameters (*e.g.*, land use and soil type). Moreover, considering the ease of examining a wide range of values, type R_ was applied to parameters with a large range. Type V_ was applied to all the other parameters.

The sensitive/dominant parameters of the hydrological model were identified first through the OAT (One-at-a-time) sensitive analysis in SWAT-CUP. It shows the sensitivity of each parameter if all other parameters are kept constant. The model calibration and uncertainty analysis were performed according to the SUFI 2 (Sequential Uncertainties Fitting Version 2) algorithm integrated in SWAT. The fitness of the model was assessed statistically using the Nash-Sutcliffe Efficiency (NSE) method (Nash, 1957) (Equation 1), Goodness of fit linear regression model (R^2) (Equation 2), P factor (percentage of observed data simulated in the model) and R factor (average thickness of the 95% predication uncertainty (95PPU) divided by the standard deviation) (Equation 3). An NSE value between 0 and 1, R^2 > 0.5, P-factor > 70% and R-factor of around 1 are considered acceptable.

$$Maximize : NSE = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad ...(1)$$

$$R^2 = \frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}} \quad ...(2)$$

$$R - factor = \frac{\frac{1}{n_j}\sum_{t_i=1}^{n_j}\left(x_s^{t_i,97.5\%} - x_s^{t_i,2.5\%}\right)}{\sigma_{oj}} \quad ...(3)$$

where *n* is the number of observations, O_i is the i^{th} observed value, $\bar{O}$ is the mean observed value, P_i is the i^{th} model-predicted value, $\bar{P}$ is the mean model-predicted value, $x_s^{t_i,97.5\%}$ is the upper boundary and $x_s^{t_i,2.5\%}$ is the lower boundary of 95PPU.

As a summary, Table 3 lists all the open-source tools used in developing the hydrological model to support reservoir pre-release decision making.

Table 3: Open-source tools used in the hydrological model

Open-source tool	Function	Link
QGIS Brighton Version	▪ Analyse vector and raster data ▪ GIS interface to run the SWAT model	http://qgis.org/downloads/QGIS-OSGeo4W-2.6.1-1-Setup-x86.exe
QSWAT	▪ SWAT plugin used to run the model in QGIS software	https://swat.tamu.edu/software/qswat/
SWAT-Editor	▪ Reading project databases ▪ Generating missing weather data ▪ Executing SWAT run ▪ Calibrating the model	https://swat.tamu.edu/software/swat-editor/
SWAT-CUP	▪ Identifying the dominant parameters & their ranges ▪ Calibrating the model ▪ Validating the model	https://www.2w2e.com/home/SwatCup
istSOS	▪ To view and download the data of 4ONSE stations	https://geoservice.ist.supsi.ch/4onse/admin/

RESULTS AND DISCUSSION

Before applying the 4ONSE meteorological data in the model, its quality was checked using data from some reference stations in Sri Lanka. Table 4 shows the coefficient of determination of all key meteorological parameters measured at 10 minutes and daily intervals.

Table 4: Coefficient of determination (R^2) between 4ONSE stations and reference stations

Parameter	Interval	R^2 value
Temperature	10 minutes	0.9678
	Daily	0.9921
Rainfall – low altitude	10 minutes	0.7292
	Daily	0.7784
Rainfall – high altitude	10 minutes	0.7448
Relative humidity	10 minutes	0.9184
	Daily	0.9811
Air pressure	10 minutes	0.9771
	Daily	0.9929
Water level	10 minutes	0.9889
	Daily	0.9916

After running the model using daily 4ONSE data with SWAT's default parameter values, several key features of simulated flow and the actual flow were observed. They are:

1. Simulated flow peaks are higher than actual flow
2. The baseflow of the simulated flow is higher than the actual flow
3. The discharge in the simulated flow shifted to the left

To correct the above issues, the model was first regionalized. Table 5 shows the related dominant/ sensitive parameters identified through the OAT analysis and applied modifications to correct the above deviations.

In the SWAT model, CN2 (curve number), CANMX (maximum canopy storage), SOL_AWC (soil available water content) and ESCO (soil evaporation compensation factor) are the parameters that contribute to the peak fluctuation of streamflow. However, CANMX was the only parameter that showed sensitivity to high peaks, especially for the dominant land use categories of coconut, rice, low-density residential, and rubber. The CANMX parameter represents the maximum amount of water that trees can be hold. This value is zero by default in the SWAT database. The peaks can be reduced by increasing the CANMX value of dominant land use classes. Since CANMX is a parameter that introduces water into the system it was taken separately and 50 runs performed, to obtain optimal values related to the four dominant land use categories. Table 6 shows the sensitive parameters and their values for daily and hourly intervals obtained during model calibration.

Table 5: Regionalized parameters

Observation	Reason	Related parameters	Applied modification
High peaks	High surface flow	CN2, SOL_AWC, ESCO, CANMX	Increase CANMX
Model over predicts the flow	High baseflow and/or little evapotranspiration	GWQMN, GW_REVAP, REVAPMN	Increase GWQMN & GW_REVAP
Discharge was shifted to left	Simulated flow leads the actual flow	SLOPE, OV_N, SLSUBBSN, CH_N2	Increase CH_N2

Table 6: Sensitive parameters and their value ranges related to daily and hourly intervals.

Sensitive parameter	Description	Type of change	Value range – daily interval	Value range – hourly interval
CN2	Initial SCS runoff curve number for moisture condition II)	R_	0.14 – 0.25	(-0.3) – 0.1
SOL_AWC	Available water capacity of the soil layer	R_	(-0.14) – 0.03	Not sensitive
ESCO	Soil evapotranspiration compensation factor	V_	0.68 – 0.95	Not sensitive
SOL_BD	Moist bulk density	R_	(-0.12) – 0.06	(-0.08) – 1.77
MSK_X	Weighting factor for wedge storage	V_	0 – 0.14	0 – 0.1
MSK_CO2	Muskingum coefficient for low flow	V_	(-0.04) – 0.59	0 – 8.1
MSK_CO1	Muskingum coefficient for normal flow	V_	0.96 – 1.31	1.0 – 5.2
ALPHA_BF	Baseflow alpha factor	V_	(-0.17) – 0.23	0 – 0.2
SOL_K	Saturated hydraulic conductivity	R_	(-1.21) – 0.06	(-0.47) – (-0.04)
CH_K2	Effective hydraulic conductivity in main channel alluvium	V_	4.27 – 6.73	1.1 – 27.3
CH_N1	Manning's "n" value for the tributary channels	V_	(-0.13) – 0.20	(-0.3) – 0.7
CH_N2	Manning's "n" value for main channel	V_	0.04 – 0.06	0 – 0.7
GW_DELAY	Ground water delay time	V_	38.90 – 89.94	Not sensitive
GW_REVAP	Groundwater "revap" coefficient	V_	0.24 – 0.45	0.1 – 0.2
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur	R_	3.14 – 4.32	0.8 – 2.0
SURLAG	Surface runoff lag coefficient	V_	Not sensitive	(-0.5) – 1.0

Except the SOL_AWC, ESCO, GW_DELAY, and SURLAG parameters, all the other parameters were received as sensitive for both daily and hourly time intervals for the Deduru Oya sub-catchment. For hourly simulation, the effect of ESCO, SOL_AWC, and GW_DELAY was not significant while SURLAG parameter was significant to simulate hourly flows.

Figure 6 shows the simulated and actual inflow in the Deduru Oya sub-catchment, after model calibration. The statistical results regarding P factor, R factor, R^2, and NSE presented in Table 7 appear to be satisfactory. The Davis rain gauge used at 4ONSE weather stations typically has a margin of error of ±4% for rainfall rates up to 50 mm/hour and ±5% for rainfall rates in the 50 mm/hr to 100 mm/hr range. This is the main reason why some peaks do not reach the desired level.

Accordingly, the calibrated parameter values of the model can be easily applied to the model to simulate the inflow of the Deduru Oya reservoir. The time interval of the model can be changed according to the needs of the decision-makers who decide on water pre-release.

Customization of weather data and optimization of parameters should be done according to the selected time interval. Moreover, the application of near real-time weather data in the model is more valid when the time required for decision-making is greater than the time required to concentrate water from the upper basin to the reservoir.

The model developed in this research cannot be directly used for flood modelling. It only helps to simulate the flow into the reservoirs / tanks and to determine the level of opening of the reservoir gates, which helps in reducing downstream flood inundation. However, the inflows simulated by the model can be applied to SWAT's reservoir management tool to estimate reservoir capacity and determine reservoir outflow.

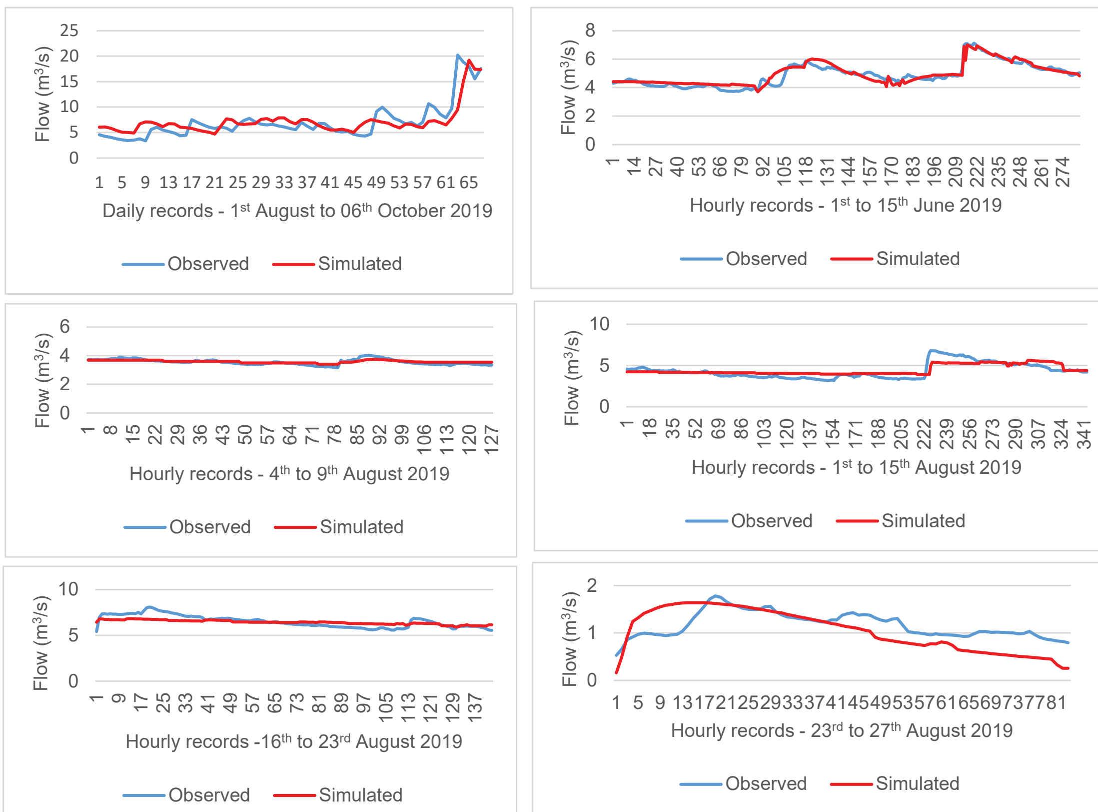

Figure 6: Simulated flow and Observed/Actual flow

Table 7: Statistical results of the hydrological model

Period	Interval	P factor	R factor	R^2	NSE
1st August to 6th October 2019	Daily	0.87	0.98	0.69	0.69
1st to 15th June 2019	Hourly	0.96	0.76	0.76	0.75
15th to 30th June 2019	Hourly	0.96	0.89	0.89	0.88
4th to 9th August 2019	Hourly	1.0	0.53	0.77	0.55
1st to 15th August 2019	Hourly	0.74	0.54	0.67	0.63
16th to 23rd August 2019	Hourly	0.83	0.00	0.67	0.43

CONCLUSION

Reservoir flood management applications require generating modelling results with the shortest lead time using near real-time meteorological data as input data. Due to the limitations of the existing setup, the incorporation of near real-time and quality hydro-meteorological input data to produce accurate hydrological estimates has never been used in Sri Lanka. Thus, this study intends to introduce a cost-effective decision support system to reservoir pre-release decision making. It is built entirely using several open source technologies for model implementation and data entry. QGIS Brighton version, QSWAT, SWAT Editor and SWAT-CUP are the open-source tools used to implement the hydrological model and Arduino, istSOS and OGS-SOS are the open-source technologies used to build meteorological stations and feed data to the model. Estimating parameter values for different time periods is tedious, time consuming, and labour and capital intensive. Therefore, the modelling approach presented in this research avoids the need for pre-specified parameter values and allows users to determine them at any time. The approach presented in this study is more appropriate for simulating reservoir inflow. If the basin has any series of tanks/cascade systems, the daily and sub-daily discharge flow of the upper basin tanks should be considered while developing the model. Furthermore, this study introduces a new approach for conducting hazard warnings in more remote environments where environmental processes cannot be realistically observed or studied due to the lack of access and facilities.

Conflict of interest statement

The authors declare that they have no conflict of interest

Acknowledgment

The 4ONSE project was funded by the Swiss National Science Foundation (SNSF).

REFERENCES

Bailey R.T., Wible T.C., Arabi M., Records R.M. & Ditty J. (2016). Assessing regional-scale spatio-temporal patterns of groundwater–surface water interactions using a coupled SWAT-MODFLOW model. *Hydrological Processes* **30**(23): 4420–4433.
DOI: https://doi.org/10.1002/hyp.10933

Bandara C.M.M. (1995). *Tank Cascade Systems in Sri Lanka: Some Thoughts on Their Development Implications*, pp 14. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Bitella G., Rossi R., Bochiccchio R., Perniola M. & Amato M. (2014). A novel low-cost open hardware platform for monitoring soil water content and multiple soil-air-vegetation parameters. *Sensors* **14**: 19639–19659.
DOI: https://doi.org/10.3390/s141019639

Cannata M., Strigaro D., Cardoso M., Sudantha B.H., Ratnayake R., Warusavitharana E.J. & Banadra P.D. (2017). 4onse D2.1 - System design report. Zenodo.
DOI: https://doi.org/10.5281/zenodo.1244162

Chemin Y., Bandara N. & Eriyagama N. (2015). A national upgrade of the climate monitoring grid in Sri Lanka. The place of Open design, OSHW and FOSS. *Geophysical Research Abstracts. EGU General Assembly*, 12–17 April, Vienna, Austria, pp. 17.

Daniele M., Facchi A., Depoli E.V., Renga F.M. & Gandolfi C. (2016). Irrig-OH: An open-hardware device for soil water potential monitoring and irrigation management. *Irrigation and Drainage* **65**(5): 750–761.
DOI: https://doi.org/10.1002/ird.1989

Dile Y., Daggupati P., George C., Srinivasan R. & Arnolde J. (2016). Introducing a new open source GIS user interface for the SWAT model. *Environmental Modelling and Software* **85:** 129–138.
DOI: https://doi.org/10.1016/j.envsoft.2016.08.004

Evans D. (2011). The Internet of Things: How the next evolution of the internet is changing everything. Cisco Internet Business Solutions Group. Available at *http://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf*

Formisano F., Massera E., De Vito S., Buonanno A., Di Francia G. & Delli Veneri P. (2015). Tinynose, an auxiliary smart gas sensor for RFID tag in vegetables ripening monitoring during refrigerated cargo transport. In: *Sensors: Lecture Notes in Electrical Engineering*, volume 319 (eds. D. Compagnone, F. Baldini, C. Di Natale, G. Betta & P. Siciliano), Springer, Cham, Switzerland.
DOI: https://doi.org/10.1007/978-3-319-09617-9_39

Ghoraba S.M. (2015). Hydrological modeling of the Simly Dam watershed (Pakistan) using GIS and SWAT model. *Alexandria Engineering Journal* **54**(3): 583–594.
DOI: https://doi.org/10.1016/j.aej.2015.05.018

Guo S., Zhang H., Chen H., Peng D., Liu P. & Pang B. (2004). A reservoir flood forecasting and control system for China. *Hydrological Sciences Journal* **49**(6): 972.
DOI: https://doi.org/10.1623/hysj.49.6.959.55728

Hart J. & Martinez K. (2015). Toward an environmental internet of things. *Earth and Space Science* **2**: 194–200.
DOI: https://doi.org/10.1002/2014EA000044

Hewlett Packard Development Company (2013). Central Nervous System for the Earth (CeNSE). Available at *http://www8.hp.com/us/en/hp-information/environment/cense.html#.WTLzUmiGM2w*

IBM (2010). A Smarter Planet. Available at *http://www.ibm.com/smarterplanet/*

Jeong J., Kannan N., Arnold J., Glick R., Gosselink L. & Srinivasan R. (2010). Development and integration of

sub-hourly rainfall-runoff modeling capability within a watershed model. *Water Resources Management* **24**(15): 4505–4527.
DOI: https://doi.org/10.1007/s11269-010-9670-4

Liang S. & Huang C.Y. (2013). GeoCENS: A geospatial cyberinfrastructure for the World-Wide Sensor Web. *Sensors* **13**: 13402–13424.
DOI: https://doi.org/10.3390/s131013402

Mesas-Carrascosa F., Verdu Santano D., Morono J., Sanchez de la Orden M. & Garcia-Ferrer A. (2015). Open-source hardware to monitor environmental parameters in precision agriculture. *Biosystem Engineering* **137**: 73–83.

Nash J. (1957). The form of the instantaneous unit hydrograph. *Comptes Rendus et Rapports Assemblee Generale de Toronto* **3: 114–121.**
DOI: https://doi.org/10.1016/j.biosystemseng.2015.07.005

Nicks A. (1974). Stochastic generation of the occurrence, pattern and location of maximum amount of daily rainfall. *Proceedings of The Symposium on Statistical Hydrology*, pp. 154–171. Government Printing Office, Washington DC, USA**.**

Prescott E., Rom C., Marchiori A. & Hayes B. (2016). HydroSense: An open platform for hydroclimatic monitoring.
DOI: https://doi.org/10.1109/SMARTCOMP.2016.7501695

Rafiei Emam A., Kappas M., Linh N.H.K. & Renchin T. (2017). Hydrological modeling and runoff mitigation in an ungauged basin of central Vietnam using SWAT model. *Hydrology* **4**(1): 16.
DOI: https://doi.org/10.3390/hydrology4010016

Rao B., Rao K. & Ome N. (2016). Internet of Things (IOT) based weather monitoring system. *International Journal of Advanced Research in Computer and Communication Engineering* **5**(9): 312–319.
DOI: https://doi.org/10.3390/10.17577/IJERTCONV6IS13149

Sabatini F. (2017). Setting up and managing automatic weather stations for remote sites monitoring from Niger and Nepal. In: *Renewing Local Planning to Face Climate Change in the Tropics* (eds. T. Pezzoli & A. Tarchiani), pp. 21–39. Springer International Publishing, Cham, Switzerland.
DOI: https://doi.org/10.1007/978-3-319-59096-7_2

Sadler J., Ames D. & Khattar R. (2014). Open-hardware meets open software for environmental monitoring. *7th International Congress of Environmental Modelling and Software*, San Diego, California, USA.
DOI: https://doi.org/10.13140/2.1.4693.8241

Saini H., Thakur A., Ahuja S., Sabharwal N. & Kumar N. (2016). Arduino based automatic wireless weather station with remote graphical application and alerts. *Proceedings of the 3rd International Conference on Signal Processing and Integrated Networks (SPIN)*, 11–12 February, Noida, India, pp. 605–609.
DOI: https://doi.org/10.1109/SPIN.2016.7566768

Samourkasidis A. & Athanasiadis I. (2014). Towards a low-cost, full-service air quality data archival system. *7th International Congress on Environmental Modelling and Software: Bold Visions for Environmental Modeling, iEMSs 2014* (eds. D.P. Ames, N.W.T. Quinn & A.E. Rizzoli), San Diego, USA, 15–19 June, pp. 1192–1199. Available at *http://www.iemss.org/sites/iemss2014/papers/iemss2014_submission_300.pdf*

Sudantha B.H., Warusavitharana E.J., Ratnayake R., Mahanama P.K.S., Cannata M. & Strigaro D. (2018). Appropriateness of low-cost sensor network for environmental monitoring in a tropical country: Experience and lessons learnt from real world deployment. *PeerJ PrePrints* **6**: e27224v1
DOI: https://doi.org/10.7287/peerj.preprints.27224v1

Sudantha B.H., Warusavitharana E.J., Ratnayake R., Mahanama P.K.S., Warusavitharana R.J., Tasheema R.P., Cannata M. & Strigaro D. (2019). 4ONSE as a complementary to conventional weather observation network. *Proceedings of the 4th International Conference on Information Technology Research (ICITR)*, 10–13 December. University of Moratuwa, Sri Lanka, pp. 1–6.
DOI: https://doi.org/10.1109/ICITR49409.2019.9407798

Takeuchi K., Hamlin M., Kundzewicz Z., Rosbjerg D. & Simonovic S. (1998). *Sustainable Reservoir Development and Management*. IAHS Publications, Wallingford, UK.

Valenzuela C., Sosa C., Castaneda M., Palomeque J. & Amaro I. (2018). Turbidity measurement system for aquaculture effluents using an open source software and hardware. *Nature Environment and Pollution Technology* **17**(3): 957–961.

Warusavitharana E.J. (2020). Semi-distributed parameter optimization and uncertainty assessment for an ungauged catchment of Deduru Oya Basin in Sri Lanka. *International Journal of River Basin Management* **18**(1): 95– 105.
DOI: https://doi.org/10.1080/15715124.2019.1656221

World Meteorological Organization (WMO) (2013). *Flood Forecasting and Early Warning***.** World Meteorological Organization.

Zhang L., Jin X., He C., Zhang B., Zhang X., Li J., Zhao C., Tia J. & DeMarchi C. (2016). Comparison of SWAT and DLBRM for hydrological modeling of a mountainous watershed in arid northwest China. *Journal of Hydrologic Engineering* **21**(5).
DOI: https://doi.org/10.1061/(ASCE)HE.1943-5584.0001313

Data availability statement

The data that support the findings of this study are available from the corresponding author, [E.J. Warusavitharana], upon reasonable request.