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Impacts of LULC Changes on Inflow Simulation of the Timah-Tasoh Reservoir Using the HEC-HMS Model

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Abstract: This study assess the impact of land use and land cover (LULC) changes on inflow simulation in the Timah-Tasoh reservoir, the largest reservoir in Perlis, Malaysia. This reservoir serves multiple purposes, including flood control, water supply, irrigation, and recreation. The study focused on the upper sub-catchments within the reservoir's catchment area, using the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) and ArcGIS to simulate rainfall-runoff under different LULC scenarios. The study are determine hydrological parameters, evaluate the performance of the HEC-HMS model during calibration and validation, and analyze the effects of LULC changes on inflow. Data from 2001-2019, provided by the Department of Irrigation and Drainage, Malaysia, were used for model calibration and validation. Model performance is satisfactory, with R-values ranging from 0.49-0.80. The study found that deforestation increased inflow by 3.9 %, while afforestation reduced it by 1.4%. These findings provide valuable insights for future hydrological modeling and land use planning in the Timah-Tasoh catchment area.

Keywords: HEC-HMS, GIS, Inflow Simulation, LULC

1. Introduction

Water resource management is critical for socio-economic growth and ecological sustainability. Despite abundant rainfall and reservoirs, Malaysia faces challenges such as water shortages, pollution, urban flooding, and environmental degradation. The Timah-Tasoh reservoir, the largest in Perlis, has experienced declining water levels, affecting agricultural activities, particularly paddy farming. Land use and land cover (LULC) changes, driven by urbanisation and deforestation, significantly impact hydrological processes by altering runoff, infiltration, and groundwater recharge [1, 2]. Rapid urbanisation reduces natural water absorption, leading to increased surface runoff, changes in streamflow, and potential flooding.

Hydrological modelling helps predict water resource availability and assess the effects of LULC changes [3]. The Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS) is a widely used tool for rainfall-runoff simulation and flood forecasting. However, the Timah-Tasoh catchment lacks extensive hydrological data, making inflow prediction challenging. While other models, such as MIKE SHE and SWAT, require extensive data and expertise, HEC-HMS offers a user-friendly interface and GIS compatibility, making it suitable for this study [4].

This research focuses on analysing the impact of LULC changes on inflow simulation for the Timah-Tasoh reservoir using HEC-HMS. The objectives include determining hydrological parameters, evaluating the model's performance, and assessing LULC change impacts. Understanding these factors will support better water resource management and land use planning to ensure sustainable water availability.

2. Data and Methods

2.1 Study Area

The study area is located in the upper sub-catchments of the Timah-Tasoh reservoir (Figure 1), the largest reservoir in Perlis, Malaysia. Situated approximately 13 km north of Kangar and near the Thailand border, the reservoir spans an average surface area of 13.33 km² with a storage capacity of 40 million m³ [2]. It serves multiple functions, including flood mitigation, water supply, irrigation, and recreation. The Tasoh and Pelarit rivers, the primary water sources for the reservoir, contribute an estimated annual inflow of 97 million m³ [5].

Changes in climate, land use and land cover (LULC), and socio-economic factors can significantly impact water quantity in the catchment. Urbanisation typically leads to higher reservoir inflow, while afforestation and reduced

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development may decrease it [6]. The reservoir's surrounding areas primarily consist of agricultural land, with plantations of rubber, paddy, and sugarcane, which can affect inflow simulation [7]. The sub-catchments, covering a total area of 173.11 km², were delineated using ArcGIS 10.7.1 to aid in hydrological modelling and analysis.

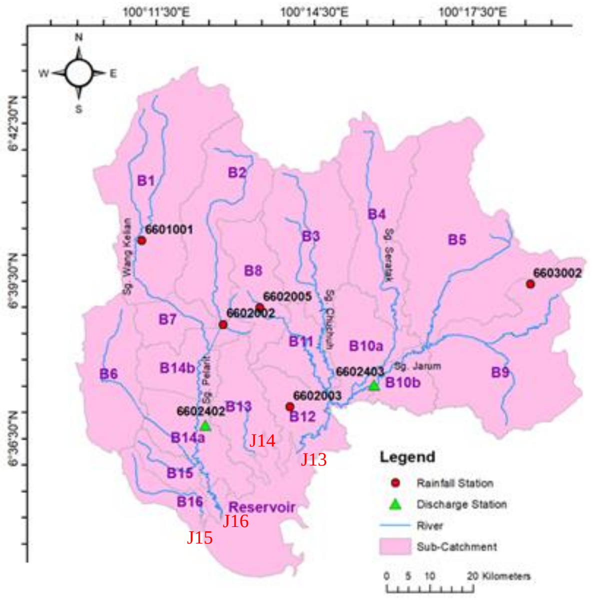

Fig. 1 – Location of the study area

In this study, at least twenty years (2000 – 2021) of daily records of rainfall and discharge data from seven gauged stations were collected from the Department of Irrigation and Drainage (DID), Malaysia. Among these stations, there were five rainfall stations, namely Wang Kelian, Kaki Bukit, Tasoh, Lubok Sireh and Padang Besar. Additionally, two discharge stations, Sg.Pelarit (J8) and Sg. Jarum (J18) represented gauged catchment. Detailed information regarding all rainfall and discharge stations utilised in this study is provided in Table 1.

Four junctions (as shown in Figure 1 and Table 1), which are J15, J16, J14, and J13, will serve as inflows to the reservoir. J15 and J14 have smaller catchment areas (less than 6.81 km^2) compared to J16 and J13, which have larger catchments (more than 63.6 km^2) and contribute a greater volume of water to the reservoir [2].

2.2 HEC-HMS

HEC-HMS, developed by the U.S. Army Hydrologic Engineering Center [8], is a comprehensive hydrological modelling system designed for simulating rainfall-runoff processes. The model consists of multiple components, including loss estimation, direct runoff, baseflow, and routing models, which collectively simulate various aspects of the runoff process [9]. For this study, the calibration was carried out to achieve reliable estimations of the parameters utilised to simulate rainfall runoff. In the modelling process, trial and error were used to change the parameter values consistently across all the different approaches. Manual calibration was performed for loss, transform, baseflow, and routing. Following the completion of the calibration process, a technique similar to the one used for the calibration was utilised for the validation. The specific model structure and the optimised parameters of HEC-HMS for the studied catchment are illustrated in Figure 2 and Tables 3-4. The details of each model can be referred to by Hassan et al. [10].

Table 1 - Detailed hydrological stations

Station No.	Station Name	Latitude (°N)	Longitude (°E)
Rainfall			
6601001	Wang Kelian	6.671111	100.1869
6602002	Kaki Bukit	6.643428	100.2101
6602003	Tasoh	6.618333	100.2447
6602005	Lubok Sireh	6.648789	100.2263
6603002	Padang Besar	6.648325	100.3142
Discharge			
6602402 (J8)	Sg. Pelarit di Kaki Bukit	6.629053	100.2041
6602403 (J18)	Sg. Jarum di Kg. Masjid	6.626261	100.2597

Table 2 – Area of each sub-catchment along with its inflow

Sub-Catchment	Area (km^2)
J15	3.39
B16	3.39
J16	63.6
B1	21.14
B2	12.33
B6	9.72
B7	3.55
B14a	7.22
B14b	6.26
B15	3.38
J14	6.81
B13	6.81
J13	99.31
B3	13.44
B4	12.58
B5	23.48
B8	7.25
B9	19.93
B10a	7.62
B10b	3.91
B11	4.81
B12	6.29
Total Sub-Catchments	173.11
Reservoir	10.23

2.3 Model Performance Evaluation

For calibration and validation, the performance of the models was evaluated continuously by using two evaluation criteria, including correlation coefficient (R) and root mean square error (RMSE), as follows:

$$R = \frac{\sum(obs - \overline{obs})(sim - \overline{sim})}{\sqrt{\sum(obs - \overline{obs})^2 \sum(sim - \overline{sim})^2}} \quad (1)$$

$$RMSE = \sqrt{\frac{\sum(obs - sim)^2}{n}} \quad (2)$$

where, obs and $\overline{obs}$ are the observed and mean observed discharge, while sim and $\overline{sim}$ are the simulated and mean

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simulated discharge, and n is the total reference. When R-values are closer to 1, the simulated model is more accurate. At the same time, lower values of RMSE show that a closer zero suggests that the model is accurate.

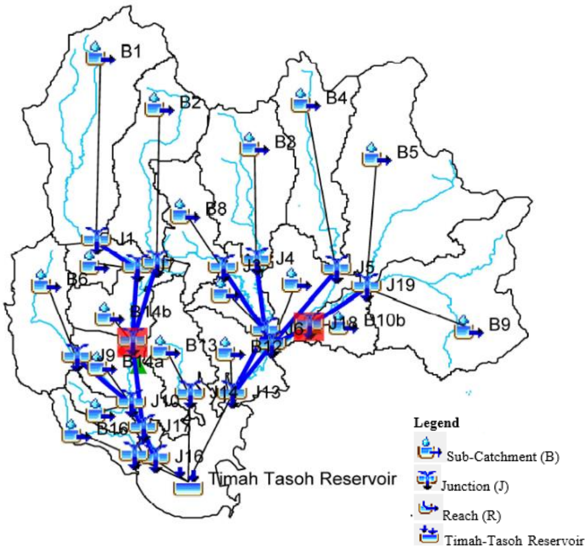

Fig. 2 – Basin model in the HEC-HMS model

Table 3 – Optimised hydrological parameters

Sub-Catchment	I_a (mm)	CN	Imp (%)	L_t (min)	Baseflow (m^3/s)
B1	39.43	56.30	3.4	8.65	0
B2	50.80	50	2	8.10	0
B3	20.55	71.20	10.5	5.54	0.90
B4	13.50	79	8	9.95	1.50
B5	21.26	70.50	15.4	4.35	0.30
B6	33.87	60	0.2	4.68	0.70
B7	22.40	69.4	6.5	1.64	0
B8	26.17	66	15	2.71	0.60
B9	16.57	75.40	20	7.47	0.50
B10a	13.10	79.50	10	5.32	1.50
B10b	22.40	69.40	15	4.22	0.03
B11	17.85	74	12.40	6.37	0.40
B12	21.77	70	10	13.61	0.50
B13	16.93	75	10	3.17	0.40
B14a	16.93	75	10	3.67	0.55
B14b	27.35	65	7.50	5.47	0
B15	22.29	69.50	4.34	0.97	0.30
B16	27.35	65	2.45	1.55	0.25

2.4 Inflow Simulation using HEC-HMS Based on LULC Change Scenarios

Agriculture, built-up areas, forests, vacant land, and water bodies were considered when analysing the land cover. Figure 3.5 shows the LULC classification in the study area.

The effects of several types of land use on the hydrological response of the Timah-Tasoh reservoir were modelled and simulated using a random future land use scenario. Future scenarios are divided into two scenarios. Scenarios 1 and 2 are deforestation and afforestation, which are low, medium, and high, respectively. The assumption was that reductions in forest area led to an increase in agricultural and built-up land. In contrast, increases in forest area resulted in agricultural and built-up land reductions, with potential proportions detailed in Table 5, modified from Adnan [11] for deforestation and proposed the value for afforestation. Deforestation was also assumed to convert forests to built-up and agriculture, which is considered deforestation and classified into Extreme 1 (50% each changed to agricultural and built-up), Extreme 2 (100% converted to agriculture), and Extreme 3 (100% converted to built-up).

Table 4 - Optimised lag values for routing

Reach	L_g (min)
R1	15.4
R2	15
R3	20
R4	20
R5	35
R6	150.3
R7	45
R8	10
R9	60
R10	140
R11	35
R12	40.5
R13	45
R14	25.4

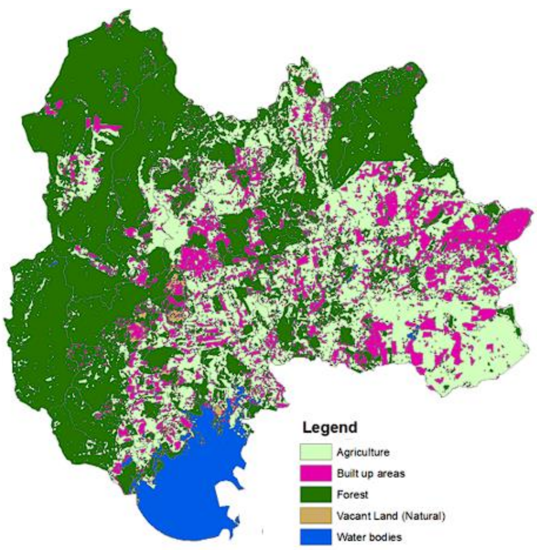

Fig. 3 – LULC for the study area

3. Results and Discussions

3.1 Performance of the HEC-HMS during the calibration and validation periods

The calibration and validation processes were done continuously to determine the best value of the hydrological parameters of J8 and J18. The HEC-HMS model was calibrated from 2001-2010 and validated from 2011-2019. Modifications were made to the parameters to balance the observed and simulated hydrographs adequately. The performance of the model during the calibration period can be shown in Table 6. In general, the model can capture the daily and monthly discharge moderately. The difference between observed and simulated peak discharge is between 56.9 – 22.1

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m^3/s and 33.1-41.5 m^3/s for daily and monthly discharge, respectively. Regarding R and RMSE, both indicators indicate moderate performance in simulated discharge, with R values of 0.4902-0.7954 and RMSE values of 3.8746 – 16.7297 m^3/s.

Table 5 – Percentage of LULC scenarios

	Scenario (%)		
Land Use	**Forest**	**Agriculture**	**Build up**
Deforestation			
Low	-20	20	0
Medium	-40	30	10
High	-60	40	20
Ext 1	-100	50	50
Ext 2	-100	100	0
Ext 3	-100	0	100
Afforestation			
Low	20	-20	0
Medium	40	-30	-10
High	60	-40	-20

Table 6 – Performance of the HEC-HMS during the calibration period (peak is the peak discharge, Obs is the observed discharge, and Sim is the simulated discharge)

Performance Indicator	J8		J18	
	Obs	Sim	Obs	Sim
Daily				
Peak (m^3/s)	50.9	73	56.9	111
R		0.4902		0.5139
RMSE (m^3/s)		3.8746		4.6306
Monthly				
Peak (m^3/s)	33.1	73	41.5	111
R		0.6898		0.7954
RMSE (m^3/s)		12.4683		16.7297

As shown in Table 7, the performance of the HEC-HMS model during the validation period is slightly lower than its performance during the calibration period in terms of R and RMSE. However, the difference in peak discharge ranges from 19.9 to 26.1 m³/s for daily discharge and from 2.4 to 28.5 m³/s for monthly discharge. Notably, the peak discharge differences during the validation period are significantly smaller, indicating improved performance compared to the findings from the calibration period. Both the calibration and validation processes show an increase in performance, which is considered satisfactory, as an R-value is greater than 0.4 and it is deemed acceptable [12]. The findings also align with previous studies, such as Ali et al. [13] and Zhang et al. [14], which reported R-values greater than 0.5 when simulating observed discharge. An overall evaluation of the models reveals that monthly simulations perform better than daily simulations. This aligns with Moriasi et al. [15], who found that model accuracy tends to decrease for shorter time intervals, such as daily data, compared to longer intervals like monthly data. Based on these results, it can be concluded that both models performed reasonably well in simulating discharge.

Table 7 – Performance of the HEC-HMS during the validation period

Performance Indicator	J8		J18	
	Obs	Sim	Obs	Sim
Daily				
Peak (m^3/s)	35.9	62.3 (26.1)	71.7	51.8 (19.9)
R		0.5559		0.5047
RMSE (m^3/s)		4.325		4.9598
Monthly				
Peak (m^3/s)	33.8	62.3 (28.5)	49.4	51.8 (2.4)
R		0.6495		0.6695
RMSE (m^3/s)		15.4336		13.5519

3.2 LULC Map Based on Scenario Conditions

The simulation of LULC changes for the future is carried out under two scenario conditions, namely deforestation and afforestation. The distribution of land use scenarios area is shown in Figures 4-6. As shown in Figure 4, it can be seen that the forest area has decreased up to 53.34 km^2 and increased for agriculture and built-up area up to 35.56 km^2 and 17.78 km^2, respectively, to represent deforestation. The study also creates a scenario with no forest area, indicating extreme deforestation, as shown in Figure 5.

For the afforestation scenario (Figure 6), forest dominated the land use, accounting for 97.67 km2 to 114.27 km^2. The scenario aligns with the scenario projected by Hu et al. [16], in which afforestation scenario should have the forest area exceeding 70% of the total for land use.

3.3 Inflow Simulations Corresponding to the LULC Scenarios

Table 8 illustrates the difference in peak discharge based on the LULC scenarios at every junction that becomes an inflow to the Timah-Tasoh reservoir. In general, the study found that the catchment is not very sensitive to land use, in which the changing of discharge simulation using the HEC-HMS model is insignificant, and the difference value is small. In terms of the deforestation scenarios (low until ext 3), it can be seen from the table that the peak discharge will increase between 1.1 and 3.9 % for all scenarios, except at J13, which decreases the peak discharge by -1.3 %. This finding occurred since, during deforestation, most of the area will be less infiltrated due to less forest-covered area and an increase in the impermeable land, which causes an increase in the peak discharge [17].

For the afforestation scenario, two distinct patterns were observed. At J13, peak discharge was decreased, with a reduction of approximately -1.4%. It can be attributed to the expansion of forest cover, which enhances infiltration, reduces surface runoff, and improves water retention in the soil. Similar findings were reported by Kabeja et al. [18] and Umukiza et al. [19].

In contrast, at J16, an increase in peak discharge was observed, ranging from 0.8% to 1.1%, which differs from the trend seen at J13. This increase could be explained by the location of the afforestation area, which is primarily concentrated in the upper parts of the catchment (as shown in Figure 6). This spatial distribution may accelerate runoff concentration downstream, contributing to the higher peak discharge at J16.

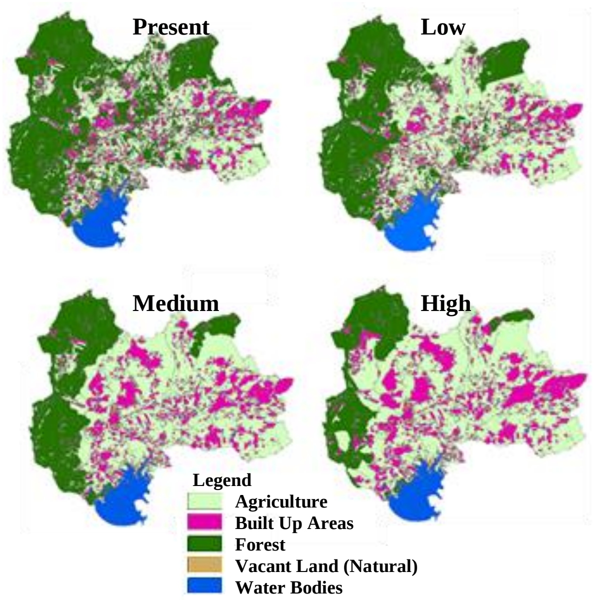

Fig. 4 – LULC classification for deforestation

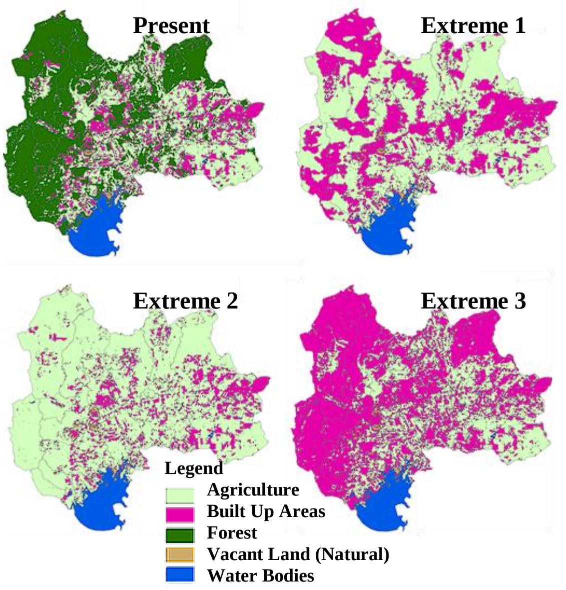

Fig. 5 – LULC classification for extreme deforestation

Overall, there is no significant difference in peak discharge across the different LULC scenarios examined in this study. Alaoui et al. [20] indicated that higher elevation sub-catchments are less affected by land use changes than lower elevation sub-catchments. Therefore, the lack of significant changes observed in this study area could be attributed to the relatively high elevation of the sub-catchments.

4. Conclusion

This study evaluates the inflow simulation of the Timah-Tasoh reservoir using the HEC-HMS model under different LULC scenarios. These LULC scenarios were developed to represent possible future land use and land cover conditions across the study area. The model's performance was satisfactory for simulating daily and monthly discharge, with an R-value greater than 0.4902.

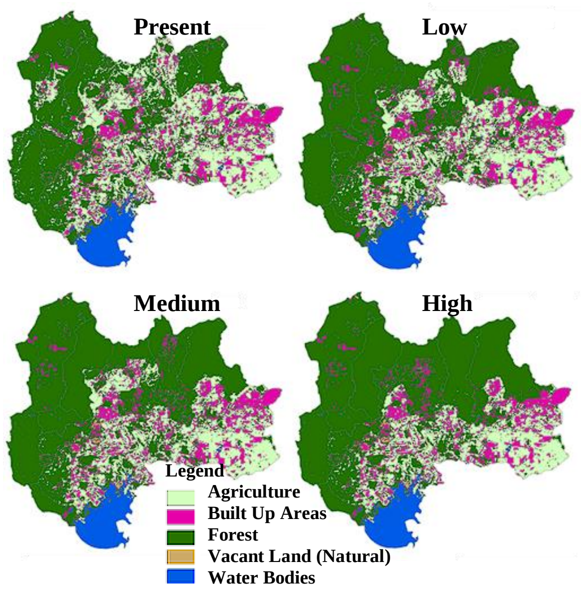

Fig. 6 – LULC classification for afforestation

Table 8 – Different in peak discharge based on the LULC scenarios (Low is the lower, Med is the medium, High is the higher, Ext 1 is the extreme 1, Ext 2 is the extreme 2, and Ext 3 is the extreme 3)

LULC Scenarios	J13	J14	J15	J16
Present (m^3/s)	207.8	13.7	7	107
Deforestation (%)				
Low	-1.3	0	0	1.1
Med	1.4	0	0	1.2
High	1.4	0	0	1.2
Extreme deforestation (%)				
Ext 1	2.6	0	0	3.7
Ext 2	2	0	0	3.4
Ext 3	2.8	0	0	3.9
Afforestation (%)				
Low	-1.4	0	0	1.1
Med	-1.4	0	0	0.9
High	-1.4	0	0	0.8

The study observed only the slightest changes in peak inflow discharge corresponding to the different LULC scenarios. Under the deforestation scenario, peak discharge increased slightly by up to 3.9 %. In contrast, there was a slight decrease in peak discharge at J13 by -1.4% under the afforestation scenario, while at J16, peak discharge increased marginally by 1.1%.

These findings support decision-making processes by enabling comparisons between land management policies and climate adaptation strategies.

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