Assessment of Sedimentation Problem in Kenyir Hydropower Reservoir

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Abstract. Sedimentation issue is becoming an emerging challenge in hydropower dam due to land use changes and frequent heavy storm in the recent decades. This study carried out an assessment on sedimentation problem in Kenyir hydropower reservoir in Malaysia based on hydrological, land use, topographic, soil erosion and dam capacity data. The results showed that the average live storage for Kenyir reservoir could be sustained at least for another 6774 years while dead storage can survive more than 5675 years. The number of year required for Kenyir reservoir to be fully deposited with sediment will be shorten to 3784 years for dead storage if 50% reduction in forest coverage.

1. Introduction
The growing need for renewable energy makes necessary to improve the management of hydropower dams in order to extend their lifespan and maintain the hydropower contribution to the global electricity production [1]. Understanding and management of sediment is very important for hydropower reservoirs in order to provide sustainable, long-term service at acceptable levels of environmental impact [2]. Accumulation of sediment in the dam impoundment (e.g., sedimentation) is considered as the major and most common threat to existing dam infrastructure. Uncontrolled human encroachment and drastic land use changes are the prominent factors that have contributed to the sedimentation problems in the reservoir [3,4,5,6]. The consequences of sedimentation problems that are expected are (1) loss of dead or/and life storage, (2) damages to turbines of hydropower plants and (3) impact to the river, especially downstream of the dam. Sediment coarser than 0.1 mm may greatly accelerate the erosion of turbines parts; even smaller grain sizes may cause damages if containing quartz [7,8,9]. It may be the main siltation problem for high head hydropower. It is evident that most hydropower schemes are located in the mountainous area with courser bed materials in the inflowing rivers. Consequently, the monitoring of sedimentation in hydropower dams is considered as a priority and immediate solutions must be implemented to improve the management of existing reservoirs, particularly those used for hydropower. Guo and Cao [2] provided the experience of Sanmenxia
Reservoir showing that the having optimal operation mode and cascade dams upstream greatly reduces the sedimentation in the downstream reservoirs and in the long run prolongs the lifespan of the downstream reservoirs. Sumi [10] present their finding on the effect of sediment flushing and environmental mitigation measures in the Kurobe River for two major dams namely Unazuki and Dashidaira. It was concluded that drawing sediment while operating at low water level significantly improves the flushing efficiency. Assessments of the rates of reservoir sedimentation are crucial for calculating a dam’s life expectancy and for optimizing dam operations, whether for purposes of irrigation, hydroelectricity or flood control [11]. Sedimentation issue is becoming an emerging challenge in hydropower dam in Malaysia due to land use changes and frequent heavy storm in the recent decades [12,13,14]. Therefore, this assessment study is aimed to provide sedimentation analysis in Kenyir hydropower dam in Malaysia based on present and future land use change scenarios.

2. Methodology

2.1. Study Area
Kenyir Dam is approximately 40 km inland from Kuala Terengganu and is located at approximate latitude 5º 1’ 20” North and longitude 102º 54’ 30” East. The Kenyir dam is built between 1978 until 1986 as a rockfill clay core dam. Kenyir Dam used to be the largest dam in Malaysia in terms of reservoir surface area and gross storage before Bakun Dam’s impoundment in 2011, with a large man-made lake surface area of approximately 369 km² at Full Supply Level (FSL), and gross storage volume of 13.6 billion m³ at FSL. The distance of dam from the main inflowing river mouth is around 60 km. In addition, Kenyir Dam commands a catchment area of 2,600 km². Kenyir reservoir has six major tributaries, namely Sg. Terengganu as the main river, Sg. Terengan, Sg. Cacing, Sg. Petang, Sg. Tembat and Sg. Petuang. Further details of Kenyir Dam are shown in Table 1 below. Kenyir reservoir catchment consists of 21 sub-catchments and the area size for each sub-catchment is summarized in Table 2. The average annual rainfall in Kenyir reservoir catchment is 4245 mm while annual evaporation rate is 1500 mm with temperature ranges between 21°C to 34°C. The time series of annual rainfall from 1987 to 2014 at Kenyir reservoir is shown in Figure 1. There are three major soil series in Kenyir reservoir catchment, which consists of 82.5% of steep land soil, 14.3% of Kuala Brang-Kedah-Serdang and 3.2% of Rengam-Bukit Temiang. The land use distribution of Kenyir catchment consists of 52.83% of natural forest, 34.23% of water body, 5.19% of transportation and road reserves, 5.0% of public utilities, 0.46% of residential, 0.33% of leisure and recreational area, 0.2% of infrastructure and utility and 1.74% of industrial area, respectively.

| Item                        | Unit | Value  |
|-----------------------------|------|--------|
| Length of Dam               | [m]  | 800    |
| Height of Dam               | [m]  | 150    |
| Spillway Length             | [m]  | 140    |
| Dam Crest Elevation         | [mRL]| +155   |
| Maximum Flood Level         | [mRL]| +153   |
| Full Supply Level           | [mRL]| +145   |
| Minimum Operating Level     | [mRL]| +120   |
| Lake Area                   | [km²]| 369    |
| Catchment Area              | [km²]| 2612   |
| Gross Storage               | [m³] | 13.6 x 10⁹ |
| Live Storage                | [m³] | 7.4 x 10⁹ |
| Name of Power Station       |      | Sultan Mahmud |
| Installed Capacity          | MW   | 4 x 100 |
| Average Annual Energy Output| GWh  | 1,600  |

Table 1. Details of Kenyir Dam
Table 2. Area size for each sub-catchment of Kenyir reservoir

| Sub-Catchment | Area (KM$^2$) | Sub-Catchment | Area (KM$^2$) |
|---------------|---------------|---------------|---------------|
| K1            | 426           | K12           | 37            |
| K2            | 117           | K13           | 55            |
| K3            | 281           | K14           | 151           |
| K4            | 211           | K15           | 74            |
| K5            | 69            | K16           | 38            |
| K6            | 100           | K17           | 98            |
| K7            | 141           | K18           | 139           |
| K8            | 127           | K19           | 126           |
| K9            | 117           | K20           | 13            |
| K10           | 96            | K21           | 4             |
| K11           | 192           |               |               |

Total sub-catchments area = 2612 km$^2$

Figure 1. Time series of annual rainfall from 1987 to 2014 at Kenyir reservoir

The design rainfall of specific average recurrence interval (ARI) at Kenyir reservoir catchment is estimated and the results are presented in Table 4. The Universal Soil Loss Equation (USLE) is used to calculate the catchment soil erosion rates in this study. The USLE is shown in Equation 1 as below:

$$A = R \times K \times L \times S \times C \times P$$  

Where,

- $A$ = Soil loss in ton/ha/yr
- $R$ = Rainfall erosivity factor (MJ mm ha$^{-1}$hr$^{-1}$)
- $K$ = Soil erodibility factor
- $LS$ = Topographic factor where $L$ is the length and $S$ is slope steepness in dimensionless unit
- $C$ = Crop management factor (represent the degree of soil erosion under crop cover compared to bare earth) in dimensionless unit
- $P$ = Conservation practice factor (represent mitigation and conservation measures taken compared to no measures taken) in dimensionless unit

For this study, the Sediment Delivery Ratio (SDR) curve proposed by Balamurugan was used to determine the sediment yield for each sub-catchment. The SDR curve is applied for whole catchments which are predominantly forested with similar sediment delivery characteristics. The SDR is inversely proportional to the catchment size. The sediment yields are computed as the product of soil erosion rate from each sub-catchment with the corresponding SDR values.

From the total sediment yield rates, the estimation of year required to fully deposit of sediment in Kenyir reservoir can be calculated by using Equation 2 below:
Year required to fully deposit of sediment = \( \frac{\text{Volume of Storage (m}^3\text{)}}{\text{Total Sediment (m}^3\text{/yr)}} \)  

(2)

3. Results and Discussion

The results of sediment yield for each sub-catchment of Kenyir reservoir catchment is presented in Table 3. For the present situation, estimation of the catchment erosion rate was based on current land use conditions. The average erosion rate across the catchment is 2.4 tonnes/ha/yr. The average erosion rate is considered as ‘low’ according to Department of Agriculture (DOA) soil erosion rankings and within expectation for a predominantly forested region of moderate elevation and slope. The estimated total annual flow and sediment transport for return periods of 2, 5, 10, 50 and 100 ARIs are summarized in Table 4. The number of years required to be fully deposited with sediment in Kenyir reservoir for dead, live and gross storages are calculated and the results are presented in Table 4. For ARIs between 2 and 100 years, the number of years required for Kenyir reservoir to be full deposited with sediment ranges from 12449 to 30212 years. The results show that the average live storage for Kenyir reservoir can be sustained at least for another 6774 years while dead storage can survive more than 5675 years.

Table 3. Estimated sediment yield for each sub-catchments of Kenyir reservoir catchment

| Sub-Catchment | Sediment yield | Sediment yield |
|---------------|----------------|----------------|
|               | tonnes/yr      | tonnes/ha/yr   | tonnes/yr | tonnes/ha/yr |
| K1            | 60114          | 1.4            | 11188     | 3.0          |
| K2            | 22770          | 1.9            | 11040     | 2.0          |
| K3            | 57749          | 2.1            | 31287     | 2.1          |
| K4            | 35884          | 1.7            | 22806     | 3.1          |
| K5            | 18248          | 2.6            | 8041      | 2.1          |
| K6            | 25443          | 2.6            | 22796     | 2.3          |
| K7            | 39528          | 2.8            | 29365     | 2.1          |
| K8            | 24434          | 1.9            | 27151     | 2.2          |
| K9            | 25779          | 2.2            | 5096      | 3.9          |
| K10           | 23904          | 2.5            | 1537      | 4.1          |
| K11           | 34532          | 1.8            |           |              |

Total sub-catchments area = 2612 km²

Table 4. Estimated sediment yield for each sub-catchments of Kenyir reservoir catchment

| Condition                          | Present catchment condition |
|------------------------------------|-----------------------------|
| Return period ARI                  | 2                           | 5                           | 10                          | 50                          | 100                         |
| Catchment rainfall                 | 411                         | 582                         | 712                         | 975                         | 1087                        |
| Peak flow (m³/s)                   | 3718                        | 5277                        | 6466                        | 8880                        | 9899                        |
| Total flow (MCM)                   | 1236                        | 1679                        | 2018                        | 2706                        | 2997                        |
| Total Sediment                      | 693238                      | 853227                      | 998355                      | 1437772                     | 1682334                     |
|                                  | m³/yr                       | 450155                      | 554043                      | 648283                      | 933618                      | 1092425                     |
| Year required to be fully deposited | Gross storage (m³)           | 30212                       | 24547                       | 20978                       | 14567                       | 12449                       |
|                                  | Live storage (m³)            | 16439                       | 13356                       | 11415                       | 7926                        | 6774                        |
|                                  | Dead storage (m³)            | 13773                       | 11190                       | 9564                        | 6641                        | 5675                        |
The future land use change conditions on runoff and sediment transports into the Kenyir reservoir are also investigated in this study. Table 5 shows the estimations of flow and sediment yield under the future land use scenario. The result show that if 10% of the forest have been converted to other purposes, the increase in peak flow and peak water elevation is minimal. However, when the conversion increases to 50%, the peak flow increased by another 370 m$^3$/yr and water level increased by about 0.1 m. The number of year required for Kenyir reservoir to be fully deposited with sediment will be shorten to 3784 years for dead storage if 50% reduction in forest coverage. Even though it seen like the Kenyir reservoir still can sustain for more than 3500 years, but it is important to conserve the catchment especially near the dam site in order to prevent the high soil erosion occurred and deposit the sediment at the water intake point of Kenyir dam.

| Condition                              | Present | Future 100 yr ARI |
|----------------------------------------|---------|-------------------|
| Percentage reduction in forest from existing coverage | -       | 10%               |
|                                        |         | 25%               |
|                                        |         | 50%               |
| Peak flow (m$^3$/s)                    | 9899    | 10011             |
|                                        |         | 10132             |
|                                        |         | 10267             |
| Total flow (MCM)                       | 2997    | 3001              |
|                                        |         | 3007              |
|                                        |         | 3018              |
| Peak water elevation (m)               | 149.94  | 149.9             |
|                                        |         | 150.0             |
|                                        |         | 150.0             |
| Total Sediment                         |         |                   |
| tonnes/yr                             | 1682334 | 1850568           |
| m$^3$/yr                               | 1092425 | 1201667           |
|                                      |         | 1365531           |
|                                      |         | 1638637           |
| Year required to be fully deposited    |         |                   |
| Gross storage (m$^3$)                  | 12449   | 11318             |
|                                        |         | 9959              |
|                                        |         | 8300              |
| Live storage (m$^3$)                   | 6774    | 6158              |
|                                        |         | 5419              |
|                                        |         | 4516              |
| Dead storage (m$^3$)                   | 5675    | 5159              |
|                                        |         | 4540              |
|                                        |         | 3784              |

4. Conclusion
The assessment of sedimentation problem in Kenyir hydropower reservoir has been carried out based on hydrological, land use, topographic, soil erosion and dam capacity data. The results showed that the average live storage for Kenyir reservoir could be sustained at least for another 6774 years while dead storage can survive more than 5675 years. The number of year required for Kenyir reservoir to be fully deposited with sediment will be shorten to 3784 years for dead storage if 50% reduction in forest coverage. Even though the sedimentation problem in Kenyir reservoir is not in critical stage but the development activities will contribute to the increasing level of sedimentation. A more comprehensive monitoring program is recommended so that the results can be used confidently in future flow and sediment load predictions.

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