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Land-use based GIS-modelling for sedimentation reduction at Bili-Bili Dam, Indonesia

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Abstract This study deals with determining land-use scenarios that will assist in reducing sedimentation at a dam site. The study site is the contributing basin of the Bili-Bili Dam, South Sulawesi, Indonesia. The land-use scenarios were formulated by using an erosion model built within a Geographic Information System framework. Input data for the model were collected using aerial photographs, satellite imagery and direct observation. Seven land-use scenarios were developed for evaluating the most suitable land use within the drainage basin. The model results show that the basin without conservation generates 1473.04 m^3 km^{-2} $year^{-1}$ of sediment. The fourth scenario (with conservation) can potentially reduce sediment to approximately 1022.72 m^3 km^{-2} $year^{-1}$, which is lower than the dead storage of Bili-Bili Dam. It is recommended that this sedimentation rate be maintained in order to reach the design life of 50 years for this dam. Based on this work, it was also determined that the existing land-use framework implemented by the local government (Gowa Regency) generates erosion rates higher than the tolerable soil loss (TSL). It is therefore suggested that the existing land use should be modified according to the scenarios developed in this work.

Key words Bili-Bili Dam; erosion; GIS; Indonesia; Jeneberang basin; land use; reservoir; sediment, Sulawesi; tolerable soil loss

INTRODUCTION

In recent decades the rapid exploitation of natural resources has increased erosion rates in Indonesia, which consequently has affected ecosystem health. This problem is highlighted in the estimated annual cost resulting from the decline in water quality that is directly attributable to erosion of agricultural land, which ranges from $2.2 billion to $7 billion. Agencies within the Department of Agriculture and Regional Planning are struggling with the question of how to manage water resources at the drainage basin scale to achieve an acceptable mix of products and services. Land-use change affects the sediment yield in water bodies (Banasik, 1989). This study examines land-use scenarios aimed at reducing the sedimentation rate at Bili-Bili Dam on South Sulawesi, Indonesia. The dam is very important to the region since it is the primary water source for the city of Makassar (population 4 million) and also supplies irrigation water for more than 10 000 ha in the Takalar and Gowa Regencies.

Large changes in flow rate (from 2.7 to 2037 m^3 s^{-1}) and extremely high sedimentation rates indicate the potential for serious land degradation within the drainage basin. In 1992, 1794 m^3 km^{-2} $year^{-1}$ of sediment flow into the dam was recorded (CTI

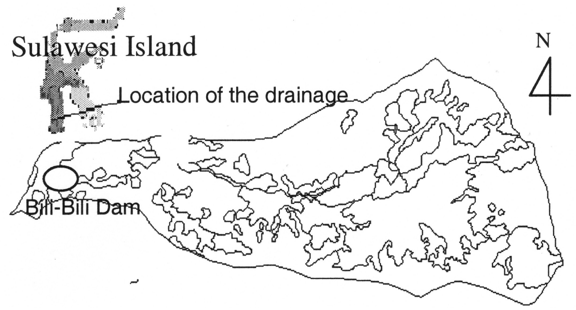

Fig. 1 Location of Bili-Bili Dam (map not to scale).

Engineering, 1993; CTI Engineering, 2001; PPLH, 2001). Clearly, this level of sedimentation threatens the lifespan of the dam. Based on this event, it became necessary to formulate a land-use scenario that could potentially reduce the sedimentation rate in the dam. The derived scenario is an important instrument for decision makers at the local government level to help produce a wise management strategy to reduce erosion rates within the drainage basin.

METHODOLOGY

The research was conducted in the Jeneberang drainage basin, the main basin where the Bili-Bili dam is located. The dam site is located 20 km from the city of Makassar, on South Sulawesi, Indonesia (Fig. 1). The drainage basin is 32 km^2 and supplies all the water to the reservoir. The scenarios were formulated using a GIS-based, interactive computer program. The computer model is designed to simulate erosion rates in the drainage basin (Munir & Suripin, 1998; Munir *et al.*, 2000, 2002). The model was developed using Borland Delphi and Map Object components. Input parameters for the model are: erosivity, erodibility, and the slope-length, land cover and conservation factors.

Erosivity factors were established using the method proposed by Bols (1976). Iso-erodent maps were developed from data for the Malino, Pallekoang, Tallue and Lebong meteorological stations, where the average annual rainfall is estimated as 3883 mm. Erodibility factors were developed from land-based surveys that were conducted by the Institution for Rehabilitation and Conservation, South Sulawesi. The soils in the basin consist of Ultisols and Entisols (USDA, 1992), of which the Ultisols are the most common. Length and slope factors were developed using digital elevation models that were generated using the IDRISI and SURFER programs. Steep slopes dominate the topography in the basin, and slopes of between 25 and 40% occupy 40% of the drainage basin. The slope-length factor varies between 0.39 and 21.44.

Land cover data were generated from aerial photographs and satellite imagery. The drainage basin is dominated by forest and arable land, with some parts of the drainage basin occupied by mixed agriculture (paddy fields and dryland agriculture). Historically, soil and water conservation projects have not been conducted in the basin, and it is estimated that no conservation practices are applied on more than 50% of the drainage basin. Small areas of the drainage basin are managed using traditional conservation

Table 1 The initial development scenarios for reducing sedimentation rate.

No.	Actions	Scenarios
1	Without conservation	–
2	Tillage for dryland agriculture parallel to contour direction	Scenario 1
3	Tillage and cropping for dryland agriculture parallel to contour, and traditional terracing.	Scenario 2
4	Tillage and cropping with mulch for dryland agriculture parallel to contour.	Scenario 3
5	Tillage and cropping rotation for dryland agriculture parallel to contour.	Scenario 4
6	Tillage and cropping rotation with mulch for dryland agriculture parallel to contour. Conservation practices (reforestation) on steep slopes (more than 40%).	Scenario 5
7	Tillage and cropping rotation with mulch and strip cropping for dryland agriculture parallel to contour.	Scenario 6
8	Tillage and cropping with mulch for dryland agriculture parallel to contour. Conservation practices (reforestation) on steep slopes (more than 40%) and fallow areas.	Scenario 7

techniques (e.g. terracing). These small conservations regions are considered in the erosion simulation. The land-use scenarios are developed based on the conservation plan of the local institution. The initial development scenarios for reducing sedimentation at the Bili-Bili Dam are described in Table 1.

Erosion rates were computed using the USLE method (Wischmeier & Smith, 1978). Sedimentation due to surface (*SEP*) erosion was computed using $SEP = E \cdot SDR$, where E is erosion rate (t ha^{-1} year^{-1}) and SDR is sediment delivery ratio computed using the formula described by Roehl (1962) $SDR = 36 \cdot A^{-0.20}$, where A is drainage area (km^2). Sedimentation rate (m^3 km^{-2} year^{-1}) was computed using a density of the soil of 1200 kg m^{-3}.

RESULTS

Dead storage of sediment (DSS)

The scenarios can be evaluated on the basis of the dead storage of sediment allocation within the Bili-Bili Dam (1100 m^3 km^{-2} year^{-1}). The reduction of sedimentation was calculated assuming that: (a) agricultural business is a priority for the local population, (b) the benefits of soil and water conservation will impact the local population widely, and (c) the cost for any conservation action is reasonable and feasible. Based on these considerations, the contribution of sediment under each scenario can be obtained as shown in Table 2.

From Table 2, it is obvious that scenario 4 (tillage and cropping with mulch for dryland agriculture parallel to the contour) generates an acceptable erosion rate with respect to the DSS of the dam (1022.72 m^3 km^{-2} year^{-1}). This value is lower than the dead storage of sediment in Bili-Bili Dam (1100 m^3 km^{-2} year^{-1}), so that this scenario meets the minimum acceptable standard for DSS. Based on the design parameters of the dam, the lifespan of the dam should be 50 years. Scenario 4 can be further developed by applying mulch combined with a vegetation cover on the cultivated area (Wischmeier & Smith, 1978). Implementation of other scenarios is possible, but also

Table 2 Erosion and sedimentation rates under various land-use scenarios.

No.	Scenario	Erosion rate (t ha^{-1} $year^{-1}$)	Sedimentation rate (m^3 km^{-2} $year^{-1}$)
1	Without conservation	163.52	1473.04
2	Scenario 1	157.04	1414.67
3	Scenario 2	132.11	1190.09
4	Scenario 3	115.84	1043.53
5	Scenario 4	113.53	1022.72
6	Scenario 5	106.37	958.22
7	Scenario 6	103.70	934.17
8	Scenario 7	90.25	813.00

more costly. The reduction of sedimentation through implementation of scenario 4 in a timely manner may be difficult, but if the benefits of such an implementation can be demonstrated and shown to be effective to the local population, implementation will be feasible (Zubair, 2001).

Evaluation of tolerable soil loss (TSL)

Scenarios can be developed not only to examine land-use patterns that will reduce sedimentation rates at the dam, but also to identify tolerable maximum erosion rates to assure optimal productivity and sustainability of agricultural land. Tolerable soil loss (TSL) estimates for the Jeneberang drainage basin were generated from soil survey information. It is concluded that soil erosion rates in the basin are generally higher than the TSL. The spatial distribution of soil erosion rates that are higher than the TSL is presented in Fig. 2.

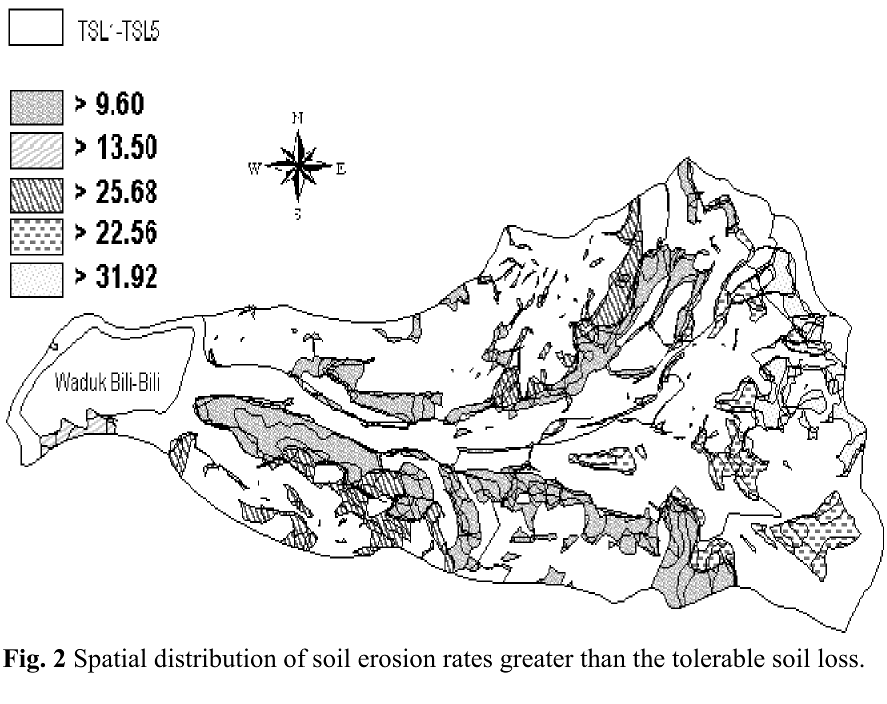

Fig. 2 Spatial distribution of soil erosion rates greater than the tolerable soil loss.

Table 3 Erosion and sedimentation rates derived from scenario 4 in the Jeneberang drainage basin.

No.	Scenario	Erosion rate (t ha^{-1} year^{-1})	Sedimentation rate (m^3 km^{-2} year^{-1})
1	Scenario 4 based on dead storage of sediment.	113.53	1022.72
2	Bank terracing on paddy fields and rotation and mulch on dryland with a 0 to 15% slope and erosion rate >TSL.	113.07	1018.57
3	Change of mixed agriculture area (grass, fallow area, plantation) with a 15 to 20% slope and erosion rate > TSL, to mixed agriculture (dryland) with bank terracing.	102.57	923.99
4	Change of area with a 25 to 40% slope and erosion rate >TSL, to agro-forestry crops (forest with mixed agriculture).	40.23	362.41
5	Underbrush area with a slope >40% are planted with fruit crops.	27.40	246.83
6	Fallow underbrush area with a slope >40% and erosion rate > TSL, are reforested.	18.08	162.87
7	Grass and dryland agriculture areas with a slope >40% and erosion rate >TSL, are reforested.	17.05	153.59

Scenarios derived from scenario 4 and used to minimize the degree by which the TSL is exceeded are described in Table 3. The average TSL for the drainage basin can be obtained by estimating the TSL for each soil type and its corresponding area. This results in an estimate of 18.30 t ha^{-1} year^{-1}. Based on the spatial pattern of erosion rates, changes to recommended land use can be obtained as shown in Fig. 3.

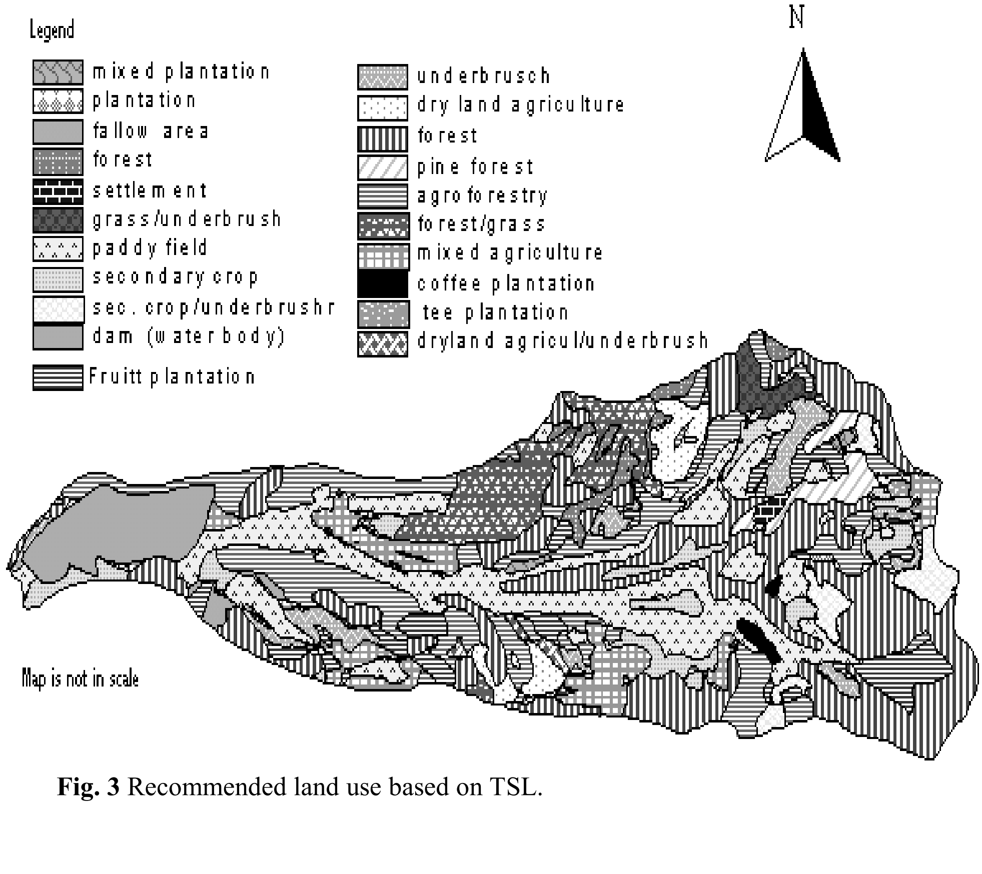

Fig. 3 Recommended land use based on TSL.

Table 3 shows that re-forestation of fallow areas with slopes greater than 40% and high erosion rates results in an estimated erosion rate of 18.08 t ha^{-1} $year^{-1}$, which is lower than the basin-wide derived TSL value. Such management measures are therefore recommended to meet both the DSS and TSL criteria for minimizing the erosion in the drainage basin.

Evaluation of spatial plan declared by local government (Gowa Regency)

In the spatial plan (RTRW, 2002) of Gowa Regency, the Jeneberang drainage basin is divided into two development zones: B and E. Zone B is centred around Parang, which serves Parangloe. Development in this zone is mainly focused on water front tourism and water resources for irrigation. Zone E is centred around Malino, which serves Tinggimoncong. Development in this zone is proposed mainly for ecotourism and agrotourism (with fruit crops, vegetables and tea plantations).

In some areas of the drainage basin, zones are proposed for conservation forest, limited production forest, and agriculture (passion fruits, cashew nuts, coffee and vegetables). The sediment contribution of each scenario based on the spatial plan developed by the local government is presented in Table 4. The sedimentation rates presented in Table 4 are generated from scenario 4 (Table 2). It is proposed that the spatial plan that is developed by the local government be abandoned to reduce the sedimentation rate in the dam.

Due to the economic orientation of the spatial plan developed by the local government, the sedimentation rate in the dam will increase. Conversely, the simulations based on scenario 4 in Table 2 were generated from a conservation point of view. It is therefore necessary to modify the existing spatial plan developed by the local government. A land capability approach may be suitable for the site specifics of the Jeneberang drainage basin. Sinukaban (1989) reported that inappropriate land use in the Jeneberang drainage basin causes tremendous sedimentation at the Bili-Bili Dam.

Table 4 Erosion and sedimentation rates under the spatial plan developed by the local government (Gowa Regency).

No.	Scenario	Erosion rate (t ha^{-1} $year^{-1}$)	Sedimentation rate (m^{-3} km^{-2} $year^{-1}$)
1	Without conservation action	163.2	1470.16
2	Protected forest	144.85	1304.86
3	Limited production forest	168.17	1514.93
4	Cultivation area (mixed agriculture)	160.96	1449.98
5	Cultivation (tree plantation)	154.24	1389.45
6	Protected forest and limited production forest	147.23	1326.30
7	Protected forest with limited production forest, and cultivation with mixed agriculture HL + HPT + KBD I	142.39	1282.70
8	Protected forest with limited production, forest, cultivation with mixed agriculture, and tree plantations	130.83	1178.56

CONCLUSIONS AND RECOMMENDATIONS

A GIS-based erosion model is a powerful instrument for simulating land-use scenarios in order to reduce sedimentation rate at the Bili-Bili Dam. The spatial plan scenario (scenario 4) generated during this study can be used as a starting point to modify the existing land-use changes proposed by the local government.

Based on the application of the erosion model, serious erosion within the drainage basin is mainly generated by dryland agriculture without conservation practices where the local slope is greater than 40%. Application of terraces, strip cropping, mulch and crop rotation within the dryland agriculture regions can be helpful in terms of reducing sediment flow into the dam. Furthermore, re-forestation of fallow areas and other arable land with slopes greater than 40% is absolutely necessary to reach the design life of the dam.

Action plans for preventing environmental degradation in the drainage basin, e.g. periodic environmental monitoring, sediment trap construction and land use optimization, should be planned by the local government. Empowering non-governmental organizations and local inhabitants of the drainage basin can prevent or minimize the environmental degradation. A land use optimization study should be conducted with the purpose of maximizing land-use benefits while minimizing environmental risks.

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