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Integration of analytic hierarchy process and weighted goal programming for land use optimization at the watershed scale

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Abstract: In recent decades, the Hulu Langat Basin in Malaysia has been exposed to extensive changes in land use pattern and consequently hydrological conditions. Maintaining a reasonable balance between environmental currents and governmental/population demands is a difficult task. In this work, 3 land use scenarios were defined, which are the present (baseline), future, and water conservation plans. Weighted goal programming (WGP), integrated with the analytic hierarchy process (AHP), was used to optimize the baseline land use scenario with consideration of water conservation outcomes and future development trend. Three types of objectives were involved in the AHP-WGP approach, i.e. social, economic, and environmental. The values of environmental objectives were estimated using the optimized Soil and Water Assessment Tool (SWAT). Four planning alternatives were defined and formulated, i.e. A1, A2, B1, and B2. The AHP-WGP approach resulted in 4 optimized land development alternatives. In terms of the water conservation objective, alternatives A1 and B1 were more desirable than alternatives A2 and B2, respectively. However, due to the existing socioeconomic-environmental circumstances within the Hulu Langat Basin, alternatives B1 and B2 were more appropriate.

Key words: Land use optimization, weighted goal programming, analytic hierarchy process, SWAT, Hulu Langat Basin

1. Introduction

Currently, environmental issues such as air and water pollution, climate change, exhaustion of fossil resources, and conservation of biodiversity are drawing increased attention from the public, stakeholders, and scholars at the global scale. It is now clearly recognized that anthropogenic activities, e.g., land use change, yield major ecological and environmental strains [1]. Ecologically, sustainable management of natural resources requires a complete and accurate accounting of the social, economic, and ecological impacts of humans. There are several conflicting objectives in land use planning, such as profit, flood and erosion control, employment, and biomass yield [2–5]. Therefore, single-objective optimization approaches such as linear programming and integer programming cannot consider the vast scope of decision variables in a framework. These approaches treat the objective function and constraints differently, thus giving preference to one or more criteria at the expense of

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others. Goal programming (GP) is a way to make the treatment of evaluation criteria more comparable [6]. For a particular problem, GP formulates all of the targets in equivalent terms and they are included in the model as constraints. In GP, the relative importance of each target can be explicitly considered by assigning weights to the deviations in the objective function. In this way, specific directions of deviation for each target can be emphasized. GP is based on the 1958 March and Simon 'satisficing' theory and represents a practical and logical approach for modeling complex, real-world problems [6,7]. The analytic hierarchy process (AHP) is a measurement theory based on expert judgment to drive priority scales using pairwise comparisons [8]. In cases with both quantitative and qualitative criteria, a combined AHP-GP approach can be useful for solving optimization problems. AHP is also used to determine the weight or priority of the objectives in a multiobjective optimization problem [9].

In recent years, there has been a clear shift toward the use of weighted goal programming (WGP) instead of lexicographic goal programming [10]. Barnett et al. [11] applied a WGP approach with multidimensional scaling for land allocation in Senegalese subsistence farms. In 1994, Njiti and Sharp [12] used a WGP approach for managing the competition and conflicting land uses in Cameron. In their study, a model was developed for land allocation among agriculture, forest, and livestock uses. Verma et al. [13] evaluated 3 types of GP, i.e. min-max, weighted, and preemptive, for a reservoir system in India for optimal monthly operation. Ragkos and Psychoudakis [14] examined the possibilities of simultaneously achieving environmental goals such as reduction of agrochemical application, irrigation water use, and acceptable farm incomes in Greece. Their results revealed considerable possibilities for input reduction and income generation, which could offer a wide range of policy options. Recently, integration of GP with other knowledge-based optimization techniques such as fuzzy logic [3,15–18] and the genetic algorithm [19,20] are being widely researched.

The Langat Basin is located at the southern part of Klang Valley, which is the most urbanized river basin in Malaysia, and it is thought that this basin is currently experiencing 'spill-over' effects due to excessive development within the Klang Valley. In recent decades, the Langat Basin has experienced rapid development towards urbanization, industrialization, and intense agriculture. The Langat Basin is also a main source of drinking water for surrounding areas and a source of hydropower, and it has an important role in flood mitigation. Over the past 4 decades, the Langat Basin has served approximately 50% of the Selangor State population. However, Selangor State is currently facing water shortage problems, especially in urban areas [21]. The Hulu Langat Basin, as the most important upstream catchment of the Langat Basin, is facing some environmental problems due to unmanaged urban and agricultural development. Currently, there are 5 water treatment plants (WTPs) and a balancing reservoir inside the Hulu Langat Basin, which secure clean water for downstream consumers. According to the proposed guidelines by the Department of Town and Country Planning and the Department of Environment, there are severe limitations for urban development and agricultural activities in the upstream of water intake points. These limitations are mostly caused by terrain and existing water supply structures within the basin. The existing development trend in the Hulu Langat Basin, which does not appear to follow the development plan prescribed by land use authorities, has caused a drastic change in hydrological status of the basin [21]. The existing development trends, especially in urban and agriculture areas, can be a serious threat for soil and water resources within the basin.

This work was aimed at optimizing the present land use scenario of the Hulu Langat Basin using an AHP-WGP integrated approach with consideration of water conservation policy and future development level in the basin.

2. Materials and methods

2.1. Study area

Hydrometeorologically, the Hulu Langat Basin is affected by 2 seasons of monsoon, i.e. the northeast (November to March) and the southwest (May to September). Average annual rainfall is about 2400 mm. The wettest months are April and November, with average monthly rainfall exceeding 250 mm, while the driest month is June, with an average monthly rainfall not exceeding 100 mm. Topographically, the Hulu Langat Basin can be divided into 2 distinct areas in reference to the Langat River, i.e. a mountainous area upstream and undulating land in the center and downstream [21–23]. The Langat dam supplies domestic and industrial water and is used to generate power supply at moderate capacity for consumption within the Langat Valley. Currently, there are 5 WTPs within the study area (Figure 1). The Sg. Lolo, Sg. Pangsoon, Sg. Langat, Sg. Serai, and Cheras Batu 11 WTPs along the Langat River produce 0.41, 1.82, 386.4, 0.9, and 27 million liters per day of clean water, respectively [24,25]. Descriptions about this basin are given and illustrated in Figure 1 and Table 1.

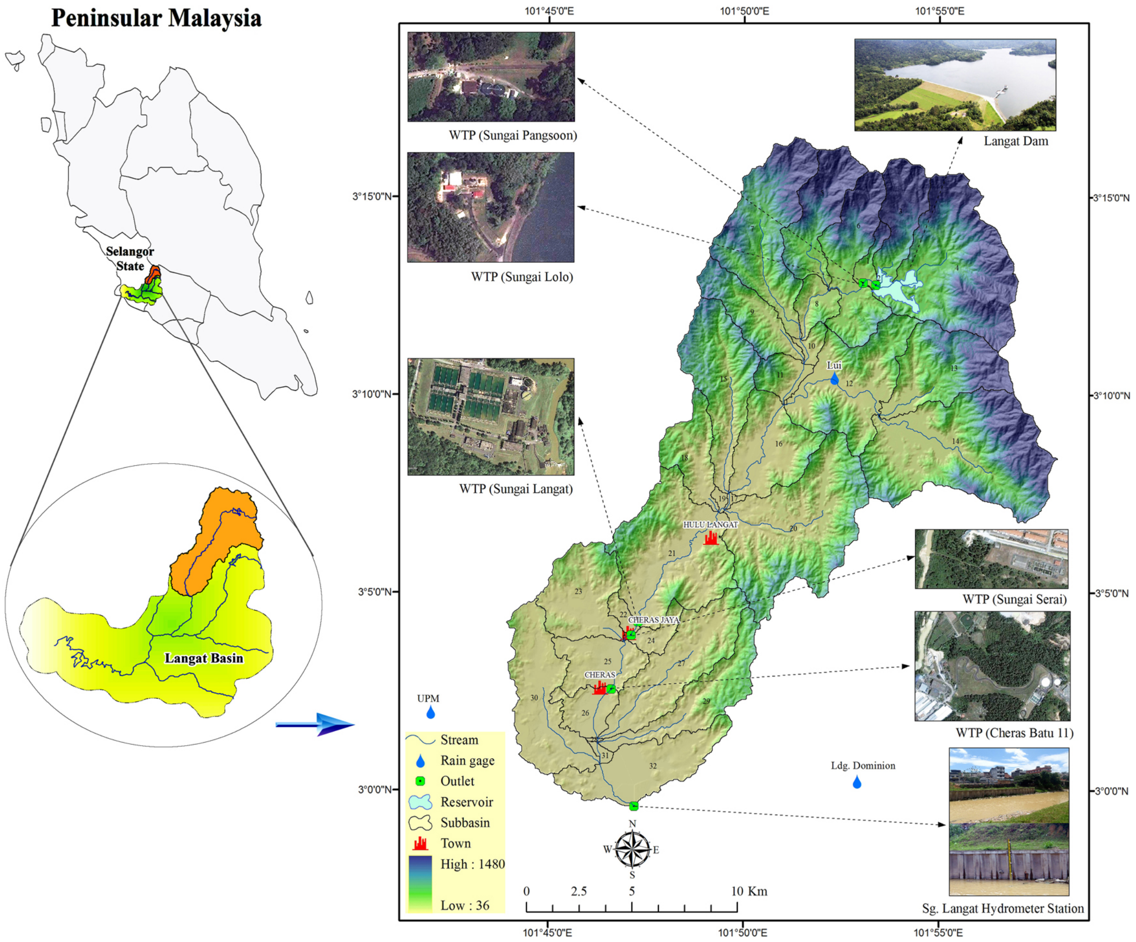

Figure 1. Geographic location and hydrological features of the Hulu Langat Basin.

2.2. Data set

Water discharge, sediment load, and precipitation data from 1984 to 2008 recorded at the Sg. Langat hydrometer and rain gauge stations for this study (Table 1) were obtained from the Department of Irrigation and Drainage of Malaysia. The utilized land use and soil maps in this work were obtained from the Soil Resource Management and Conservation Division, Department of Agriculture, Malaysia (Figure 2). Land use maps were reclassified into 9 categories, as represented in Figure 2.

Table 1. General information on the Hulu Langat Basin.

	Properties
Main river	Langat
Geographic coordinates	3°00′N to 3°17′N, 101°44′E to 101°58′E
Drainage area (km^2)	390.26
Basin length (km)	34.5
Average slope (%)	29.5
Max. altitude (m)	1480
Min. altitude (m)	36
Ave. altitude (m)	278
Ref. hydrometer station	Sg. Langat
Annual water discharge ($\times 10^6$ m^3)	289.64
Annual sediment load ($\times 10^3$ t)	146.6
Annual runoff (mm km^{-2})	742.16
Annual sediment yield (t km^{-2})	375.65
Ref. rainfall station	UPM Serdang, Kg. Lui, Ldg. Dominion
Precipitation (mm)	2453
Land cover*	Forest (54.6%), cultivated rubber (15.6%), orchards (2%), urbanized area (15%), horticulture and crops, oil palm, lake, and mining land (12.8%)

*Based on the 2006 land use map.

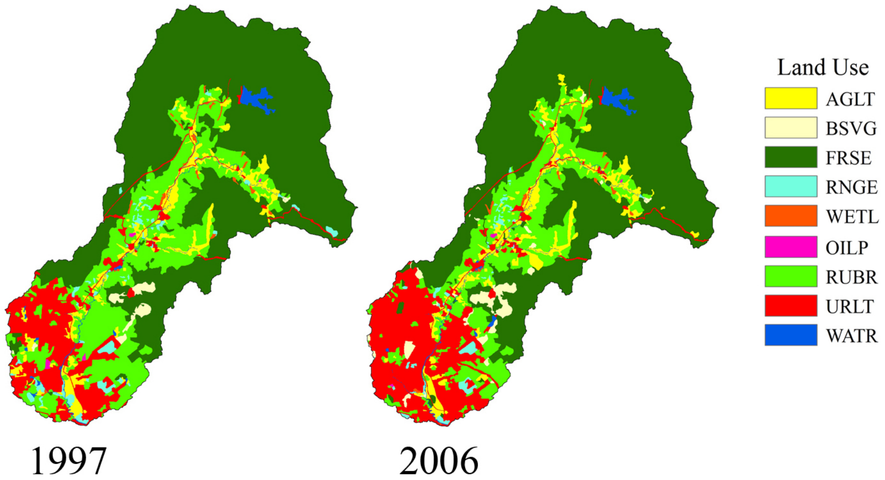

Figure 2. Land use maps used in this study.

2.3. Computational framework

The computational framework of this study is depicted in Figure 3. This work was carried out using 4 main steps, which are as follows:

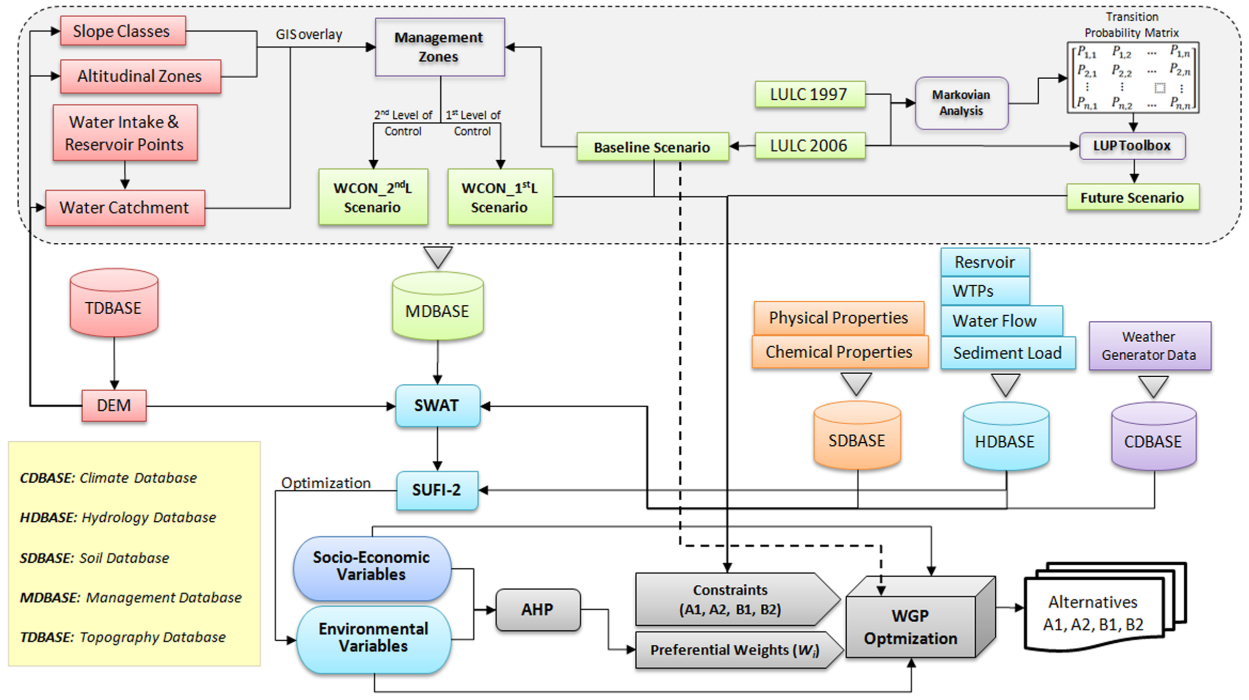

Figure 3. Computational framework of this study.

- First step: Construction of databases (topography, climate, soil, hydrology, and management); the management database contains spatial (GIS overlay) and stochastic (Markov chain analysis) techniques for extracting water conservation and future land use scenario.
- Second step: Soil and Water Assessment Tool (SWAT) simulation and its optimization using SUFI-2.
- Third step: Determining the weight of desired objectives using AHP.
- Fourth step: Optimization of the baseline land use scenario using the WGP approach and based on the defined alternatives.

Details of the above steps are discussed in the following sections.

2.4. Scenario development

2.4.1. Baseline scenario

The land use map dated 2006 was introduced as the baseline (present) scenario to be optimized and compared with the future and water conservation scenarios.

2.4.2. Future scenario

If we assume that the development trend in the period of 1997–2006 continues until 2020, we can project future land use condition for the year 2020. The year 2020 is the target time in which Malaysia will be a fully developed country (http://unpan1.un.org/intradoc/groups/public/documents/APCITY/UNPAN003223.pdf). In this study, the Markov approach [26] was utilized to extract the transition probability matrix for future simulation according to the rate of development during the period of 1997–2006. After computation of the transition probability matrix, the land use map dated 2006 was updated based on the values of that matrix using the land use update toolbox in ArcSWAT.

Table 2 shows a significant increase in the proportion of urban/built-up area in the Hulu Langat basin, mostly including urban and rural residential areas (URLT) and a significant decrease in rubber plantation (RUBR) proportion in 2020 in comparison with those proportions of the baseline scenario. Other land use categories will change marginally in the year 2020.

Table 2. Area of different land use categories across the total landscape and relative changes to the baseline scenario.

	Area (ha)			
Land use Scenari	Baseline	Future	Water conservation	
	2006	2020	WCON_1stL	WCON_2ndL
AGLT	2240	2310	316	2200
BSVG	760	730	300	300
FRSE	21,480	21,230	22,250	22,160
RNGE	420	440	418	420
WETL	150	130	148	150
OILP	20	20	6	20
RUBR	6850	4850	10,972	6750
URLT	6120	8370	3630	6040
WATR	420	380	420	420
	Relative changes to the baseline scenario (%)			
AGLT	0	3.13	–85.89	–1.79
BSVG	0	–3.95	–60.53	–60.53
FRSE	0	–1.16	3.58	3.17
RNGE	0	4.76	–0.48	0.00
WETL	0	–13.33	–1.33	0.00
OILP	0	0.00	–70.00	0.00
RUBR	0	–29.20	60.18	–1.46
URLT	0	36.76	–40.69	–1.31
WATR	0	–9.52	0.00	0.00

2.4.3. Water conservation scenario

As mentioned previously, there are 5 WTPs along the Langat River within the Hulu Langat Basin and the catchment area upstream of the WTP located at Cheras Batu 11 was discretized as the water catchment area. Based on the Guideline of Uphill Development (Department of Town and Country Planning, 1995), Environmental Quality Order (Department of Environment, 1987), and Riverfront Development Guideline (Department of Irrigation and Drainage, 1993), as cited by Anuar et al. [27], 4 management zones, i.e. conservation, preservation, control, and free, were defined within the Hulu Langat Basin (Table 3; Figure 4).

WCON_1stL and WCON_2ndL are water conservation scenarios based on the first level and the second level of control, respectively (Table 3). As presented in Table 2, agricultural activities in the Hulu Langat basin including horticulture crops (AGLT), barren or sparsely vegetated lands including bare land and sand/stone mining activities (BSVG), oil palm plantation (OILP), and URLT in the WCON_1stL scenario show 86%, 60%, 70%, and 41% reduction in areal proportions as compared to those of the baseline scenario, respectively. The WCON_1stL scenario plays an influential role in soil and water conservation; therefore, 60% and 3.6% increases in RUBR and evergreen forest (FRSE) acreage in this scenario are expected as compared to the baseline scenario.

In the WCON_2^{nd}L scenario, BSVG and FRSE show the highest areal changes as compared to those of the baseline scenario. In the same scenario, although the areal changes of AGLT, RUBR, and URLT are minimal, their influences are relatively considerable toward soil and water protection.

Table 3. Management plan for each zone in water conservation scenario.

Management zone	Properties	Activities allowed	Immediate action
Conservation	Upstream of the dam	No development allowed except very passive activities such as research, education, and nature tourism	Need to be conserved and controlled strictly, especially for approved development inclusive of the development project nearby the reservoir
Preservation	Altitude > 300 m, slope > 25°, upstream of the water intake point	No development allowed except very passive activities such as research, education and nature tourism, agro-based tourism, recreation, and controlled logging activities	Same as above, and camping activities are not allowed within the existing water catchment area boundary
Control (first level)	Altitude: 0–300 m, slope: 0°–25°, upstream of the water intake point	Low-scale development (environmentally friendly)	Monitoring, assessing, and reducing proposal at hill slope; development at 25° slope is not allowed immediately
Control (second level)		Very controlled logging, certain types of crops, certain developments allowed; no mining activity allowed and no nuclear and radioactive-based activities allowed	Industrial activities not allowed, especially at the bank of river
Free	Downstream of the water intake point	Without any limitations in development	Existing developments remain active

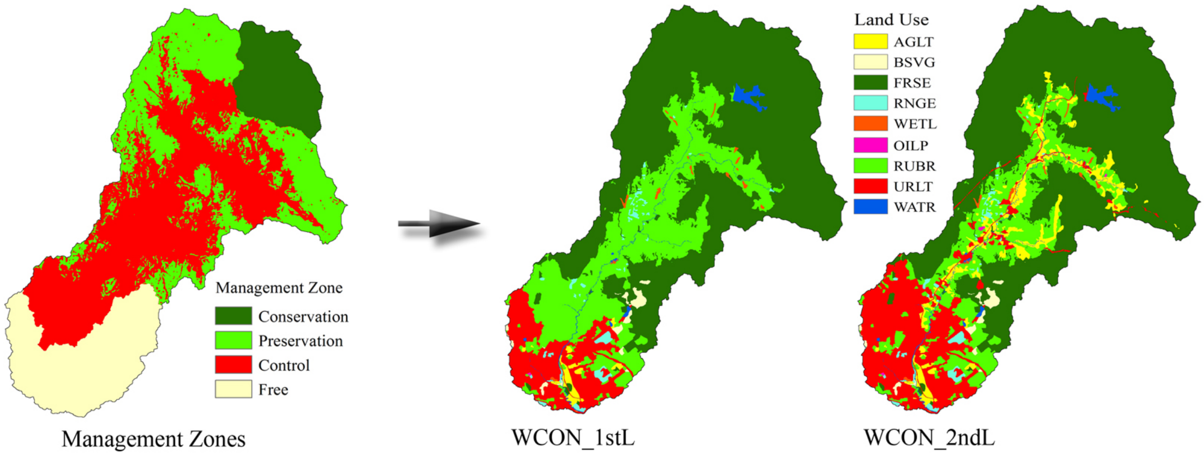

Figure 4. Water conservation scenarios and management zones.

2.5. Hydrological analysis

In this work, an optimized SWAT was used for hydrological analysis of the selected land use scenarios. SWAT as a watershed scale model predicts the impact of land management scenarios on water, sediment, and agricultural chemical yields in a spatially large and complex watershed due to varying soils, land use, and management conditions over a long period of time [28]. The sequential uncertainty fitting, version 2 (SUFI-2) algorithm in the SWAT Calibration and Uncertainty Procedures interface [29,30] was used for calibration and uncertainty analysis.

2.6. Land use optimization

At the Hulu Langat Basin, with regard to present and future land use scenario, 6 options for land development can be classified as follows:

1. After 2006, rural and urban development within the Hulu Langat Basin must be stopped.
2. After 2006, the development trend will continue until 2020 without any limitation.
3. After 2006, the baseline scenario with some minor alterations in land use acreage changes to the WCON_2^{nd}L scenario. The WCON_2^{nd}L scenario will then continue until 2020, while its function will be marginally more environmentally friendly than the baseline scenario.
4. After 2006, the baseline scenario with a high amount of transition cost changes to the WCON_1^{st}L scenario. The WCON_1^{st}L scenario with an influential role in soil and water conservation will then continue until 2020.
5. After 2006, the baseline scenario with some limitations in land use transition changes to the WCON_1^{st}L scenario. The optimized scenario will then continue until 2020. This option would impose a lesser amount of transition costs than the fourth option in order to capture all or parts of the WCON_1^{st}L objectives.
6. After 2006, the development trend will continue until 2020, but with some limitations in land use transition. This option is aimed at reaching the development level of urbanized areas and agricultural activities in 2020 and capturing a possible level of environmental targets contained in the WCON_1^{st}L scenario.

Having looked at these options, we can say that the first option is rejected due to the existing development trend within the basin. The second option does not follow the water conservation objectives outlined by the Department of Town and Country Planning and the Department of Environment. Thus, this option is also rejected. The third option seems reasonable; however, its outcomes do not match the water conservation objectives. The fourth option is extremely costly due to a large acreage of agriculture and urban area that should be changed to other categories. Therefore, this option is also rejected. The fifth and the sixth options are more reasonable to apply than the other options due to lower transition costs and moderate level of the achieved outcomes.

In this work, an integration of AHP and WGP was developed to plan the land use scenarios based on the fifth and the sixth options.

2.6.1. Fundamental theory

2.6.1.1. Weighted goal programming (WGP)

WGP is a distance metric-based variant of GP to solve multiobjective optimization problems. A multiobjective optimization problem can be formulated as follows:

$$Minimize Z(x) = [Z_1(x), Z_2(x), Z_3(x), ..., Z_p(x)], \tag{1}$$

subject to:

$$x \in X,$$

where Z(x) is a p-dimensional objective function, x is an n-dimensional vector of decision variables, and X is the feasible region [13].

GP seeks 'satisfaction' rather than 'optimization'. GP is concerned with achieving prespecified targets or goals. In GP, all objectives are represented using a single objective function to solve multiobjective problems. Each objective function receives a different weight according to its importance. WGP forms a single objective function as the weighted sum of various objective functions. WGP is formulated based on the following generalized form:

$$Minimize \sum_{i=1}^{p} (w_i^+ d_i^+ + w_i^- d_i^-), \tag{2}$$

subject to:

$$Z_i\left(x\right) + d_i^- - d_i^+ = G_i \text{for} i = 1, 2, ..., p, \tag{3}$$

$$x \in X,$$

$$x,\, d_i^+,\, d_i^- \geq 0, \tag{4}$$

where w_i^+ and w_i^- are positive numerical weights corresponding to positive and negative deviations to the ith objective, d_i^+ and d_i^- are deviations of the ith objective (Z_i) from the target value (G_i), and w_i^+ and w_i^- are nonnegative [13].

In GP, the decision maker must decide which deviational variable is unwanted. The unwanted deviations must be penalized in an achievement (or objective) function. There are 3 basic types of penalization in association with the deviational variables (Table 4). A typical type I goal would involve cost, where any positive deviation above the goal level would be penalized. A typical type II goal would involve profit, where any negative deviation below the goal level would be penalized. A typical type III goal would involve a workforce-level target, where any negative or positive deviation from the target level would be penalized [10]. In this work, a working matrix was created in Microsoft Excel for WGP optimization.

Table 4. Algebraic significance of goal types in relation to deviational variables (adapted from Jones and Tamiz [10]).

Type	Variables to be penalized
I	d_i^+
II	d_i^-
III	$d_i^+ + d_i^-$

2.6.1.2. Normalization of the objective function

Due to different units of the studied objectives, the percentage normalization method was utilized to normalize the objective function. In this method, each deviation is turned into a percentage value away from its target level. Thus, all deviations are measured in the same units [10]. The general form of a normalized objective function is as follows:

$$Minimize \sum_{i=1}^{p} (\frac{wp_i}{TL_i})\,(d_i^+ + d_i^-), \tag{5}$$

where wp_i is the predefined weight of the ith objective and TL_i is target level of the ith objective.

2.6.1.3. Analytic hierarchy process (AHP)

AHP was used to determine the weights of driving objectives. AHP is a measurement theory founded on expert judgment to drive priority scales using pairwise comparisons. In this method, comparisons are made based on a scale of absolute judgment that shows how much more one element prevails over the other for a given attribute [8] (Table 5). However, the judgment may be inconsistent [31]. Considering n elements to be compared ($C_1 \ldots C_n$), a_{ij} denotes the relative weight or priority of C_i over C_j. $A = (a_{ij})$ is a square matrix of order n with the constraints $a_{ij} = 1/a_{ji}$, for $i \neq j$, and $a_{ii} = 1$. Such a matrix is considered as a reciprocal matrix. When the weights are transitive, they will be consistent and $a_{ik} = a_{ij}.a_{jk}$ for all i, j, and k. In this condition, $A\omega = \lambda\omega$, ω is an eigenvector (of order n) and λ is an eigenvalue. For a consistent matrix, $\lambda = n$. Human judgments are inconsistent to a greater or lesser degree, and therefore in matrices concerning human judgment, the condition $a_{ik} = a_{ij}.a_{jk}$ will not be reliable. In such a case, $A\omega = \lambda_{max} \times \omega$ and $\lambda_{max} \geq n$. The difference between λ_{max} and n is an indicator of the inconsistency of the judgment. The consistency index (CI) can be measured by $(\lambda_{max} - n) / (n - 1)$. The consistency ratio (CR) is calculated as follows:

$$CR = \frac{CI}{RI}, \tag{6}$$

where RI is the random consistency index as shown in Table 6. If the CR exceeds 0.1, the set of judgments may be too inconsistent to be reliable, and a CR of 0 means that the judgments are perfectly consistent [32]. This work was performed using a Microsoft Excel worksheet developed by Goepel [33].

Table 5. Rating scale utilized in AHP (adopted from Saaty [8]).

Intensity of importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation

Table 6. Random consistency index (adopted from Coyle [32]).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

2.6.2. Model variables

Four types of variables were considered in this work, which are as follows:

- Land use variable: This variable involves 9 land use categories, i.e. AGLT (X_1), BSVG (X_2), FRSE (X_3), range and idle grassland (RNGE) (X_4), wetlands comprising swamps and marshlands (WETL) (X_5), OILP (X_6), RUBR (X_7), URLT (X_8), and bodies of water (WATR) (X_9). The total landscape area is 38,460 ha and the area of each category is shown in Table 7.

- Social variable: The most important social variable in the Hulu Langat Basin is water supply for downstream consumers. In fact, the Hulu Langat Basin must be conserved to secure enough water yields for operational WTPs within the basin. The target level of water supply in this study was computed as 468,752,143.4 m^3 $year^{-1}$ (Table 7). This target level took into account the amount of water needed for operational WTPs along the Langat River, the 47% projected growth rate of domestic/industrial water demand in 2020 as compared to that in 2006 [34], and the available demand for irrigation and other downstream uses. There is no significant difference between irrigation water demand of 2006 and 2020 [34].

- Environmental variables: Sediment load (SEDL), total biomass yield (BIOM), and surface runoff (SURQ) were considered as the environmental variables in this work. These variables were estimated using SWAT modeling. Based on the outcomes of WCON_1^{st}L, target values of SEDL, BIOM, and SURQ are 34,780.8 t $year^{-1}$, 424,634.9 t $year^{-1}$, and 183,408,332.2 m^3 $year^{-1}$, respectively. Biomass production of the urbanized area was negligible in the watershed under study (Table 7).

- Economic variable: Due to existing economic activities, and especially agricultural activities by smallholders within the basin, annual net income (NINC) was considered as an economic variable for land use optimization in this work. This variable was set at a lower level of priority than the social and environmental objectives. The NINC of 127,127,348.8 Malaysian ringgit (MR, equal to US$ 0.31 in October 2014) per year as prescribed by the WCON_1^{st}L scenario was targeted for GP (Table 7). Annual net income of different land uses was extracted from the statistics presented by the Department of Agriculture (www.doa.gov.my), Department of Statistics (www.statistics.gov.my), Department of Minerals and Geosciences (www.jmg.gov.my), Department of Forestry (www.forestry.gov.my), and selected literature sources [35–42]. Due to the complexity of urban/industrial activities and undocumented processes within the urbanized areas, NINCs from such activities are not captured in the formal statistics and consequently cannot be modeled in this study.

2.6.3. Weights of objectives

According to Table 8, the water yield (WYLD) and SEDL objectives were situated at the highest level of priority in WGP, while NINC was situated at the lowest priority. The BIOM objective, weighted at 12%, would be more influential in WGP than SURQ, which was weighted at 7%. The CR value was less than 10%; therefore, the set of judgments in AHP were consistent.

2.6.4. Model formulation

According to the fifth and sixth options for the watershed land development, as discussed in Section 2.6, 2 development alternatives are desired, as follows:

2.6.4.1. Alternative_A

In this alternative, after 2006, the baseline scenarios with some constraints in land use transitions change to the WCON_1^{st}L scenario and continue until 2020. Due to the economic importance of horticultural lands and croplands for smallholders within the basin, Alternative_A can be modeled with (Alternative_A1) or without (Alternative_A2) limitation in horticulture/cropping activities.

Table 7. Values of different variables for land use categories and total landscape.

Land use variable	Objective variable*				
	WYLD (m^3 ha^{-1} $year^{-1}$)	SEDL (t ha^{-1} $year^{-1}$)	BIOM (t ha^{-1} $year^{-1}$)	SURQ (m^3 ha^{-1} $year^{-1}$)	NINC (MR ha^{-1} $year^{-1}$)
X1	12,661.10	1.94	3.17	1508.10	11,413.54
X2	14,096.00	4.61	3.29	2867.20	100.00**
X3	11,945.20	0.01	16.20	4620.70	2080.00
X4	14,309.40	4.10	3.30	2994.90	500.00
X5	12,309.80	0.61	6.34	2592.10	1290.00
X6	10,765.10	0.01	14.76	1785.00	1125.00
X7	10,931.80	0.01	5.46	1687.20	7000.00
X8	16,448.60	14.82	0.00	13,925.10	0.00
X9	0.00	0.00	0.00	0.00	0.00
Total landscape	WYLD (m^3/year)	SEDL (t/year)	BIOM (t/year)	SURQ (m^3/year)	NINC (MR/year)
Baseline	479,276,702.0	100,644.6	397,610.4	203,271,157.0	118,696,730.5
WCON_1^{st}L	468,752,143.4	34,780.8	424,634.9	183,408,332.2	127,127,348.8
WCON_2^{nd}L	479,233,784.0	89,559.2	407,708.2	202,925,123.0	118,908,588.9
Future	486,506,599.0	161,979.5	381,625.6	225,281,158.0	104,956,878.3

*Based on 2006 land use map

**With consideration of mining activities

Table 8. Rating values represented in AHP matrix with final weights of the objectives.

	WYLD	SEDL	BIOM	SURQ	NINC	NPE*	Weights
WYLD	1	1	4	6	8	39.4%	39%
SEDL	1	1	3	5	7	37.3%	37%
BIOM	1/4	1/3	1	2	4	11.7%	12%
SURQ	1/6	1/5	1/2	1	2	6.9%	7%
NINC	1/8	1/7	1/4	1/2	1	4.7%	5%
Eigenvalue (Lambda) = 5.064, consistency ratio (CR) = 1.4%							

*: NPE: Normalized principal eigenvector.

2.6.4.1.1. Alternative_A1

This alternative was formulated using the weight coefficients of penalized deviations as follows:

$$MinZ = 0.0000000832d_1^- + 0.0000165d_2^- + 0.0000000393d_3^- + 0.0000000654d_4^+ 0.001064\, d_5^+, \tag{7}$$

subject to:

$$12661.1X_1+14096.0X_2+11945.2X_3+14309.4X_4+12309.8X_5+10765.1X_6+10931.8X_7+16448.6X_8+ d_1^- - d_1^+ = 468752143.4, \tag{8}$$

$$3.17X_1+3.29X_2+16.20X_3+3.30X_4+6.34X_5+14.76X_6+5.46X_7 + d_2^- - d_2^+ = 424634.9, \tag{9}$$

$$11413.5X_1+100X_2+2080X_3+500X_4+1290X_5+1125X_6+7000X_7 + d_3^- - d_3^+ = 127127348.8, \tag{10}$$

$$1508.1X_1+2867.2X_2+4620.7X_3+2994.9X_4+2592.1X_5+1785.0X_6+1687.2X_7+13925.1X_8+ d_4^- - d_4^+ = 183408332.2, \tag{11}$$

$$1.94X_1+4.61X_2+0.01X_3+4.1X_4+0.61X_5+0.01X_6+0.01X_7+14.82X_8 + d_5^- - d_5^+ = 34780.78, \tag{12}$$

$$X_1+X_2+X_3+X_4+X_5+X_6+X_7+X_8+X_9=38460; X_1=316; X_3\geq 21480; X_5\leq 150; X_8\leq 6120; X_8\geq 3630; X_9=420, \tag{13}$$

where Eqs. (8) through (12) are achievement functions for WYLD, BIOM, NINC, SURQ, and SEDL, respectively. Eq. (7) is an objective function and Eq. (13) is the set of model constraints.

2.6.4.1.2. Alternative_A2

This alternative was formulated similar to Alternative_A1, but using the following set of constraints:

$$X_1+X_2+X_3+X_4+X_5+X_6+X_7+X_8+X_9=38460; X_1\leq 2240; X_1\geq 316; X_5\leq 148; X_8\leq 6120; X_8\geq 3630; X_9=420. \tag{14}$$

2.6.4.2. Alternative_B

In this alternative, after 2006 the development trend will continue until 2020, but with some constraints for land use transitions. This alternative also can be modeled with (Alternative_B1) or without (Alternative_B2) limitation in horticulture/cropping activities.

2.6.4.2.1. Alternative_B1

This alternative was also formulated like the previous alternatives; however, the following set of constraints was used:

$$X_1+X_2+X_3+X_4+X_5+X_6+X_7+X_8+X_9=38460; X_1=316; X_3\geq 21230; X_5\leq 130; X_8\geq 8370; X_9=420. \tag{15}$$

2.6.4.2.2. Alternative_B2

To model this alternative, the following set of constraints was used:

$$X_1+X_2+X_3+X_4+X_5+X_6+X_7+X_8+X_9=38460; X_1\geq 2240; X_1\leq 2310; X_3\geq 21230; X_5\leq 130; X_8\geq 8370; X_9=420. \tag{16}$$

The objective function and the set of achievement functions were the same as in the other alternatives.

3. Results and discussion

3.1. Alternative_A1

After optimization, BSVG, RNGE, WETL, and OILP, which had a total area of 1350 ha, changed to FRSE and RUBR categories. Based on the constraint defined for horticulture/cropping activities, AGLT acreage was reduced to 316 ha after optimization. According to the outlined environmental objectives for Alternative_A1, URLT acreage was reduced to 4400.2 ha after optimization (Table 9). Table 10 shows that AHP-WGP was 100% successful in achieving the target level of SURQ and NINC objectives. In addition, AHP-WGP was 99.8% and 99.5% successful in achieving the target level of WYLD and BIOM, respectively. However, due to high sediment transport capacity of the direct runoff evacuated from urbanized areas, the achieved SEDL did not match the target level (i.e. 90% deviation from the target value of SEDL). AHP-WGP enhanced NINC and BIOM quantity to 7.1% and 6.3%, respectively, as compared to those at baseline. AHP-WGP also reduced SURQ and SEDL values to 10% and 34.3% in comparison with those at baseline. WYLD was reduced to 3.34% as compared to the baseline, which was close to the target value of WYLD.

Table 9. Land use area before and after optimization in different alternatives (in ha).

Land use	Alternative_A1			Alternative_A2			Alternative_B1			Alternative_B2		
	Baseline	Achieved	Loss/Gain	Baseline	Achieved	Loss/Gain	Baseline	Achieved	Loss/Gain	Baseline	Achieved	Loss/Gain
AGLT	2240.00	316.00	–1924.00	2240.00	2240.00	0.00	2240.00	316.00	–1924.00	2240.00	2240.00	0.00
BSVG	760.00	0.00	–760.00	760.00	0.00	–760.00	760.00	0.00	–760.00	760.00	0.00	–760.00
FRSE	21,480.00	22,306.13	826.13	21,480.00	23,381.85	1901.85	21,480.00	21,230.00	–250.00	21,480.00	21,230.00	–250.00
RNGE	420.00	0.00	–420.00	420.00	835.71	415.71	420.00	0.00	–420.00	420.00	0.00	–420.00
WETL	150.00	0.00	–150.00	150.00	0.00	–150.00	150.00	0.00	–150.00	150.00	0.00	–150.00
OILP	20.00	0.00	–20.00	20.00	0.00	–20.00	20.00	3801.09	3781.09	20.00	2882.52	2862.52
RUBR	6850.00	11,017.70	4167.70	6850.00	7501.27	651.27	6850.00	4322.91	–2527.09	6850.00	3317.48	–3532.52
URLT	6120.00	4400.17	–1719.83	6120.00	4081.17	–2038.83	6120.00	8370.00	2250.00	6120.00	8370.00	2250.00
WATR	420.00	420.00	0.00	420.00	420.00	0.00	420.00	420.00	0.00	420.00	420.00	0.00

Table 10. Optimization results and deviation amount from target value in different alternatives.

Objective	Baseline	Target	Achieved	Deviation from target (%)	Deviation from baseline (%)
	Alternative_A1				
WYLD (m^3/year)	479,276,702.00	468,752,143.40	463,272,005.99	–1.17	–3.34
SEDL (t/year)	100,644.60	34,780.78	66,156.76	90.21	–34.27
BIOM (t/year)	397,610.40	424,634.88	422,517.68	–0.50	6.26
SURQ (m^3/year)	203,271,157.00	183,408,332.20	183,408,332.20	0.00	–9.77
NINC (MR/year)	118,696,730.47	127,127,348.76	127,127,348.76	0.00	7.10
	Alternative_A2				
WYLD (m^3/year)	479,276,702.00	468,752,143.40	468,752,143.40	0.00	–2.20
SEDL (t/year)	100,644.60	34,780.78	68,563.73	97.13	–31.88
BIOM (t/year)	397,610.40	424,634.88	429,601.57	1.17	8.05
SURQ (m^3/year)	203,271,157.00	183,408,332.20	183,408,332.20	0.00	–9.77
NINC (MR/year)	118,696,730.47	127,127,348.76	127,127,348.76	0.00	7.10
	Alternative_B1				
WYLD (m^3/year)	479,276,702.00	468,752,143.40	483,448,587.40	3.14	0.87
SEDL (t/year)	100,644.60	34,780.78	124,949.98	259.25	24.15
BIOM (t/year)	397,610.40	424,634.88	424,634.88	0.00	6.80
SURQ (m^3/year)	203,271,157.00	183,408,332.20	229,205,666.82	24.97	12.76
NINC (MR/year)	118,696,730.47	127,127,348.76	82,301,685.75	–35.26	–30.66
	Alternative_B2				
WYLD (m^3/year)	479,276,702.00	468,752,143.40	486,928,886.30	3.88	1.60
SEDL (t/year)	100,644.60	34,780.78	128,663.30	269.93	27.84
BIOM (t/year)	397,610.40	424,634.88	411,686.21	–3.05	3.54
SURQ (m^3/year)	203,271,157.00	183,408,332.20	228,771,242.23	24.73	12.54
NINC (MR/year)	118,696,730.47	127,127,348.76	96,189,939.03	–24.34	–18.96

3.2. Alternative_A2

After optimization, BSVG, WETL, and OILP, which had a total area of 930 ha, changed to FRSE, RNGE, and RUBR categories. Based on the defined development plan for horticulture/cropping activities, AGLT acreage did not change after optimization. After optimization, URLT acreage decreased to 4081.2 ha, which showed a higher reduction in urbanized area as compared to Alternative_A1 (Table 9). AHP-WGP was 100% successful in achieving the target levels of WYLD, SURQ, and NINC (Table 10). Due to a large coverage of FRSE (i.e. 23,381.85 ha), the BIOM value reached 429,601.6 t year^{-1}, which was 1.2% greater than the target level. However, the combined effect of urban/industrial and agricultural activities with the increase of rangeland acreage restricted AHP-WGP's ability to reach the target level of the SEDL objective. In this case, the achieved SEDL deviated 97% from the target level.

3.3. Alternative_B1

After optimization, BSVG, RNGE, and WETL, which had a total area of 1330 ha, changed to OILP and URLT. Based on the constraint defined for horticulture/cropping activities, AGLT acreage was reduced to 316 ha after optimization. FRSE acreage was changed to 21,230 ha, which shows an area reduction of 250 ha. In comparison to the baseline, FRSE and RUBR showed an area reduction of 250 ha and 2527.1 ha, respectively. Meanwhile, OILP acreage changed to 3801.1 ha after optimization, which amounts to an increase of 3781.1 ha in area (Table 9). As mentioned previously, Alternative_B1 was aimed at reaching the future level of urbanized area with a possible level of WCON_1stL environmental objectives. Thus, the urbanized acreage in this alternative increased up to 8370 ha (37%). AHP-WGP was 100% successful in achieving the target value of BIOM. BIOM also showed an increase of 6.8% in comparison to that of the baseline. WYLD, however, showed a positive deviation (+3.14%) after optimization. Meanwhile, SURQ and NINC showed 25% and –35% deviations from the target levels, respectively. After optimization, SEDL deviated by +259% (i.e. 2.34 t ha^{-1} year^{-1}) from the target level. However, deviation of the achieved SEDL from that in the future scenario is –23%. This indicates that AHP-WGP optimization is able to reasonably reduce SEDL into the future. Due to the defined constraint for horticulture/cropping activities and reduction of RUBR acreage, NINC showed a decrease of 30.7% as compared to that at baseline.

3.4. Alternative_B2

After optimization, BSVG, RNGE, and WETL, which had a total area of 1330 ha, changed to OILP and URLT. In this alternative, horticulture/cropping activities were not constrained. Thus, AGLT acreage did not change after optimization. FRSE and RUBR acreages declined to 21,230 ha and 3317.5 ha, which amounts to an area reduction of 1% and 50%, respectively, in comparison to those of the baseline. OILP acreage was changed to 2882.5 ha after optimization, which amounts to an area increase of 2862.5 ha. URLT acreage with 37% areal increase, in comparison with that at baseline, changed to 8370 ha (Table 9). After optimization, WYLD with a deviation of +3.9% from the target level was achieved beyond 100%. Although the BIOM quantity was 3.5% higher than that at baseline, it deviated –3% from the target level. SURQ and NINC showed 25% and –24% deviations from the target level, respectively. SEDL deviated by 270% (i.e. 2.44 t ha^{-1} year^{-1}) from the target level. However, deviation of the achieved SEDL from that in the future scenario is –21%. As in Alternative_B1, this indicates that AHP-WGP optimization is able to reasonably reduce SEDL into the future. Reduction of RUBR acreage caused a 19% decrease in NINC as compared to that at baseline.

Figure 5 depicts the total sum of unwanted deviations (Z) versus total sum of loss and gain in developed lands (i.e. AGLT and URLT). Alternative_B2, which had the largest gain of developed lands, showed the largest deviation from the target values. Conversely, Alternative_A1, which had the largest loss of developed lands, showed the lowest deviation from the target values.

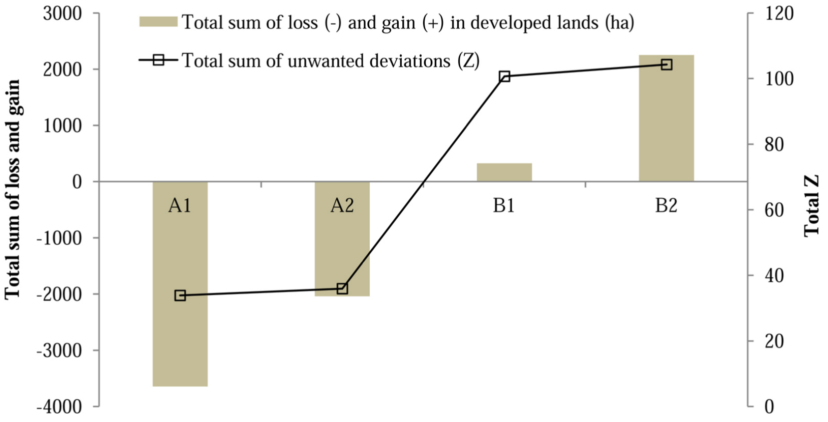

Figure 5. Total Z versus total sum of loss and gain in developed lands.

Alternative_A1 was more capable of capturing the outlined objectives in comparison to Alternative_A2. However, Alternative_A1 resulted in more losses in developed lands than Alternative_A2. Alternative_A2 yielded

0.06 t ha^{-1} $year^{-1}$ sediment in excess to that in Alternative_A1. However, due to influence of horticultural activities and crop production on household economic status of smallholders within the basin, this excess amount of SEDL can be ignored. The defined environmental objectives in Alternative_B1 were more achieved than those in Alternative_B2. However, NINC in Alternative_B2 was 11% more than that in Alternative_B1, which was mainly derived from agricultural activities.

The decision about which alternative is practical at the Hulu Langat Basin depends on the proposal of land use planners. However, based on existing socioeconomic-environmental conditions and development trends within the Hulu Langat Basin, alternatives B1 and B2 are more applicable.

Results of this study verified that the AHP-WGP approach was able to solve land use optimization problems and led to a possible level of satisfaction for each land use alternative. The results also showed a successful linkage between socioeconomic aspects and environmental outcomes at the watershed scale as emphasized by Sadeghi et al. [43], Gezelius and Refsgaard [4], Peel and Lloyd [44], Shively and Coxhead [45], Mohseni Saravi et al. (2003) [7], and Recatala et al. [46]. In addition, application of SWAT for hydrological analysis of different land use scenarios, as explored in other studies [47–54], could assist in a deterministic computation of environmental variables. Several studies [6,9,10,55–57] reported the advantage of a combined AHP-GP approach for multicriteria decision making. Similarly, this work showed that integration of AHP and WGP was useful in determining the weight of decision variables.

4. Conclusion

The preferential weights of 39%, 37%, 12%, 7%, and 5% were assigned for WYLD, SEDL, BIOM, SURQ, and NINC, respectively, using AHP. A CR value of 0.14 indicated that the set of judgments was consistent.

After AHP-WGP optimization, Alternative_B2 showed the largest deviation from the target levels, while Alternative_A1 showed the lowest deviation from the target levels. AHP-WGP optimization resulted in higher achievement of the outlined objectives for Alternative_A1 than for those in Alternative_A2. However, AHP-WGP optimization resulted in more loss in developed lands for Alternative_A1 as compared to Alternative_A2. The defined environmental objectives in Alternative_B1 were more achieved than those in Alternative_B2. However, annual net income in Alternative_B2 was 11% more than that in Alternative_B1. Due to the economic importance of horticultural and crop lands, alternatives A2 and B2 were more beneficial to watershed stakeholders than alternatives A1 and B1, respectively. However, in terms of the water conservation objective, alternatives A1 and B1 were more desirable than alternatives A2 and B2, respectively. Given the current socioeconomic-environmental conditions within the Hulu Langat Basin, alternatives B1 and B2 were more applicable.

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