Water Resources Management **17:** 1–17, 2003.

Modelling Optimum Sites for Locating Reservoirs in Tropical Environments

SERWAN M. J. BABAN* and KAMRUZAMAN WAN-YUSOF
The Centre for Caribbean Land and Environmental Appraisal Research (CLEAR), Department of Surveying and Land Information, The University of the West Indies, St. Augustine, Trinidad, West Indies; School of Engineering, Universiti Teknologi, MARA (UiTM), Shah Alam, Selangor, Malaysia (author for correspondence, e-mail: sbaban2001@yahoo.com)*

(Received: 8 January 2002; in final form: 7 November 2002)

Abstract. A team of specialists normally carries out the task of locating reservoir sites based on general guidelines, technical knowledge and experience. Consequently, the procedures used are not based on a defined criteria in addition to being time consuming and expensive. Furthermore, the failure of a number of dams and the increase in environmental awareness will require the inclusion of environmental and social factors in the processes besides economy. In this study, a criteria was developed and implemented to locate potential sites for reservoirs in the Langkawi Island, Malaysia based on all relevant factors including: topography, geology, hydrology, land use/cover types and settlements. A satellite imagery and digitized geological and elevation maps were utilized to generate the necessary data layers for the developed criteria. Then IDRISI, a raster based GIS was employed to implement the criteria using the Boolean and the Weighted Linear Combination (WLC) methods. The Boolean method produced five reservoir sites with the 70 Mld water capacity, two of which corresponded well with a field-based study. Whilst the proposed site with the 90 Mld water capacity did not correspond with the field based study. The WLC method produced five sites with the 70 Mld water capacity, three of which matched those of the field study. Whilst for the 90 Mld water requirement, two potential sites were produced and both have matched those of the field study. The outcomes indicated that the developed criteria were sensitive to physical, environmental and economical settings on the Langkawi Island. Furthermore, GIS and remote sensing can be useful tools for generating, manipulating and handling relevant data layers and ultimately providing management options for decision makers.

Key words: GIS, locating reservoir sites, tropical environments, Malaysia

1. Introduction

In simple terms, reservoir means a construction that holds a volume of water, and dam is the structure, which holds back the water (Brassington, 1995). This definition indicates the need to examine both the reservoir and dam site locations, as one needs to know the capabilities of the foundations to withstand the weight of both the volume of water in the reservoir and the materials for dam construction. Therefore, choosing a suitable site is a crucial phase in reservoir construction. A well-selected site will not only give the optimum benefits but its aesthetic value may also create a recreational area surrounding the reservoir. Conversely, a poorly selected site could cause a detrimental effect on the life downstream of the reservoir. In 1963, for example, more than 300 million metres of rock slid into the reservoir site of the St. Vaiont Dam in Italy. This generated flood waves, which overtopped the crest of the dam by 100 m and killed 3000 people downstream (Henderson-Sellers, 1979). An investigation, at a later date, established that the rock material on the reservoir side slope became saturated due to the impoundment of water and, as a result, the slope became unstable and started to slide into the reservoir (Nelson, 1991). This example shows the importance of preliminary investigations and reconnaissance survey in selecting and locating reservoir sites. Prior to the United Nations Conference on Environment and Development in 1972, the economic importance of a reservoir project preceded all other considerations. Since then, environmental awareness and concern has been growing steadily, accordingly decision-makers have had to take into consideration not only the technical design and economic factors but also local and regional environmental and social impacts of a proposed reservoir. As a result, they have to handle and analyse large data sets (Baban, 1999). Despite having established dam design criteria, general guidelines and recommended considerations as well as technical knowledge and experience, there is no certainty that the resulting design criteria can be applied to other reservoir sites with similar conditions (Wilson and Marsal, 1979). These requirements and pressures have made it necessary to develop a clear criteria for locating reservoir sites in addition to a more effective system in decision-making, i.e. one which can handle a large number of data sets and provide assistance to decision makers (Baban and Flannagan, 1998). Remote sensing and GIS have the capability to handle, analyse and manipulate all relevant information layers involved such as the topography, economic and environmental data, in relation to reservoir site selection. In addition, remotely sensed data can enable the decision-makers to investigate a wider area of potential sites in a shorter period of time and at lower cost (Baban, 1999). It can also outline areas of structural weakness through mapping the extent of major geological lines pertaining to faults and strikes (Thomas, 1976; Avery and Berlin, 1992). As reservoir site selection involve large data sets, GIS can be used to maintain and manipulate the data in order to extract the necessary information and to utilise the information in the decision-making process (Guptill, 1989). A further important advantage of using GIS in site selection is its visualisation capabilities (Heywood *et al.*, 1998). The visual outcome of the final image will assist the user in decision-making by giving several alternatives through simulating different scenarios showing the most and least suitable locations for development (Alber *et al.*, 1991). Remote sensing and GIS applications in reservoir site selection to date include mapping some factors including the size of the catchment area for determining the runoff volume; land use/cover to determine the retention of runoff or to the contribution of sediment; and to estimate the amount of agricultural land lost following inundation by water (Legg, 1992). Furthermore, Gismalla and Bruen (1996) have successfully identified several locations for the small-scale hydropower plant in Tanzania based on hydrological factors such as the runoff volume, the coverage of population distribution relating to potential users and economic factors. Each of these factors was analysed and manipulated using GIS, then a final map of the potential sites was produced.

In Malaysia, the Langkawi Island has become a popular destination for both domestic and foreign tourist in the last decade (Jusoff and Hassan, 1996). Consequently, Langkawi Island faces the possibility of having water shortages in the future and building reservoirs has been promoted as a possible solution to meet the future demand of water supply (Baban and Wan-Yusof, 2001a). This article aims to develop, implement and evaluate criteria to identify suitable reservoir sites on the Langkawi Island with the view to satisfy water demands in the future. The implementation will be carried out using remote sensing, GIS, the Boolean and the Weighted Linear Combination (WLC) methods. The usefulness of the criteria and the methodology will be evaluated.

2. Selecting Potential Sites for Reservoirs

Reservoir site investigations are often carried out by a team of specialists. However, it is impractical for such a team to survey all potential areas, because this will incur a much higher cost. In order to minimise costs, investigations are targeted to areas likely to yield viable sites (Gismala and Bruen, 1996). Site investigations also include studies of environmental impact assessment; water quality; and surveying of physical aspects such as hydrology, geology and topography (Thomas, 1976). The main disadvantages of these procedures are that they are time consuming and very expensive, especially when employing a specialist team to produce a detailed site survey. These restrictions have put pressure on researchers to set objective criteria in the reservoir-planning phase. Initially, economic considerations were emphasised in the site selection as long as the reservoir served the purpose of supplying water for drinking and irrigation. However, due to poor considerations in the planning stage, the number of accidents with reservoirs has increased. An example was the collapse of the Teton Dam in Idaho, U.S.A. in 1976 which killed 14 people and caused damage to the value of (US)$ 400 million (Henderson-Sellers, 1979). These incidents have alerted engineers and surveyors and they have begun to include stability and safety factors in their design. In the last decade, environmental and social issues in reservoir construction have been raised. Recently, environmentalist movements have gained momentum, and their resistance to some reservoir projects has been rewarded. An example is the case of Bakun Dam in Malaysia. It was estimated to cost (US)$ 5.5 billion, would flood almost 300 square miles of rainforest and would force about 5000 people from their homes (see Rainforest Action Network, 1994 at *http://nativenet.uthscsa.edu/archive/nl/9409/0019.html*). The project was shelved in 1997 due to constant pressure from the local and international environmentalist groups (see McCully, 1997 at *http://forests/ic.wirc.edu/ric/wrr37/Bakundam.html*). Thus, the designers and the decision makers are obliged to include environmental and social factors in the design and planning considerations.

Factors influencing reservoir and dam site selection include;

(i) *Economy*

Cost-benefit analysis need to consider the area to be impounded according to a land evaluation as cropland, forest and built-up areas (Legg, 1992; Avery and Berlin, 1992).

(ii) *Hydrology and hydraulics*

Basically, a dam needs to be located where there is a suitable storage area for flood control, power requirements, irrigation, and/or water supply (ASCE-USCOLD, 1967).

(iii) *Topography*

Topography determines the surface configuration (size and shape) and the ratio between surface and volume of the site. These in turn will determine the type of dam to be constructed. For example, with a concrete dam, the site must have narrow deep valleys and large stream flows, whereas wide valleys and small stream flows favour earth dam. A preferable dam is a narrow channel section with minimum quantities of material for dam construction (Thomas, 1976; Stephens, 1991).

(iv) *Geology*

Geology is an important consideration for an adequate foundation for the dam and a leak-proof reservoir (ASCE-USCOLD, 1967; Avery and Berlin, 1992; Legg, 1992). For a desirable foundation and abutment; igneous rocks such as granite; metamorphic rocks, such as quartzite; sedimentary rocks such as thick-bedded and flat-lying sandstones and limestones are among the most satisfactory materials (Avery and Berlin, 1992). A site where an active fault exists should never be considered (ASCE-USCOLD, 1967).

(v) *Points of abstraction and supply*

This will determine the head of water available for the abstraction and demand points. It will also determine whether the supply will be by gravity or require pumping. Location will also dictate the length of pipelines to convey the water to the demand centre (Schwab *et al.*, 1996).

(vi) *Environmental considerations*

This is a relatively new undertaking in the consideration but has become of wide concern by the decision-makers and the public. These include settlement relocation, flooding agricultural land, drowning wildlife and flooding areas with archaeological value (Thomas, 1976). However, the impact of dams and reservoirs on the environment can be minimised by taking certain mitigation steps such as maintaining regulated flows in the reservoir to enhance fish and aquatic habitat and using water aeration methods to maintain the reservoir's water quality (Murphy, 1977; Jonge *et al.*, 1996).

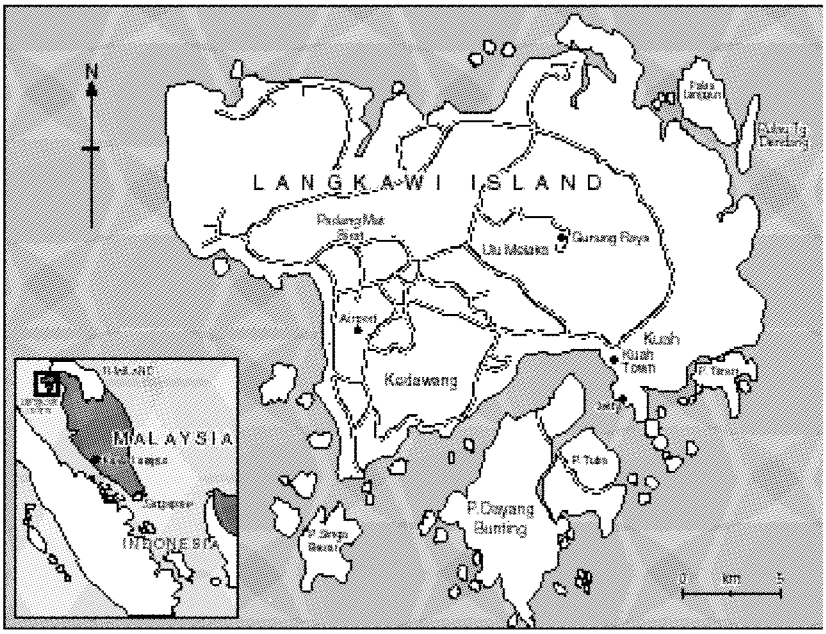

Figure 1. The study area.

3. The Study Area

Langkawi Island lies off the northwest coast of Peninsular Malaysia and is located approximately at latitude 6°20′N and longitude 99°40′E (Figure 1). It has an area of 362 km^2. Langkawi Island is mainly covered by forest (52%), mangroves (11%), rubber (12%), agricultural land (18%) and newly expanding urban areas (5%) (Baban and Wan-Yusof, 2001a). The topography varies from flat coastal plains, hilly areas to rugged mountains. Its climate is influenced by the two wet monsoons in April and May, when the monthly rainfall average is over 180 mm, and during August and October when the average reaches over 220 mm. Its annual average rainfall is between 1600–2000 mm. The daily average temperature is about 31 °C (Shaaban and Sahat, 1996; Baban and Wan-Yusof, 2001a). Most streams have small catchment areas and they tend to flow rapidly from the mountain to the sea. As such, their flow tends to cease during periods of dry weather (Syed, 1992). The economical prosperity over the past three decades in Malaysia and the declaration of the Langkawi Island as a duty free area in 1987 made the island the focus for recreation activities in Malaysia (Jusoff and Hassan, 1996). Consequently, the island has been undergoing rapid development in terms of expanding road networks and the construction of hotels and holiday complexes. The influx of tourists to the Island has increased at a rate of 30.7% in the year 1988 to 1989 (Jusoff and Hassan, 1996). As a consequence of these developments, the Langkawi island faces the possibility of having water shortages in the future. A study, which was

Table I. Total water demand (Mld) for the Langkawi Island until 2015 (adapted from Syed, 1992)

District	2000	2005	2010	2015
Ayer Hangat	4.85	7.49	10.28	14.70
Bohor	1.31	1.96	2.79	3.52
Kedawang	5.68	7.51	9.45	11.25
Kuah	15.24	21.47	28.84	37.20
Padang Mat Sirat	8.35	10.65	13.57	18.64
Ulu Melaka	1.77	2.64	3.49	4.31
Total	37.20	51.72	68.42	89.62

conducted to quantify the future demand of water supply, has concluded that the total water demand might triple in the period 1993–2001 (Table I) (Syed, 1992).

4. Methodology

An examination of the total water demand for the Langkawi Island, taken into account the physical characteristics of the island, required land surface area, and population distribution, will raise the question of how many reservoirs should be built. For example, if a single reservoir is built in the year 2015, a storage capacity of 32 850 × 10^3 m^3 yr^{-1} is required to sustain water consumption of 90 Mld (Table II). Therefore, by taking the minimum dam height as 15 and 50 m for the maximum, the water surface area will be between 2190 × 10^3 m^2 (219 ha) and 657 × 10^3 m^2 (65.7 ha), respectively. This will certainly require an enormous land surface area and will incur high cost in land acquisition. Furthermore, a single reservoir will also add extra costs in pipelines to supply the whole Island. Therefore, under these circumstances, it is more practical and cost-effective to have at least two reservoir sites; not only will this reduce the required land surface area but also, it will cut the cost of pipelines considerably. Accordingly, if two reservoirs were developed, the water demand would be reduced to 35 Mld in 2010 (Table II). This would require a water storage capacity of 16 425 × 10^3 m^3 yr^{-1} and a surface area of 85.2 and 25.5 ha for dam heights of 15 and 50 m, respectively. Similarly, in 2015, the water demand from each reservoir would be ca. 45 Mld. Therefore, a surface area of 109.5 and 32.85 ha for dam heights of 15 and 50 m, respectively, would be required.

4.1. DEVELOPING RESERVOIR LOCATION CONSTRAINTS CRITERIA

Factors influencing reservoir site selection includes topography (slope/aspect), hydrology (rainfall, river discharge), geology (mineral), soil, land use/cover (agri-

Table II. Surface area required for the proposed two reservoirs in the Langkawi Island

	2010		2015	
Water demand for a single reservoir (Mld)	70		90	
Water demand for each reservoir (Mld)	35		45	
Dam heights (m)	15	50	15	50
Surface area (ha)	85.2	25.5	109.5	32.85
Storage capacity	16425×10^3 m^3		32850×10^3 m^3	

culture, forestry), road network and development plan (Adinarayana *et al*., 1995; Gismala *et al*., 1996). However, increasingly socio-economic and environmental factors are also being considered (Murphy, 1977). It is more viable and humane to locate a reservoir site near to demand points as well as minimising settlement relocation or flooding areas with historical archeological value. Based on these factors and the development guidelines by Langkawi District Council (1992), criteria for locating reservoir in the Island was developed (Table III). The constraints criteria indicate that reservoir sites should not be in the vicinity of densely populated areas must be located on land providing a strong foundation and there should not be any development in the forest reserve areas, hence constraint criteria 1, 2 and 3. From an economic point of view, development costs dictate the acquisition of high-grade land, hence factor 4. In minimising the cost of pumps and gaining the hydraulic head for abstraction, factor 5 was included to ensure that water flows by gravity as well as conveying water to the demand area. Factor 6 was included to avoid any slope failure, and slopes up to 11° are recommended in the literature and within the upper limit set by the Langkawi Structure Plan (Adinarayana *et al*., 1995; Stephens, 1991; Langkawi District Council, 1992). Constraint 7 was included to account for the projected demand for water supply in the Island. Total water demand was projected to be 70 megalitre/day (Mld) in 2010 and based on the topographical features of the reservoir basin, the recommended dam heights are between 15 and 50 m (Syed, 1992).

4.2. IMPLEMENTING THE CRITERIA USING MULTI-CRITERIA EVALUATION (MCE) APPROACHES

Using GIS will require creating information layers corresponding to each constraint. The relevant information obtained for the Langkawi Island were converted into the required constraint layers as in Table IV using IDRISI, a raster based GIS. The necessary constraint layers for the study area were derived from various sources including a land use/cover map of the Langkawi Island produced from satellite data of 1995 and field data (Baban and Wan-Yusof, 2001a). This map was used to extract information and construct layers of information for constraints I, 4

Table III. Reservoir location constraints criteria

Criteria		Consideration
The dam and reservoir site must:		
1.	Not be located in or near settlement areas	Safety
2.	Be on granite and/or metamorphic rock	Safety
3.	Avoid forest reserved areas	Resources/environment
4.	Avoid high grade agricultural land value areas	Resources/economic
5.	Be at an altitude of between 25–90 m	Hydraulic/economic
6.	Be on a gentle slope of $0''$-11°	Environmental/safety
7.	Have a sufficient volume to provide the necessary volume	Consumption/economic

Table IV. Data and data sources used to create various information layers for the criteria

Criteria	Data	Source
1	Urban areas	Satellite image
2	Elevation/topography	Digitised Elevation Map
3	Geology	Digitised Geology Map
4	Agricultural land classification	Satellite image
5	Agricultural land classification	Satellite image
6	Topography	Digitised Elevation Map

and 5, i.e. to identify urban areas, to protect agricultural and forest areas, respectively. Topography was derived from a Digital Elevation Model (DEM) digitised from a topographic map of Langkawi Island at a scale of 1:50 000 (Taher, 1996). Similarly, geology was also derived from digitising a geological map at a scale of 1:200 000 (Mohamad and Kiat, 1996). The data used to create each layer, the criterion it corresponds to and data source are shown in Table IV. This process is usually followed by allocation of weights to each constraint layer, multiplying each layer by its weight and then successively multiplying the result by each of the constraints to combine all the layers. These operations are labeled as a multicriteria evaluation (MCE) (Heywood *et al*., 1998). In this study, two MCE approaches were considered for combining the information layers Boolean and Weighted Linear Combination (WLC) methods.

4.2.1. *Using the Boolean Method*

In this method, all the criteria are reduced to constraint Boolean images of areas, which are suitable and not suitable. Furthermore, all the layers are considered

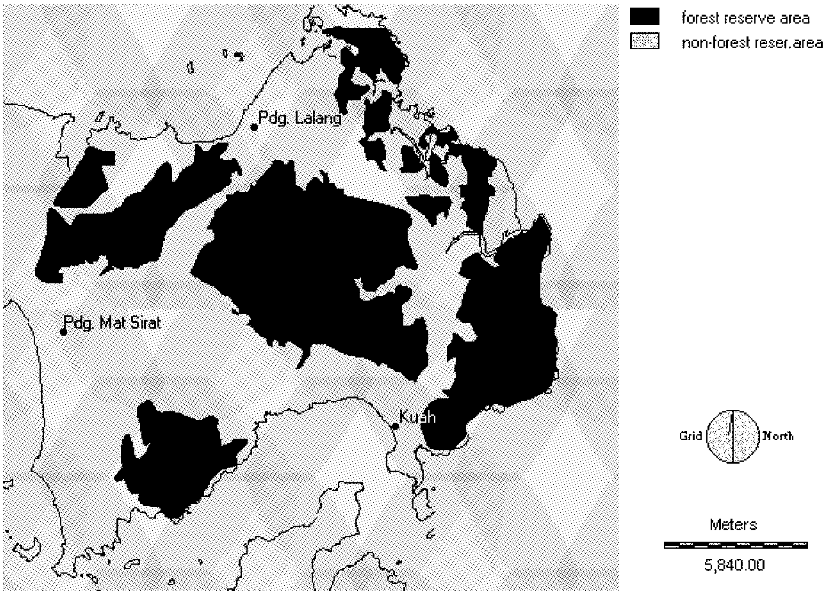

Figure 2. Forest reserve areas.

equally important and are given an equal weight (Heywood *et al.*, 1998). This procedure was applied to all the information layers using the MCE function in IDRISI in order to produce the necessary constraint images. For example, Figure 2 marks forest reserved areas, which are clearly defined (in black) as being not suitable for consideration based on the developed criteria (Table III). The constraint layers were subsequently overlaid consecutively; by using the OVERLAY multiply function to produce a single suitability Boolean image. Subsequently, the suitable areas in the last Boolean image were regrouped to determine the surface area. The output image was achieved using GROUP to assign identifiers to unite groups of pixels and AREA function was used to calculate area for each group. Finally, the RECLASS function was used to select only those areas (groups) that can comply with the specified surface areas (Table II) for reservoirs with 70 Mld water capacity (Figure 3) and reservoirs with 90 Mld water capacities, only one potential site at Ayer Hangat (Figure 3).

4.2.2. *Using the Weighted Linear Combination (WLC)*

In this method the constraint layers need to be standardised to a continuous scale of suitability from 0 (the least suitable) to 255 (the most suitable) (Eastman, 1997). Therefore, all the constraints in the criteria (Table III) were standardised and re-scaled into 0 to 255 from the least suitable to the most suitable areas. For example in the case of the height constraint which will need to be taken into consideration to access gravitational pressure in order to deliver water by gravity, thus the higher

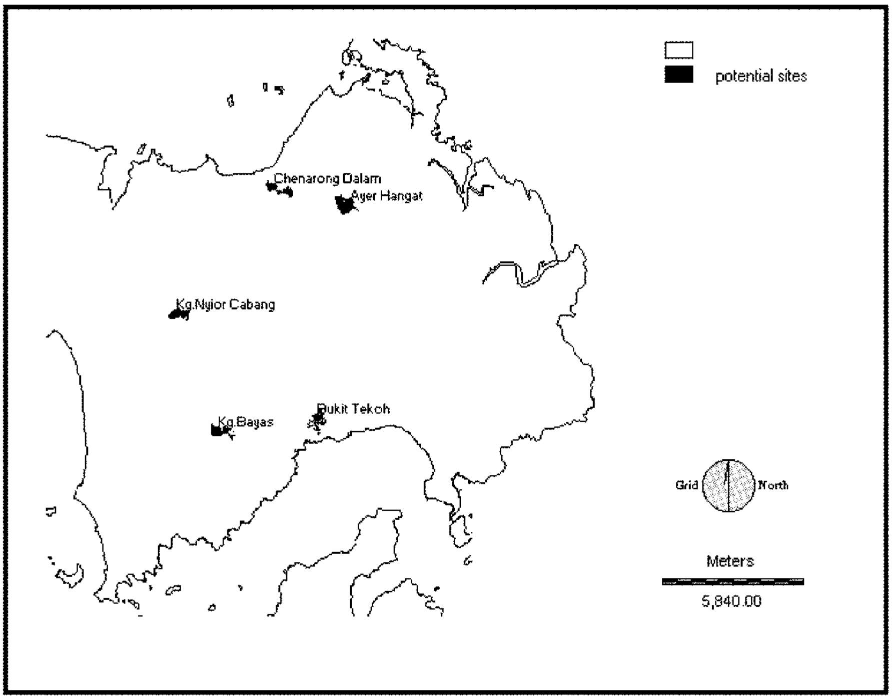

Figure 3. Potential reservoir sites with 70 Mld water capacities using the Boolean method.

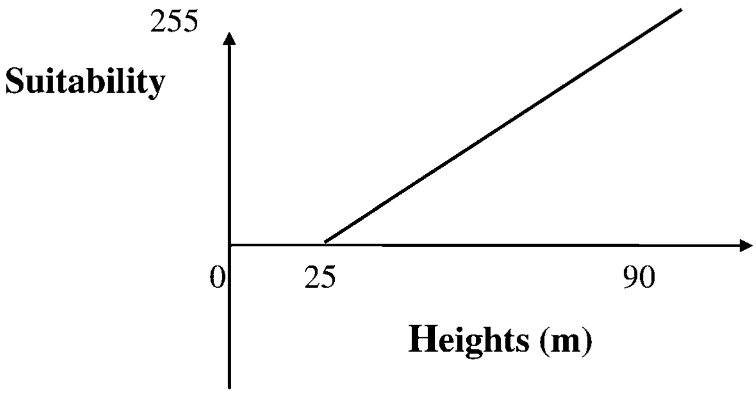

Figure 4. Linear relationship of suitability against height (adopted from Syed, 1992).

the elevation the greater will be the hydraulic pressure head. A study carried out in the Island suggested that the range of elevation suitable for reservoir is between 25 and 90 m above sea level (Syed, 1992). In order to transfer this range into a continuous scale of suitability a simple linear relationship was used with a height of 25 m as the least suitable and a height of 90 m as the most suitable (Figure 4).

Table V. A pairwise comparison matrix for assessing the comparative importance of factors to reservoir site selection

	Slope factor	Height factor	Erosion factor	Agricultural factor
Slope factor	1			
Height factor	1/3	1		
Erosion factor	1	5	1	
Agricultural factor	1/7	1/3	1/7	1

In this approach, weights will need to be assigned to each constraint layer based on pairwise comparisons associated with the Analytical Hierarchy Process where every possible pairing and the ratings are arranged on a 9-point continuous scale (Saaty, 1977). In this study, ratings between the relative importance of two factors involved were considered and the weight scale was entered into a pairwise comparison matrix for assessing the relative importance of the constraints to reservoir site selection (Table V).

The procedure in the WLC requires that the principal eigenvector of the pairwise comparison matrix be computed to produce the best-fit set of weights. Subsequently, the best acceptable fit of the respective weights are used in the Multi Criteria Evaluation function (MCE) to calculate the weighted linear combination (WLC) using the constrains in the criteria. The principal eigenvector was calculated by taking the square reciprocal matrix of pairwise comparisons between the criteria and these weights would sum to 1. This result could be achieved by calculating the weights with each column and then averaging over all columns (Eastman *et al*., 1993). The WEIGHT function in IDRISI, which operates on this principle, was used to determine the best fit of weight factors (Table VI). The erosion factor for example was given the highest weight because a suitable reservoir site in the Langkawi Island must avoid highly erodible areas (Baban and Wan-Yusof, 2001b). The slope factor was given more weight than other factors because areas with steep slopes have a greater tendency to experience landslides and increase the erosion risk. An index of consistency, known as a consistency ratio (CR), was also determined to be 0.06. The CR indicates the probability that the matrix ratings are randomly generated and the value should be less than 0.10, otherwise the matrix rating should be re-evaluated (Saaty, 1977). Subsequently, the acceptable best fit of the respective weights were used in the Multi Criteria Evaluation function (MCE) to calculate the weighted linear combination (WLC) using the factors (slope, height, land value, and erosion) and constraints (forest reserve, settlement zone, and geological foundation) images. In order to select only those areas (groups) that can comply with the specified surface areas (Table II), the GROUP, AREA and RECLASS functions of IDRISI were used. The outputs

Table VI. The weights derived by computing the principal eigenvector of the pairwise comparison matrix

Factor	Factor weight
Slope	0.37
Height	0.14
Erosion	0.44
Agricultural	0.05

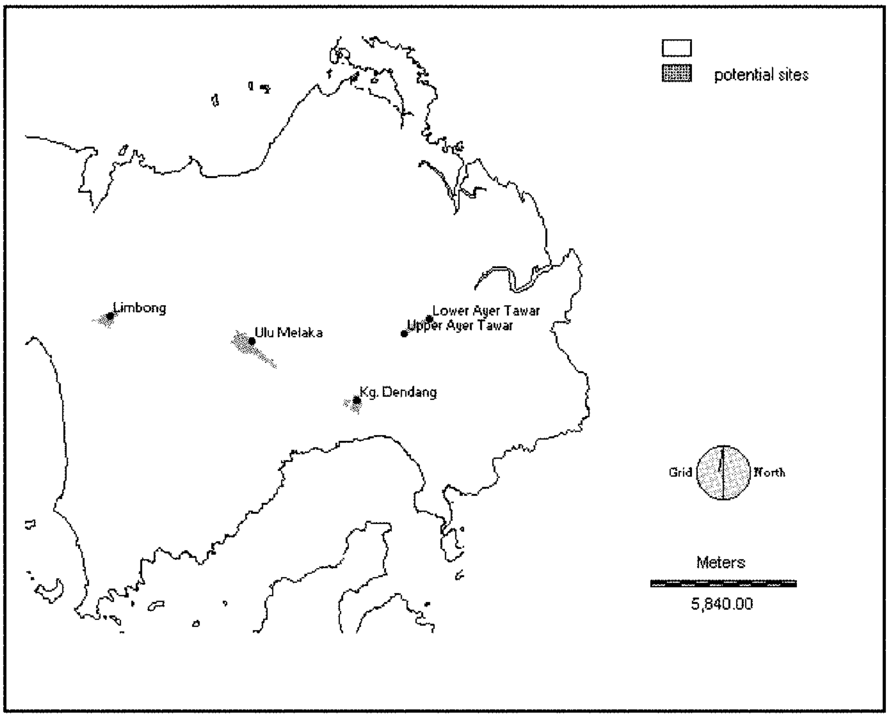

Figure 5. Potential reservoir sites with 70 Mld water capacities using the WLC.

represent potential sites with the highest suitability for reservoirs with 70 Mld water capacity (Figure 5) and reservoirs with 90 Mld water capacity, two potential sites namely: Limbong and Ulu Melaka (Figure 5).

5. Results, Evaluation and Discussions

The outcome of potential sites from the Boolean approach (Figure 3) has satisfied all the constraints in the criteria. The reservoir sites selected were within the surface area required, were outside the settlement zone, located at an altitude between 25 and 90 m, were on a gentle slope of 0 to 11°, have a strong foundation on either granite or metamorphic rock, and were not within the forest reserve areas. However, in terms of numbers of suitable sites Figure 3 shows two potential sites in the north, one on the west, one on the southwest and one on the southern part of the Island for the 70 Mld water capacity and only one site, Ayer Hangat, in the north of the Island for the 90 Mld water capacity. This mainly due to the fact that the Boolean approach is very conservative in terms of risk. Therefore, it produced absolute sites i.e. there were no trade-offs with other constraints criteria. Consequently, suitability in one criterion cannot compensate for a lack of suitability in any other image. Whilst, the WLC approach produced 5 potential reservoir sites for 70 Mld (Figure 5) and 2 sites for the 90 Mld water capacity, Limbong and Ulu Melaka (Figure 5). The sites on both outcomes are located around the central region of the Island. These potential sites are more practical due to their central locations, as this will reduce costs in pipeline distribution throughout the Island.

The WLC method which uses a continuous scale has an advantage over the Boolean in that it will avoid the hard Boolean decision of defining any particular area as absolutely suitable or not. In fact, the factors assigned to each criterion had been more flexible. This allowed the factors to compensate for each other while maintaining all of the variability in the continuous suitability data. A low suitability aggregate in one factor for any given area had been compensated for by a high suitability aggregate in another factor. For example, areas with a slope factor with high suitability were compensated for by a low suitability in an agricultural factor. In the resultant image, that location had a high suitability score. This approach can trade-off among the factors, but the degree to which it will influence the result was severely limited by its low factor weight. As a result, this gave more allowance in the selection for the suitability areas. Thus, the WLC was an averaging technique and balances between extreme risk taking and risk aversion (Eastman, 1997).

In order to evaluate the outcomes from this study, the proposed reservoir sites using both methods were compared to field based study conducted to locate reservoir sites on the Langkawi Island. This study was founded on topography, catchment areas, hydrology; land use/cover, accessibility and socio-economic factors. The study has identified six possible reservoir sites (Figure 6) (Syed, 1992). These areas are the Limbong, Ulu Melaka, Upper Ayer Tawar, Lower Ayer Tawar, Batu Asah and Langkanah. Through comparison, it is evident that two of the potential sites with the 70 Mld water capacity (Kg. Nyior Cabang and Bukit Tekoh) using the Boolean method (Figure 3) corresponded well with the field-based study areas (Figure 6). Whilst the proposed site for the 90 Mld water capacity in did not correspond with the sites on Figure 6. The proposed reservoir sites at Limbong, Lower Ayer Tawar and Upper Ayer Tawar (Syed, 1992) matched the proposed sites, using the WLC method, in Figure 5 for a 70 Mld water capacity, whilst Limbong and Ulu Melaka reservoir sites matched the proposed sites with the 90 Mld water capacity (Figure 5).

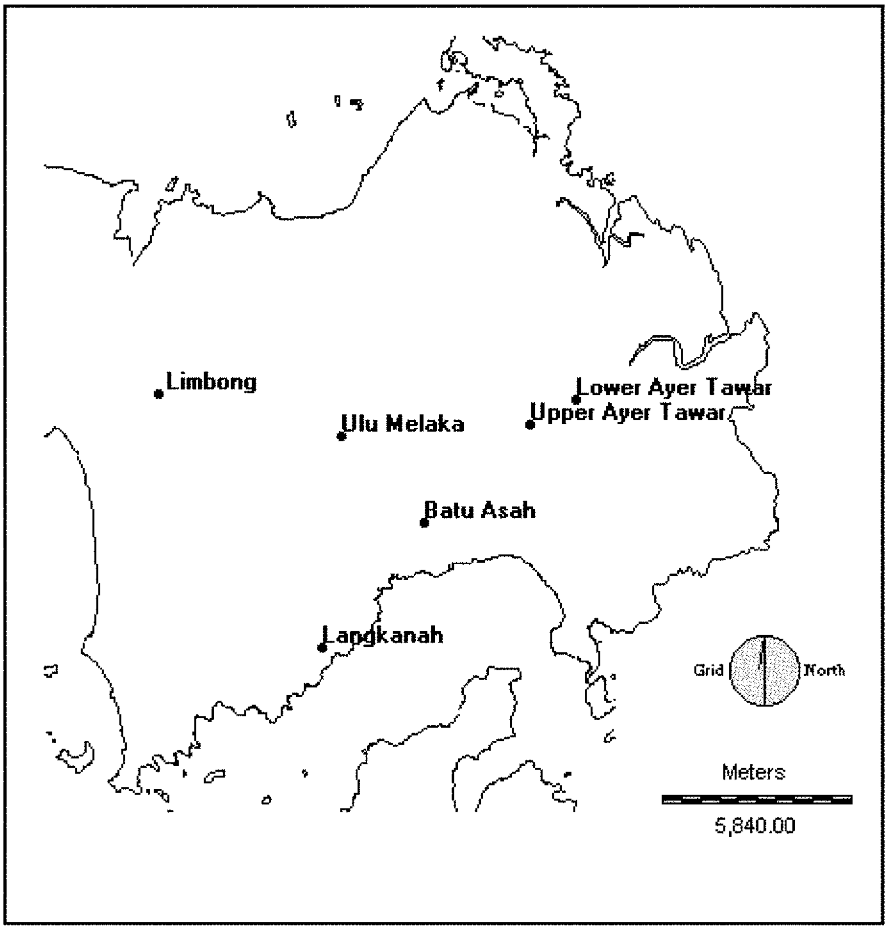

Figure 6. Potential reservoir sites based on a field based study (adopted from Syed, 1992).

6. Conclusion

A set of criteria was developed to locate suitable reservoir sites in Langkawi Island. The criteria chosen are extensive, taking into consideration all relevant constraints based on hydrology and hydraulics, topography, geology, economy, site location in relation to the points of abstraction and supply and environmental implications. The main considerations being safety, economy and the environment.

Two approaches were considered for reservoir site selection: Boolean and Weighted Linear Combination. The Boolean technique is more direct in its approach to decision making and is very conservative in taking risk. Reservoir sites located by using this approach were scattered over the Island. Two potential sites with the 70 Mld water capacity (Kg. Nyior Cabang and Bukit Tekoh) (Figure 3) corresponded well with the field-based study areas (Figure 6). Whilst the proposed site with the 90 Mld water requirement did not correspond with the sites on Figure 6. In the Weighted Linear Combination technique, this flexibility in assigning constrain factors allows these factors to compensate for each other. For the proposed 70 Mld water requirement, three potential sites (Limbong, Lower Ayer Tawar and Upper Ayer Tawar) matched those of the field study whilst for the 90 Mld water requirement, two potential sites (Limbong and Ulu Melaka) matched those of the field study.

Although the GIS methodology makes the decision-making process more objective, there is still an element of subjectivity associated with the allocation of map weights and scaling. This also allows flexibility to the planners to incorporate varying degrees of importance to each criterion based on their experience. Through experience, a good and sound judgment in the evaluation of environmental, social and political constraints could produce the best alternative decisions.

Overall, this study has shown that the criteria chosen were sensitive and extensive. Furthermore, it has demonstrated the effectiveness of using remotely sensed data in providing the necessary spectral and spatial information for generating information layers for reservoir site selection criteria. The GIS as a decision-making tool, has facilitated combining various information layers as well as implementing the necessary analysis on the data.

References

Adinarayana, J., Rama, N. and Gopal Rao, K.: 1995, ‘An integrated approach for prioritisation of watersheds’, *J. Environ. Manage.* **44**, 375–384.

Albers, B., Dobbins, J. and Buja, K.: 1991, ‘Planning Paradise’, *Geo Info Systems*, 27–38.

Avery, T. E. and Berlin, G. L.: 1992, ‘Engineering Applications’, in *Fundamentals of Remote Sensing and Airphoto Interpretation*, 5th ed., Maxwell Macmillan International, pp. 349–351.

ASCE-USCOLD: 1967, ‘Design Criteria for Large Dams: Introduction’, in *Joint Asce-Uscold Committee on Current United States Practice in: The Design and Construction, of: Arch Dams, Embankment Dams, Concrete Gravity Dams*, American Society of Civil Engineers (Asce) and United States Committee on Large Dams (USCOLD). Published by ASCE, New York, pp. 131.

Baban, S. M. J.: 1999, ‘Use of remote sensing and GIS in developing lake management strategies’, *Hydrobiologia* **395/397**, 211–226.

Baban, S. M. J. and Flannagan, J.: 1998, ‘Developing and Implementing GIS- Assisted Constraints Criteria for Planning Landfill Sites in the U.K.’, *Plann. Pract. Res.* **13**, 139–151.

Baban, S. M. J. and Wan-Yusof, K.: 2001a, ‘Mapping land use/cover distribution in mountainous tropical environments using remote sensing and GIS’, *Int. J. Remote Sensing* **22**(10), 1909–1918.

Baban, S. M. J. and Wan-Yusof, K.: 2001b, ‘Modelling soil erosion in tropical environments using remote sensing and geographical information systems’, *Hydrol. Sci. J.* **46**(2), 191–198.

Brassington, R.: 1995, ‘Building a New Source’, in *Finding Water: A Guide to the Construction and Maintenance of Private Water Supplies*, 2nd ed., John Wiley & Sons Ltd., Chichester, pp. 72–115.

Eastman, J. R., Kyem, P. A. K., Toledano, J. and Jin, W.: 1993, ‘GIS and Decision Making’, in *Explorations in Geographic Information Systems Technology*, Vol. 4, United Nations Institute for Training and Research, Palais de Nations, Geneva, pp. 111.

Eastman, J. R.: 1997, ‘Multi-Criteria Evaluation – Boolean and Weighted Linear Combination’, in *Idrisi for Windows Version 2.0*, Clark Labs for Cartographic Technology and Geographic Analysis. Idrisi Production, Clark University, pp. 77.

Gismalla, Y. A and Bruen, M.: 1996, 'Use of GIS in Reconnaissance Studies for Small-scale Hydropower Development in a Developing Country: A Case Study from Tanzania', in K. Kovar and H. P. Nachtnebel (eds), *Hydro GIS '96: Application of Geographic Information Systems in Hydrology and Water Resources Management, Proceedings of the Vienna Conference*, AIMS Publ. No. 235, pp. 307–312.

Guptill, S. C.: 1989, 'Evaluation geographical information systems technology', *Photogr. Engin. Remote Sensing* **35**(11), 1583–1587.

Henderson-Sellers, B.: 1979, 'The History of Water Supply', in *Reservoirs*, The MacMillan Press Ltd., London and Basingstoke, U.K., pp. 11–19.

Heywood, I., Cornelius, S. and Carver, S.: 1998, *An Introduction to Geographical Information Systems*, Prentice Hall, U.K.

Jusoff, K and Hassan, H. Md.: 1996, 'Forest recreation planning in Langkawi Island, Malaysia', *Internat. J. Remote Sensing* **17**(18), 3599–3613.

Langkawi District Council: 1992, *Langkawi Structure Plan 1990–2005*, prepared by Langkawi District Council in Co-operation with Federal Department of Town and Country Planning Peninsular Malaysia Northern Regional Office, Ministry of Housing and Local Government, State Department of Town and Country Planning Kedah Darulaman and French Consultant Team, Ministry of Foreign Affairs, France, Section 5, pp. 1–22.

Legg, C.: 1992, 'Water Supply and Waste Disposal', in *Remote Sensing and Geographical Information Systems: Geological Mapping, Mineral Exploration and Mining*, Ellis Horwood, Chichester, U.K., pp. 131–137.

Jonge, T., Kok, M., and Hogeway, M.: 1996, *Modelling Floods and Damage Assessment using GIS*, IAHS Publications, No. 235, pp. 299–306.

Mohamad, I. C. and Kiat, A. N.: 1996, 'Hydrogeology of Pulau Langkawi', in *Seminar on Hydrology on Small Islands in Langkawi, Kedah*, published by the Department of Irrigation and Drainage, Malaysia, Section 1, Paper 2.

Murphy, M.: 1977, 'Planning and Environmental Studies', in A. R. Golze (ed.), *Handbook of Dam Engineering*, Van Nostrand Reinhold Co., London, pp. 1–96.

Nelson, K. D.: 1991, 'Investigating and Planning', in *Design and Construction of Small Earth Dames*, Inkata Press, Melbourne, Australia, pp. 7–20.

Saaty, T. L.: 1977, 'A scaling method for priorities in hierarchical structures', *J. Math. Psychol.* **15**, 234–291.

Schwab, G. O., Fangmeier, D. D. and Elliot, W. J.: 1996, 'Surface Water', in *Soil and Water Management Systems*, 4th ed., John Wiley & Sons, Inc., printed by Courier/Stoughton, U.S.A., pp. 191–209.

Shaaban, A. J. and Sahat, R.: 1996, 'Hydrological Characteristics and Surface Water Availability of Pulau Langkawi', in *Seminar on Hydrology on Small Islands, Langkawi, Kedah, Malaysia*, 29 December 1996, published by the Department of Irrigation and Drainage, Malaysia, Kuala Lumpur, Malaysia, Section 1, Paper 1.

Stephens, T.: 1991, 'Site Selection', in *Handbook on Small Earth Dams and Weirs. A Guide to Siting, Design and Construction*, Cranfield Press, Cranfield, U.K., pp. 15–23.

Syed, M.: 1992, *Review of Surface Water Resources and Water Supply System, Detailed Design and Construction Supervision of Immediate Works in Pulau Langkawi. Water Resources Study – A Final Report*, Syed Muhammad, Hooi and Binnie Limited Company, Kuala Lumpur, pp. 76.

Taher, B.: 1996, 'Developing an Environmental GIS Database for Pulau Langkawi', in *Seminar on Hydrology on Small Islands, Langkawi, Kedah, Malaysia*, 29 December 1996, published by the Department of Irrigation and Drainage, Malaysia, Kuala Lumpur, Malaysia, Section 4, Paper 8.

Thomas, H. H.: 1976, 'Investigations', in *The Engineering of Large Dams*, Part 1, John Wiley & Sons, London, U.K., pp. 70–79.

Wilson, S. D. and Marsal, R. J.: 1979, 'Introduction', in *Current Trends in Design and Construction of Embankment Dams*, prepared for Committee on International Relations (Chairman: C. S.

Ospina), International Commission on Large Dams (ICOLD) and Geotechnical Division, ASCE (Chairman: W. F. Swinger), published by ASCE, New York, U.S.A., pp. 107.