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A STUDY ON THE IMPROVEMENT OF RESERVOIR WATERSHED MANAGEMENT PRACTICES IN TAIWAN

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Key Words **:** Decision support system (DSS), reservoir, watershed management, modeling, zoning

ABSTRACT

In recent years, watershed development is restricted for the purpose of source water protection. Watershed management agencies have struggled trying to balance environmental protection and resident demands for development. Foreign experiences have shown that watershed classification and zoning practices can be an effective approach to solving such conflicts. In this article, a watershed is divided into three zones: a restricted development zone (Zone I), a conditional development zone (Zone II), and a permissible development zone, which represents the rest of the watershed or Zone III. In Taiwan, there are still questions about how to delineate various zones in a watershed. The present paper will describe a method for developing a decision support system for delineating watershed zones. The method is water-quality based and considers factors such as bio-degradation of organic pollutants; sediment removal rates; runoff detention time, and others. Weighting indices are incorporated to address social/economical concerns. A case study using the Mingder Reservoir Watershed is presented to illustrate the proposed method. It is proposed that a GIS-based decision support system to be developed by using the approach described in the present paper for managing reservoir watersheds in Taiwan.

INTRODUCTION

There are currently more than sixty major and minor reservoirs in Taiwan, which are the main water source for the island nation of twenty-three million populations. Concerning with the ever-increasing water demand and recognizing the need for protection the environment, the government on Taiwan has begun to examine the use of better reservoir maintenance and watershed management approaches to enhance water supplies, rather than seeking new dam sites. More and more water utilities and responsible governmental agencies are attempting to address reservoir water quality and quantity issues through efficient and effective watershed management methods. One of the basic tools used in watershed management practices is DSS. It has been widely recognized that, for many reservoirs in Taiwan, pollution from non point sources (NPS) plays a significant, and sometimes dominant, role in water quality deterioration [1]. The essence of a successful reservoir watershed management involves water quality control (specifically, NPS control) by using best management practices (BMPs), which are being promoted in Taiwan as an effective means to mitigating nonpoint source pollution.

Since protecting water resources and improving water quality often involve very complicated tasks, decision-makers need appropriate analytical tools for evaluating management alternatives. Currently, one of the most powerful tools used to assist decision-making is DSS that can simplify and standardize watershed management work tasks such as evaluating water quality, defining mitigation zones, and identifying the sources of pollutants. As a matter of fact, DSS was first employed as an important tool for water resources planning. Many countries have spent lots of efforts in enhancing the efficiency of DSS in the last couple of decades. Lately, researchers have been focusing on developing and applying user-friendly graphical user interfaces (GUI), which are incorporated into DSS systems. This improvement not only makes DSS simpler but also helps the decision-makers evaluate a large number of management alternatives directly and effectively.

There is an abundance of literature, which addresses the application of various land management strategies for balancing the need of pollution control

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and local land development such as land use planning and zone-oriented control methods. The present paper describes a proposed strategy based on the zoning approach for the protection of drinking reservoir watersheds in Taiwan.

The US Environmental Protection Agency (USEPA) suggests that local governments use zoning and land development regulations to protect their source waters in terms of mitigating the potential risks of development impact on water quality. In most cases, the degree of restrictions placed on land use activities varies with the distance to the source water in question. Another example of using the zoning practice was presented by Freedman (1994) [2], in which the history and progress of watershed zoning management in North Carolina (NC) are described. In 1989, the North Carolina General Assembly ratified the Water Supply Watershed Protection Act, which mandated the adoption of minimum statewide water supply protection standards and reclassification of all existing surface water supply watersheds [3]. According to the Act, a water supply watershed is divided into five distinct zones and different land development strategies and wastewater discharging controls are implemented. In New Jersey [4], source water watersheds are also divided into five zones, which are: water zone, non-development buffer zone (or buffer strip), special restriction zone, State standard zone A, State standard zone B.

Numerous studies show that a well-forested buffer strip can be a very effective means of pollution control [5-8]. Also, various models can be found in the literature, which simulate the pollutant removal rate by buffer strips of different vegetation combination, soil type and buffer width. For example, Flanagan et al. [9] employed the model CREAMS to illustrate the sediment removal rate under sheet flow conditions by a filter strip. Grass buffer strips were studied by Dillaha et al. [10] and Lee et al. [11]. The authors demonstrated the effectiveness of the grass buffers in removing nutrients from runoff by using the mathematical model GRAPH. Narumalani et al. [12] applied remote sensing and geographic information systems (GIS) to delineate and analyze watershed land cover characteristics and to develop buffer zones around surface waters. In another example, Xiang [13] used a GIS-interface with a runoff detention time model to illustrate buffer strip effectiveness in an agricultural watershed. All these references help indicate that a mathematical model linked with GIS databases can be a very useful tool as a decision support system for watershed management.

Morton described how computers and analytical models could help or support managers in making key decisions [14]. The Better Assessment Science Integration Point and Nonpoint Sources Model (BASINS) [15], for example, is a multipurpose environmental analysis system and is now widely applied to supports

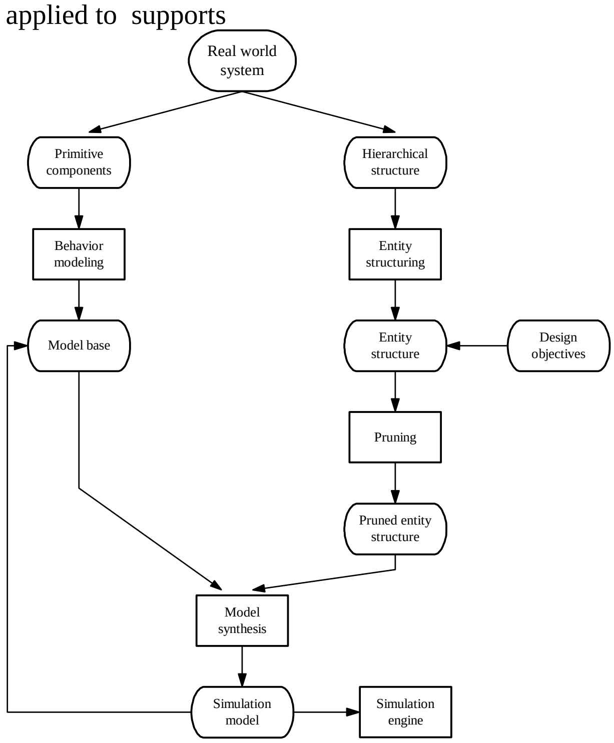

Fig. 1. Model base management flowchart [29].

the development of total maximum daily loads (TMDLs). Other similar systems include BESTAQAU [16], which was developed for agricultural pesticide and crop control management. WATERSHDSS [16] organizes a user platform, a multi-function Internet linkage, an educational component, and other features to provide functions including professional search, water quality data information, DSS for land use and pollution control planning, etc.. From these example applications, it is obvious that a current watershed DSS is usually developed to: exchange, transmit and analyze data and other information; evaluate and investigate watershed problems; and evaluate feasible management schemes. A GIS interface is a necessity for ease of data entry and presentation.

METHODOLOGY

I. Model Management

Model management (Fig. 1) is one of the most important aspects of a DSS. Similar to data management, model management should include the representation of a model base structure and the design of a model base system. Data management is considered a well-established research area because of the matured technology in database modeling, database design and database management systems. However, model management is a relatively new field of research [17].

The model base discussed in this paper includes a reservoir watershed predictive model base sub-

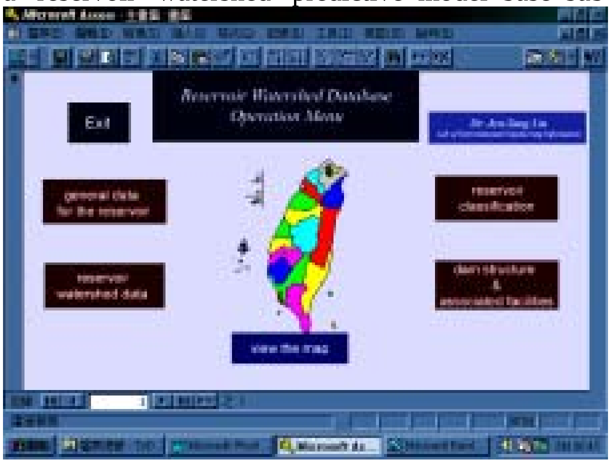

Fig. 2. Opening page of the Taiwan reservoir data base system.

system and a database sub-system, which is a combination of general databases and spatial databases. Since the purpose of establishing a watershed database is to provide the fundamental source information needed in a decision-making process, the content of the database subsystem for Taiwan will normally need to include the following basic data groups: general data for the reservoir; reservoir classification; reservoir and watershed data; and dam structure and its associated facilities (Fig. 2).

II. Reservoir Classification

Due to the steep terrain and short length of rivers in Taiwan, many reservoirs have been built for water supply and other purposes over the years. There are currently more than sixty major reservoirs or water-supply structures such as weirs in Taiwan. The first step of reservoir watershed management is to classify the reservoirs so the relative importance of each reservoir can be assigned. There are a number of ways of reservoir classification in use currently: (a) reservoir category based on hydrological regulations; (b) reservoir category defined by the Construction and Planning Administration of the Ministry of Interior; (c) the sites of reservoirs (namely on-stream or off-stream); (d) geographic location; and (e) function and purpose. The first two ways of classification are universally used in Taiwan, and the rest are adopted by agencies according to specific demands of reservoir management. However, most of the classification principles still vary from agency to agency in Taiwan and have not been made uniform yet so far. In this paper, an objective-oriented classification [18] is adopted (Table 1). If reservoirs serve as only one purpose, the weight of buffer width sets more in which with purpose of public supply, irrigating and industrial water supply in order. Multi-purpose reservoir, contrarily, the widths of each zone in the watershed are delimited according to the ratio of objectives that aimed to. In this research, the purpose of a reservoir is decided to be the parameter of the widths of restricted development zone.

III. Zoning Approach: Models for Buffer Width Determination

A number of models have been presented in the literature for determining the width of the protective buffer zone for a reservoir. Examples of such models include organic matter degradation curves; suspended solids removal curves; the runoff detention time model, and hydrological models, etc.

1. Organic Matter Decay Predicting Method

It is based on the first order decay assumption for organic matter. Equation 1 describes the change of the biochemical oxygen demand (BOD) in a non-tidal stream. It is assumed that the same relationship could be applied in an overland flow situation such as a vegetative buffer zone [19-20].

$$BOD_x = BOD_0 \cdot e^{-k_r t} \quad (1)$$

$$v = \frac{1}{n} R^{2/3} S^{1/2} \quad (2)$$

$$B_w = V \cdot t \quad (3)$$

where BOD_x = BOD remaining at x distance, or t day travel time downstream
BOD_0 = Initial BOD
k_r = BOD decay coefficient
t = time
v = flow velocity
n = Manning's roughness coefficient
R = hydraulic Radius
S = slope
B_w = buffer zone width

After the decay curve of the target pollutant, in this case the BOD, is determined, the proper buffer width can be estimated. Based on the desirable pollutant removal rate (η) for a certain reservoir watershed, the required travel time can be calculated from Equation 1 and from Equations 2 and 3 the desired buffer width, B_w ,can be calculated. A similar concept was presented by Wen [21] as an overland flow system (OLFS) model:

$$\frac{L}{L_0} = ae^{-bx/q^c} \quad (4)$$

where L_0 represents the BOD, or a target organic pollutant, concentration at the origin; L is the remaining BOD or the target pollutant at "*x*" flow distance downstream; q is the hydraulic loading rate, and a, b and c are coefficients.

2. Method based on Suspended Solids Removal

If suspended solids (SS) removal is selected to be the keystone pollutant, the method proposed by Wong et al. [19] is often mentioned; it is well documented and has been used in a number of studies. This method employs a monograph to determine vegetative filter strip or buffer widths. In the nomograph the required buffer width is related to such variables as slope, Manning roughness coefficient, and the desired removal rate. For example, when slope= 2%, n = 0.20, and the desired removal rate = 95%, a buffer width of 61 m is required.

Table 1. Reservoirs classified by designated objectives.

Objective	Reservoir	*Number*
Public supply	Hsiaochi Reservoir of Penghu, Yonghoshan Reservoir, Yuanshan Dike, Feitsui Reservoir, Zhitan Dike, Mingder Reservoir, Chintan Weir, Shinshan Reservoir, Nuannuan (Hsishi) Reservoir, Chengching Lake Reservoir, Boushan Reservoir, Hsian Reservoir of Penhu, Donewei Reservoir, Hsingren Reservoir, Lantan Reservoir, Ganghsihsian Weir of Donggang Creek, Chikan Reservoir of Panghu, Jingmian Reservoir, Renyi Reservoir, Chenggong Reservoir	20
Irrigation	Deryan Bei Reservoir, Hutou Bei Reservoir, Yanshui Bei Reservoir, Neipuzi Reservoir, Dapu Reservoir, Jantan Reservoir, Pazigan Reservoir, Guanyin Lake, Toushe Reservoir, Chingchao Lake, Longluantan Reservoir	11
Hydroelectricity	Shuilan Dike, Longhsi Modulating Pool, Liwu Dike, Twolong Dike, Baishanyan Dike, Shachi Reservoir of Minghu, Chonggui Modulating Pool, Wushe Reservoir, Aooneda Dike, Chingshan Modulating Pool, Tianloon Modulating Pool, Guishan Dike, Ayu Dike, Luohou Dike, Gookuan Reservoir, Cukeng Dike, Woojie Modulating Pool, Xipan Modulating Pool	18
Multipurpose	Zonehwa Dike, Fongshan Reservoir, Agongden Reservoir, Zengwen Reservoir, Jianshanbei Reservoir, Shiman Reservoir, Luliao Creek Reservoir, Baiheh Reservoir, Sun Moon Lake Reservoir, Derji Reservoir, Wushantou Reservoir, Shigang Dike	13

3. Riparian Buffer Detention Time (RBDE) Model

One of the factors contributing to the effectiveness of a riparian buffer is the type of underlying soil in the buffer strip. If all other factors such as width, slope, and vegetation are equal, the soil type can cause wide variations in the pollutant removal efficiency. RBDE was proposed by Phillips [22-23] for the purpose of establishing a proper riparian buffer zone. RBDE can be divided into two individual models: runoff detention time model (M_D) [22], and hydraulic model (M_H) [23].

M_D is the detention time version of RBDE that evaluates the time a buffer holds the flow of water within its boundaries. Detention time is significant for non-conservative pollutants that undergo a decay process while being transported by runoff. This version is appropriate for calculating the removal of pollutants such as nitrate, bacteria and oxygen demand that depend on time more than the energy of overland flow [23]. Sediment is an example of a pollutant that depends more on energy because water with more energy can keep more sediment suspended. For the detention version of this equation, Phillips has assumed that the concentration of these solid-phase pollutants can be directly related to time. M_H and M_D can be calculated as:

$$M_H = B_b / B_r = (K_b / K_r)(L_b / L_r)^{0.4}(s_b / s_r)^{-1.3}(n_b / n_r)^{0.6} \quad (5)$$

$$M_D = B_b / B_r = T_b^* / T_r^* = (n_b / n_r)^{0.6}(L_b / L_r)^2 (K_b / K_r)^{0.4}(s_b / s_r)^{-0.7}(C_b / C_r) \quad (6)$$

where b represents the proper buffer width, and r denotes a reference buffer width, B_b /B_r the buffer effectiveness ratio, T_b^* /T_r^* the runoff detention index, n the Manning coefficient, L the buffer strip width, K the hydrological transmission coefficient, S the slope and C is the soil moisture capacity. It should be noted that in the RBDE method, the reference buffer width, B_r, is the width that is required to provide a removal rate under "average" runoff conditions, and for a "representative" set of physical characteristics such as soil type, land cover, roughness coefficient, and topography.

If equation 6 is solved for L_b, and the decision-making factor B_b /B_r is substituted by a constant p that can be adjusted for regional differences (in general p=1), the proper buffer width, thus, is calculated as:

$$L_b = L_r[(B_b / B_r)(n_r / n_b)^{0.6}(K_r / K_b)^{0.4}(s_r / s_b)^{-0.7}(C_r / C_b)]^{0.5} \quad (7)$$

$$B_b / B_r = p \quad (8)$$

$$L_b = p^{0.5} L_r[(n_r / n_b)^{0.6}(K_r / K_b)^{0.4}(s_r / s_b)^{-0.7}(C_r / C_b)]^{0.5} \quad (9)$$

It should be noted that in the RBDE method, the reference buffer width, B_r, is the width that is required to provide a removal rate under "average" runoff conditions, and for a "representative" set of physical characteristics such as soil type, land cover, roughness coefficient, and topography.

Whichever of the above methods is chosen, it is suggested that the following basic principles be followed in determining the proper buffer width. (a) Select the appropriate method for the target pollutant.

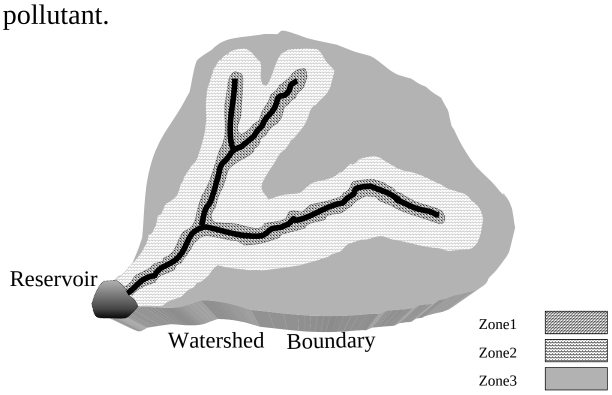

Fig 3. An illustration of the proposed zoning approach.

For example, if the target pollutant were organic matter, then the organic matter decay curve method would be appropriate. By the same token, the solids removal method would be suitable for total suspended solids as the target pollutant, and the RBDE method would be good for nutrients (namely nitrogen and phosphorus) as target pollutants. (b) Use the watershed average slope as a factor in choosing the appropriate method. It is suggested that for slope less than 14%, the suspended solids removal method would be suitable. The organic matter decay method, and the RBDE method are appropriate for mild-slope areas, while the hydraulic model would be better for relatively higher slope areas.

4. Structure of the Zone Model for Reservoir Protection

Considering the various factors discussed above, a three-zone land use management strategy, shown in Fig. 3, was proposed for protecting reservoir water quality in Taiwan [20]. An equation was developed to calculate the required width of the zones in a three-zone reservoir protection scheme as follows:

$$B_{w0} = F(X_1, X_2, X_3, X_4, \cdots\cdots) \quad (10)$$

$$B_{w1} = W_f \times B_{w0} \quad (11)$$

$$B_{w2} = I_{r0} \times B_{w0} \quad (12)$$

$$B_{w3} = B_T - B_{w2} - B_{w1} \quad (13)$$

where,

B_{w0} = appropriate buffer width
B_{w1} = width of restricted development zone (Zone I)
B_{w2} = width of conditional development zone (Zone II)
B_{w3} = width of admissible development zone (Zone III)
W_f = weight index, which is a soil- erosion-related weight factor k
I_{ro} = reservoir objective index
B_T = the distance between river and watershed divide
X = environmental parameters determining water discharging quality

The rationale behind the proposed method for determining the various zone widths in the three-zone management strategy can be described as follows: The buffer width, Bw_0 , is determined based on water quality, not administrative, considerations. The width of effective buffer zone is various due to different environmental background condition, but mostly in the range between 30m to 50m is suggested [24]. The width of the no-development zone, Bw_1, is taken as multiples of the buffer width. The multiplying factor, W_f , is related to the erosion potential of the soil in the region as shown in Table 2. The width of the conditional development zone, Bw_2, is calculated by applying a weighting factor to the buffer width. The weighting factor, I_{ro}, is related to the designated use of the reservoir in question, as shown in Table 3. The rationale behind this is that the zone width should be wider if a reservoir is a drinking water source, and can be allowed to be narrower if the reservoir water is used for a less or purpose.

After the buffer, the no-development and the conditional development zones are delineated; the remainder of the watershed is designated as the “permissible” development zone, in which all development is allowed, provided that a set of minimum requirements for controlling point and nonpoint sources of pollution is complied with.

The proposed zone allows a decision maker to strike a reasonable balance between the protections of the lifeline resource, i.e., water, and the need for development in watersheds so that people’s needs could be satisfied and the economy can be sustained. The zones are delineated on the basis of water-quality considerations and not on a subjective or administrative basis that has been used for many years in Taiwan. Such “arbitrary” delineation methods have been very controversial and resisted by property owners. Many view the existing methods “too stringent” and intrusive with respect to private property rights. The structure of the zone management model system is shown in Fig. 4.

A CASE STUDY: THE MINGDER RESERVOIR WATERSHED

It has been documented that the major water quality problems of the Mingder Reservoir are sediment deposition [25] and eutrophication, with the latter being under control since 1997 [26]. The main tar- get pollutant in the case study of watershed zoning management is therefore suspended sediment or SS. Of the several methods described earlier in this paper, the suspended solids removal method presented by Wong [19] is selected to calculate the buffer strip width. Data on three parameters are needed for the computation, namely, the average watershed slope ($S\%$), the desired removal rate (T_R), and the Manning's roughness coefficient (n). After the required buffer strip is obtained, the widths of the three management zones can be calculated by using Equations 10 through 12.

Table 2. Suggested values of W_f.

Soil factor	Suggested W_f value
Low erosion soil (soil erodibility index: k* < 0.20)	2.0
Middle erosion soil (soil erodibility index: 0.20 < k* < 0.40)	2.0 – 3.0
High erosion soil (soil erodibility index: k*> 0.40)	3.0 – 4.0

* k is soil erodibility (t·ha·y/ha·mj·mm) defined by Universal Soil Equation (USLE), and W_f is suggested according to watershed geological and soil condition.

Table 3. Suggested values of reservoir objectives index I_{ro}.

Zone	Reservoir objective	Geographic location	I_{ro}*
I	Public supply	On-stream	15
		Off-stream	12
II	Irrigation	On-stream	10
		Off-stream	8
III	Industrial supply (others)	On-stream	5
		Off-stream	3

* I_{ro} is adjustable according to the water quality standards of distinct reservoir objectives, and it can be decided through a public hearing procedure.

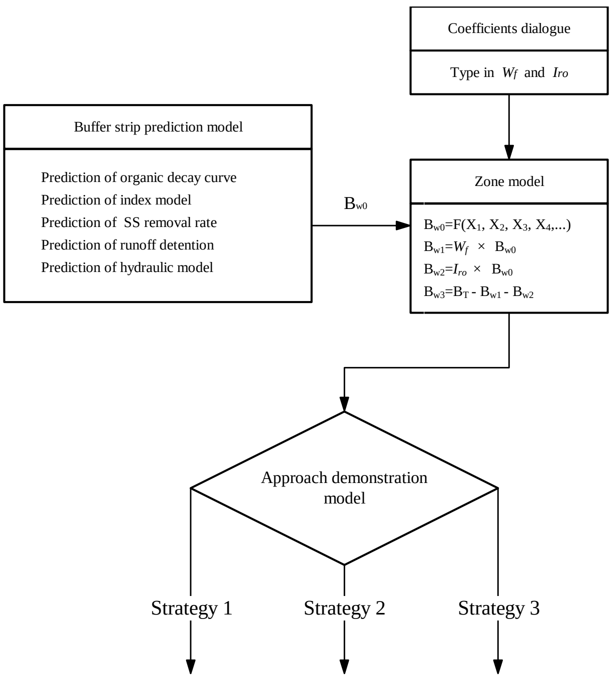

Fig. 4. Structure of zone model base [17].

The following data is employed in the Mingder Reservoir case study:

- $S\%$: The Mingder Reservoir Watershed was divided into 72 equal-sized (500 m × 500 m) sites with each contains 100 (50 m × 50 m) equal-size cells. Slopes were determined from the 1/5000 scale regional topographic maps. Defining cells into Group A (average slope 4.4) and Group B (average slope 6.6) after sampling.
- I_{ro}: Because Mingder is an on-stream type of reservoir that was designed for satisfying public supply and irrigation demand; the value of I_{ro} is set as 15.
- T_R: The desired removal rate for SS was set to be 90%.
- n: The roughness coefficient was set to be 0.35.
- k: according to current investigation [27], within Group A area, mostly is low erosion soil (k = 0.18 < 0.20), thus W_f = 2; within Group B area, mostly is middle erosion soil, W_f = 2~3 (average 2.5).

Using the suspended solids removal method, the Mingder Reservoir watershed was delineated in accordance with the three-zone management scheme proposed in this study (Fig. 5). The three zones, namely, Zone I, Zone II, Zone III, had land areas of 12.7%, 45.7%, and 41.6% of the total watershed area, respectively (Table 4). In a 1997 survey [25], the vast proportion of the Mingder watershed was found to be covered by bamboo trees (5,384.76 hectares, about 88.16% of the watershed area). Agricultural land use came in second (349.87 hectares, or 5.75% of the watershed area), of which rice farms were the most prominent (207.23 hectares). Based on the information regarding current land uses found in Zone I (Fig. 6), the result of the proposed zoning delineation would impact significantly private agricultural lands, thus intensive communication, negotiations and unwilling conflicts must be expected in the process of allocating proper zone width.

Table 4. Results of the Mingder reservoir watershed zoning calculations.

	Zoning approach				
	Zone I	Zone II	Zone III	Buffer zone*	
Width (m)	86-160	645-1,000	—	30	50
Area (km^2)	7.6	27.4	25.0	2.8	4.6
% of watershed	12.7	45.7	41.6	4.6	7.6

* The figures are base on the Water and Soil Conservation Regulation.

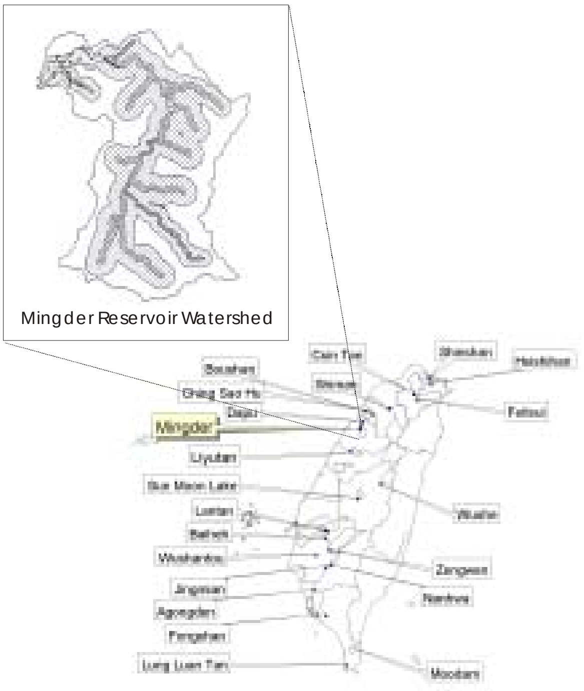

Fig. 5. The illustration of Mingder Reservoir watershed zones.

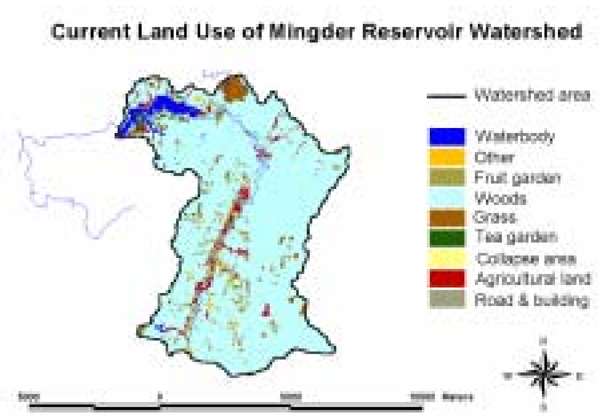

Fig. 6. Current land use type and distribution in the Mingder Reservoir watershed.

CONCLUSIONS

In the present paper, a three-zone management scheme is proposed for managing reservoir watersheds in Taiwan. Zones within watershed are delineated using a water-quality based approach, rather then a mostly administrative type of delineation method being applied at the present time. The quantitative approach is easily incorporated into a decision support system for reservoir watershed management, as demonstrated herein with a case study of the Mingder Reservoir Watershed in Northern Taiwan. It is expected that the proposed approach should be applicable in other parts of the world where urbanization and economic development are of paramount importance for maintaining the wellbeing of the people.

In the proposed zoning approach, there still exist some uncertainties that a decision-maker needs to deal with. For example, the weighting coefficients W_f and I_{ro}, are somewhat subjectively determined. The method of calculating average slope for the watershed also can be improved. Another important ingredient of a successful program is the availability of basic data. Unfortunately, there is evidence indicating that past efforts on implementing watershed-monitoring programs have been "fragmented, duplicative and wasteful" [28]. Much progress has been made during the last two decades in the area of data collection, especially in the developed countries. However, for many developing countries, there still is a strong need for data collection and importantly, for the development of uniform sampling and analytical protocols, improving both field and laboratory quality control procedures, and, therefore, making basic watershed data more available in standardized formats.

Watershed zoning is a multidisciplinary effort that utilizes knowledge from hydrological, hydrographical, biological, ecological and social sciences. The proposed three-zone management plan attempts to integrate a physically based approach into a management scheme, which also includes social-economical considerations in providing decision-makers with a tool for implementing watershed management plans.

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Discussions of this paper may appear in the discussion section of a future issue. All discussions should be submitted to the Editor-in-chief within six months.

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台灣水庫集水區管理改善之研究

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摘　　要

近年來的集水區發展已轉向以水源保護為主要目標，集水區管理相關單位亦以調和環境保護與居民權益為職志。在國外實際案例中，分級分區管理措施確能調和此類土地利用與水資源保育的衝突。本文所謂分級分區管理是將集水區劃分為限制發展區(第一區)、條件發展區(第二區)及容許發展區(第三區)三種分區管理。國內對如何分級分區之研究尚屬發展階段，因此本文嘗試找出分級分區之決策因子，藉有機物衰減曲線、懸浮物質去除、逕流遲滯時間等方法建立推估模式，同時將社經因子納入考量及利用 GIS 圖層管理功能，進而建構決策支援系統，最後以明德水庫集水區為例進行實例分析。