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A system dynamic based DSS for sustainable coral reef management in Kenting coastal zone, Taiwan

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ABSTRACT

Kenting is located at the southern end of Taiwan, and is famous for its abundant marine resources, especially diverse coral species. This beautiful coastal zone attracts millions of tourists every year. However, growing human activities and increasing land reclamation pressure have resulted in negative impact to the coral reef ecosystem. Thus, exploring an integrated approach for sustainable coral reef management is urgently needed. The current study adopts the integrated coastal zone management (ICZM) concept and develops a system dynamic (SD) based decision support system (DSS). The SD model, built as a DSS to facilitate scenario analysis, can solve the complex coastal zone management problem. Four subsystems, socio-economic, environmental, biological, and management, join with the SD model configuration for integrated assessment of the particular problem. The model identifies four critical management strategy variables, including land development, wastewater treatment, local fish consumption rate, and entrance fee collection, and presents users with a user-friendly DSS interface. Several scenario analyses are conducted and presented in this paper. Decision makers can also fine tune DSS variables and evaluate preferable scenarios through simulations. Sustainable management strategies for the coral reef ecosystem can hopefully be developed using the DSS and implemented in the near future.

1. Introduction

Coral reefs, particularly fringing reefs, are often located close to the coast and should be considered as parts of the coastal zone. They are one of the most important ecosystems on Earth in terms of productivity and biological diversity (Connell, 1978). Besides, coral reefs serve people in multiple ways, such as providing seafood, recreational possibilities, coastal protection, and aesthetic and cultural benefits (Done et al., 1996). However, extensive coastal development pressures from increasing demands for industry, tourism, housing, transportation, and other human activities, have a major impact on coral reefs. Westmacott et al. (2000) suggested that the coral reef sustainability may best be addressed by appropriate coastal zone management.

Coastal zones are complex regions influenced by numerous interrelated issues, including socio-economic, administrative, and hydrological systems. Multiple human-interest convergence, such as tourism, agriculture, raising stock, fisheries, and other industries, makes these areas the most populated yet fragile regions in the world. Recuperation and conservation efforts to sustain natural resource and environment quality are therefore critical. However, coastal zone management faces serious challenges. Inefficient cross-organizational cooperation deserves particular attention, since effective management strategy cannot succeed without

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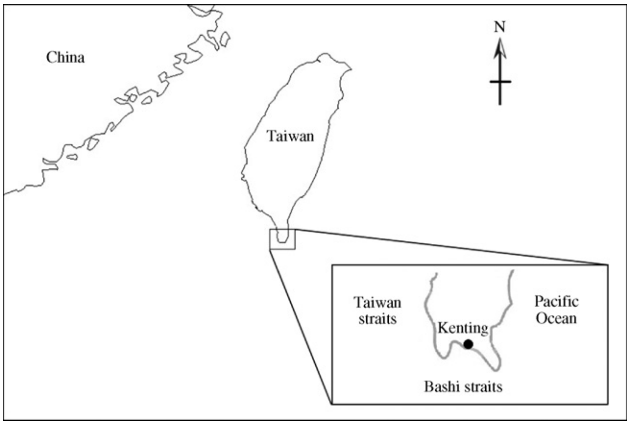

Fig. 1 – Location of Kenting.

considering system coexisting entities. Therefore, exploring an integrated approach for dealing with coastal zone management problems is strongly needed. Integrated coastal zone management (ICZM) has become the global guideline for environmental planning and management in coastal area (Cicin-Sain and Knecht, 1998).

Kenting is located at the southern tip of Taiwan, on the Hengchun Peninsula, with the Pacific Ocean to the east, the Taiwan Straits to the west, and the Bashi Straits to the south, as shown in Fig. 1. With its unique spatial location, where the famous Kuroshio current brings abundant marine organisms, Kenting coastal water nourish 60% of coral species found in the world. The abundances of marine resources in Kenting have drawn the worldwide attentions from academic communities, and ocean lovers. Meanwhile, by providing a variety of scenic resources, this tiny coastal zone is one of the most popular resorts in Taiwan. Kenting attracts million of tourists every year, who enjoy not only sightseeing, but also many recreational activities and the taste of fresh seafood. Consequently, the public sector are confronted with the over-developed tourism which usually accompanying with serious problems, such as increasing land reclamation pressure, depletion of coral reef fish stocks due to overfishing, and degradation of the marine resources.

Uncoordinated human activities in the coastal zone can cause severe impact on marine environment. Bryant et al. (1998) observe that more than 80% of Southern Asia coral reefs are at risk, primarily owing to human impact. Many studies, as summarized by Moberg and Folke (1999), also indicated that unsustainable use of coastal and marine resources by human activities would destroy the resilience of coral reefs. There are some nature threats to coral reefs in Kenting, such as intrusion of unusual cold water mass, typhoon, and El Nino. Natural disturbances behave like random discrete events appearing occasionally, whereas human-induced disturbances function like continuous events occurring all the time. Nyström et al. (2000) explained the interactions between the two types of disturbances. The natural disturbance regime affects the dynamic development of coral reefs; nevertheless, the chronic stress by human activities would alter the capacity of reefs to cope with natural threats, thus leading to unpredictable synergistic effects. To mitigate human-induced effect, the goal of the current study is to develop effective coastal zone management strategies toward sustainable coral reef ecosystem. Therefore, the factors of nature disturbances are excluded from the modeling process.

A system-dynamics-based (SD) decision support system (DSS) developed in this study and based on the ICZM concept, incorporates multidisciplinary research efforts with coastal zone management dynamics for effective decision-making. An SD model formulation does not require a complex mathematical system presentation and therefore allows for much easier system integration compared with traditional system analysis techniques. The dynamic behavior of and the interactions among Kenting socio-economic, environmental, and ecological factors can be seamlessly coupled using the SD modeling software STELLA®. This tool also facilitates DSS building, providing a user-friendly interface that allows decision makers or stakeholders to perform effective scenario analysis for sustainable coral reef management under the ICZM framework.

2. Methods

The ICZM is a dynamic, continuous, and iterative process designed to promote sustainable management of coastal zones (EC, 1999). Coastal areas have traditionally been regarded as indistinct from the "wider environment" and have consequently suffered from lack of policy and regulatory coordination (Huggett, 1998). There is growing realization with the passage of time, that the coast is not only a complex natural environment but also a complex policy area where numerous agencies with differing, but often overlapping objectives, responsibilities, and powers operate (Scottish Office, 1997). Sustainable coastal zone management strives for maximum long-term social good, including environmental, ecological, economic, social, and cultural considerations.

Integrated management is the ICZM conceptual framework, aggregating not only target area terrestrial and marine components, but also spatial and temporal dimensions of focus issues. Achieving such integrated management requires that ICZM utilize a range of core management principles. For example, it seeks to balance benefits among economic development, human uses, and natural resources of the coastal zone over a long time period. All activities should also be confined by natural dynamics and carrying capacity limits. In practice, ICZM implementation should encompass information collection, planning, decision-making, and implementation management and monitoring, as suggested by the European Commission in 1999.

System dynamics is a powerful yet simple method that uses causal-loop and stock-flow diagrams for describing interrelated systems. It is therefore easy for SD to model dynamic and complex components as an integrated system. Various system elements with long lasting influences simultaneously affect many coastal zone management problems. SD capability of dealing with complex, nonlinear, and feedback-loop structures inherent in social and physical systems make it appropriate for ICZM use. SD provides users with better understanding of system dynamic behavior by giving insight into feedback processes.

A great deal of literature has shown SD as a proper method to reveal complex and dynamic behavior of such integrated sustainable management systems. Meadows et al. (1972) discussed the WORLD3 model in their book, "*The Limits to Growth*", based on SD thinking. The model analyzes possible relationships between population, pollution, natural resources, and economic growth on planet Earth. SD models assess sustainable development on global and national scales and are well suited for local scale sustainable management. Fletcher (1998) employed SD as a decision support tool to manage water resource shortage. Jessup (1998) evaluated brown trout population and habitat quality by building a SD model which integrated land disturbance and imperviousness in the watershed. The simulation of various watershed development strategies showed the trout population cannot recover with more than 15% of impervious surface. Cavallaro and Ciraolo (2002) used SD to formulate a dynamic model for interpreting the phenomena affecting the Salina Island, Italy, and for assessing local government policies. Elrefaie and Herrmann (2003) created a SD model to combine the economic, ecological and social aspects for the sustainable planning of tourism activities in the coastal nature conservation, Egypt. Dyson and Chang (2005) forecasted municipal solid-waste generation in a fast-growing urban region by SD modeling. Lee and Chang (2006) performed strategic analysis for a sustainable urban river aquatic environment in Kaohsiung, Taiwan using the system dynamic approach. Bald et al. (2006) developed a SD model to find the best management strategy, which maximizes captures and minimizes the stock looses in a sustainable manner, between Aketxe and Gaztelugatxe coastal areas of the marine reserve.

Information-based technologies (IT) promise new capabilities for enhancing environmental management potential, especially decision support systems (DSS). DSS concepts are generally interactive, computer-based systems designed to support decision makers dealing with semi-structured or unstructured problems through data and model utilization (Turban and Aronson, 1998). A well-designed DSS may capably analyze potential management alternative outcomes, reducing decision makers' need to deal with minute IT details (Argent and Grayson, 2001). DSS applications for environmental management, such as storm sewage discharges, municipal and industrial solid-waste, chemical emergency preparedness and response, and forest management, have been very fruitful (Chang and Wang, 1996; Chang et al., 1997; Rauscher, 1999; Reda and Beck, 1999).

3. Model development

This study purposes to develop an SD simulation model and decision support functionalities using STELLA® software, which can evaluate coastal zone management strategies for Kenting coral reef sustainability. The modeling process is divided into three hierarchical tiers, as shown in Fig. 2—the physical level, the SD modeling level, and the decision-making level. The physical level identifies current situations and potential problems in Kenting, that is, marine resources and aquatic environment degradation under pressure from human activity. Explicit mechanisms behind this complex interaction are collected and reviewed. The SD modeling level simulates human impact on the environment and ecosystem based on physical level studies. SD model configuration is further partitioned into four subsystems—socio-economic, environmental, ecological, and management. The cause–effect diagram shows subsystem relationships. The decision-making level performs certain scenario analysis following SD model formulation and validation. Users experiment with preferable scenarios by adjusting important system variables through a user-friendly interface.

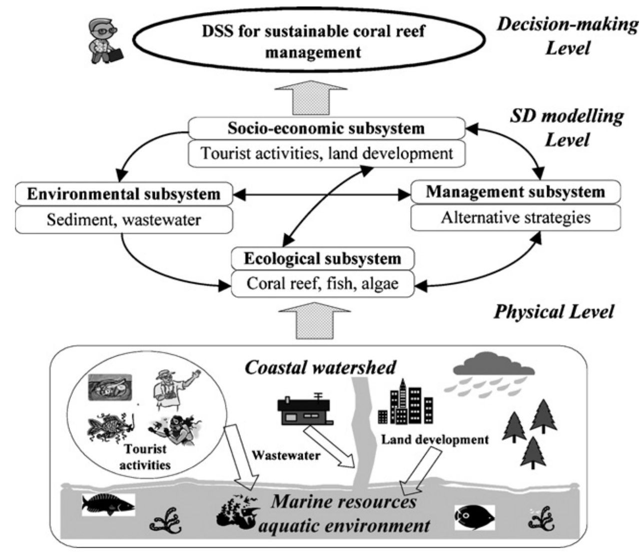

Fig. 2 – Modeling process in developing the SD-based DSS.

The SD modeling approach uses causal-loop diagrams to show a system's feedback structure. A casual-loop diagram is similar to a network chart, showing cause–effect relations among system variables (represented as nodes) using causal links (displayed as oriented arcs). Cause–effect variable pairs positively related are represented by a plus sign added to the link; otherwise, a minus sign results. A casual-loop diagram generally comprises several positive–negative-feedback-loop structures with closed circulation configurations. A positive-feedback-loop could trigger an embedded system variable growth process over time, possibly leading to system loss of control and collapse. A negative-feedback by contrast, seeks a goal and responds through achieving a stable state.

The left side of Fig. 3 shows the macro-view of causal-loop diagram for the current Kenting coastal zone. One positive-feedback-loop and one negative-feedback-loop, which all start and end with *Tourist activity* node, appear in the system concurrently. The negative-feedback-loop describes the following relations: the increasing *Tourist activity* would reduce *Coral reef coverage*, and consequently the declining *Coral reef coverage* should suppress *Tourist activity*. However, the delay between *Coral reef coverage* and *Tourist activity*, along with the positive-feedback-loop, would eventually cause the coral reef extinction. The causal-loop diagram of the proposed SD model for sustainable coral reef management is displayed on the right side of Fig. 3. The central node, which is *Sustainable management strategies*, links with all key elements in the

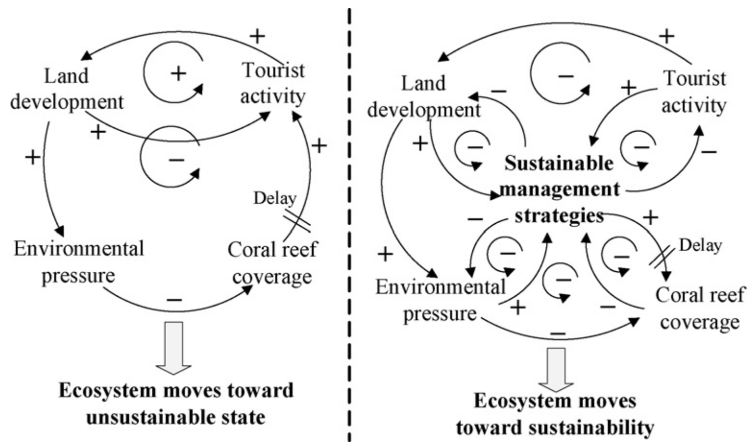

Fig. 3 – Macro-view of the causal-loop diagrams for the original and the proposed SD models.

system and generates several negative-feedback-loops. These negative-feedback-loops would mitigate the negative human impact to the coral reef ecosystem and move the system state toward sustainability. Four subsystems in the SD model are detailed as follows.

3.1. *Socio-economic subsystem*

The socio-economic subsystem presents critical socio-economic factor interactions such as tourist activities and land developments. The willing to pay (WTP) index, showing whether tourists will visit again, serves as the bridge for connecting the key factors in all subsystems. The WTP is evaluated using contingent valuation to show object marginal valuations under study, depending on both current and future (or expected) utilization patterns. WTP highly relates to the tourist population and represents tourist degree of attraction. Park et al. (2002) for example, developed a WTP model for the Florida Keys showing prices snorkelers are willing to pay to preserve coral reef water quality and health. The SD model employs Eq. (1), a revised version of Chan's suggestion (2001) for calculating WTP in Kenting. The WTP model, formulated according to tourist travel experiences using key parameters of facility quality (FQ), nature quality (NQ), and quantity of travel annually (QT), is shown in Eq. (1).

$$\mathrm{WTP} = 1.46 - 0.84 \times \mathrm{QT} + 0.68 \times \mathrm{NQ} + 0.224 \times \mathrm{FQ} \qquad (1)$$

Fig. 4 is the stock-flow diagram of the socio-economic subsystem. The variable WTP links two key elements in the system, which are the land area under construction and the accumulated tourist number, each represented by the stock variables BUILDING and TOURIST accordingly. FQ, used for WTP calculation, is affected by the facility demand (FD) that is the deviation of TOURIST and F_CP, tourist capacity sustained by current facilities. Multiplying B_CONV, a constant of tourist number served per ha, by CONC, total land development area, can find a F_CP value. Furthermore, the stock variable CONC accumulates the land area under construction from the stock variable BUILDING, and thus the linkage between WTP and BUILDING is identifiable. Confined by the allowable land development area (B_AREA), BUILDING varies

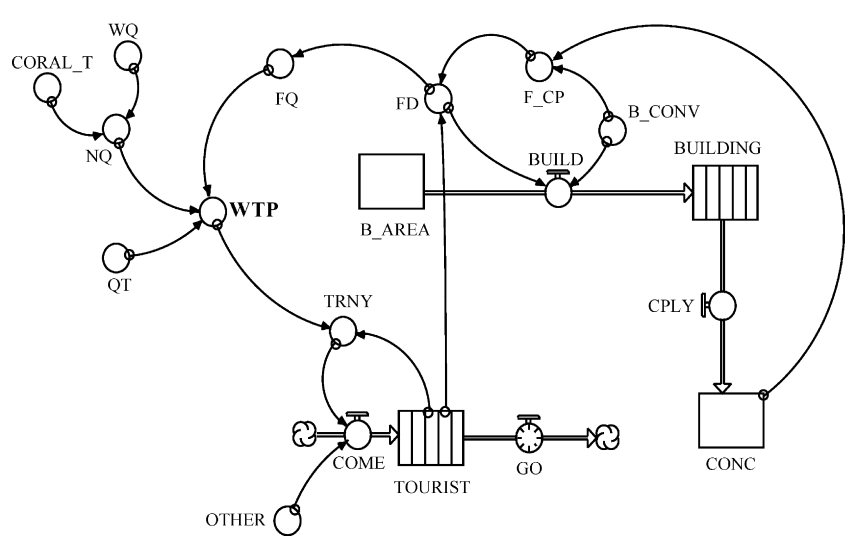

Fig. 4 – Stock-flow diagram of the socio-economic subsystem.

depending on two flow rate variables, which are monthly land area under construction (BUILD) and monthly land area finishing construction (CPLY).

WTP, on the other hand, links with the variable TRNY, stands for the number of tourist visited again. A higher WTP value suggests more tourists will come back due to good traveling experience. Besides, about 24% of tourists who are not inspired by the past experience would constitute the rest of tourist number according to the study of Gao (1995). This type of tourists, denoted as OTHER, then joints with TRNY for determining the flow rate variable COME, tourists arrival per month. TOURIST, designed as a “conveyer”, is another form of stock variable in STELLA®, which is to accumulate the last 12-month tourists counted from the current month. This system formulation can comprehend simply the long-term tourist variations and the WTP effect. Furthermore, the socio-economic subsystem has strong connections with the environmental and the ecological subsystems to address the integration issue as required by the complex coastal management problem. For example, tourist satisfactions on water quality (WQ) and coral reef (CORAL_T) set up the variable NQ, which influences the WTP calculation as shown in Eq. (1). Meanwhile, monthly tourists would inevitably affect BOD discharged in the environmental subsystem and monthly fish catch in the ecological subsystem.

3.2. *Environmental subsystem*

Two major indicators, sediment and biochemical oxygen demand (BOD), used in the environmental subsystem, assess marine aquatic environment status. Sediment amount is calculated using the universal soil loss equation (USLE). The USLE is frequently applied in rural areas to predict average annual erosion rate based on rainfall patterns, soil types, topography, crop systems, and management practices. Potential long-term average soil loss in tonnes per acre per year, denoted as A, is calculated by Eq. (2), which involves the multiplication of five factors. R is the rainfall and runoff factor varied with geographic location. K is the soil erodibility factor, which is soil particles susceptibility to detachment and transport by rainfall and runoff. LS is the slope length-gradient factor—the steeper and longer the slope, the higher the erosion risk. C is the crop/vegetation and management factor and determines soil and crop management system relative effectiveness in terms of preventing soil loss. Lastly, P is the support practice factor, reflecting the effects of practices that reduce the amount and rate of water runoff, thus reducing erosion amount.

$$A = R \times K \times \mathrm{LS} \times C \times P \tag{2}$$

Water pollution caused by over-developed tourism in Kenting severely affects near-shore water quality. Among the pollutants, BOD is the most significant, directly related to marine aquatic environment integrity. BOD measurement in the proposed SD model takes point- and non-point-source pollution impact into account. Domestic sewage generated by residents and tourists contributes to major point-source pollution, while surface runoff created by rainfall delivers the greatest non-point-source pollution, which is calculated using the Rational Formula derived from rainfall–runoff relationships.

3.3. *Ecological subsystem*

The major ecological subsystem concern is to outline a reasonable marine ecosystem structure involving coral, fish, and algae elements. Ecosystem intrinsic functions are very complex, and some are either highly uncertain or remain unknown to scientists. Simple cause and effect mechanisms therefore acquired from related research assumably preserve major system interactions. Over-enriched nutrients, which provide good living conditions for algae, are generally considered the major cause of coral reef ecosystem degradation (Littler and Littler, 1984). Szmant (2002) showed that unhealthy coral reefs generally exhibit a shift from high to low coverage accompanied by increasingly high coverage and biomass of algae. Competition between corals and algae can presumably be realized, and such interaction is therefore implemented in the SD model. Fang (1989) also mentioned a positive correlation existence between coral and fish amounts, and Chen (2002) found that algae grow quickly with herbivorous fish reduction. Crabbe and Smith (2003) pointed out that sediment severely affects the Sampela Scleractinian coral community, leading to coral suffocation. Lastly, human activities in near-shore water such as diving and other recreational sports, can directly damage coral reefs. The LTER (long-term ecological research) monitoring results in Kenting (Shao and Jan, 2002) found that coral reef coverage in some popular sites is less than in protected sites.

The ecological subsystem stock-flow diagram, based on the above relative studies is represented in Fig. 5. The kernel of the diagram illustrates competition between coral and algae for open space. The model is based on a two-species colonization model described by Hannon and Ruth (1997). There are three stock variables, which are the open space that can be colonized and one each for the space (coverage) occupied by coral and algae. Three types of system flow rates include: algae colonization rate (A_COLONY), coral reef colonization rate (C_COLONY), and replacement rate between two species (C_DISPLACE). Reasonable mechanism adoption allows each flow rate unique determination by the variables connected with it. For example, C_COLONY links with the coral extinction coefficient (EC), the coral colonization coefficient (CC), the occupied coral area (CORAL), and the open space (OPEN), hence Eq. (3) computes C_COLONY involvement in all these variables. Multiplying CC by the product of CORAL and OPEN describes converting available space for coral reef colonization. Such analogism is based on the law of mass action where chemical reaction rate is proportional to the product of the concentrations of chemicals participated. The net C_COLONY needs to substrate coral reef loss due to coral reef extinction at a rate EC. The A_COLONY flow rate can be estimated using a similar equation by replacing CC with CA, EC with EA, and CORAL with ALGAE. Meanwhile, Eq. (4) calculates the replacement rate between coral and algae (C_DISPLACE) by applying the same concept of mass action.

$$\mathrm{C\_COLONY} = \mathrm{CC} \times \mathrm{CORAL} \times \mathrm{OPEN} - \mathrm{EC} \times \mathrm{CORAL} \tag{3}$$

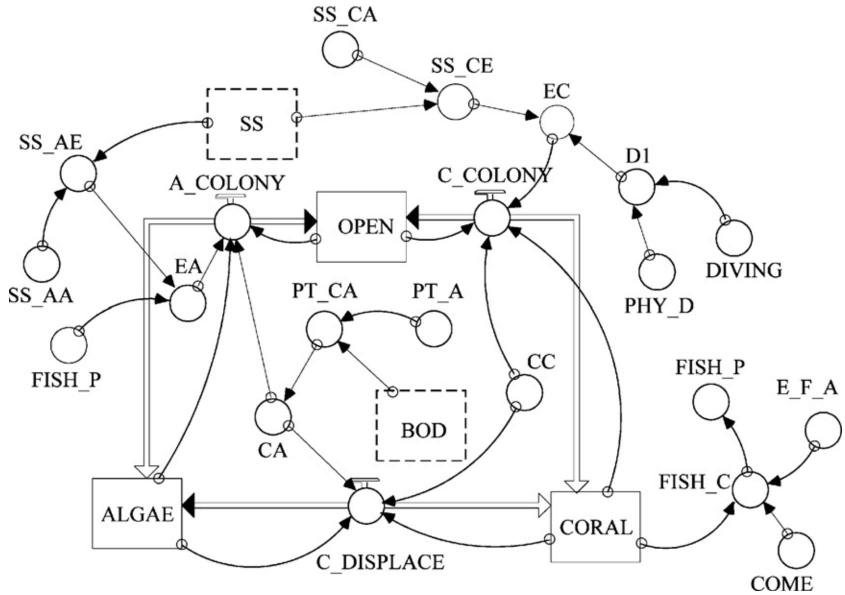

Fig. 5 – Stock-flow diagram of the ecological subsystem.

$$\mathrm{C\_DISPLACE} = (\mathrm{CC} - \mathrm{CA}) \times \mathrm{CORAL} \times \mathrm{ALGAE} \qquad (4)$$

Coral reef and algae competition highly relates to the external factors in the other subsystems. Pollution amounts (BOD) in the environmental subsystem contribute to algae growth (PT_CA) and consequently enhance algae's colonization capability (CA). Sediment (SS) on the contrary, also derived from the environmental subsystem, causes both coral reef (SS_CE) and algae (SS_AE) death, and eventually affects coral reef (EC) and algae (EA) extinction coefficients. Herbivorous fish amounts also suppress algae growth, that is, increasing algae death. Thus, the algae death rate by fish grazing (FISH_P), contributed directly to the algae extinction coefficient (EA), has an inverse relationship with the monthly catch of fish (FISH_C). Furthermore, the variable FISH_C relates to monthly tourists (COME), local fish consumption rate by tourists (E_F_A), and coral reef coverage (CORAL). Human activities also negatively impact the coral reef extinction coefficient (EC). Two variables, including diving (DIVING) and other recreational sports (PHY_D), assumably contribute to coral reef death (D1) due to human activities, subsequently affecting the coral reef extinction coefficient (EC). All the variables involved in these subsystems of the SD model are summarized in Appendix A.

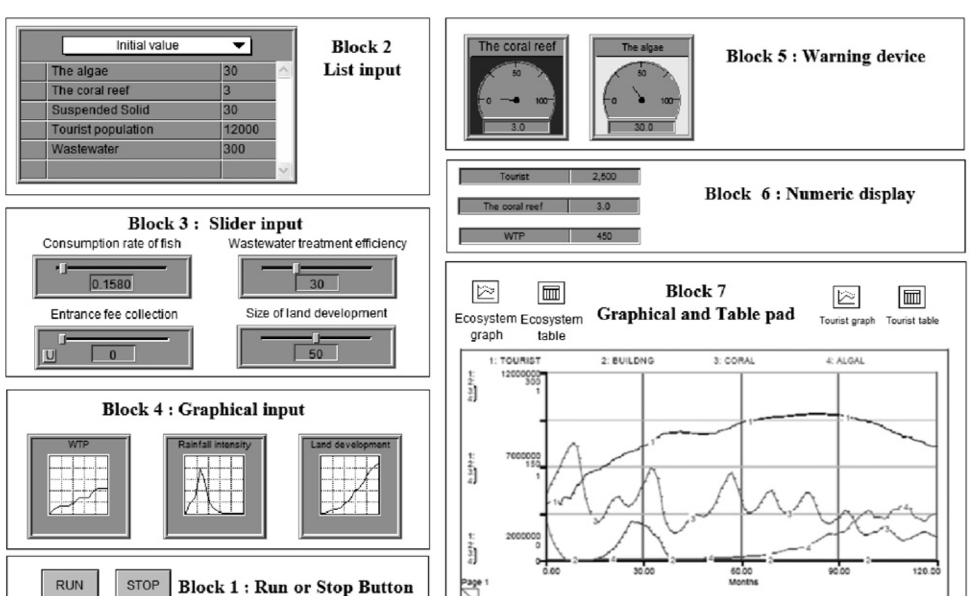

Fig. 6 – A user interface for the proposed SD-based DSS.

3.4. Management subsystem

The management subsystem enables users to perform scenario analysis in which system variables and managerial planning relations are adjusted according to designated strategies. Decision makers in this way, can evaluate diverse strategies and provide strong decision support functionalities. Four major management strategies cover land development, wastewater treatment, coral reef fish consumption, and entrance fees collection issues. Land development limitation could mitigate sediment impact on coral reefs. Kenting domestic water pollution can gradually reduce by enhancing wastewater treatment capacities. Coral reef fish consumption by tourists encourages over-fishing, deteriorating ecosystem integrity. Therefore, local fish consumption amount is the important system factor, and should be kept as low as possible. The public sector could also resort to charging admission to enter Kenting. While tourist numbers are expected to decrease if such a strategy were implemented, human activity impact on the coral reef ecosystem could be lessened. Each proposed single strategy further aggregates to build more complex management strategies.

3.5. DSS user interface

An effective and user-friendly interface is critical when implementing any type of DSS. The SD software STELLA® facilitates user interface building processes by providing a visualized toolbox, such that model developers can easily design their favorite interface by just clicking and dragging, plus a few keystrokes. There are four types of user interface modules in the toolbox—buttons, input devices, output devices, and warning devices. Each module can be configured to associate with certain variables or parameters in the SD model. A model builder can then build an appropriate and user-friendly interface according to system and user's demands. A user unacquainted with many SD modeling details can in this way easily operate the system for scenario analysis.

An example of the main control screen of an SD-based DSS developed in the current study is given in Fig. 6. Blocks

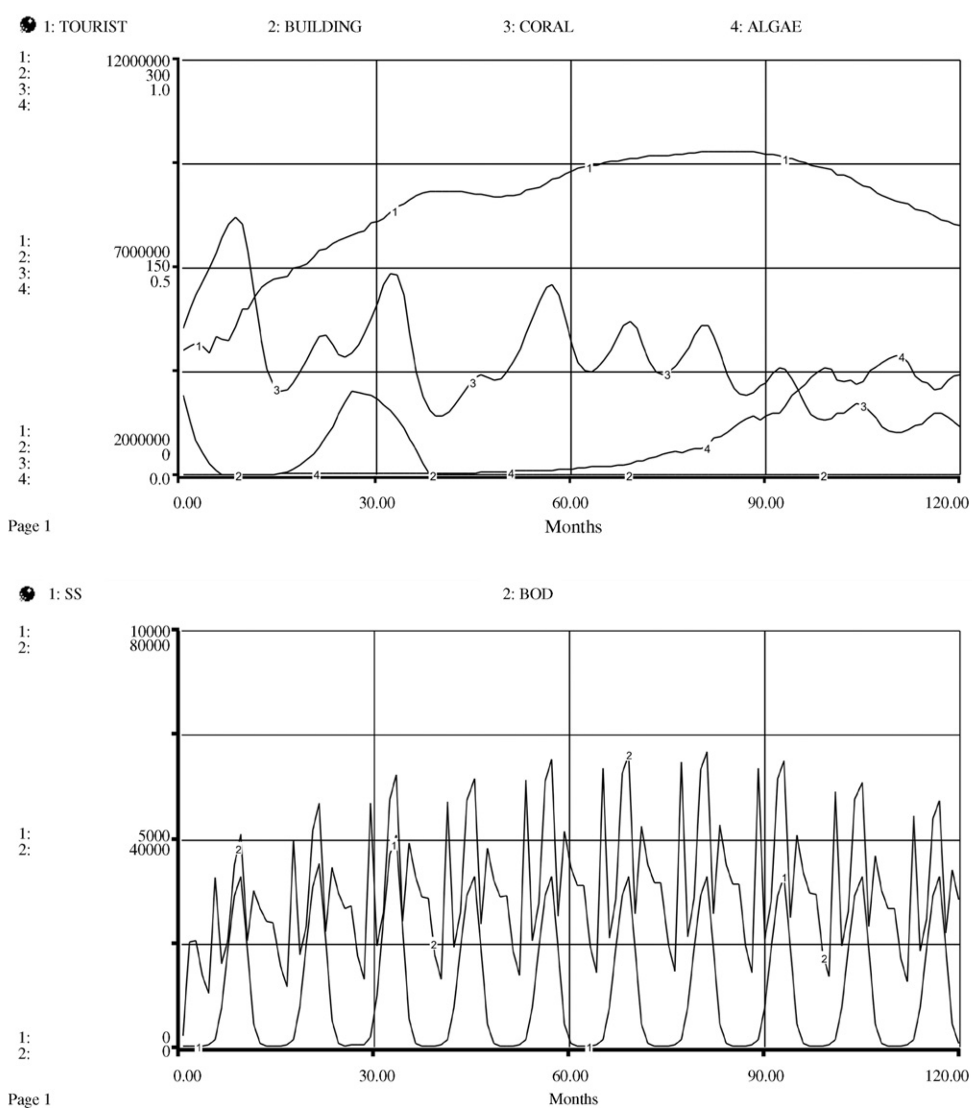

Fig. 7 – System performances under "zero action" scenario.

on the left-hand side of the user interface prompt users to set up the desired simulation scenario. Variables or parameters with a single value in the SD model can be initialized using the list input device as shown in block 2. Similarly, the time-series data can be configured to characterize any given situation using the graph input device in block 4. The slider input device in block 3 regulates sensitive factors, such as land development size and BOD removal rate in this study. Once a user completes input variable configuration and parameters, she or he can press the "Run" button in block 1 to commence a simulation run.

The right-hand side of the interface is designed as an information display centre. The numeric display module in block 6 keeps updating key variable values. Speed meters in block 5 serve as warning devices in which abnormal situations are signaled by visual and audio effects during a simulation run. For example, if coral reef coverage is below a pre-set threshold representing aquatic environment critical state, then a text message, such as "dangerous for the ecosystem," and an audible warning activates to alert users. Lastly, SD model results are illustrated in detail using a graph pad or table pad, as shown in block 7. Each proposed management strategy is evaluated effortlessly using a DSS through the user interface. The SD-based DSS could help a decision maker find effective solutions for sustainable coral reef management in Kenting.

4. Results and discussion

The DSS allow users to evaluate the system performance based on the future trends of the corresponding simulations for the next 10 years. The current study considered only human-induced disturbances which would affect coral in a more persistent manner than what natural threats would do. To take the chronic human impact into account, it is thus appropriate to simulate the coral reef ecosystem over the 10-year period. The long-term development of the coral reefs under designate coastal zone management strategies can be clearly perceived. Critical parameters related to managerial strategies in the current study are identified as land development, wastewater treatment, coral reef fish consumption, and entrance fee collection. Two types of time-series figures

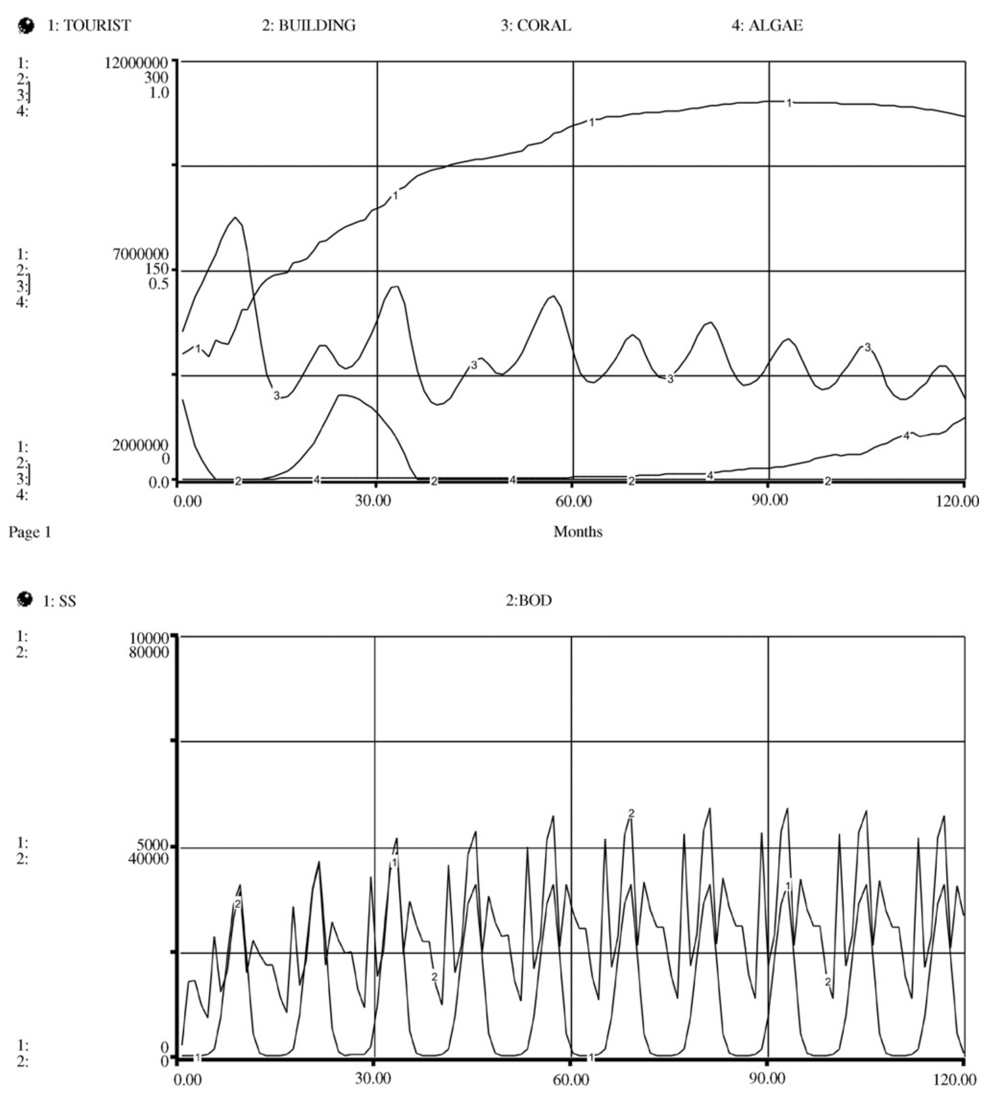

Fig. 8 – System performances under "30% waste water treatment" scenario.

were plotted to record variables related to system performance throughout the simulation. The first illustrates stock variable status in socio-economic and ecological subsystems, including accumulated tourists in last 12-months (TOURIST), land development pressure mainly from construction (BUILDING), percentage of coral reef coverage (CORAL), and percentage of algae coverage (ALGAE). The second shows key environmental factors of sediment (SS) and BOD.

Several scenario analyses, based on a single management strategy and one composite strategy, were conducted using the DSS to demonstrate system performances under corresponding management strategies. More complex scenario analyses, such as joint various management strategies step by step, can be easily achieved using the DSS for decision makers. According to sensitivity analysis, the reasonable ranges of some influential parameters are prescribed in Table 1. Sensitivity analysis is to identify if a model behaves as expected when important parameters are varied over the plausible range of uncertainty. In assessing sensitivity to parametric assumptions, the researchers tested a wide range of uncertainty starting from the original value of each parameter. The results implied the parameter adjustment under those sensitive ranges would preserve the validity of the SD model. These sensitive parameters also represented the important factors of the managerial strategies in ICZM. Therefore, the user interface of the DSS would confine users' selections of these parameters to the prescribed intervals.

Table 1 – Important parameters and ranges

Managerial parameter	Prescribed range
Future land development area allowed	0–1000 ha
Efficiency of waster water treatment facility	0.0–0.8
Consumption rate of coral reef fish	0.0–0.2 kg/person
Entrance charge fee	0–200 New Taiwan (NT) Dollar

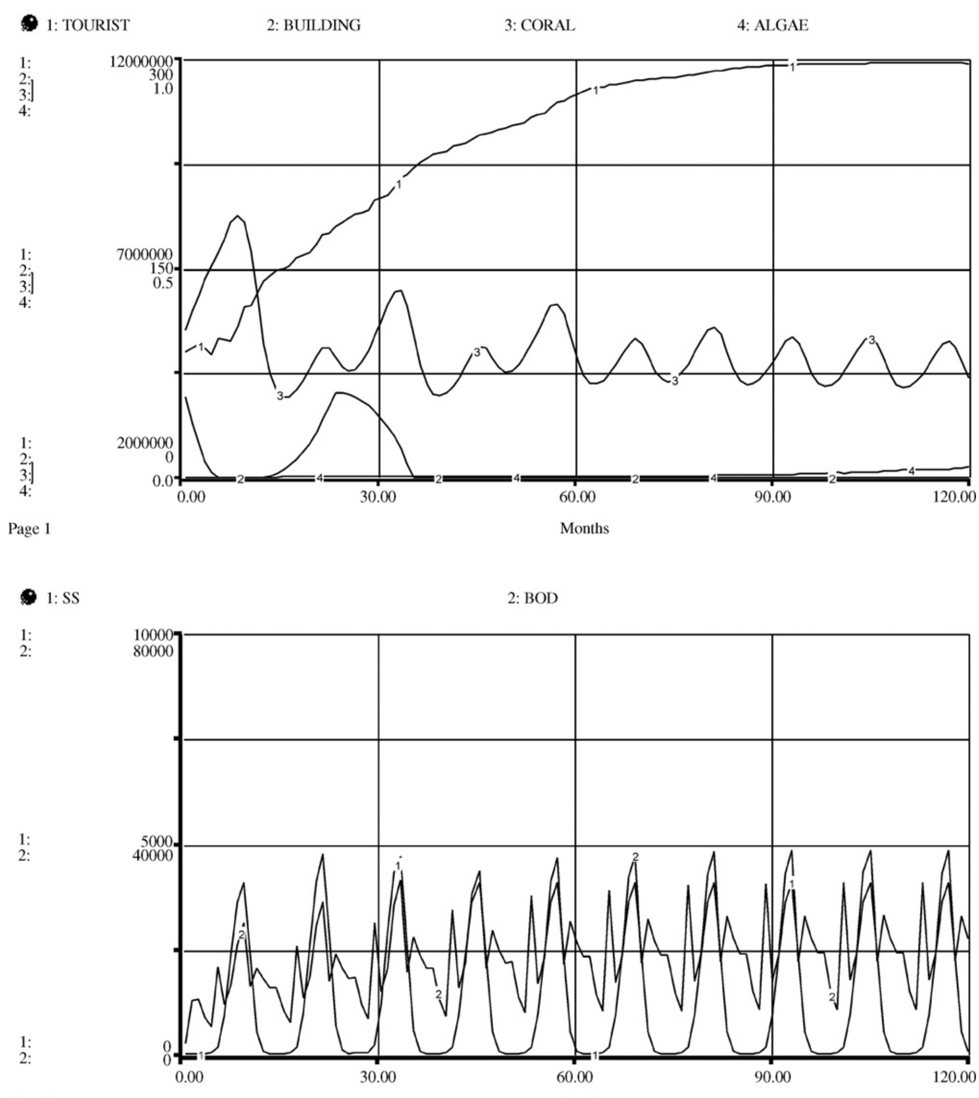

Fig. 9 – System performances under "50% waste water treatment" scenario.

4.1. *Model structure assessment test (zero action)*

The current study conducted several SD model tests as suggested by Sterman (2000), including boundary adequacy test, structure assessment test, dimensional consistency test, parameter assessment test, integration error test, and sensitivity test. The proposed SD model is not for precise quantification, but for an integrated complex system demonstration showing a reasonable long-term trend. Therefore, structure assessment is the major concern of model testing which verifies model structure consistency with relevant system descriptive knowledge. The zero action scenario in this case was configured to examine whether simulated results preserve ecological system relations. This scenario also serves as the baseline for later comparison with various management strategies. The "zero action" assumes that no additional management strategies are adopted, except the 60 ha future land development area legally granted by the administration.

The result is shown in Fig. 7. Since the initial aquatic environment was set to favor coral reef growth, coral reef coverage increases at simulation beginning while algae coverage decreases. During the busy tourist season, which is also the wet season in Kenting, tourist impact and sediment reduces coral reef coverage. Construction inevitably increases soil erosion, which is easily flushed into the near-shore water during the wet season. The initial construction phase fortunately begins during the dry season of the second year, based on tourism demands, giving the coral reef a chance to grow. But when there is no more available development space in Kenting at the end of the third year, sediment effect causes direct damage to the coral reef, with an even lower coral reef coverage than previous years. This situation satisfies Crabbe's study (2003) of sediment as it relates to coral reef.

Tourist growth drops slightly after the third year due to coral reef ecosystem deterioration, but picks up again thanks to coral recovery. The tourism boom and severe pollution, mainly from BOD discharge however, causes eutrophication and algae (anemone) bloom, jeopardizing coral reef habitats. More tourists also imply over-fishing and recreational activity pressures, all negatively impacting the coral reef. Coral reef coverage therefore begins to fade, and by the eighth year, algae becomes the dominate species, surpassing coral cov-

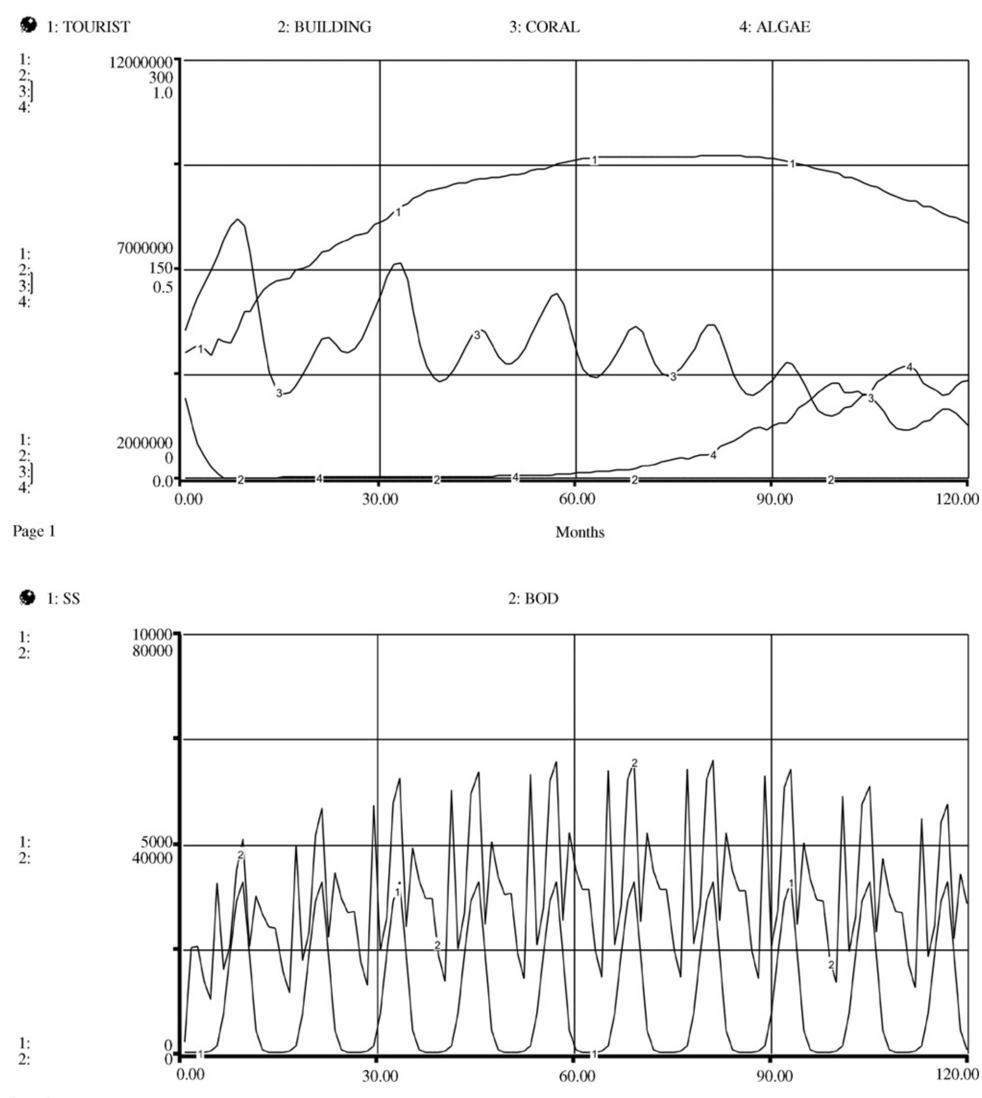

Fig. 10 – System performances under "no construction" scenario.

erage. The simulated results reveal qualitative experiences as mentioned by Littler and Littler (1984), Fang (1989), Chen (2002), and Szmant (2002). Therefore, the proposed SD model is consistent with relevant real system knowledge. Coral reef coverage drops to a very low level at simulation end, indicating an unsustainable coral reef ecosystem under the zero action scenario.

4.2. *Wastewater treatment efficiency (30%)*

BOD discharge has strong ecosystem impact, and thus an engineering approach by building a wastewater treatment facility is intuitive. Thirty percent of wastewater treatment efficiency was configured for this scenario analysis to investigate the mitigating effect of this strategy. Tourist numbers grow steadily in the simulation reaching a higher plateau than that of the "zero action" scenario as Fig. 8 shows. Even with more tourists, the current scenario remains at a lower BOD level, as shown in Fig. 8, compared to the baseline scenario. Construction activities in the second and third years heavily influence the coral reef as in the baseline scenario. Later coral reef coverage shows stable fluctuation implying that the current strategy creates a sound aquatic environment for coral reef. As simulation reaches a point where tourists plateau, algae begin to increase and coral begin to decline. Coral reef coverage drops to the same level as algae after a decade. This phenomenon shows that 30% wastewater treatment efficiency accommodates increasing tourism to a certain capacity without coral reef ecosystem deterioration. However, once tourist numbers exceed this capacity, the current strategy can no longer sustain a good living environment for the coral reef. Therefore, more effective strategies are needed to deal with the long-term unsustainable problem.

4.3. *Waste water treatment efficiency (50%)*

This strategy was setup based on the same rationale as the previous one, except that treatment efficiency was raised from 30 to 50%. The shortcoming identified in the previous scenario can hopefully be resolved. The 50% treatment efficiency strategy discharges less BOD into the Kenting water, as shown in Fig. 9. Tourist numbers grow faster and higher than the

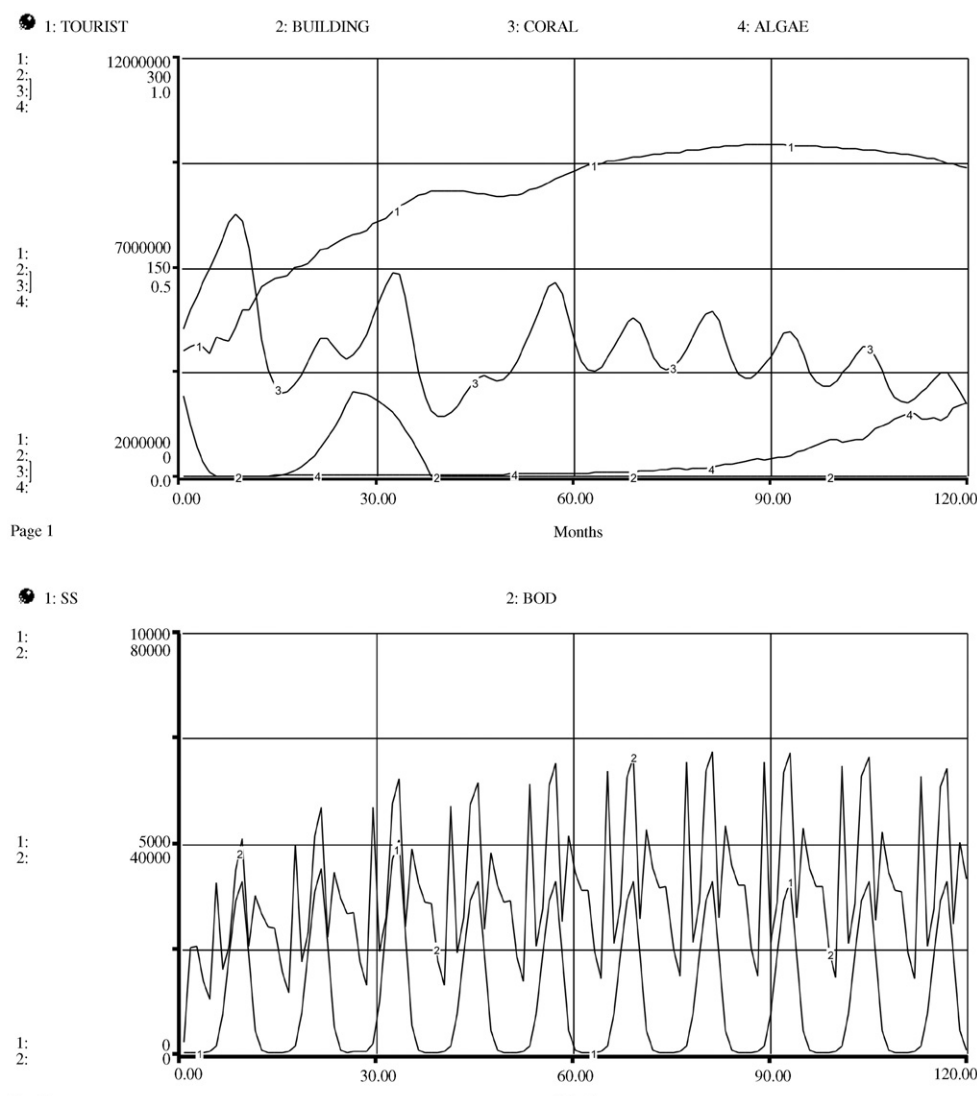

Fig. 11 – System performances under "0.1 consumption rate of coral reef fish" scenario.

previous scenario, reaching a steady state at simulation end. Although tourism development is prosperous, it does not create too much harm to the coral reef due to effective human pollution reduction. Coral reef coverage remains stable after the third year, while algae keep at very low coverage with little lift at simulation end. Results suggest that the current strategy accommodates more tourists, and preserves an acceptable aquatic environment for the coral reef ecosystem. However, implementation cost for such a strategy can be very high, and should be considered by a decision maker when planning management strategy.

4.4. *No construction*

This scenario bans all land development in the Kenting coastal zone, including the 60 ha of legal land. Coral reef coverage improves at the end of the third year compared to the baseline scenario, as results show in Fig. 10. Tourist numbers increase steadily and reach a peak in the sixth year. But aquatic environment degrades with more tourists, as shown by a coral reef coverage decline trend. Algae meanwhile begin colonizing the open space previously occupied by the coral reef by the seventh year. The ecosystem situation eventually becomes similar to the baseline scenario, suggesting that the current scenario does not ameliorate coral reef sustainability in the long-term except for minor improvement seen in the third year.

4.5. *Consumption rate of coral reef fish (0.1)*

Coral reef fish consumption by tourists, set to 0.158 originally, positively relates to local fish catch, thus negatively relating to the algae extinction rate. The total amount of fish taken from the coral reef ecosystem, is derived by multiplying the number of tourists by consumption rate. This scenario shows how the ecosystem would respond to this strategy if the fish consumption rate reduced to 0.1. Key patterns shown in Fig. 11 are generally similar to those in the "no action" scenario except that the algae does not grow as fast in the second half of the simulation and barely becomes the superior species at

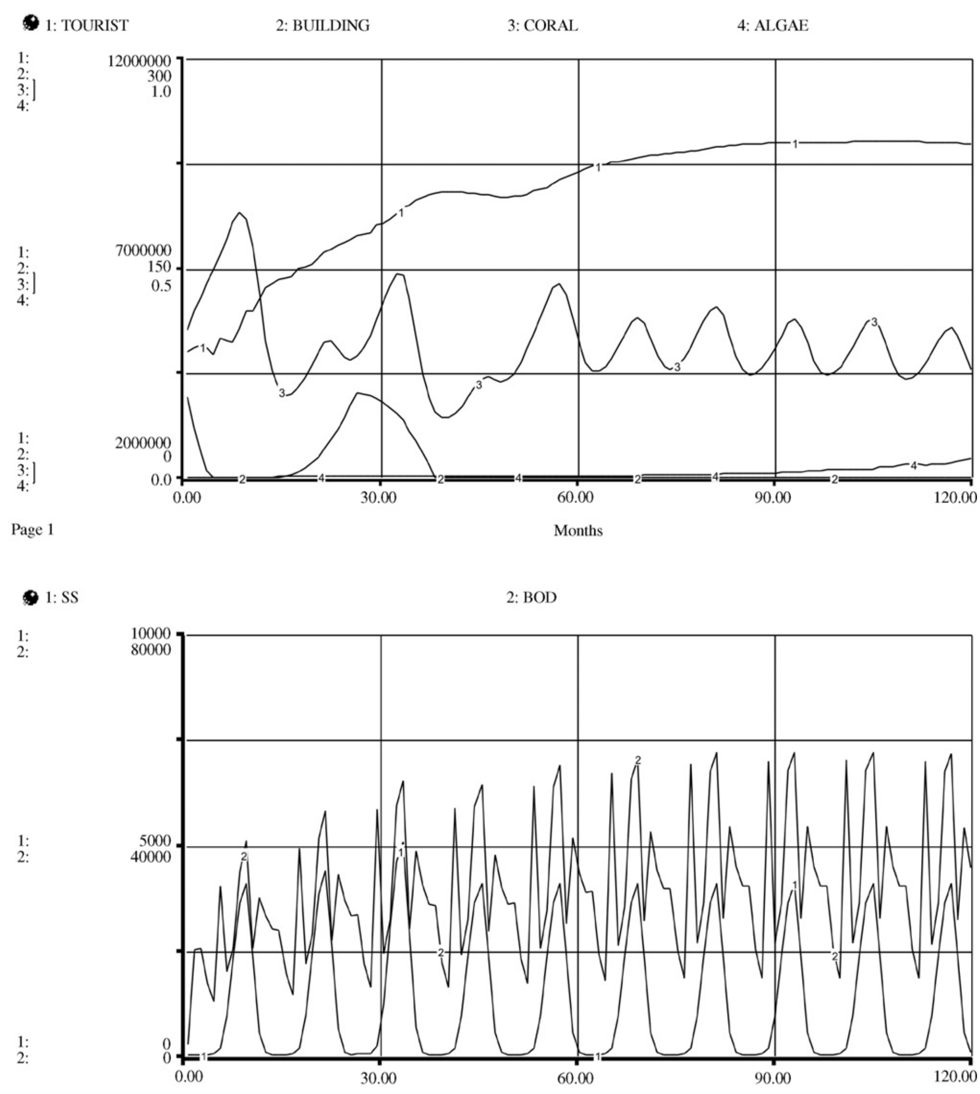

Fig. 12 – System performances under "0.05 consumption rate of coral reef fish" scenario.

the end. This phenomenon indicates that coral reef fish can restrain algae growth, which is good not only for the coral reef, but also enhances undersea scenery with more coral reef fish swimming around.

4.6. Consumption rate of coral reef fish (0.05)

The previous scenario encourages a lower fish consumption rate set to 0.05 to form this scenario. The tourist pattern is the same as the previous scenario aside from no declining trend after the eighth year as shown in Fig. 12. The coral reef remains dominant over the algae throughout the 10-year span due to little rise in algae coverage at simulation end. Results imply that a self-regulating function in nature effectively balances competition between species, such as no obvious algae emergence, if human disturbance is kept to a minimum. Extensive environmental education programs should be launched as early as possible for management strategy implementation as suggested in this scenario, and the effects may take years to manifest.

4.7. Entrance fee charge (NT 50)

The entrance fee charge scenario uses the economic approach for suppressing tourist numbers, such that less human disturbance is possible and coral reef conservation is achieved. Acquired money can also allocate to sustainable coral reef management by implementing strategies in previous scenarios. The scenario significantly effects low numbers of tourists compared to the other scenarios, as shown in Fig. 13. Land development is consequentially put back 1 year due to less tourism demand, and a small sediment increase is observable during the third and fourth year. Coral reef status maintains a fair condition with stable fluctuation after construction end. Algae coverage starts to expand at a very low pace until the simulation final quarter. The current scenario generally provides a sustainable coral reef management strategy for the public sector, with good coral reef coverage and an additional budget. This solution is contestable in the social aspect however, and requires a common consensus from both public and private stakeholders before implementation.

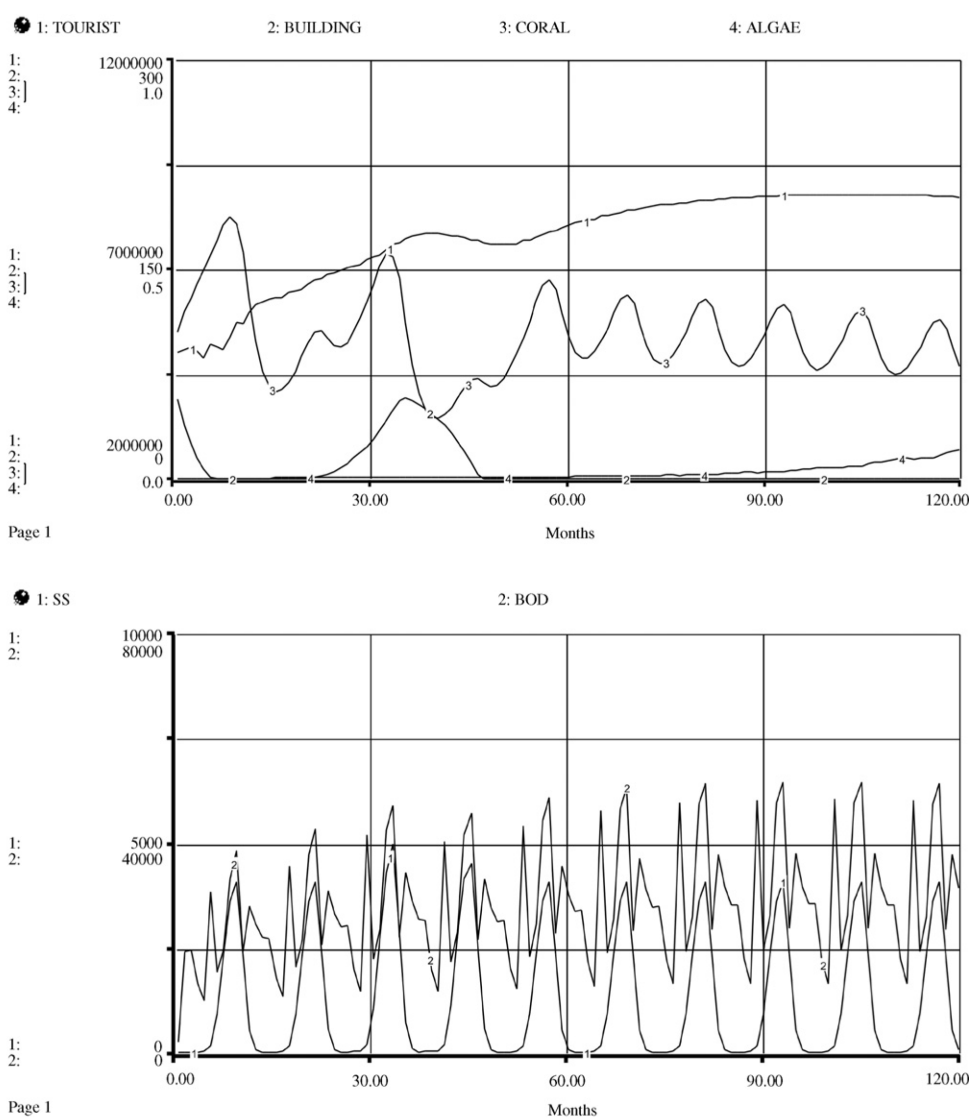

Fig. 13 – System performances under "NT 50 entrance fee collection" scenario.

4.8. *Composite strategies*

The SD-based DSS is also capable of evaluating composite strategies, such that decision makers can have more flexible options. One scenario is setup for the demonstration, which covers the multiple strategies of expanding land development area to 600 ha, 10% of wastewater treatment efficiency, 0.1 of coral reef fish consumption rate, and NT 50 of entrance fee charge. The results, as shown in Fig. 14, indicate larger scale constructions occur during the span of second and fifth years, which associates with the peak sediment SS in the fourth year due to the policy of encouraging more land development. Nevertheless, the total land development area is 167 ha at the end of simulation, which is far below the granted limit. This outcome reveals a moderate tourist growth rate owing to the entrance fee charge restrains the Kenting coastal zone from being over-developed. Although, the coral reef coverage drops during the land development period, it recovers gradually and reaches a stable state afterward. Simple wastewater treatment and moderate coral reef fish consumption rate can all contribute to the sustainability of coral reef and the low algae coverage even with growing tourists. Financial supports for the proposed coastal zone management strategies are feasible, since the public sector will collect the revenue around 400 millions NT dollar per year under this scenario.

One additional function, other than decision support, provided by the SD model is to assist environmental education. As mentioned in the scenario analyses, the current management and social system may not accept some of the proposed strategies, such as restricted coral reef fish consumption and entrance fee collection. To reform the situations, the public sectors should promote the campaigns for raising awareness about marine environmental issues and encouraging political attention to those issues. If a vivid and animated simulation game based on the SD model were available, it could be used to demonstrate how the tourism and the coral reefs in Kenting will develop in the future under users' selections of management strategies. In this regard, the decision makers may expand the SD-based DSS as a way to help people learn about conservation issues and the need to implement the sustainable management strategies.

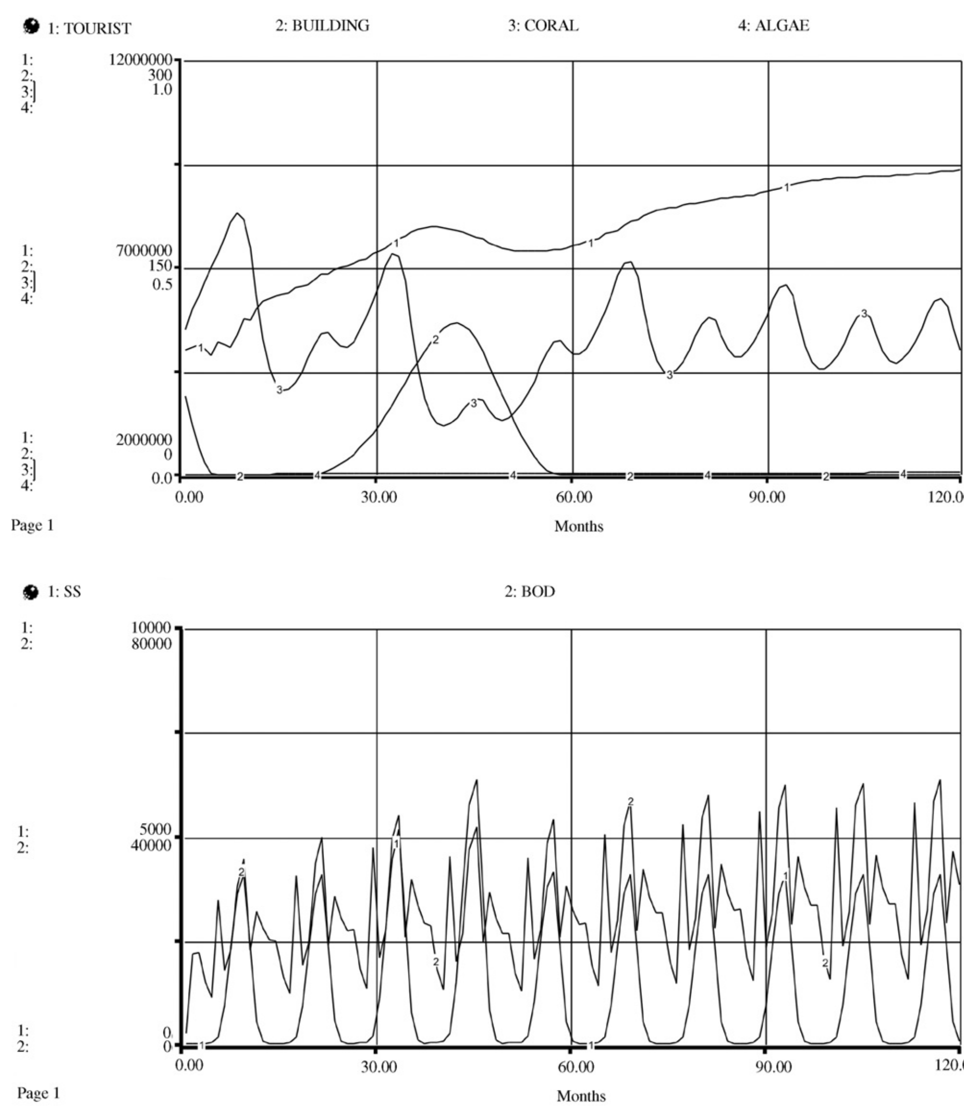

Fig. 14 – System performances under a "composite strategies" scenario.

5. Conclusion

This paper presents an SD-based DSS to implement the ICZM concept for sustainable coral reef management in Kenting. The ICZM concept appropriately deals with coastal zone management issues full of dynamic complexity involving several intricate subsystems of socio-economy, ecology, and the environment. SD is a powerful approach among available techniques that incorporates multidisciplinary research efforts and deals with the dynamic nature of the management problem for effective decision-making. This study takes full advantage of the SD modeling approach and outlines the benefits of clear conceptualization, fast programming, easy model adaptation, and accessible user interface. Seven strategies are presented in this paper for scenario analyses using the DSS, and the approach of 50 NT dollars entrance fee charge is shown to have the best results. A decision maker or stakeholder can also directly manipulate the system variables based on preferable strategies through the user-friendly interface provided by the DSS. The benefit of using such SD-based DSS is therefore obvious: managerial efficiency of coastal zone management enhances and leads to coral reef ecosystem sustainability in Kenting.

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Appendix A

– Summary of variables used in the system dynamic model

Notation of variable	Explanation
A	Potential long-term average soil loss in tons per acre per year
A_COLONY	Algae colonization rate
ALGAE	Occupied area by algae
B_AREA	Area available for development
B_CONV	Tourist number served per hectare
BOD	Biochemical oxygen demand
BUILD	Monthly land area for construction
BUILDING	Area under construction
C	Crop/vegetation and management factor
C_COLONY	Coral colonization rate
C_DISPLACE	Replacement rate between coral and algae
CA	Algae colonization coefficient
CC	Coral colonization coefficient
COME	Tourists arrival per month
CONC	Total developed land area
CORAL	Occupied area by coral
CORAL_T	Tourist satisfactions on coral reefs
CPLY	Monthly land area finishing construction
D1	Coral death due to recreational sports
DIVING	Diving activities
E_F_A	Local fish consumption rate by tourists
EA	Algae extinction coefficient
EC	Coral extinction coefficient
F_CP	Tourist capacity under current facilities
FD	Facility demand
FISH_C	Monthly catch of local fish
FISH_P	Algae death rate by fish grazing
FQ	Facility quality
GO	Tourist leave per month
K	Soil erodibility factor
LS	Slope length-gradient factor
NQ	Nature quality
OPEN	Open habitat space for coral and algae
OTHER	Number of tourist other than TRNY
P	Support practice factor
PHY_D	Recreational sports other than diving
PT_A	Growth rate of algae contributed by BOD
PT_CA	Quantity of algae growth per unit area contributed by BOD
QT	Quantity of travel annually
R	Rainfall and runoff factor
SS	Sediment
SS_AA	Death rate of algae caused by sediment
SS_AE	Quantity of algae death per unit area due to sediment
SS_CA	Death rate of coral caused by sediment
SS_CE	Quantity of coral death per unit area due to sediment
TOURIST	Number of tourist
TRNY	Number of tourist visited again
WQ	Tourist satisfactions on water quality
WTP	Willing to pay

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