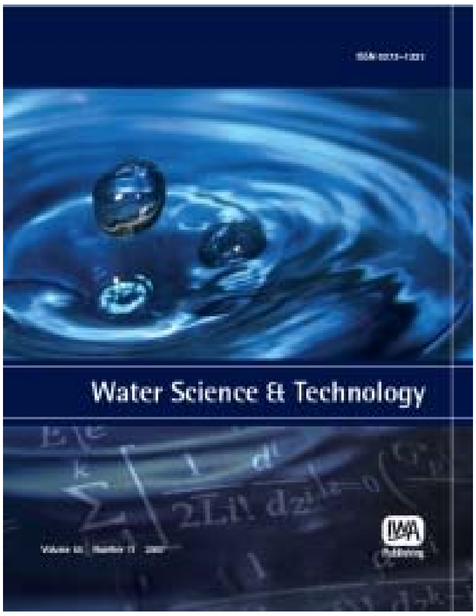
Water Science & Technology

# Appropriate wastewater treatment systems for developing countries: criteria and indictor assessment in Thailand

W. Singhirunnusorn and M. K. Stenstrom

## ABSTRACT

This paper presents a comprehensive approach with factors to select appropriate wastewater treatment systems in developing countries in general and Thailand in particular. Instead of focusing merely on the technical dimensions, the study integrates the social, economic, and environmental concerns to develop a set of criteria and indicators (C&I) useful for evaluating appropriate system alternatives. The paper identifies seven elements crucial for technical selection: reliability, simplicity, efficiency, land requirement, affordability, social acceptability, and sustainability. Variables are organized into three hierarchical elements, namely: principles, criteria, and indicators. The study utilizes a mail survey to obtain information from Thai experts—academicians, practitioners, and government officials—to evaluate the C&I list. Responses were received from 33 experts on two multi-criteria analysis inquiries—ranking and rating—to obtain evaluative judgments. Results show that reliability, affordability, and efficiency are among the most important elements, followed by sustainability and social acceptability. Land requirement and simplicity are low in priority with relatively inferior weighting. A number of criteria are then developed to match the contextual environment of each particular condition. A total of 14 criteria are identified which comprised 64 indicators. Unimportant criteria and indicators are discarded after careful consideration, since some of the indicators are local or site specific.

**Key words** | appropriate wastewater treatment systems, criteria and indicator assessment, developing countries, multi-criteria

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## INTRODUCTION

Appropriate technology suitable for local conditions has been one of the key solutions to overcome operational failures of wastewater facility management in many developing countries. The term “appropriate” thus conveys the notions of feasibility and pragmatism for a specific circumstance. In *sustainable* terms, appropriateness also signifies the logic for meeting people’s needs in the best possible way with two preconditions–the availability of local resources and the limitation of local conditions. The suitable option is, therefore, not only a system providing the best performance at least cost, but is also sustainable in terms of meeting local needs–socio-cultural acceptability, technological and institutional feasibility, economical affordability, and environmental acceptability (Mara 1996; Sarmento 2001; Ujang & Buckley 2002).

The top-down approach for urban wastewater management has been applied in both developed and developing countries, despite the contextual differences in economic, social, and cultural conditions. Decision makers in many countries choose to apply the conventional wastewater treatment techniques widely utilized in developed nations, and ignore the local contextual conditions and constraints, particularly the affordability, skills, and political will of the relevant authorities. Such advanced technologies are not only unaffordable, they are also too complicated to operate and maintain (Van Lier & Lettinga 1999). As a result, a

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number of treatment plants constructed in developing countries had to be abandoned due to the failure to provide necessary operation and maintenance. In the case of Thailand, for instance, the recent survey by the Pollution Control Department (PCD) showed that only 20% of municipal-scale wastewater treatment systems were in operational condition. The rest were defective and needing refurbishment or equipment replacement (PCD 2003).

The purpose of this paper is to devise a comprehensive approach for selecting appropriate wastewater treatment systems in Thailand. Apart from a technical aspect of technologies, the study integrated social, economic, and environmental aspects to develop a set of criteria and indicators (C&I) useful for evaluating appropriate systems. The study takes the C&I approach to develop the selection framework appropriate to the context of Thailand. The well constructed set of C&I can be used to express what appropriate wastewater treatment systems mean for a specific location and can be incorporated within the selection process of wastewater treatment system for the community.

## BACKGROUND

### Concept and scope of appropriate wastewater treatment systems

Factors determining appropriate wastewater treatment technologies differ from place to place according to the unique local urban contexts. Contextual differences exist even among developing countries. Therefore, appropriate technology for Thailand might not be suitable for other developing countries. The term "appropriate" conveys the notions of suitability and reliability in a given circumstance. Apart from the technical factors, there are other factors that define the reliability and suitability aspects of technologies–such as financial, institutional, temporal, and environmental reliability and suitability (Ujang & Buckley 2002). The suitable option is, therefore, not only a system providing the best performance at least cost, but it should also be sustainable in terms of meeting the local needs–socio-cultural acceptability, technological and institutional feasibility, economical affordability, and environmental acceptability (Mara 1996; Sarmento 2001; Ujang & Buckley 2002).

In recent years, studies concerning appropriate wastewater treatment technologies and the selection process in developing countries have become important issues, gaining recognition in the fields of environmental engineering and facility planning as illustrated by Reid (1982), Ellis & Tang (1991), Elimam & Kohler (1997), Krovvidy (1998), Rodriguez-Roda *et al.* (2000) and Balkema *et al.* (2001). Many studies in the past centered on the traditional optimization approach by means of mathematical methods, focusing on the solution of systems with highest performance and least costs (Mishra *et al.* 1974; Ellis & Tang 1991). Nonetheless, researchers have recently begun to consider local factors, such as socio-economic, political, and institutional situations, which have been considered among the prime barriers preventing the success of implementing the selected technology.

A large body of literature has already listed the important factors, which must be considered when evaluating and selecting wastewater treatment technologies. Traditionally, the process of evaluation and selection is one of the most challenging phases of treatment plant design. The process should achieve the most appropriate treatment system, capable of meeting standards and requirements. These factors are then reformulated into criteria, which are associated with the engineering rules in designing, constructing, and operating the system i.e. influent wastewater characteristics (flow and quality), efficiency, land requirement, and process reliability (Melcalf & Eddy 1991). While the economic, social, and institutional factors are still constraints in the system design, other attributes, such as simplicity, social acceptability and sustainability, should also be considered in choosing the treatment technologies for developing countries.

### Selection criteria of appropriate wastewater treatment systems

The following section summarizes seven important elements, which are intended to summarize the technical, socio-economic, and environmental aspects of the appropriate systems (Figure 1).

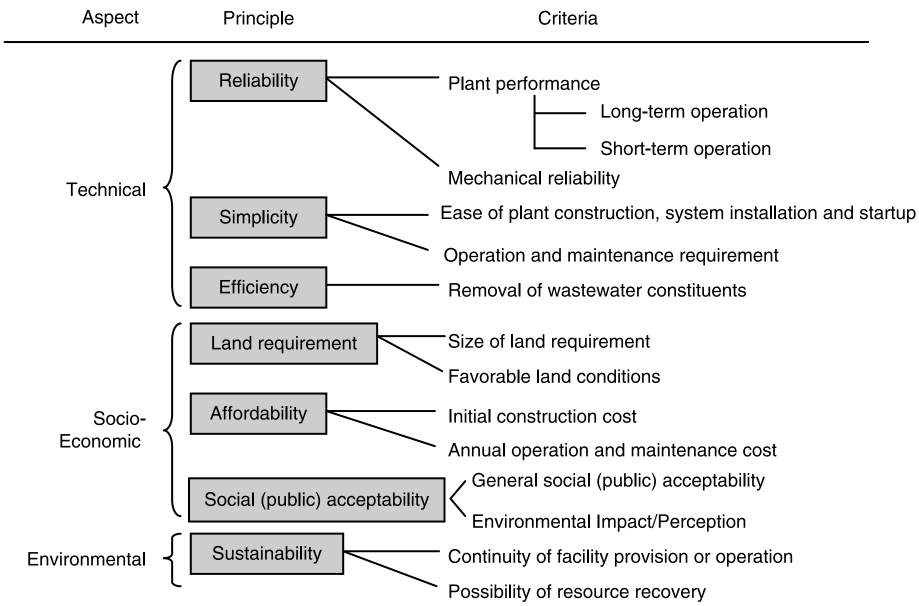


**Figure 1** | Summary of the conceptual variables determining the selection of appropriate wastewater treatment systems for developing countries.

## Technical aspects

- *Reliability*: Reliability of the system is defined as the possibility of achieving adequate performance for a specific period of time under specific of conditions (Von Sperling & Oliveira 2007). This study considers two major aspects of reliability for the wastewater treatment process–plant performance and mechanical reliability. Reliability of the treatment system can be assessed by means of: (1) the variability of treatment effectiveness under normal and emergency operation, (2) the probability of mechanical failures, and (3) the impacts of failures upon effluent quality (Eisenberg *et al.* 2001). Measuring the variation of product quality reflects the robustness and the way the process responds to changes in wastewater characteristics (Metcalf & Eddy 1991; Von Sperling 1996; Eisenberg *et al.* 2001).
- *Simplicity*: Simplicity of wastewater treatment is one of the most crucial attributes in the selection process of the treatment systems, particularly for developing countries. In countries where unskilled labor is cheap and available, the reduced construction cost can be achieved with self-help labor (Choguill 1996). However, lack of skilled workers presents a major constraint when decision makers choose a sophisticated treatment system in remote areas. Operational and maintenance simplicity should be a prime concern, since simplicity could determine the long-term operating success of the system.
- *Efficiency*: Wastewater must be treated to the extent that the final water quality will comply with the regulatory standard or requirements. Most conventional wastewater treatment processes have been designed primarily to remove the suspended and dissolved organic constituents (Parr *et al.* 1999). The organic matter in wastewater, is usually measured in terms of biochemical oxygen demand (BOD), and is one of the most important parameters determining the effluent quality. Another important objective of wastewater treatment is to reduce the pathogenic microorganisms from wastewater. Contamination with infectious microorganisms such as those from human waste can cause acute localized impacts on public health. Nutrients, mainly nitrogen and phosphorus, can cause eutrophication through accumulation in regional surface water, while nitrate can cause health threatening ground water contamination (Pegram *et al.* 1999).

## Socio-economic aspects

- *Land requirement*: The availability of the land is another major constraint determining the choice of wastewater treatment systems. In most cases, space sufficiency means not only the space to accommodate the size of the present facilities, but also the possibility for future expansion. Since most wastewater treatment systems are located outdoors, it may cause negative environmental impacts, such as noise and odor, on the surrounding residences. Therefore, system site and plot size should be sufficient to provide a buffer to minimize the visual, odor and noise impacts. Under this criterion, land properties or geo-morphology e.g., topography, soil conditions, and level of groundwater, are also important factors determining the technical feasibility of construction and operation of a particular system.

- *Affordability*: The financial aspect considers not only the initial cost for construction and installation, but also the ability of the local community to pay for the continuing operation and maintenance costs. System design with "affordability" in mind must include the selection of a technology that users are able-to-pay for. Treatment cost must reflect the level of household income and expenses (Sarmento 2001). In the developing countries' context, the ability-to-pay is an important issue, reflecting the reasonable amount of payment that the user is able to pay for, which is, in turn, determined by the type of wastewater treatment.
- *Social (public) acceptability*: Social norms and traditions are also important in the designing of treatment system, which aims to meet the local needs and be sustainable. Some knowledge and attitudes to environmental issues can also influence perceptions of people, their awareness and susceptibility to any development project (Kalbermatten *et al.* 1982). Social acceptance will depend on people's experiences, social background, and secular knowledge (Pickford 1995). In addition, people may also have concern about environmental nuisances (Tsagarakis *et al.* 2001). Systems located close to the community and sensitive ecosystems should have minimal noise, odor, and visual impacts.

### Environmental aspects

- *Sustainability*: The study considers two aspects of sustainability–(1) the continuity of operation and (2) the environmental sustainability. For the continuity of the project, it needs to be financially and operationally self-sufficient (Pybus & Schoeman 2001). The treatment system should be affordable, meet the needs of the local community, and be maintainable by locals. The latter aspect of environmental sustainability involves the survival of the environment itself. The selected technology applicable for the treatment system must have the least adverse environmental effects and should be able to recover renewable resources from the treatment systems, such as being able to reuse treated wastewater for irrigation, recharge groundwater, produce biogas, and recycle organic matter. In developing countries, treated wastewater and products from the treatment processes are considered as resources. The water with nutrient content, in particular, is very useful for agriculture activities provided that the effluent is treated properly (Kalbermatten *et al.* 1982; Pickford 1995; Parr *et al.* 1999). Recycled material such as biosolids can be utilized as crop fertilizer or soil conditioners for non-agricultural land.

## METHODS

### Developing criteria and indicators

The study applies processes of conceptualization and operationalization, which are commonly used in the social sciences as part of the scientific research method. Conceptualization is the process by which a concept in research is clarified (conceptual definition). The succeeding operationalization procedure involves taking these specific conceptualized constructs and translating them into specific measures or indicators (operational variables) that can be used to collect data (Babbie 2005). The study employed both objective and subjective approaches to create questions or specific measures. The developing process of criteria and indicator involves the following steps:

- Specify the conceptual definition of "appropriate wastewater treatment system", and the conceptual variables;
- Identify the dimension of interests in each conceptual variable;
- Operationalize the conceptual variables into specific measures and indicators (operational variables);

- Organize all relevant variables (conceptual and operational) into three hierarchical elements (Mendoza *et al.* 1999; Mendoza & Prabhu 2000):
- *Principles*, which are normative and broadly defined, refer to the main ideas or concepts of appropriate wastewater treatment systems for developing countries.
- *Criteria* demonstrate the dimension of interests in each principle needing to be assessed. They, nevertheless, still have conceptual characteristic.
- *Indicators* are the components or variables indicating the state or conditions required by each criterion.

The study uses hierarchical structure to create strong links between the upper-level ideas (Principles) and the dimension of interests (Criteria) down to the measurable components (Indicators) so that the final set of C&I will be meaningful, coherent and comprehensive (Mendoza *et al.* 1999; Mendoza & Prabhu 2000). The well constructed set of C&I can be used to express what appropriate wastewater treatment system means to assess performance of the existing treatment systems, and to incorporate within the selection process of wastewater treatment system for the community.

Based on the literature review, conceptual definitions of appropriate wastewater treatment systems are specified. The study identifies *seven important elements*, which determine a particular appropriate system. These elements include reliability, simplicity, land requirement, affordability, efficiency, social acceptability, and sustainability. The set of conceptual and operational variables is organized into three hierarchical elements and evaluated in the expert survey. Appendix 1 shows the list of C&I in detail.

## Assess criteria and indicators

The initial set of generated C&I assessed by means of a multiple criteria analysis (MCA) method was used as a basis toward the selection of final C&I which are applicable to the final wastewater system selection model. The study used two MCA approaches, ranking and rating, to evaluate and select the C&I set (Mendoza *et al.* 1999; Mendoza & Prabhu 2000). An interdisciplinary expert group was asked to evaluate and rank the relative importance of each component in relation to the upper-level element and to the overall selection process of appropriate domestic wastewater treatment systems for Thailand.

### Expert survey

The study utilized a structured questionnaire to obtain information from experts–academicians, practitioner (consultants/plant designers), and government officials–who have been working in the field of wastewater treatment and management in Thailand. The schedule was conducted by mail from January to March, 2007. A total of 33 experts participated in the questionnaire survey and assessment (21% response rate).

### Data analysis

In this study, C&I are elements representing Principles, Criteria or Indicators which can be systematically evaluated by means of the MCA method. Ranking and Rating are two simplest MCA techniques, with minimal relative comparisons, that can be used in a C&I assessment (Mendoza *et al.* 1999; Mendoza & Prabhu 2000).

**Table 1** | Relative weights of principles calculated by ranking and rating method

| | Average | | SD | | Relative weights (all votes) | | |
|---|---|---|---|---|---|---|---|
| Principle | Ranking | Rating | Ranking | Rating | Ranking | Rating | Combined |
| P1. Reliability | 7.6 | 19.6 | 1.4 | 15.9 | 15 | 17 | 16 |
| P2. Simplicity/Complexity | 6.1 | 13.2 | 2.1 | 16.1 | 12 | 11 | 12 |
| P3. Efficiency | 7.6 | 19.9 | 1.2 | 15.4 | 16 | 17 | 16 |
| P4. Land Requirement | 6.1 | 14.0 | 1.8 | 15.7 | 12 | 12 | 12 |
| P5. Affordability | 7.2 | 18.8 | 1.9 | 16.7 | 15 | 16 | 15 |
| P6. Social Acceptability | 7.1 | 16.2 | 1.7 | 15.9 | 14 | 14 | 14 |
| P7. Sustainability | 7.4 | 16.0 | 1.6 | 15.5 | 15 | 14 | 14 |

- *The Regular Ranking Method* analyzes each element by assigning a rank depending on the perceived importance. Ranks are assigned according to a nine-point scale (1, weakly important; 3, less important; 5, moderate; 7, more important; 9, extremely important).
- *The Rating Method* is similar to ordinary ranking, where decision elements are assigned 'scores' ranging from 0 to 100, and the total score for all the elements must add up to 100. The relative weight of each element thus plays an importance role against the rest of the other elements. Such scoring method is able to differentiate the extent of significance among the entire set of composite elements.

*Calculation of Relative Weight* is done by means of assembling the ranks and rates from the experts' responses, where generalization of relative importance for each decision making element can be accomplished basing on a pattern found among the responses. The relative weighting can be calculated by dividing the actual weight of a particular element by the sum of all weights and multiplied by 100. The resultant element weighting is then utilized as basis for C&I formation.

For ranking, the relative weight can be calculated as follows:

$$w_{ji} = \left[\sum_k r_{ji} / \sum_j \sum_j r_{jki}\right] \times 100 \qquad (1)$$

Where, $j$ is a criterion with $m$ indicators described as $C_j \epsilon$ $(I_{j1}, I_{j2} \ldots, I_{jm})$; $r$ is the ranking given by an expert $k$ to the respective indicators of criterion $j$ as $r_{jk1}, r_{jk2} \ldots, r_{jkm}$; and $w_{ji}$ is the relative weight, for indicator $i$ $(i = 1,2,\ldots m)$.

For Rating, since weights of decision elements are assigned explicitly summing to 100 points, the weights of all elements can be described using the following logical formula: $0 \leq w_{ji} \leq 100$; and $\Sigma w_{ji} = 100$ for all $i$.

*Combined Weight* reflects the combination of two levels of weights. Firstly, it reflects all votes allocated to each elements by the two different techniques. Secondly, the relative weights from ranking and rating techniques are combined to reflect the overall weight of each decision element.

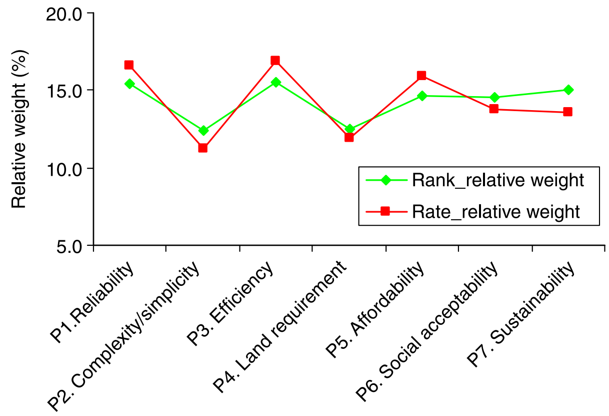


**Figure 2** | Relative weights from ranking and rating techniques.

## RESULTS AND DISCUSSION

Ranking and rating methods are used as screening tools for deciding whether a particular C&I should be included, and which composite weights could be the ultimate measure for the final justification explained in the final selection.

### Principle level

The principle level, which comprises 7 major system attributes, incorporates three crucial aspects for selecting treatment technologies: technical, socio-economic, and environmental aspects. Table 1 shows the average votes and relative weights obtained from raking and rating methods. The data show that, at this level, experts are consistent in their judgments while using the ranking and rating approaches. Figure 2 shows the consistency of relative weight allocated to each element by the two different techniques.

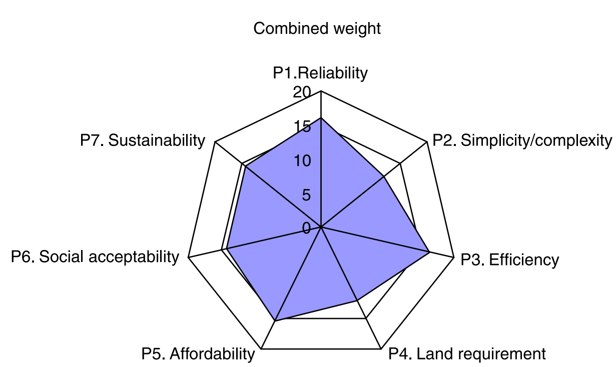


**Figure 3** | Combined weights of the principles.

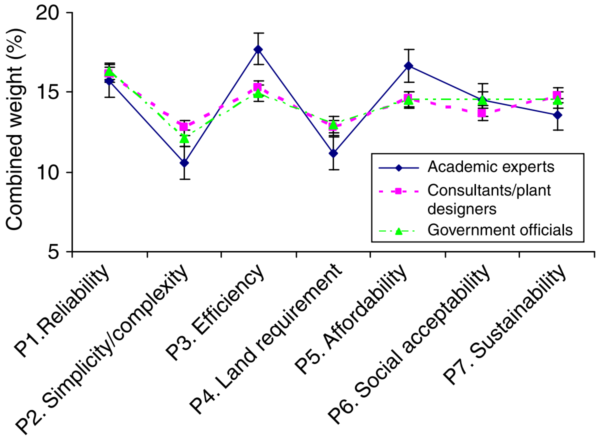


**Figure 4** | Combined weights of the principles from different groups of experts.

Figure 3 shows the combined weights at the principle level derived from groups of expert respondents. The result shows, basing on the overall weight summation, that P3 (Efficiency), P1 (Reliability), and P5 (Affordability) are among the most important elements, followed by P7 (Sustainability) and P6 (Social Acceptability); P2 (Simplicity) and P4 (Land Requirement) are found low in priority, indicated by their relatively lower weights. The low weighting of 'Simplicity' might be attributed to the perception that it does not contribute to 'Reliability' and 'Affordability'. This finding may be a partial reason for the current operational failure of treatment facilities in Thailand, which neglected the simplicity of systems and the limitation of local skill and resources in the system selection process. In the case of 'Land Requirement', it may be considered low in priority because most of municipal wastewater treatment projects are situated on publicly owned land.

Figure 4 shows the combined weights from different groups of experts. Consultants/plant designers and government official agree closely. These practitioners are mostly involved in hands-on operations, and show slightly higher weights for Simplicity, Land Requirement, and Sustainability when compared to the other groups' values. The academic experts, on the other hand, express higher priorities for the Efficiency and Affordability of the system.

At this level, the overall composite weights show slight differences among principles. It is therefore difficult to judge whether the lower weighted principles (i.e. Simplicity and Land Requirement) are sufficiently low to be eliminated from the list.

## Criteria level

The second stage of the study identifies the respective criteria for each of the aforementioned principles. The objective of this process is to denote the meaning and conditions of each principle, by which 14 criteria are identified and empirically operationalized via 64 indicators for the succeeding stage. Figure 5 shows the relative importance of the entire set of criteria with the exception of 'Efficiency' in the third Principle, since it had only one criterion. All criteria under principles P1 (Reliability) and P6 (Social Acceptability) are relatively important. None of them has significantly low weight. Thai experts rated criteria C2.2 (Operational and maintenance requirement), C4.1 (Size of land requirement), C5.2 (Annual operation and maintenance cost), and C7.1 (Continuity of system provision/operation) the most important criteria under

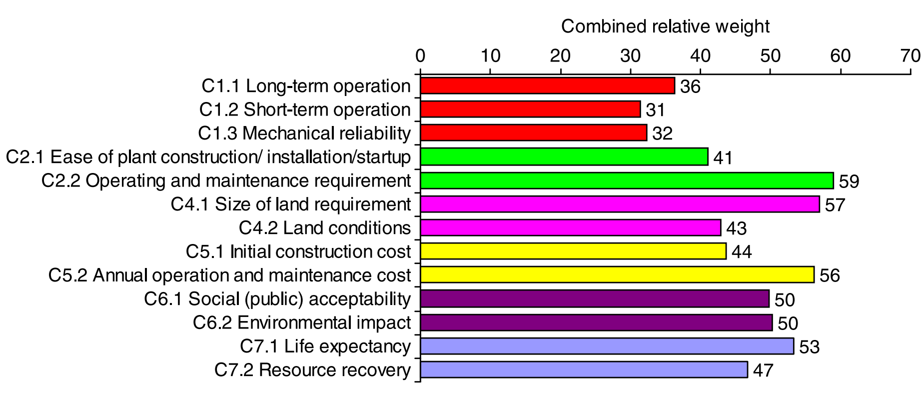


**Figure 5** | Combined weights of the criteria.

their respective principles. None of the criteria will be eliminated from the list until the indicator level has been analyzed. Some criteria such as C2.1, C4.2, and C5.1 might need close attention due to their low relative weights.

## Indicator level

In this stage, a total of 64 indicators are identified in relation to criteria in the preceding state. The assessment at this level is crucial to developing a set of measurable variables. Ranking and rating methods are utilized for the screening and selection of indicators from a pool of them. Indicators with significantly low weights are deemed to be eliminated with care, since some of them are local or site specific. Different local/community scenarios and resource availability are also taken into account in the final selection process.

Figure 6 shows the composite weight of indicators for all criteria with the exception of C1.3, 4.1, and 7.1. Indicators under these criteria are somewhat equally weighted in importance for each category. The results of composite weight clearly differentiates and prioritizes indicators for each criterion, from which the following postulations are applied:

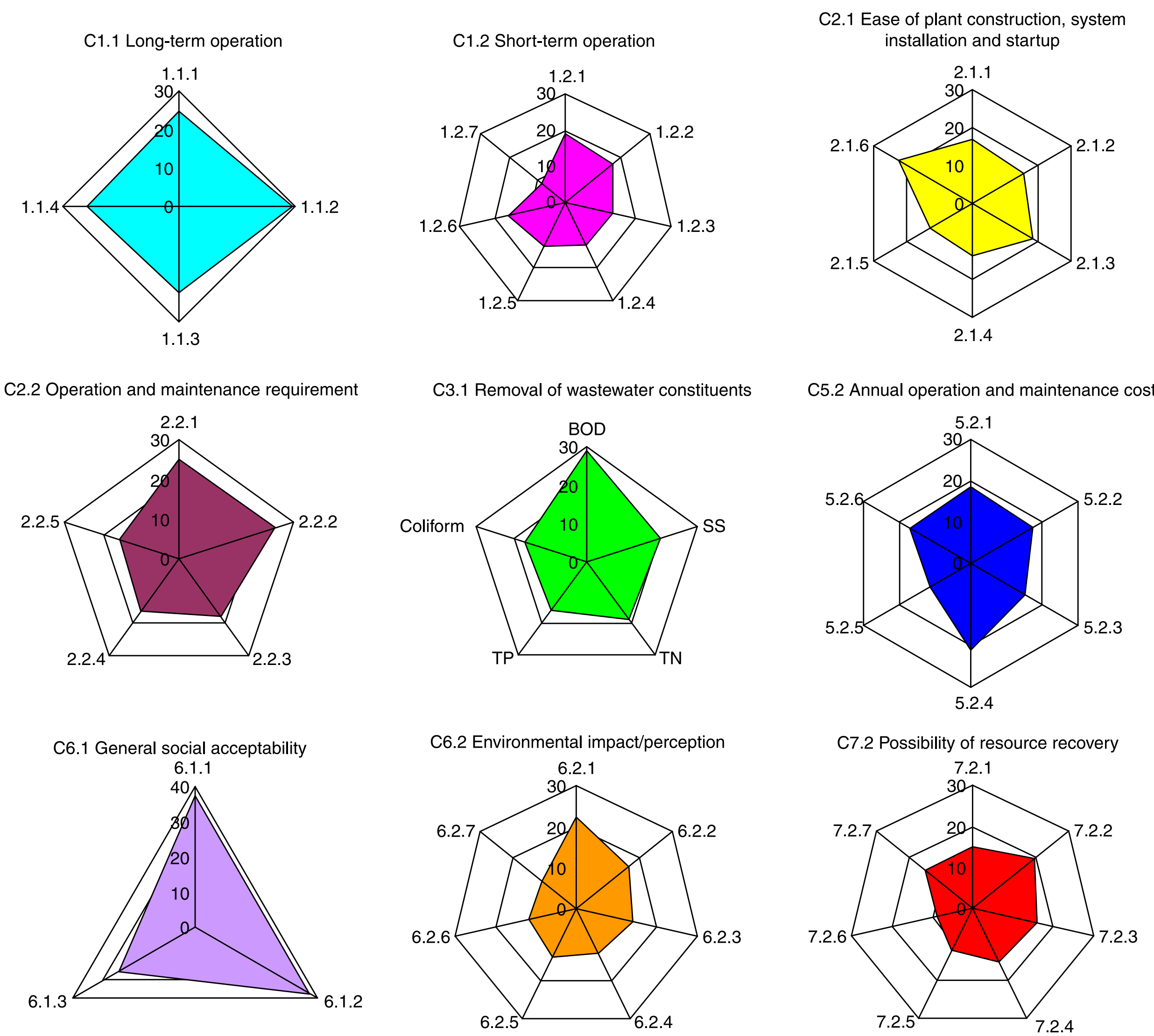


**Figure 6** | Relative importance of indicators (combined weights).

(1) Thai experts expressed very low ranking and rating for indicator I1.2.7 (the effect of weather variation on system performance). Since fluctuation of seasonal temperature is usually low in Thailand, most experts did not expect any seasonal impact on the performance of wastewater treatment. Nonetheless, Thailand is located within the tropical monsoon zone, and large amount of rain water could dilute the influence and eventually affect the plant performance, particularly the system with biological treatment processes. The study thus retains the indicator at this stage considering only the effect of rain water discarding the impact of temperature.

(2) Under criterion C2.1, indicators I2.1.4 and I2.1.5 that are representing the time requirement for construction and system installation reflect the lowest combined weights. Experts might not equate time requirement with construction simplicity. Contrarily, indicator I2.1.6 (time required for start-up a system) receives the highest rating in terms of importance. The study thus retains all indicators in the C2.1 category, which included all 'time requirement' indicators on the list.

(3) Indicators I2.2.4, I5.2.5, and I6.2.7 are eliminated for the following reasons. Indicator I2.2.4 (special O&M requirements) is eliminated due to its similarity to I2.2.1 (skill and personnel requirement), while indicator I5.2.5 (administration cost) only partially represents the amount of O&M cost. Wastewater treatment plant operation, on the other hand, has very little impact on indicator I6.2.7 (traffic impact).

(4) The study retains the rest of low weight indicators including I2.2.5 (special manufactured/imported equipment), I6.2.6 (landscape/visual impact), I7.2.5 (irrigation of food crop), and I7.2.6 (groundwater recharge). Being site specific issues, these indicators might be of interest in specific circumstances. Indicator I7.2.5, for instance, would be important in the area surrounded by agricultural production.

### Selection of final criteria and indicators

As stated before, different aspects of local/community conditions and resource availabilities are taken into consideration before selecting the final list. In addition to the assessment in the preceding section, the selection of final C&I is also based on the following guidance criteria:

1. The four major aspects of appropriate wastewater treatment systems including technological, social, economic, and environmental aspects are considered collectively.
2. Be simple to allow understanding, interpreting, and presenting by specialists as well as lay persons (i.e. local authorities and community organizations).
3. Be applicable across the range of all the wastewater treatment options under consideration.
4. Be sufficiently practical to obtain numerical data or qualitative information.

## CONCLUSIONS

The study produces selection criteria for the technical, socio-economic, and environmental aspects and is applicable for evaluating appropriate wastewater treatment alternatives for Thailand. The final set of C&I is derived from seven principles including reliability, simplicity, efficiency, land requirement, affordability, social acceptability, and sustainability. The results demonstrate the potential for using the two methods as screening tools. The composite weights derived from the ranking and rating methods can explain and justify the final selection measures of C&I. The C&I approach from this study can serve as a model for collection of the decision-making variables and measurements at the local level. Based on these principles, a set of 14 criteria, 61 indicators, and 74 measurable variables are developed and used to assess the operating wastewater treatment systems in Thailand (in the follow-up study). The set of criteria selected will determine the outcome of the decision being made as well as the method of comparison (decision support process). The collected data will be also complied vis-à-vis local conditions to develop a decision making model for selecting appropriate wastewater treatment systems.

## REFERENCES

Babbie, E. 2005 *The Basics of Social Research*, 3rd edition. Wadsworth, Belmont, CA.

Balkema, A. J., Preisig, H. A., Otterpohi, R., Lambert, A. J. D. & Weijers, S. R. 2001 Developing a model based decision support tool for the identification of sustainable treatment options for domestic wastewater. *Water Sci. Technol.* **43**(7), 265–269.

Choguill, C. L. 1996 Ten steps to sustainable infrastructure. *Habitat Int.* **20**(3), 389–404.

Eisenberg, D., Soller, J., Sakaji, R. & Olivieri, A. 2001 A methodology to evaluation water and wastewater treatment plant reliability. *Water Sci. Technol.* **43**(10), 91–99.

Elimam, A. A. & Kohler, D. 1997 Two engineering applications of a constrained shortest-path model. *Eur. J. Oper. Res.* **103**, 426–438.

Ellis, K. V. & Tang, S. L. 1991 Wastewater treatment optimization model for developing worlds. I: model development. *J. Environ. Eng.* **117**(4), 501–518.

Kalbermatten, J. M., Julius, D. S., Gunnerson, C. G. & Mara, D. D. 1982 *Appropriate Sanitation Alternatives: A Plan and Design Manual (World Bank Studies in Water Supply and Sanitation; 2)*. The John Hopkins University Press, Baltimore, USA.

Krovvidy, S. 1998 Intelligent tools for wastewater treatment design. *Comput. Aided Civil Infrastructure Eng.* **13**, 219–226.

Mara, D. D. 1996 *Low-Cost Urban Sanitation*. John Wiley & Sons, West Sussex, UK.

Mendoza, G. A. & Prabhu, R. 2000 Development of a methodology for selecting criteria and indicators of sustainable forest management: a case study on participatory assessment. *Environ. Manage.* **26**(6), 659–673.

Mendoza, G. A., Macoun, P., Prabhu, R., Sukadri, D., Purnomo, H. & Hartanto, H. 1999 *Guidelines for Applying Multi-Criteria Analysis to the Assessment of Criteria and Indicators*. Center for International Forestry Research (CIFOR) Special Publication.

Metcalf & Eddy 1991 *Wastewater Engineering: Treatment, Disposal, and Reuse*. Metcalf & Eddy, Inc. 3rd edition revised by Tchobanoglous, G. & Burton, F.L., McGraw Hill Inc. International.

Mishra, P. N., Fan, L. T. & Erickson, L. E. 1974 Application of mathematical optimization techniques in computer aided design of wastewater treatment systems. Water-1974: II, municipal waste treatment. *AIChE. J.* **71**(145), 136–153.

Parr, J., Smith, M. & Shaw, R. 1999 Wastewater treatment options. In: Shaw, R. (ed). *Running Water: More Technical Briefs on Health, Water And Sanitation*. Water and Environmental Health at Loughborough (WELL). http://www.lboro.ac.uk/well/resources/technical-briefs/64-wastewater-treatment-options.pdf

PCD (Pollution Control Department) 2003 Survey Report: The Evaluation of System Efficiency of Municipal Wastewater Treatment Plants in Thailand. Domestic Wastewater Division, Water Quality Management Bureau, PCD. (*in Thai*).

Pegram, G. C., Quibell, G. & Hinsch, M. 1999 The nonpoint source impact of Peri-urban settlements in South Africa: implications for their management. *Water Sci. Technol.* **39**(12), 283–290.

Pickford, J. 1995 *Low-Cost Sanitation: A Survey of Practical Experience*. SRP, Exeter, London, UK.

Pybus, P. & Schoeman, G. 2001 Performance indicators in water and sanitation for developing areas. *Water Sci. Technol.* **44**(6), 127–134.

Reid, G. W. 1982 *Prediction Methodology for Suitable Water and Wastewater Processes*.

Rodriguez-Roda, I., Poch, M. & Bañares-Alcántara, R. 2000 Conceptual design of wastewater treatment plants using a design support system. *J. Chem. Technol. Biotechnol.* **75**, 73–81.

Sarmento, V. 2001 *Low-Cost Sanitation Improvements in Poor Communities: Conditions for Physical Sustainability*. PhD Dissertation. University of Leeds, Leeds, UK.

Tsagarakis, K. P., Mara, D. D. & Angelakis, A. N. 2001 Wastewater management in Greece: experience and lesson for developing countries. *Water Sci. Technol.* **44**(6), 163–172.

Ujang, A. & Buckley, C. 2002 Water and wastewater in developing countries: present reality and strategy for the future. *Water Sci. Technol.* **46**(9), 1–9.

Van Lier, J. B. & Lettinga, G. 1999 Appropriate technologies for effective management of industrial and domestic wastewaters: the decentralized approach. *Water Sci. Technol.* **40**(7), 117–183.

Von Sperling, M. 1996 Comparison among the most frequently used systems for wastewater treatment in developing countries. *Water Sci. Technol.* **33**(3), 59–72.

Von Sperling, M. & Oliveira, S. M. A. C. 2007 Reliability analysis of stabilization ponds systems. *Water Sci. Technol.* **55**(11), 127–134.

## APPENDIX 1

### Summary of principle, criteria, and indicators

| Concepts (principles) | Dimension of interest (criteria) | Specific questions or measures (indicators) |
|---|---|---|
| *Technical aspects* | | |
| P1. Reliability | C1.1 Long-term operation (events occurring over the lifetime of the system) | I1.1.1 What is the possibility that the plant will operate "properly" over its life expectancy? |
| | | I1.1.2 What is the possibility that the effluent will consistently meet the requirements? |
| | | I1.1.3 How often could shutdowns occur due to hardware or process problems? |
| | | I1.1.4 What is the possibility that system failures can cause violations of effluent quality? |
| | C1.2 Short-term operation (events occurring during annual operation) | How well can the process respond to the variation of the following influent characteristics? |
| | | I1.2.1 High flow rate |
| | | I1.2.2 Periodic shock BOD loading |
| | | I1.2.3 Extremely low BOD loading |
| | | I1.2.4 Toxic contaminations (Pesticides, Heavy metal, etc.) |
| | | I1.2.5 How often will the process be upset due to the variation of influent characteristics? |
| | | I1.2.6 How do such occurrences (system upset) affect the quality of the effluent? |
| | | I1.2.7 How does weather variation affect system performance? |
| | C1.3 Mechanical reliability | I1.3.1 How often would unplanned maintenance events be caused due to mechanical (component) failures? |
| | | I1.3.2 What is the possibility that mechanical (component) failures can cause violations of effluent quality? |
| P2. Simplicity/complexity | C2.1 Ease of plant construction, system installation and startup | I2.1.1 What is the overall complexity of plant construction? |
| | | I2.1.2 What is the overall complexity of system installation? |
| | | I2.1.3 How difficult will it be to start the system? |
| | | I2.1.4 How much time is needed for plant consruction? |
| | | I2.1.5 How much time is needed for system installation? |
| | | I2.1.6 How much time is needed to start-up the system? |
| | C2.2 Operation and maintenance requirement | I2.2.1 Complexity of operation and maintenece |
| | | I2.2.2 Skill and personnel requirement |
| | | I2.2.3 Time requirement for training |
| | | I2.2.4 Special operating and maintenance requirements |
| | | I2.2.5 Special manufactured or imported equipment and spare parts |
| P3. Efficiency | C3.1 Removal of wastewater constituents | I3.1.1 Removal efficiency of BOD |
| | | I3.1.2 Removal efficiency of Suspented Solids |
| | | I3.1.3 Removal efficiency of Total Nitrogen |
| | | I3.1.4 Removal efficiency of Total Phosphours |
| | | I3.1.5 Removal efficiency of pathogens |

**Appendix 1** | (*continued*)

| Concepts (principles) | Dimension of interest (criteria) | Specific questions or measures (indicators) |
|---|---|---|
| *Socio-economic aspects* | | |
| P4. Land requirement | C4.1 Size of land requirement | I4.1.1 Total area of wastewater treatment facility |
| | | I4.1.2 Plant footprint |
| | | I4.1.3 Buffer zone around the plant facility |
| | C4.2 Favorable land conditions | I4.2.1 Impact of groundwater level on the system operation |
| | | I4.2.2 Impact of soil type on the system operation (i.e. infiltration effect) |
| | | I4.2.3 Flooding risk |
| P5. Affordability | C5.1 Initial construction cost | I5.1.1 Construction cost (excluding land cost) |
| | | I5.1.2 Land cost |
| | | L5.1.3 Cost subsidy from the government |
| | C5.2 Annual operation and maintenance cost | I5.2.1 Operational cost (excluding energy cost) |
| | | I5.2.2 Maintenance cost (material and eqipment) |
| | | I5.2.3 Personnel cost |
| | | I5.2.4 Energy cost |
| | | I5.2.5 Administration cost |
| | | I5.2.6 Source of revenue for operation and maintenance |
| P6. Social (public) acceptability | C6.1 General social (public) acceptability | I6.1.1 Public acceptability of the system operation |
| | | I6.1.2 Public support for wastewater fee collection (fee collection rate) |
| | | I6.1.3 Public participation in system operation and maintennce |
| | C6.2 Environmental impact/perception | I6.2.1 Odor production |
| | | I6.2.2 Noise impact |
| | | I6.2.3 Breeding insects and other parasites |
| | | I6.2.4 Aerosal production |
| | | I6.2.5 Groundwater quality impact |
| | | I6.2.6 Landscape/visual impact |
| | | I6.2.7 Traffic impact |
| *Environmental aspects* | | |
| P7. Sustainability | C7.1 Continuity of system provision or operation | I7.1.1 Life expectancy of the system |
| | | I7.1.2 Possibility to upgrade or extend the plant operation for future development |
| | | I7.1.3 Limitation factors (i.e. cost, land and technology) for the system upgrade or extension |
| | C7.2 Possibility of resource recovery | I7.2.1 By-pproduct (biogas) |
| | | I7.2.2 Ability to reuse the treated wastewater |
| | | I7.2.3 Non-contact irrigation |
| | | I7.2.4 Irrigation of non-food crops |
| | | I7.2.5 Irrigation of food crops |
| | | I7.2.6 Groundwater recharge via surface infiltration |
| | | I7.2.7 Recycling of organic matter or fertilizer |