PREDICTION OF RURAL WATER SUPPLY SYSTEM SUSTAINABILITY USING A MATHEMATICAL MODEL

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Abstract

One of Millennium Development Goals (MDGs) targets is halving the proportion of people without access to safe drinking water and basic sanitation facilities in 2015. Government of Indonesia will develop water services in the future, particularly for rural poor communities, to achieve the target. It is expected that developed water supply systems for the poor in the future are sustainable. However, it is difficult to ensure the success of the developed systems. In order to know the success or failure of the developed systems, a tool to predict sustainability of water supply system in the future is needed. Study on rural water supply systems sustainability using a mathematical model has resulted in prediction of the sustainability. The model is obtained from data analysis of rural water supply systems in Brantas River Basin, East Java, Indonesia using the structural equation modeling (SEM). The data were quantitative and qualitative ones that consist of physical condition of region, social economic, water supply management, as well as water quality. Results of the study are mathematical equation of sustainability model, level of sustainability, and recommended methodology for decision-making of rural water supply projects. This model needs nine data input, they are availability of water sources, selection of technology, investment cost, technical operation, institutional management, existence and ability of operator, availability of spare parts, operation cost, and community participation. The prediction produces sustainability index that can be classified into three levels, they are low sustainability (index = 0.052 to 1.320), moderate sustainability (index = 1.321 to 1.914), and high sustainability (index = 1.915 to 2.507).

Keywords: prediction, sustainability, water supply, structural equation modeling

1. INTRODUCTION

Many water supply developments in Indonesia were not successful in era 1970-2000. Less community participation and less acceptability to new technologies were the causes of development failures in some developing countries (Carter, Tyrell, and Howsam, 1999; Brikké and Bredero, 2003). Lenton and Wright (2004) identified some constraints of success of water supply development, i.e. political, financial, institutional, and technical factors. Water supply systems for the poor often had constraints such as lack of fund for the procurement of facilities and cost of operation and maintenance.

Some constraints above cause many people do not have gotten water services. Bosch *et.al.* (2006) reported that about 1.3 billion people of the third world had no access to adequate safe water. In Indonesia, 67.3% of rural population received clean water. By refer to Millennium Development Goals (MDGs), in which one of the targets is halving the proportion of people without access to safe drinking water and basic sanitation facilities in 2015, the government has carried out and will continue to improve water services in Indonesia, particularly for rural poor communities. The water services can be improved if water supply systems are sustainable.

In environmental research, SEM has been used for investigating the interaction of submersed plants with environmental factors (Hung, Asaeda, and Manatunge, 2007). SEM has also been used for exploring occupational lead exposure pathways (Hwanga *et al*., 2002), a study to find the environmental behavior structure and socio-economic conditions of hillside farmers (Bayard and Jolly, 2007), and exploring the relationship between benthic invertebrates and physiochemical variables of water, and investigating their direct and indirect effects on waterbird feeding activities (Liang, Shieh, and Fu, 2002). Arhonditsis *et al*. (2006) applied SEM to explore ecological pattern for assessing the known relative role of several ecological processes to determine the level of water quality variables of management interest. Hurlimann *et al*. (2008) developed and tested a model to explain and predict components of community satisfaction with recycled water use (for non-potable use) through the dual water supply system. Porter *et al*. (2005) built a model of community acceptability of urban water supply systems.

Sustainability of the developed water supply systems can be predicted by modeling. This paper discusses prediction of rural water supply systems sustainability using a mathematical model. Mathematical model is build from data of rural water supply systems in Brantas River Basin, East Java, Indonesia. The model is analyzed by using the structural equation modeling (SEM); a statistical method of multivariate analysis. SEM with latent variables is routinely used in social science research, and is of increasing importance in biomedical applications (Dunson, Palomo, and Bollen, 2005).

2. METHOD

Location and Sample

The study was undertaken in the Brantas River Basin, East Java, Indonesia. In this area, there are 360 rural water supply systems by pipeline. The water supply systems were built by government and managed by communities. Among the water supply systems, many systems were operated successfully and the others fail. Samples for the study were taken in 24 villages in nine regencies and involve 364 respondents. Survey was carried out in March-June 2008.

Survey Method and Variable Measurement

The study was conducted using a case study approach. Data collection conducted by observing rural water supply facilities, interviewing water committees and water users, and analyzing some documents. The data were quantitative and qualitative ones that consist of physical condition of region, social economic, and water supply management, include water quality. All data were quantified and grouped to each variable.

Development of Data-Driven Model

The model built in this research was a qualitative one; the model based on qualitative data; and can be applied to predict a phenomenon based on qualitative data. Development of the model begins from the theoretical model that was tested by using indication test and causality test. For development of this model, 314 data series (from 20 villages) and 35 data series (from 3 villages) were needed for training or developing model and for validating model, respectively. The development of model used SEM. SEM with the complete structure consists of two main parts, the measurement model (relationship between observed and latent variables) and the structural model (which describes the relationship among latent variables). The model is expressed as mathematical equations. The two types of equation are described as follow:

1. Measurement model equation:
    - Equation of measurement model of independent variables:

$$X = \Lambda_x \xi + \delta \qquad \text{(Eq. 1)}$$

    - Equation of measurement model of dependent variables:

$$Y = \Lambda_y \eta + \varepsilon \qquad \text{(Eq. 2)}$$

2. Structural equation:

$$\eta = B\,\eta + \Gamma\xi + \rho \qquad \text{(Eq. 3)}$$

where:

X = a $q\times1$ vector of observed variables of ξ

Λ_x = a $q\times n$ matrix of coefficients relating X to ξ

ξ = a $n\times1$ vector of independent latent variables

δ = a $q\times1$ vector of measurement errors for X

Y = a $p\times1$vector of observed variables of η

Λ_y = a $p\times m$ matrix of coefficients relating Y to η

η = a $m\times1$ vector of dependent latent variables

ε = a $p\times1$ vector of measurement errors for Y

B = a $m\times m$ matrix of coefficients for the independent latent variables

Γ = a $m\times n$ matrix of coefficients for the dependent latent variables

ρ = a $m\times1$vector of latent (structural) errors

Development of Mathematical Equation

Based on results of SEM, the mathematical equation is developed. The equation consists of vectors and matrices that are constructed from model. The equation can be used for predicting sustainability of rural water supply systems. Solution of this equation is obtained with the help of *Matlab* software.

3. RESULTS AND DISCUSSION

Factors Affecting Sustainability

The mathematical model is built from modeling with SEM. The SEM shows the factors that influence sustainability as illustrated in Figure 1. Magnitude of the influences is shown by the regression weight and loading factor values as listed in Table 1. Error of model that is expressed as root mean square error of approximation (RMSEA) is 0.081. The influence of some variables to the sustainability that is resulted by this study, confirms many previous studies in some developing countries as described in Table 2.

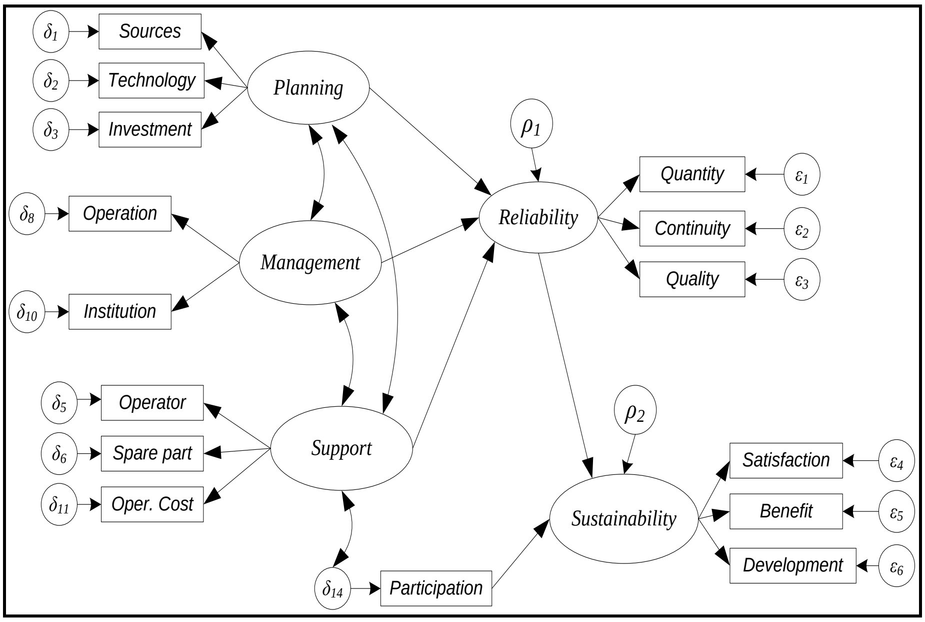

Figure 1. Path Diagram of Model That Expresses Influences of Variables to The Sustainability

Table 1. Regression Weight Estimate and Loading Factor of Model

Relationship			Estimate	Standardized Estimate	S.E.	C.R.	P
Reliability	←	Planning	0.198	0.679	0.022	9.022	***
Reliability	←	Management	0.082	0.153	0.036	2.247	0.025
Reliability	←	Support	0.099	0.210	0.037	2.659	0.008
Sustainability	←	Reliability	0.951	0.948	0.087	10.891	***

Table 2. Regression Weight Estimate and Loading Factor of Model (continuation)

Relationship			Estimate	Standardized Estimate	S.E.	C.R.	P
Sustainability	←	Participation	0.057	0.103	0.027	2.134	0.033
Sources	←	Planning	0.420	0.723	0.028	14.850	***
Technology	←	Planning	1.000	0.863			
Quantity	←	Reliability	2.517	0.993	0.168	14.948	***
Continuity	←	Reliability	1.000	0.582			
Quality	←	Reliability	0.383	0.360	0.062	6.175	***
Satisfaction	←	Sustainability	1.739	0.625	0.166	10.505	***
Benefit	←	Sustainability	1.000	0.407			
Development	←	Sustainability	1.000	0.659			
Operation	←	Management	1.000	0.774			
Institution	←	Management	1.035	0.658	0.068	15.147	***
Spare part	←	Support	0.457	0.722	0.030	15.166	***
Operator	←	Support	1.328	0.942	0.054	24.548	***
Operation cost	←	Support	1.000	0.653			
Investment	←	Planning	0.118	0.370	0.018	6.508	***

Remarks: *** : $p<0.001$

Table 3. Factors Affecting Sustainability and Refferences

Factors	References
Selection of technology	Davis and Brikké (1995); Mwanza (2003); Galvis (2005); Masduqi *et al.* (2007); Pushpangadan and Murugan (2008)
Availability of water sources	Mwanza (2003); Bhandari and Grant (2007); Pushpangadan and Murugan (2008) ; Rietveld *et al.* (2009)
Investment Cost	Sutton (2004)
Existence and ability of operator	Musonda (2004); Hoko and Hertle (2006); Bhandari and Grant (2007); Davis and Iyer (2002); Katz and Sara (1998); Tarquino (2001)
Availability of spare parts	Musonda (2004) and Davis and Iyer (2002)
Operation cost	Brikké dan Bredero (2003); Satterthwaite, McGranahan, and Mitlin (2005)
Technical operation	Carter, Tyrrel, and Howsam (1999); Brikké and Bredero (2003); Sarmento (2001); Rietveld, Haarhoff, and Jagals (2009); Davis and Brikké (1995)
Community participation	Kaliba (2002); Hoko and Hertle (2006); Mwanza (2003); Lockwood (2004); Satterthwaite, McGranahan, and Mitlin (2005); Katz and Sara (1998); Sarmento (2001); Davis and Iyer (2002); Masduqi *et al*. (2007)
Institutional management	Media (1999); Musonda (2004); Pushpangadan and Murugan (2008); Kaliba (2002); Davis and Iyer (2002)

Mathematical Model of Sustainability

Model of rural water supply system as depicted in Figure 1 is illustrated again in Figure 2 on how mathematical equations are constructed, where λ is loading factor of relationship between observed and latent variables, γ is regression coefficients between exogenous (independent) and endogenous (dependent) variables, and β is regression coefficient between endogenous and other endogenous variables. Basic equations of SEM are Equation (1), (2), and (3).

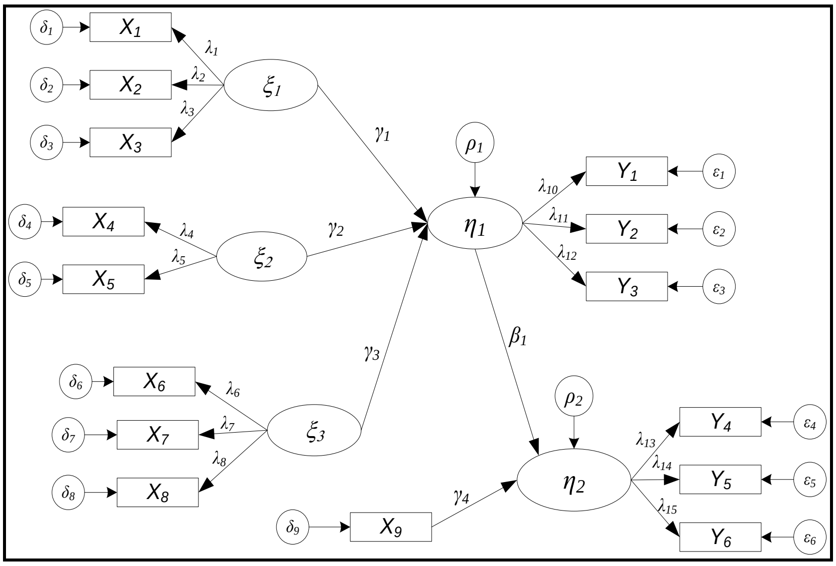

Figure 2. Model of sustainable water supply system by mathematical notation

By substituting Equation (1) and Equation (2) into Equation (3), the model of sustainability equations are obtained as follows:

$$\eta = B\eta + \Gamma \frac{X - \delta}{\Lambda_x} + \rho \tag{Eq. 4a}$$

$$\eta = B * \eta + \Gamma * (\Lambda_x \backslash (X - \delta)) + \rho \tag{Eq. 4b}$$

In Equation (1) to Equation (4b), there are matrices of vectors that can be obtained from the model (Figure 1 and Table 1).

By entering the matrices and vectors above, Equation (4b) becomes Equation (6).

This equation can predict the reliability (η_1) and predict the sustainability (η_2) with $R^2 = 0.913$. This equation is solved with the help of *Matlab*. Equation (5) is an equation for obtaining latent variables. To obtain observed variables (indicators), Equation (2) need to be rearranged to become Equation (6) and solved:

$$\begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0.948 & 0 \end{bmatrix} x \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix}_{assumption} + \begin{bmatrix} 0.679 & 0.153 & 0.210 & 0 \\ 0 & 0 & 0 & 0.103 \end{bmatrix} x \left(\begin{bmatrix} 0.723 & 0 & 0 & 0 \\ 0.863 & 0 & 0 & 0 \\ 0.370 & 0 & 0 & 0 \\ 0 & 0.774 & 0 & 0 \\ 0 & 0.658 & 0 & 0 \\ 0 & 0 & 0.942 & 0 \\ 0 & 0 & 0.722 & 0 \\ 0 & 0 & 0.653 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \backslash \left(\begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \end{bmatrix} - \begin{bmatrix} 0.022 \\ 0.046 \\ 0.012 \\ 0.027 \\ 0.056 \\ 0.012 \\ 0.010 \\ 0.069 \\ 0.037 \end{bmatrix} \right) \right) + \begin{bmatrix} 0.001 \\ 0.001 \end{bmatrix} \tag{Eq. 5}$$

$$Y = \begin{bmatrix} Y_1 \\ Y_2 \\ Y_3 \\ Y_4 \\ Y_5 \\ Y_6 \end{bmatrix} = \begin{bmatrix} 0.993 & 0 \\ 0.582 & 0 \\ 0.360 & 0 \\ 0 & 0.625 \\ 0 & 0.407 \\ 0 & 0.659 \end{bmatrix} x \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} + \begin{bmatrix} 0.001 \\ 0.022 \\ 0.011 \\ 0.054 \\ 0.058 \\ 0.015 \end{bmatrix} \tag{Eq. 6}$$

Sustainability index

Sustainability index is an index that states total value of three indicators of sustainability, namely user satisfaction, financial benefits, and possible development of system (Y_4, Y_5, and Y_6). Value of each indicator is made based on the assessment criteria that has highest possible value of 1 and the lowest value of 0. Thus, value of sustainability index will range from 0 to 3. Sustainability index can be used to classify sustainability. Sustainability is classified into three types, namely high, medium, and low sustainability.

This classification is made by considering the following:

1. results of simulation using the model show that maximum and minimum value of sustainability index that may occur are 2.507 and 0.052, respectively,
2. the average value of sustainability index in the study area is 1.6169,

3. the standard deviation of sustainability index in the study area is 0.2969.

Based on these considerations, classification of sustainability is determined to be three levels as follows:

- **Low sustainability,** if sustainability index = 0.052 to 1.320
- **Moderate sustainability,** if sustainability index = 1.321 to 1.914
- **High sustainability,** if sustainability index = 1.915 to 2.507

Prediction of Sustainability

As a follow-up of the study, decision-making methodology for implementation of rural water supply system is arranged. This methodology includes the steps that must be done before a project plan is implemented. These steps can be seen in Figure 3.

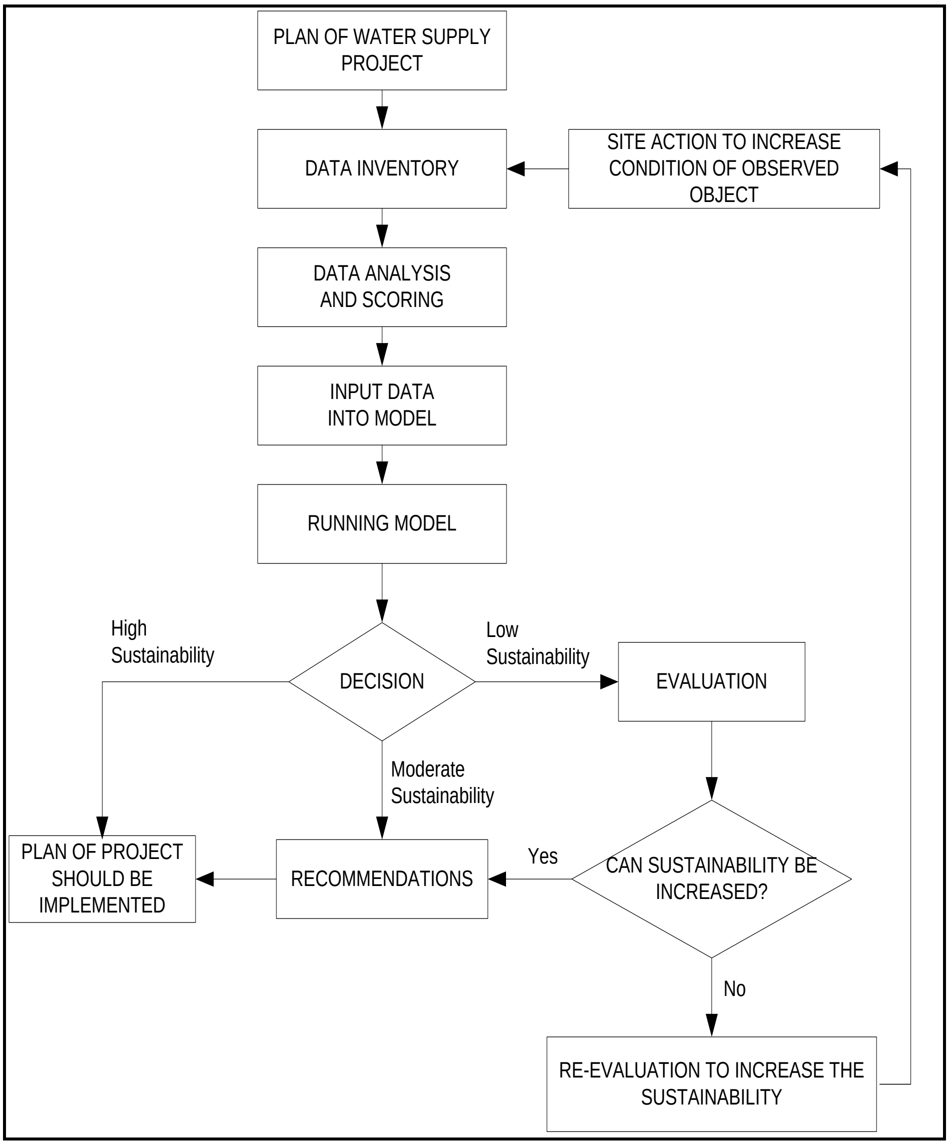

Figure 3. Decision-making Methodology for Implementation of Rural Water Supply Systems

Water project is begun by a project plan. The plans come from government, community, or third parties. Before the plan is implemented, this plan should be tested to know possibility of system sustainability. The first step is data inventory. Types of data to be collected are nine independent variables that are required for running the sustainability model, they are:

a. Availability of water source (X_1); data of water sources in the local area with sufficient discharge, history of water sources, good quality and safe to be consumed.
b. Selection of technology (X_2); data about type of planned water supply technology. The types of technology are pipeline system and its equipments, such as raw water collections, presence of pump, water reservoirs, pipeline network configuration, service systems, and water meters.
c. Investment cost (X_3); data about sources of fund for development of water facilities and amount of available fund compared to required fund.
d. Technical operation (X_4); data on the ease of water facilities operation, the possibility of damage occurrence, and the ease of repair if there is damage.
e. Institutional management (X_5); data about institution that will be formed to manage water, including institutional training plan.
f. Existence and ability of operator (X_6); data of local human resources that are hoped to be the operator of water facilities and/or training plan of technical operation for local people.
g. Availability of spare parts (X_7); data on ease of getting spare parts for component of technology used. This is related to availability of spare parts in the local area or a nearby places and the speed to get them.
h. Operation cost (X_8); data of sources of fund for operating facilities and amount of available fund compared to required fund.
i. Community participation (X_9); data on the form of public participation in planning of water facilities, technology selection, socialization, implementation, and operation.

In the future, more data, both existing and estimate or potential occurrence, should be collected. The collected data may be qualitative or quantitative one. The data must be changed to be quantitative one in the range of 0 - 1 for each variable. By using the sustainability model as formulated in Equation (5) and Equation (6), model output, i.e. reliability of the system (Y_1, Y_2, and Y_3) and sustainability of the system (Y_4, Y_5, and Y_6) are obtained. Sustainability index is totalizing three indicators. Sustainability model is applied to predict the sustainability of a water supply system that will be built in a village.

Based on the value of sustainability index, there are three possible levels of sustainability, namely high, moderate, and low. When the sustainability is high, then it is decided to implement the project plan. When the sustainability is moderate, recommendations are given to improve the sustainability index, so that project plan can be implemented. When the sustainability is low, recommendations will be given to increase sustainability or it is decided to delay the implementation of the project plan.

4. CONCLUSION

This study carried out in rural area of Brantas River Basin in Indonesia. Results of the study are mathematical equation of sustainability model, level of sustainability, and recommended methodology for decision-making of rural water supply project. This methodology includes the steps that must be done before a project plan implemented.

The mathematical equation can predict the sustainability (η_2). This equation needs nine data, they are availability of water source, selection of technology, investment cost, technical operation, institutional management, existence and ability of operator, availability of spare parts, operation cost, and community participation. The prediction result is sustainability index that is classified into three levels, they are low sustainability (index = 0.052 – 1.320), moderate sustainability (index

= 1.321 – 1.914), and high sustainability (index = 1.915 – 2.507).

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