# INTER-BASIN APPROACH BASED ON SYSTEM DYNAMICS SIMULATION FOR FIVE DAMS

**VICKY ARIYANTI**
*INACOLD*

**AGUS RUDYANTO**
*Ministry of Public Works and Housing, Directorate General of Water Resources*

**RADHIKA**
*Ministry of Public Works and Housing, Center for Water Research and Development*

## ABSTRACT

*Batam is an island located at the border of Indonesia and Singapore. It uses self-provision for its water supply, and it depends on rainwater harvesting to survive. This research uses the logic of action-reaction on the water balance, including water supply and demand, also the concurring interventions. The methodology uses a model of system dynamics simulation to calculate the water balance of the five reservoirs' operation on the island. The model uses Powersim software, which helps in calculating the numerical analyses of the five dams' water balance. In this research, the inflow of five reservoirs used the monthly series data from 2003 until 2015 to simulate the data from 2009 until 2048 with the assumption that the hydrology condition is recurring in the future. The reservoir capacity is analyzed by using the formula of the continuity concept. Based on the current condition, Batam's water balance will have a deficit within the coming ten years. It shows the needs of future water supply. The simulation helps in projecting future conditions using a dynamic approach. The model can be further developed to add new water supply infrastructures or alternatives to recycling wastewater and seawater reverse osmosis.*

## 1. INTRODUCTION

Worldwide, decision-makers needed effective solutions for water problems. These solutions were handled through a systems approach, which understands the structure of complex water problems from its interrelationships, patterns, and processes instead as static objects (Simonovic & Fahmy, 1999) . The approach proposes the following tasks: (1) structure development, (2) selection of policy, (3) selection of policy evaluation indicators, and (4) dynamic system simulation. The system dynamics simulation is used to analyze all decision variables to better understand the dynamics and complex systems (Ahmad & Prashar, 2010; Stave, 2003) . It suggests the changes be made in the decisions and the feedbacks (Sharawat, Dahiya, Dahiya, & Kumari, 2014) , which in this paper refers to the hydrological cycle and the water supply condition.

Batam Island is a part of Riau Islands and located at the boundary location between Singapore-Indonesia. The island does not have groundwater basin, thus it relies heavily on the inadequate water supply from the hydrological condition (BWS Sumatera IV, 2019). The geological condition of the island consists of old magmatic rocks, and clastic sediments from Mesozoic age (63 to 181 million years old), which have undergone weathering processes and erosion (Sukiyah, Isnaniawardhani, Sudradjat, & Erawan, 2018) . This island is also determined as free trade and harbor zone. Consequently, it leads to the requirement of supporting facilities to fulfill water demands for domestic, municipal, and industrial sectors, which amounted to 5,564 l/sec (BWS Sumatera IV, 2019). The map of the study location is presented in Figure 1.

The island is completed with reservoirs as rainwater storage to meet these water demands. In each of these reservoirs, since it was built specifically for water supply, the operating system is based on a sub-system of water availability, water demands, reservoir condition, the interest of the owner, institutional arrangement, and hydrological cycle. In each of the sub-systems, decision-making processes are at interplays, which can be modeled in system dynamics simulation. This paper aims to project future conditions.

**Figure 1**. Research location in the river area of Riau islands

## 2. METHODS

The methods for systems dynamic approach was first developed since 1950 at by a leading scholar, Jay Forrester at MIT (Massachusetts Institute of Technology). It was developed as a response to the complexity of social systems, scientific methods, and concepts of non-linear dynamics applicable to physical, biological, and technical issues (Sterman, 2002) . It is divided into three steps. Step 1 defines the real system model, which calls for closed causal models. Step 2 leads to the formulation of a simulation comprised of all variables of the dynamic system. Later this translates into equations. Step 3 is about the simulation model, which covers the logical criteria of a model and usually includes the use of software with logical checks. The model for simulation comprised of stock, flow, converter, and connector. Stock represents the current condition, while flow represents actions, converter represents the input and output, and the connector represents the causal relation between stock and flow. This model is visualized as follows in Figure 2.

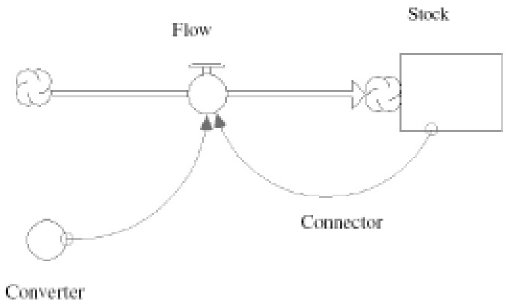


**Figure 2** : Stock, flow, converter, and connector

## 3. FINDINGS

Based on the steps of system dynamics simulation methods, the following findings are presented as (1) the real system model, (2) the formulation, and (3) the simulation. Each step was taken consistently as research stages and explained in this section.

### 3.1 The real system model

The real system is modeled based on reservoir simulation and its behavior analysis. It starts with the logical causal loop of the reservoir behavior. Therefore, the following indicators are use inflow, demand, capacity or storage, and water availability, outflow, and intervention, including evaporation, seepage. The initial causal loop is visualized as a closed-loop as follows:

In Figure 3 the causal loop explains the interrelations between inflow and outflow to the condition of storage in the reservoir, based on the water availability and demand, but also the intervention. Within the intervention, it includes the seepage, evaporation, technological advancement, or anything that causing the inflow-outflow loop not running in a simple manner.

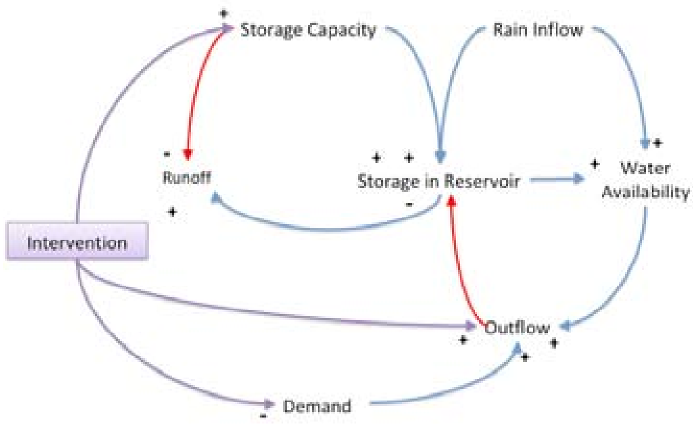


**Figure 3** : Reservoir system model

### 3.2 The Formulation

Based on the model above, we decided to use the formula of continuity concept (McMahon, Vogel, Pegram, Peel, & Etkin, 2007) :

$$S_{t+1} = S_t + Q_t - D_t - \Delta E_t - L_t$$

with the boundary: $0 \leq S_{t+1} \leq C$ and $D_t \leq Kap$,

t = time interval (usually 1 month);

$S_{t+1}$ = storage at the end of time interval-t;

$S_t$ = reservoir storage at the beginning time interval-t;

$Q_t$ = inflow during the time interval-t;

$D_t$ = demand during the time interval-t;

$\Delta E_t$ = evaporation during the time interval-t;

$L_t$ = seepage during the time interval-t;

C = active benefit capacity of reservoir; and

Cap = capacity of intake.

All the indicators in the model are covered in this formula, inflow, outflow, demand, storage, and capacity, also interventions, such as seepage and evaporation. In this research, the five reservoirs in Batam Island are linked into one holistic model; with each of the reservoirs has its model. The available series of monthly data is used for the simulation.

### 3.3 Simulation

Based on the causal loop, a better inclusion between the formula and the real-world model is developed. Each of the indicators in the formula is visualized in the causal loop model in a reservoir as follows, which in this example is using the reservoir of Duriangkang Dam:

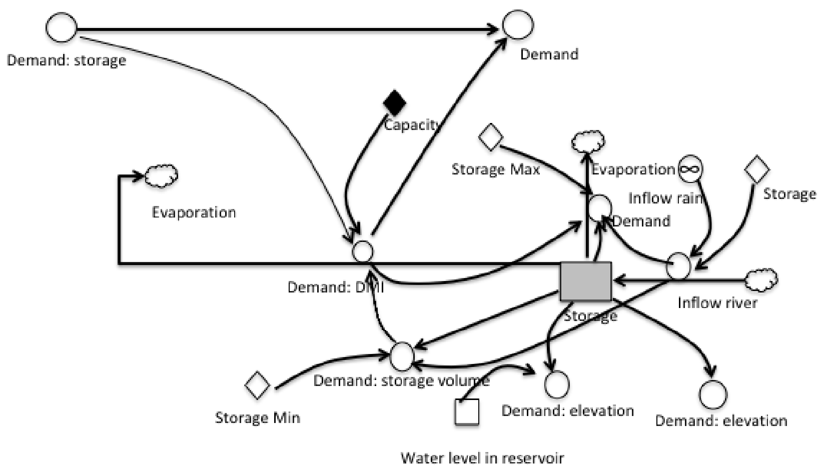


**Figure 4**. Duriangkang Reservoir Simulation Model

The series of data for water availability is taken from 2003 to 2016. The simulation relapses the data for the year 2009 to 2048 with a stable hydrological assumption for the future. The simulation also follows stages as follows, (1) calibration of hydrological data, (2) simulation model for five reservoirs, and (3) water balance analysis.

For the first stage, the calibration is needed for the water level at the reservoirs, with only two out of five reservoirs have complete data, which are the Muka Kuning Reservoir and Duriangkang Reservoir. Based on the calibrations, both the Muka Kuning and Duriangkang have consistent data shown from 2011 to 2014. The results of these calibrations presented in diagrams (figure 5) below.

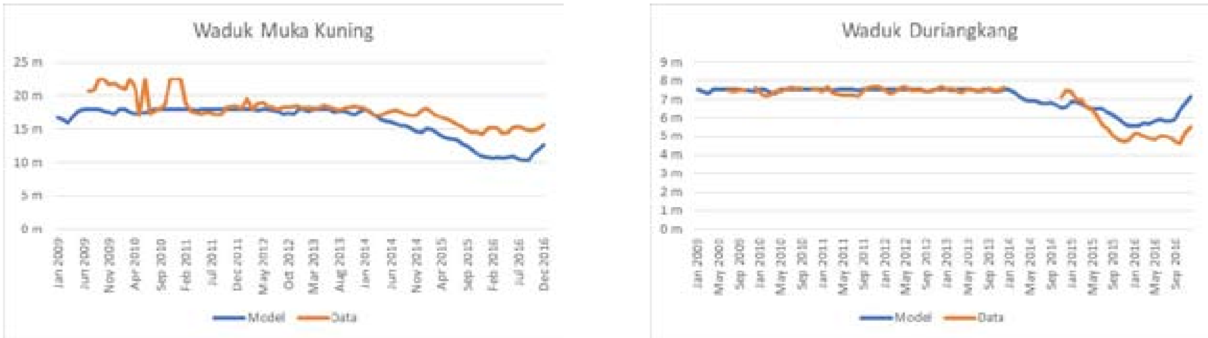


**Figure 5 :** Water level in Muka Kuning Reservoir and Duriangkang Reservoir

These diagrams show the recorded data and their correlation. Based on the data, there is a slight difference of 0.75m for Muka Kuning and 0.92 m for Duriangkang between the recorded data and the model. It is assumed that the causes are the model is purely analyzed and generated by a computer, the recorded data is affected by human error, and the five reservoirs' operation are interdependent, which might affect the water levels in one reservoir to the other reservoirs.

The second stage is the formulation of a holistic simulation model for the five reservoirs. These five interlinked reservoirs are the existing ones in 2017, namely Sei Harapan, Sei Ladi, Muara Kuning, Duriangkang, and Nongsa. It also considers the nine districts' water demands of the Batam Islands. The software for this model is Powersim, which is not only used for water balance simulation, but also commonly used for other system dynamics simulations in other disciplines, for example, macroeconomic modeling, biological habitat modeling, and others.

Therefore, the model visualized in the Powersim software is presented as follows (figure 6). The district nodes represented in yellow boxes and the reservoirs in the blue boxes. Each of the districts and the reservoir have their model within the boundary of their system dynamics. These models are interlinked and based on hydrological and geomorphological conditions of the island. This arrangement is based on the actual conditions of inter-basin transfers throughout the island, and it reflects a simplified model of the real world in a system dynamics model. The model also amplifies the common interventions interrelating with each reservoir as they are connected as one system.

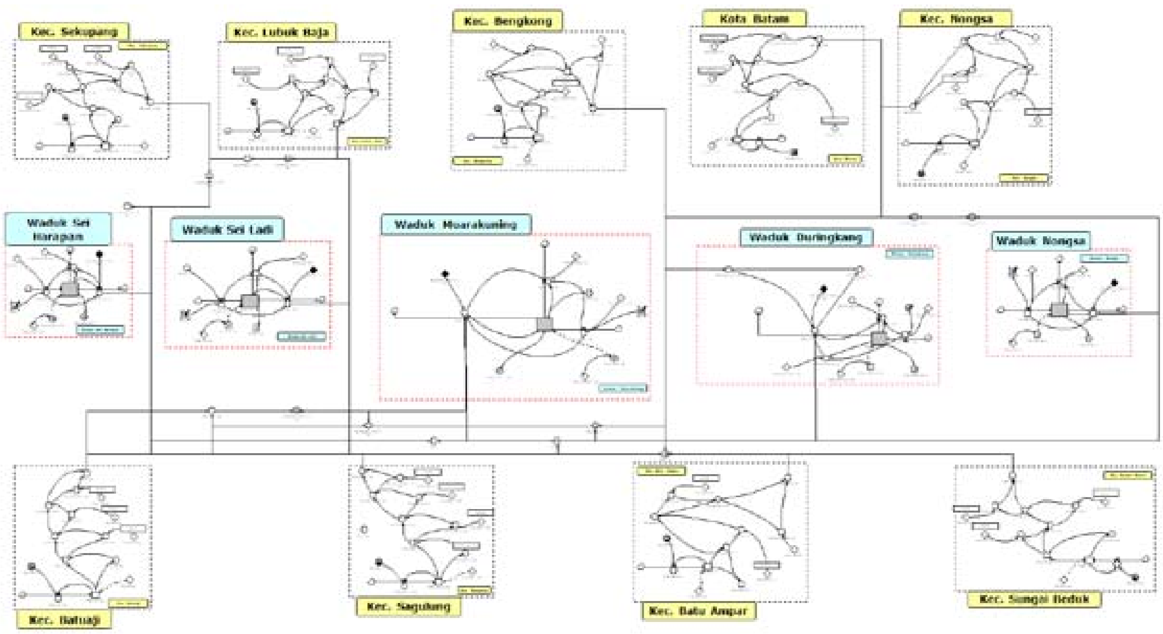


**Figure 6 :** The Real World Model on Five Reservoirs

The third stage is the running of the simulation. It starts with the software simulation, which enables flexible interrelations and inter-basin transfers between the five reservoirs and nine districts. The simulation resulted in Table 1. It highlights the water supply deficit within the coming ten years for Batam Island, which is also visualized in Figure 7.

**Tabel 1** : Water Balance of Batam Island

| Time | Supply ($m^3/s$) | Demand ($m^3/s$) | Balance ($m^3/s$) | Fresh water fulfillment (%) |
|---|---|---|---|---|
| Jan 1, 2018 | 2.58 | 2.58 | 0.00 | 100.00 |
| Jan 1, 2019 | 2.68 | 2.68 | 0.00 | 100.00 |
| Jan 1, 2020 | 2.79 | 2.79 | 0.00 | 100.00 |
| Jan 1, 2021 | 2.90 | 2.90 | 0.00 | 100.00 |
| Jan 1, 2022 | 3.02 | 3.02 | 0.00 | 100.00 |
| Jan 1, 2023 | 3.13 | 3.13 | 0.00 | 100.00 |
| Jan 1, 2024 | 3.25 | 3.25 | 0.00 | 100.00 |
| Jan 1, 2025 | 3.37 | 3.37 | 0.00 | 100.00 |
| Jan 1, 2026 | 3.49 | 3.49 | 0.00 | 100.00 |
| Jan 1, 2027 | 3.60 | 3.60 | 0.00 | 100.00 |
| Jan 1, 2028 | 3.55 | 3.72 | -0.17 | 95.37 |
| Jan 1, 2029 | 3.40 | 3.84 | -0.43 | 88.67 |
| Jan 1, 2030 | 3.50 | 4.17 | -0.67 | 83.84 |
| Jan 1, 2031 | 3.49 | 4.29 | -0.80 | 81.46 |
| Jan 1, 2032 | 3.71 | 4.41 | -0.70 | 84.14 |
| Jan 1, 2033 | 3.72 | 4.52 | -0.80 | 82.31 |
| Jan 1, 2034 | 3.73 | 4.85 | -1.12 | 76.85 |
| Jan 1, 2035 | 3.70 | 4.96 | -1.26 | 74.63 |
| Jan 1, 2036 | 3.37 | 5.07 | -1.70 | 66.51 |
| Jan 1, 2037 | 3.42 | 5.17 | -1.75 | 66.09 |
| Jan 1, 2038 | 3.56 | 5.27 | -1.71 | 67.53 |
| Jan 1, 2039 | 3.73 | 5.36 | -1.63 | 69.54 |
| Jan 1, 2040 | 3.73 | 5.45 | -1.72 | 68.41 |
| Jan 1, 2041 | 3.55 | 5.58 | -2.03 | 63.64 |
| Jan 1, 2042 | 3.40 | 5.66 | -2.26 | 60.10 |
| Jan 1, 2043 | 3.50 | 5.73 | -2.24 | 60.99 |
| Jan 1, 2044 | 3.49 | 5.80 | -2.31 | 60.22 |
| Jan 1, 2045 | 3.71 | 5.87 | -2.16 | 63.17 |
| Jan 1, 2046 | 3.72 | 5.93 | -2.21 | 62.71 |
| Jan 1, 2047 | 3.72 | 5.99 | -2.26 | 62.25 |

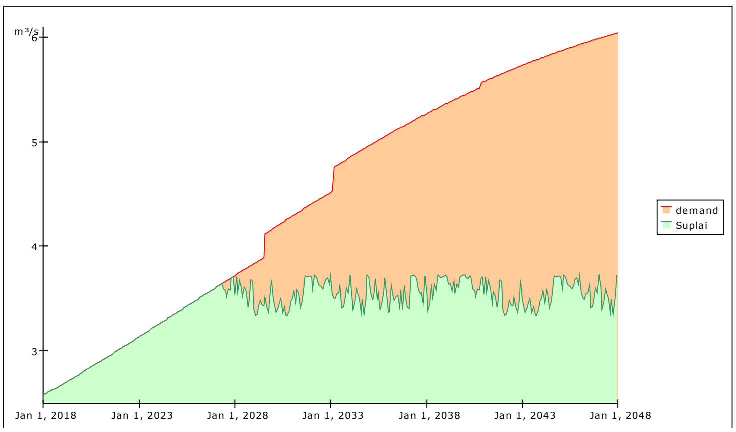


**Figure 7**. Existing Water Balance for Batam Island

Based on this simulation result, additional interventions are needed to supply the water to meet future demands. These interventions include adding new dams, also other alternatives, such as recycled wastewater (RWW), and seawater reverse osmosis (SWRO). Especially, the interventions of new dams are added to the simulation model. These dams are based on Riau Archipelago Basin Water Resource Management Plan or RPSDA WS Kepulauan Riau (BWS Sumatera IV, 2019) , which includes Batam as one island. These dams are as follow, including the year of implementation, such as in 2023: Rempang, Tembesi, Sei Gong, 2028: small dams, 2033: more small dams, 2038: Rempang 2, Rempang Utara, Sei Golang. Based on these interventions, the following diagram is produced (figure 8). It presents the condition of the new water balance after additional interventions are proven to have a surplus. Out of the potential 9.16 m3/sec, this intervened water balance provides 9.28 m3/sec with a demand of 9.15 m3/sec; the surplus is about 0.13 m3/sec. The supply is above the potential, as it also included recycled water as an alternative solution.

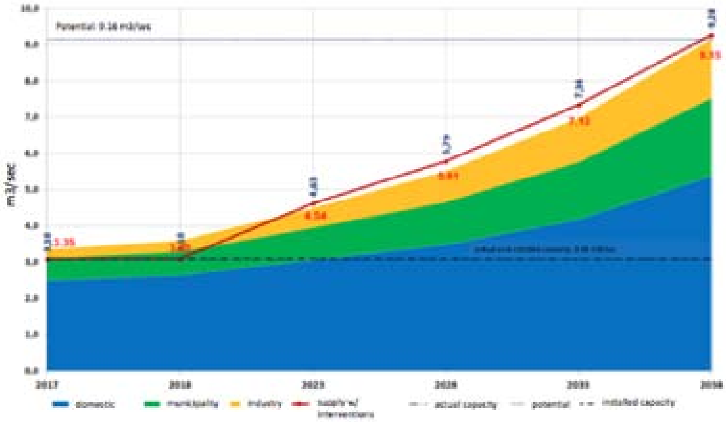


**Figure 8**. Intervened Water Balance for Batam

The system dynamics simulation by Powersim in this research is proven to be flexible; it can be added with new interventions with no time constraint (less than a day). The simulation is also proven to be accurate compared to the more complex simulation used to produced the RPSDA WS Kepulauan Riau. This approach is much robust, especially to model the inter-basin transfer and understanding the water supply system.

## 4. CONCLUSIONS

The system dynamics simulation used in this paper proves to be a robust approach for a holistic understanding of a water supply system. Several points can be concluded as follow, based on our observation:

1. The simulation needs to follow the three stages provided as a guideline, but the implementation can differ for each case. It provides a transparent and flexible, also easiness' in producing the model. Its primary concern would be to develop the real-world model to include all indicators needed for the study and link the causal loop between the indicators. The more complex the model, the more indicators are needed.
2. In our study, the inter-basin transfer is not as complex as another case, where the dams were built mainly for water supply purposes, and the geological condition is relatively homogenate. Therefore, it was somewhat easier to be a test case. Although there is no limitation in the simulation, this research has a limitation in the focus of the study.
3. The first simulation presented the result that Batam Island has increasing population growth from 257,674 population in 2017 with 1.12 m3/s water demand 658,625 population in 2017 with the water demand of 3.31 m3/s. The limitation of water volume and the permanent intake capacity of the five existing reservoirs resulted in the deficit of water supply in the upcoming ten years.
4. The second simulation with the interventions of newly added dams will provide the demands up to 2038 with a surplus of 0.13 m3/s. However, the model can still be upgraded with additional interventions on SWRO and more efforts on RWW.

## REFERENCES

Ahmad, S., & Prashar, D. (2010). Evaluating municipal water conservation policies using a dynamic simulation model. *Water Resources Management, 24*(13), 3371-3395.

Minister of public works and housing decree no.569/KPTS/M/2019 on basin water resources management plan of riau islands, (2019).

McMahon, T. A., Vogel, R. M., Pegram, G. G., Peel, M. C., & Etkin, D. (2007). Global streamflows–Part 2: Reservoir storage–yield performance. *Journal of Hydrology, 347*(3-4), 260-271.

Sharawat, I., Dahiya, R., Dahiya, R., & Kumari, S. (2014). System dynamics approach: A novel water resource management tool. *Int.J.Environ.Res.Dev, 4*, 297-302.

Simonovic, S. P., & Fahmy, H. (1999). A new modeling approach for water resources policy analysis. *Water Resources Research, 35*(1), 295-304.

Stave, K. A. (2003). A system dynamics model to facilitate public understanding of water management options in las vegas, nevada. *Journal of Environmental Management, 67*(4), 303-313.

Sterman, J. (2002). System dynamics: Systems thinking and modeling for a complex world.

Sukiyah, E., Isnaniawardhani, V., Sudradjat, A., & Erawan, F. (2018). The geologic potentials of riau islands province and its development design. *Jurnal Perspektif Pembiayaan Dan Pembangunan Daerah, 5*(3), 181-190.