Water Cycle Analysis System Dynamics Model for Designing Optimal Water Reclamation Scheduling

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Abstract

A water cycle analysis System Dynamics model for scheduling reclaimed water production to achieve low energy consumption for water reclamation and to ensure the high quality of the reclaimed water is proposed. A water cycle has various types of water flow and storage, so System Dynamics is suitable for modeling and simulating it. In addition, by using System Dynamics modeling software, various types of models for water cycle analysis can be modeled comparatively easily and used to design an optimal scheduling. The model must be able to analyze water quality and energies for water distribution and treatment as well as water flow and storage in order to schedule optimal production. It therefore consists of three components: water flow, water quality, and energy models. We constructed a water flow model that can handle various types of water flow, including tap water supply, reclaimed water supply, wastewater, treated water, and reclaimed water. The Energy model computes the energy consumption of the pumps and blowers used in water distribution and water treatment systems, and the water quality model computes the water quality of treated wastewater and reclaimed water. Our constructed model was used to schedule water reclamation production to reduce the energy consumed during the water reclamation process and to ensure high quality of the reclaimed water. Simulation results showed that the proposed model is effective for designing an optimal reclaimed water production scheduling.

Key Words: Water Cycle, System Dynamics Model, Reclaimed Water, Water Reclamation Production Scheduling

1. Introduction

Water demand is rapidly growing due to economic progress and urbanization, and it has led to water scarcity in various regions in the world (COCN, 2008). One solution to this problem is to reclaim water from industrial and domestic wastewaters. Efficient operation of water reclamation plants is required to reduce the energy and cost consumed by the plants.

System Dynamics methodology has been used in the past for efficient water management (Bhatkoti et al. 2011, Goldani et al. 2011, Adeniran et al. 2010). In prior research, long-term planning and assessment models were utilized to appropriately manage water source and water supply. Short-term scheduling or planning technology has also been utilized to achieve efficient water management that reduces the environmental load (Kurisu et al. 2011, Adachi et al. 2009, Dohgami et al. 2007, Bunn 2006, Arniella et al. 2007, Ulanicki et al. 2007). We used the System Dynamics methodology to model a water cycle system and determine optimal short-term scheduling for reclaimed water production.

We first constructed a System Dynamics model for water cycle analysis. A water cycle is made up of various types of water flow and storage, so System Dynamics is suitable for modeling and simulating it. The model must be able to analyze water quality and energies for water distribution and treatment as well as water flow and storage in order to schedule optimal production. It therefore consists of three components: water flow, water quality, and energy models. We constructed such a model and used it to schedule reclaimed water production to reduce energy consumption and to ensure reclaimed water of a high quality. In Section 2, we explain exactly how the System Dynamics model for water cycle analysis works. In Section 3, we discuss our application of the model to the design of an optimal scheduling that reduces energy consumption and cost during the water reclamation process. We conclude the paper in Section 4.

2. System Dynamics Model for Water Cycle Analysis

2.1 Overall Structure

The overall structure of a water cycle analysis System Dynamics model is shown in Fig. 1. This particular model is for analyzing a water cycle in an industrial complex. It consists of three sub-models: water flow, water quality, and energy models. The water flow model can handle various types of flow and storage, including tap water flow, reclaimed water flow, wastewater flow, treated water flow, reclaimed water flow, storage in factories, storage in a sewage treatment process, storage in a water reclamation plant, and storage in a water distribution reservoir. The energy model computes the energy consumption of booster and circulation pumps and blowers for water distribution and water treatment on the basis of various computed flows. The water quality model chiefly computes the quality of the treated wastewater flowing out of an activated sludge treatment process on the basis of the quality of the inflow to the process and an approximately formulated dynamic model of quality response.

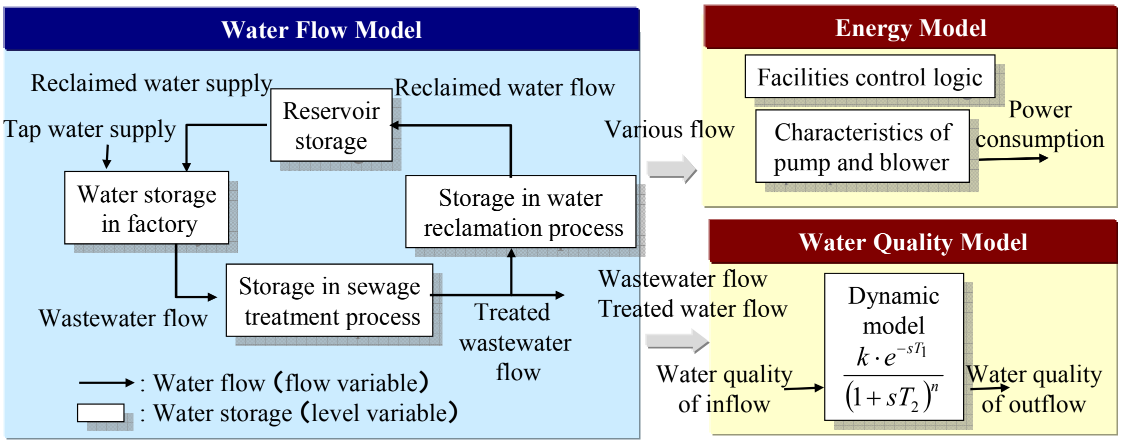

Fig. 1 Overall structure of water cycle analysis System Dynamics model.

2.2 Water Flow Model

A System Dynamics model for analyzing water flow and storage is shown in Fig. 2. Tap and reclaimed water is supplied to factories in an industrial complex. After the supplied water is temporally stored in factories, it is discharged as wastewater into a sewer pipe. This delay is assumed to be approximately a first order lag system. A part of this wastewater evaporates or infiltrates underground. Wastewater is treated and purified in a settling basin, a primary sedimentation tank, an activated sludge treatment tank, and a final sedimentation tank. A part of the treated wastewater is sent to a reclamation plant where it is further purified for reuse as reclaimed water, while the other part is discharged into an artificial river. Sand filtration and chemical precipitation are typically utilized in the water reclamation process. Reclaimed water is sent to a distribution reservoir and then supplied to various factories in accordance with diurnal demand. The treated water flow colored red in Fig. 2 is scheduled on the basis of the demand forecast for reclaimed water. Since the scheduling affects energy consumption and/or the running cost of the water reclamation process, it needs to be designed appropriately with proper consideration given to the operating environment.

A simulation example of water flow and storage is shown in Fig. 3. Here, the treated water flow (scheduled flow) was given as an almost constant value and the demands of tap water and reclaimed water were given as trapezoid wave. The amount of water in the reservoir cyclically fluctuated due to gaps between supply and demand.

A water flow model in a case that uses membrane bioreactor (MBR) and reverse osmosis (RO) plants for sewage and reclamation treatment processes is shown in Fig. 4. The main structural difference from the model in Fig. 2 is that a regulating tank is provided to regulate the amount of wastewater flowing into the MBR plant. The simulation result (not presented in this section but shown in Fig. 10 and discussed later) is similar to that of the case in Fig. 3.

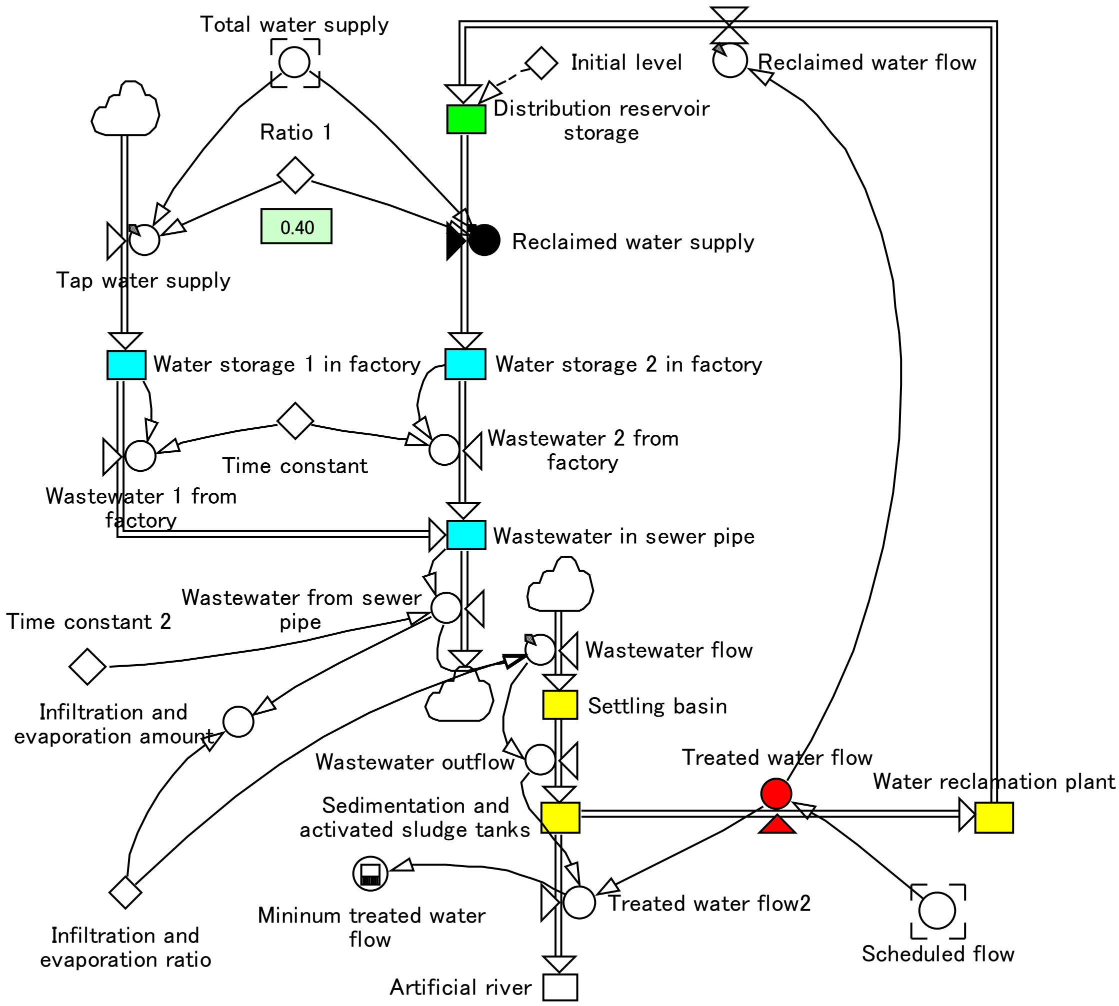

Fig. 2 System Dynamics model for analyzing water flow.

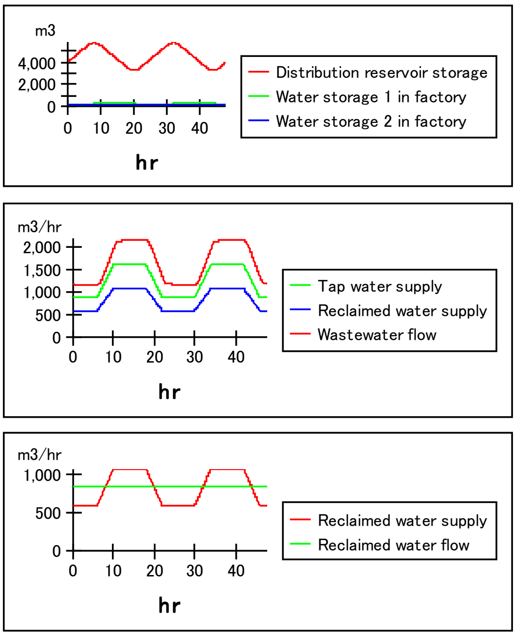

Fig. 3 Simulation example of water flow and reservoir storage.

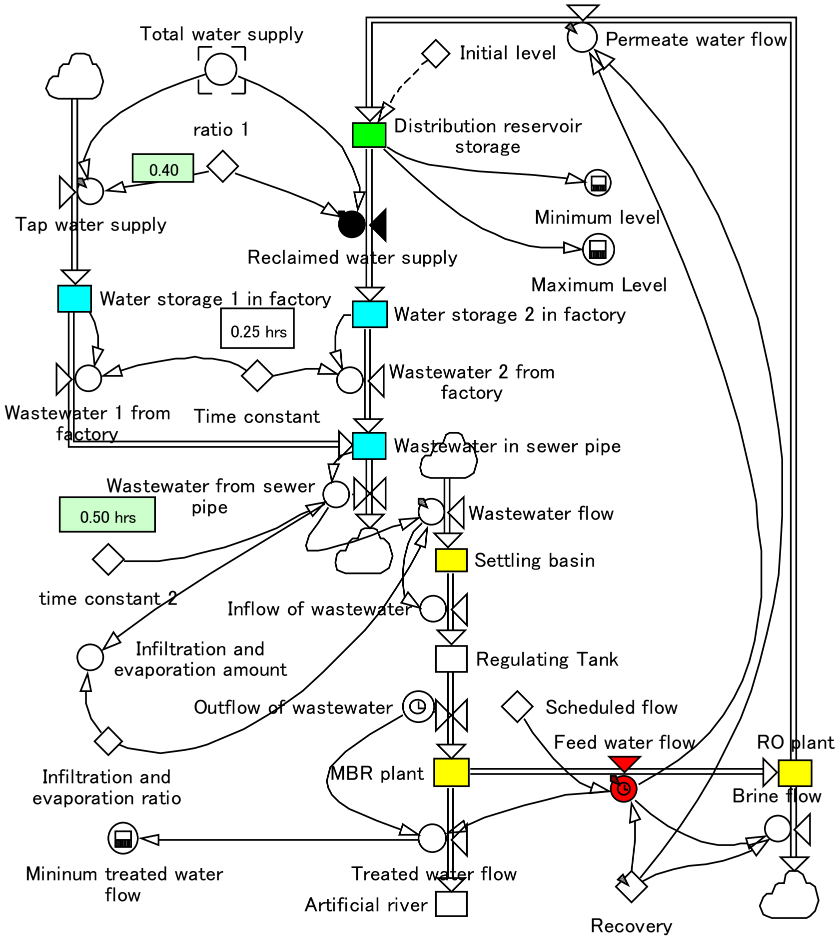

Fig. 4 System Dynamics flow model of water cycle system with MBR and RO plant.

2.3 Energy Model

A System Dynamics model for computing the energy consumption of booster pumps for tap and reclaimed water distribution is shown in Fig. 5. Tap water is supplied through a relay point by a waterworks company. Discharge pressure for tap water distribution is assumed to be 0 because the pressure of receiving water at the relay point is large enough. Discharge pressure of the booster pump for distributing reclaimed water is set so that the pressure at the end node in the distribution network is kept at a constant value of about 15 m. Electric power for reclaimed water distribution is computed on the basis of the discharge pressure and the water flow. Cumulative energy consumption is computed by integrating the electric power. A simulation example is presented in Fig. 6. Under the condition of high water demand, discharge pressure is high and consumes a lot of the pump's electric power because pressure loss in the distribution network is heavy and thus high pressure is required to keep the pressure at the end node constant.

A System Dynamics model for computing the electric power consumption of a sewage pump, a sludge circulation pump, a treated water circulation pump, and a blower used in a sewage treatment process that includes an activated sludge treatment process is shown in Fig. 7. In this process, target flow rates for the sludge circulation and treated water circulation are determined on the basis of the wastewater flow rate. Thus, the electric power consumption of each device mainly depends on the wastewater flow rate. Here, the linear functions of the wastewater flow rate were used to calculate the energy consumption of each device. A flow rate of air supplied by a blower was considered to be an approximate function of the wastewater flow rate and biochemical oxygen demand (BOD) concentration in wastewater flowing into the treatment plant because the blowers need to supply with oxygen that bacteria in the plant requires for endogenous respiration and oxidation of an organic matter, and the amount of the oxygen is mainly determined by the wastewater flow rate and the BOD concentration. The electric power consumption of the blower was computed based on the calculated air flow rate. Cumulative total energy consumption for the sewage treatment process was computed by integrating the sum of the electric power consumption of each device. A simulation example of the energy consumption of pumps and blowers used in the sewage treatment process is shown in Fig. 8. The energy consumption of the blower is the largest, and the cumulative energy consumption is much larger than that of the water distribution.

The System Dynamics model for computing the energy consumption of an RO booster pump is shown in Fig. 9. This particular RO plant is for desalinating wastewater, and it consumes a lot of energy because the booster pump needs to maintain a high pressure in order to separate water and salt content by membrane filtration. The RO plant consists of several RO membrane module units. The model computes the energy consumption of RO booster pumps from the number of driving units and feed flows to RO membrane modules by using the pump energy characteristics curves. A simulation example of the energy consumption of RO pumps is shown in Fig. 10. The demand for reclaimed water was assumed to fluctuate cyclically on weekdays and be constant on the weekend. In this case, the number of driving units was scheduled in accordance with the demand for reclaimed water, and the distribution reservoir storage fluctuates on weekdays due to the gap between supply and demand and is constant on a weekend.

These energy models can be used to design an optimal scheduling to reduce energy consumption in a water cycle system.

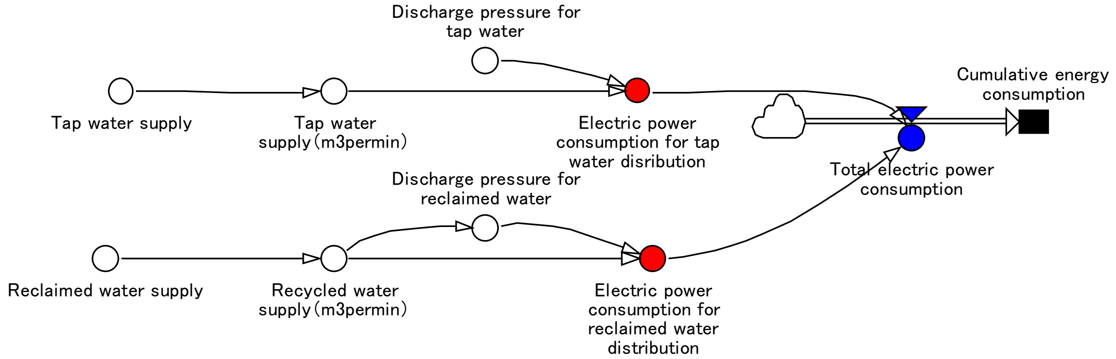

Fig. 5 System Dynamics model for analyzing energy consumption of water distribution pump.

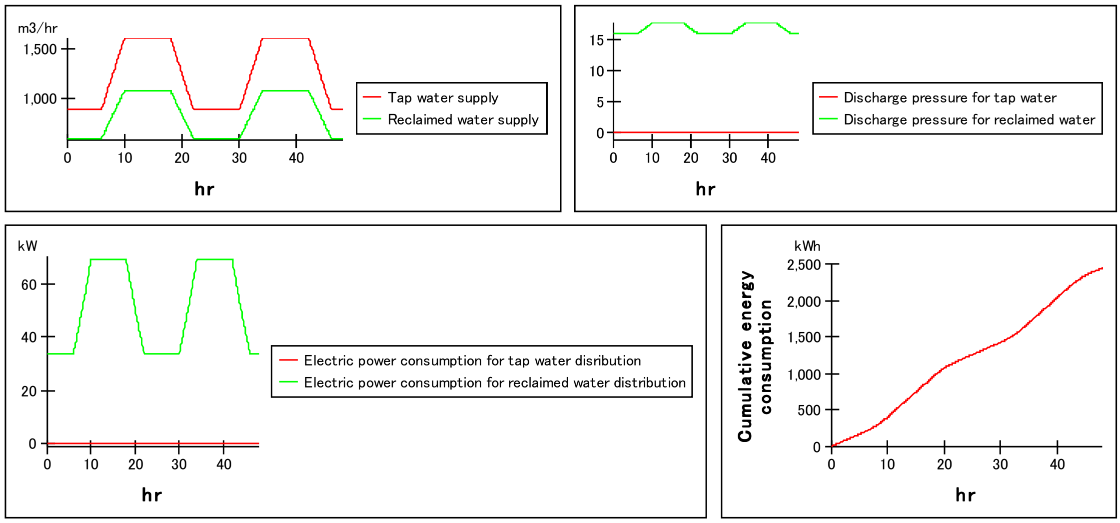

Fig. 6 Simulation example of energy consumption of water distribution pump.

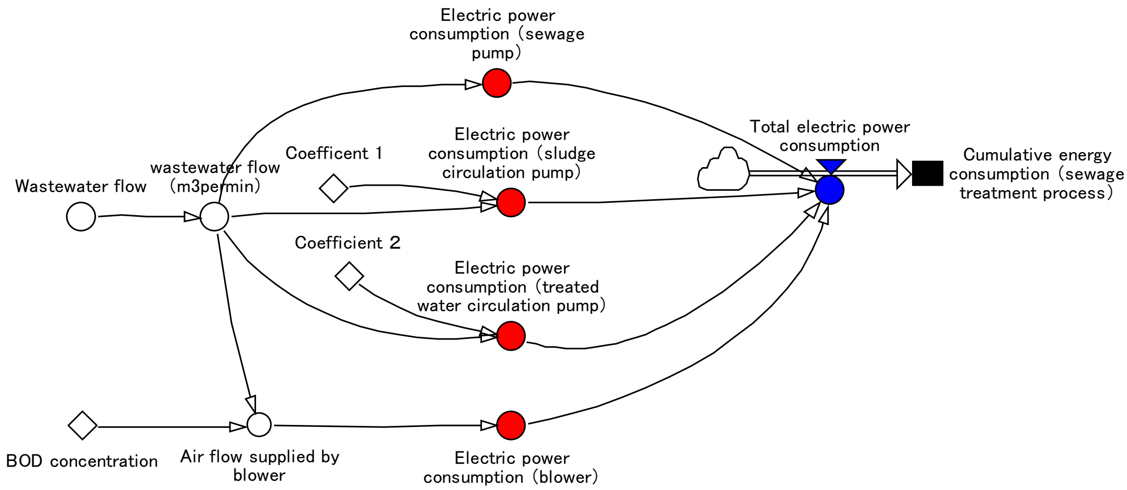

Fig. 7 System Dynamics model for analyzing energy consumption for sewage treatment process including activated sludge treatment process.

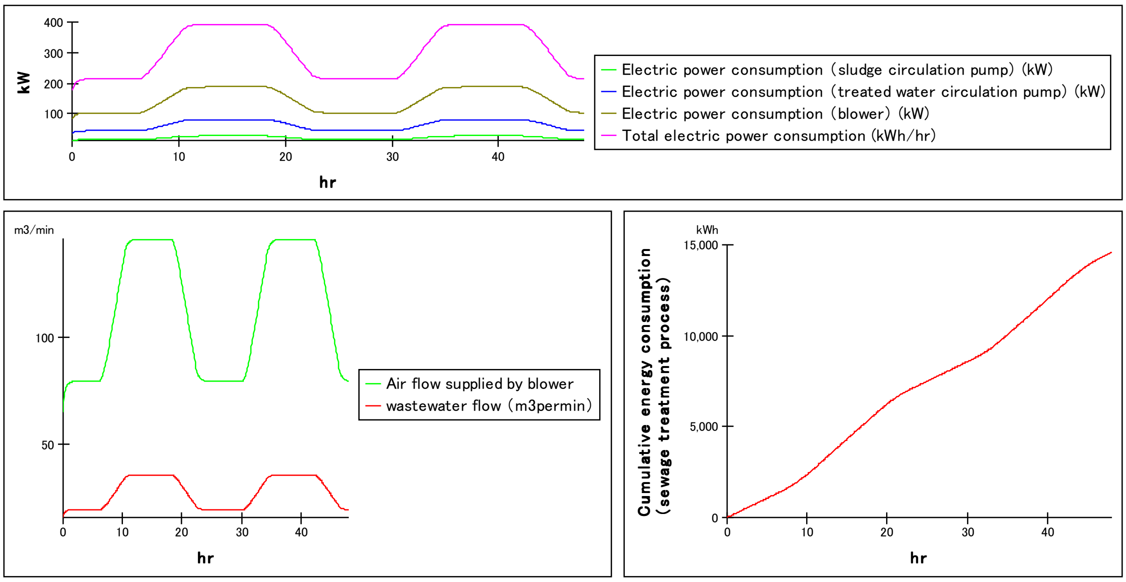

Fig. 8 Simulation example of energy consumption of sewage treatment plant.

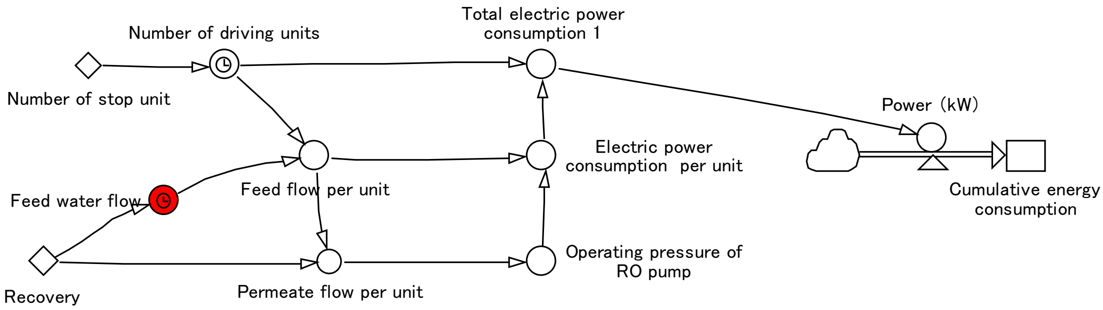

Fig. 9 System Dynamics energy model of RO plant.

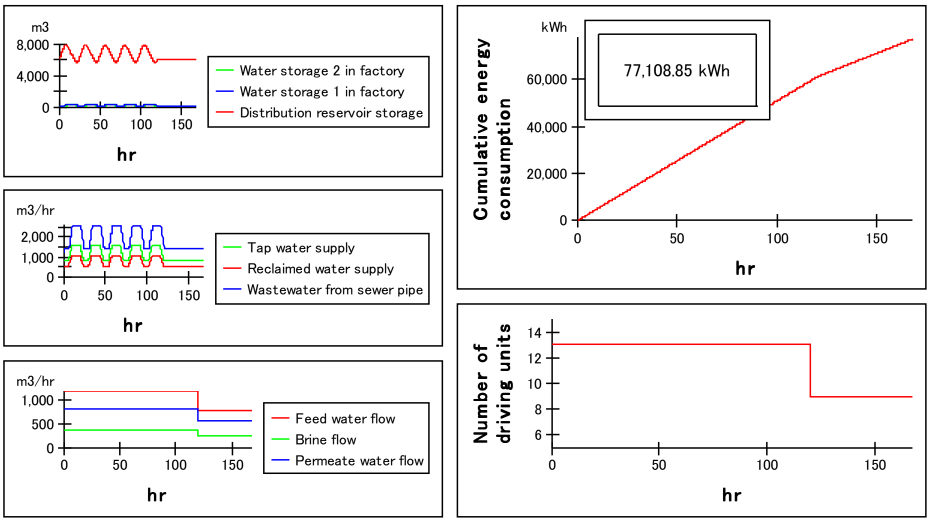

Fig. 10 Simulation example of energy consumption of RO plant.

2.4 Water Quality Model

A System Dynamics model for computing water quality is shown in Fig. 11. The model computes the BOD, total nitrogen (TN), and total phosphorus (TP) concentrations of the wastewater treated by a sewage treatment process on the basis of those of the wastewater and wastewater flow rate. There is a well-known water quality model for the sewage treatment process (an activated sludge treatment process) advocated by the International Water Association (IWA) (Henze et al. 2000). However, this model is extremely complicated and needs to simultaneously solve many differential equations derived from material transportation equations and reaction formulas to determine the quality of the treated wastewater. Instead of using that model, we selected a simple dynamic model (shown in Fig. 11) consisting of a steady-state model for components removal and a dynamic model for the response delay of water quality. Most of the BOD, TN, and TP contained in the wastewater are eliminated by the treatment process, although some remains in the treated wastewater. The steady-state model is for expressing this process. The model provides a stationary relationship between the quality (BOD, TN, and TP concentrations) of the wastewater and that of the treated wastewater. The System Dynamics model in Fig. 11 first computes the quality of treated wastewater in a steady state by using the steady-state model. The quality of treated wastewater generally starts to change several hours after the wastewater quality or wastewater flow rate changes. We have approximately formulated this response delay as a second order lag plus dead time. A higher order delay may be used in other cases. The delay is expressed in the latter part of the System Dynamics model in Fig. 11. Finally the BOD, TN, and TP concentrations of the treated wastewater in transition are computed.

The model for computing the average concentration of BOD in a distribution reservoir is shown in Fig. 12. (The model for TN and TP can be constructed using the same structure.) The average concentration of BOD in the distribution reservoir is computed from the concentration of BOD in the reclaimed water, the reclaimed water flow rate, and the reclaimed water supply rate. The BOD concentration of reclaimed water is calculated by multiplying the BOD concentration of the treated wastewater by elimination coefficient. In this study, we assumed a value of 0.8.

A simulation example of water quality is shown in Fig. 13. Here, the concentration of each component contained in the wastewater and the scheduled flow—that is, the flow of the treated wastewater sent to the reclamation plant—was considered to be almost constant. The BOD, TN, and TP concentration of treated wastewater fluctuates with a response delay of several hours compared to the wastewater flow rate. The average BOD concentration in the reservoir also changes with a response delay compared with the BOD concentration of the reclaimed water. This water quality model can be used to design a reclaimed water production scheduling that improves the water quality of the distribution reservoir.

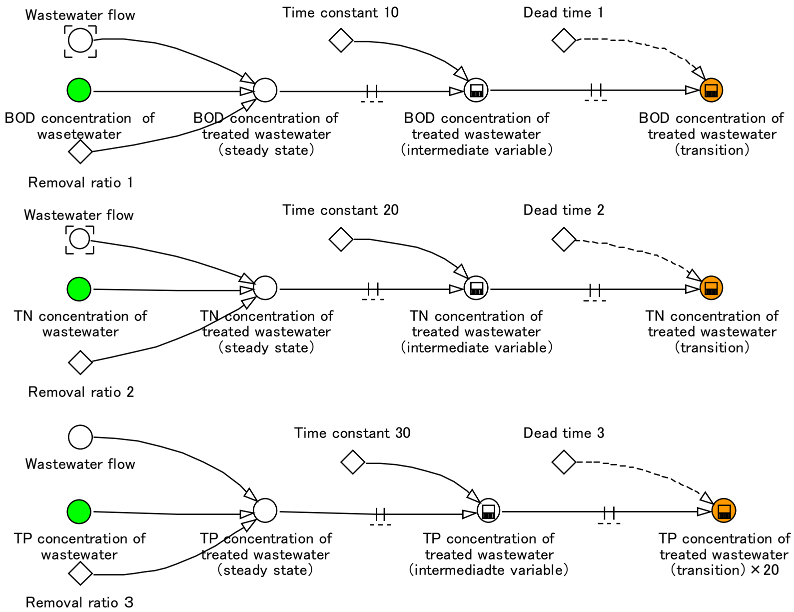

Fig. 11 System Dynamics model 1 for analyzing water quality.

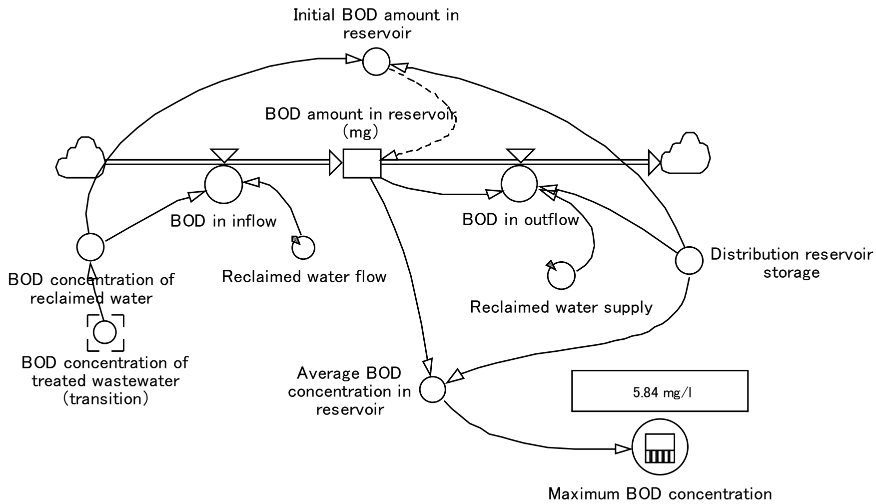

Fig. 12 System Dynamics model 2 for analyzing water quality.

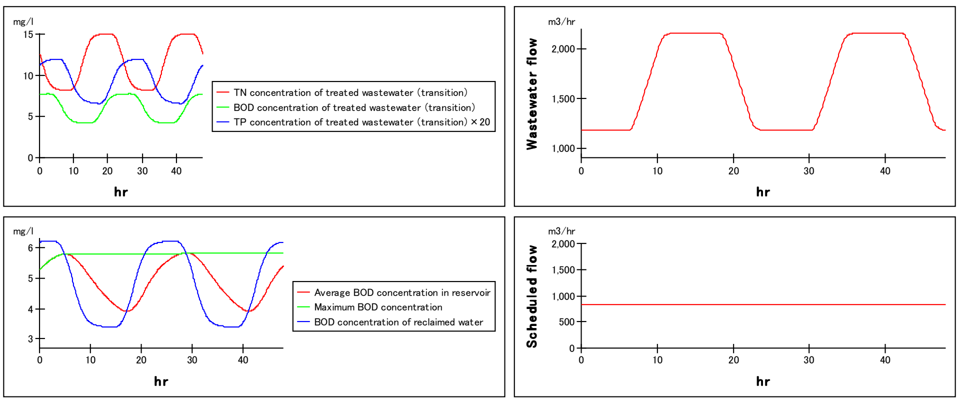

Fig. 13 Simulation example of water quality.

3. Water Reclamation Scheduling Using Water Cycle Analysis System Dynamics Model

3.1 Water Reclamation Scheduling for Improving Quality of Reclaimed Water

The System Dynamics models of water flow and water quality shown in Figs. 2, 11, and 12 were used to derive an optimal water reclamation scheduling that reduces the BOD concentration of reclaimed water in the distribution reservoir. By using an optimization engine (GA: Genetic Algorithm) of a System Dynamics tool, the flow rate of treated wastewater sent to a reclamation plant and the initial level of reservoir storage were scheduled to minimize the maximum value of average BOD concentration time series of reclaimed water in the reservoir under the following constraints: 1) reservoir storage is within upper and lower limits, 2) the flow rate is over 0 and less than the wastewater flow rate, and 3) the level of reservoir storage returns to its original level in 24 hours. The scheduling result is shown in Fig. 14. The maximum value of average BOD concentration in the reservoir has been minimized by preferentially sending the treated wastewater with low BOD concentration to the water reclamation plant and by not sending the treated wastewater with high BOD concentration to the plant. The maximum value was reduced from 5.84 mg/l to 4.19 mg/l, or by about 28 %. This reduces the overall running cost of the water reclamation process.

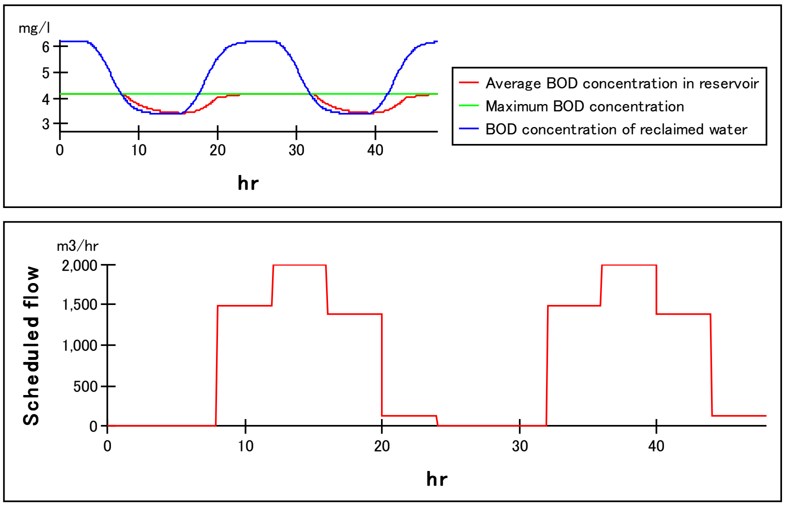

Fig. 14 Example of optimal scheduling of treated water supply.

3.2 Feed Flow Scheduling for Minimizing Energy Consumption of RO Booster Pump

The System Dynamics models for computing water flow and energy shown in Figs. 4 and 9 were utilized to derive an optimal scheduling of feed flow to the RO membrane module that minimizes energy consumption of RO booster pumps. By using an optimization engine (GA: Genetic Algorithm) of a System Dynamics tool, the feed flow and initial level of the reservoir storage were scheduled to minimize energy consumption during one week under the following constraints: 1) reservoir storage is within upper and lower limits, 2) the feed flow rate is over 0 and less than the wastewater flow rate, and 3) the level of reservoir storage returns to its original level in 24 hours. The difference from the case in Fig. 10 is that number of driving units was kept constant at 13. The scheduling result is shown in Fig. 15. The energy consumption was reduced from the 77108 kWh in Fig. 10 to 73369 kWh (or, by about 4.8 %) because driving all units at comparatively low discharge pressure on the weekend is more effective in regard to energy consumption than stopping four units and driving nine units at high discharge pressure.

A result that the level of the reservoir storage is back to its original level within a week is shown in Fig. 16. Energy consumption was reduced to 72216 kWh (or, by about 6.3 %), which is a better result than the one in Fig. 10, because a small fluctuation of the feed flow that results in low energy consumption was achieved by effectively using the storage capacity of the reservoir.

As demonstrated by the above examples, the System Dynamics model is effective in the design of an optimal scheduling that reduces energy consumption.

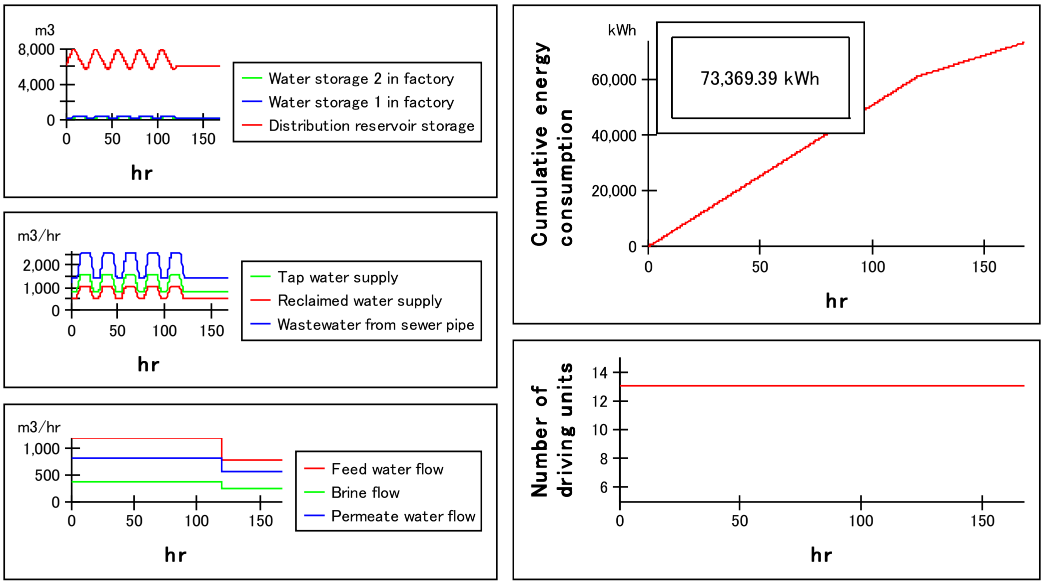

Fig. 15 Example 1 of scheduling of feed flow to RO plant.

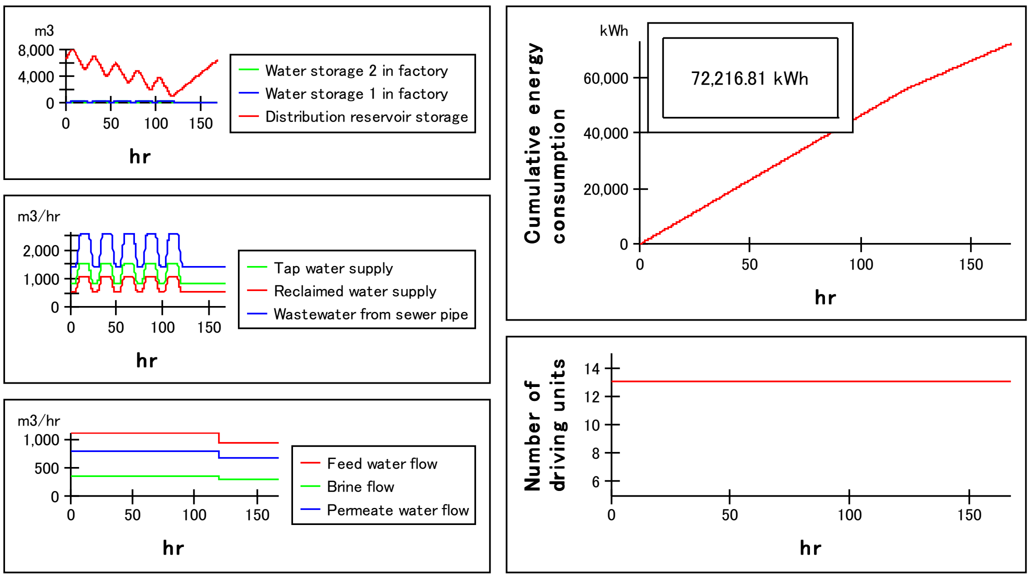

Fig. 16 Example 2 of scheduling of feed flow to RO plant.

4. Conclusion

We proposed a System Dynamics model for scheduling water reclamation to achieve low energy consumption and to ensure the high quality of reclaimed water. Two optimal scheduling schemes were derived by using the model. One is treated water supply scheduling for the water reclamation plant that improves water quality in the distribution reservoir. The other is feed flow scheduling for RO plants that reduces the energy consumption of the booster pumps used in RO membrane filtration. Simulation results showed that the proposed model is effective for deriving an optimal scheduling in reclaimed water production.

We believe the model can be applied to deriving optimal scheduling in water distribution and wastewater treatment processes as well as the water reclamation process. Moreover, the model can be applied to the design of control algorithms for water treatment plants and to the optimal design of facility capacity (such as distribution reservoir capacity) to minimize the cost of a life cycle. In our future work, we will apply the proposed model to the design of various optimal schedules for actual systems.

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