

Information Integration Type Chaos Theory-Based Demand Forecasting for Predictive Control of Waterworks

Keywords Water supply management, Demand forecasting, Predictive control, Chaos theory, Automation, Automatic control, Efficiency optimizing, Energy saving, Manpower saving, ICT, Big data

Abstract

We developed a real-time demand prediction system that operators can use easily. This system is based on “Chaos Theory-based demand forecasting.” It has been actively used in the waterworks field.

Going forward in the waterworks industry, it is generally considered necessary to promote a wider city water service area, labor saving for the facility maintenance and management, and efficient use of energy. To support the operation to realize this, we have developed an “Information Integration Type Chaos Theory-Based Demand Forecasting for Predictive Control of Waterworks.” This is a technology to improve forecasting accuracy and in particular, for the improvement of long-time forecasting accuracy. This forecasting co-relates the data with chaotic characteristics such as quantity of water distribution with the plant operation-related seasonal data, such as the four seasons, year, and holidays. In so doing, this technology provides highly accurate demand forecasting from a short-term through long-term period while keeping the easy-to-manage feature.

1 Preface

In Japan, by simply turning a faucet, one can get drinking water, anytime, anywhere, and any quantity. A water system giving such services is a lifeline indispensable for people’s lives.

Securing clean water sources, water purification treatment, transportation of heavy water, water sterilization for safety, storing water free from contamination, and facilities of waterworks are essential factors. In addition, there are many people involved with daily water system maintenance and management. These people are making efforts to maintain a safe and stable water supply. In the field of water supply control, a technology of demand forecasting based on the Chaos Theory is playing an important role.

In order to meet the requirements of an efficient water system, we provide a technology called “demand forecasting based on the Chaos Theory.” It can predict a real-time water-supply demand in water supply systems by combining the monitoring and control system. In addition, we also provide a “water supply automatic control system” by applying

of the above technology. This system has been adopted by many water utilities.

This paper introduces the outline of an “Information Integration Type Chaos Theory-Based Demand Forecasting for Predictive Control of Waterworks” to improve accuracy of forecasting as a step forward in our demand forecasting technology based on the chaos theory.

2 Demand Forecasting Based on the Chaos Theory and Water Supply Control

Fig. 1 shows the relationship between water supply system and water supply management. Raw water is taken from dams or rivers (collectively called “water sources”). After going through various water systems such as a water purification plant and water distribution stations, clean and safe drinking water is available in each household. Considering overall water supply systems and controlling various water supply facilities, such water control is called “water supply operation control.”

At a water purification plant (a vital facility of

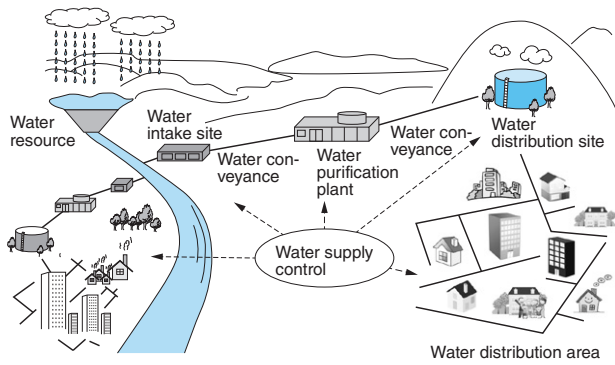


Fig. 1 Relationship between Water Supply System and Water Supply Control

The water supply system supplies tap water after going through various processing facilities which start from a water resource. Water supply control means the control of overall waterworks-related facilities.

waterworks), water is purified with the use of chemical reactions and physical effects which take several hours for processing. More time is needed to transport the treated water to other locations. In particular, since large cities are distant from water resources, more time is needed for water distribution. As aforementioned, it takes a substantial amount of time for the production and transportation of water. In the control logic, this time is treated as a time lag. For the effective control of these factors, a function of demand forecasting is needed to foresee future demand for water in order not to be affected adversely by the time lag. To realize efficient operation and stable control, a highly accurate demand forecasting technology is indispensable for water supply control.

Around the 1980s, researchers such as Floris Takens clarified the usefulness of the Chaos Theory. Around that time, we researched programs on the Chaos Theory to explore application possibility to demand forecasting and fault judgments. The demand forecasting based on the Chaos Theory introduced here is drawing on the results of our past research programs.

The most significant feature of demand forecasting by the Chaos Theory is the high accuracy in forecasting. More advantages as listed below.

- (1) Forecasting is performed hourly. Updated results of forecasting are always available.
- (2) Manual data inputs by operators on weather, temperature, etc., are not required.
- (3) Tuning for the forecasting algorithm is not required.

In the case of demand forecasting by the Chaos Theory, all necessary information can be

Table 1 Comparison between Demand Forecasting by Chaos Theory and Conventional Prediction Method

The major feature of the demand forecasting by the Chaos Theory is its high prediction accuracy. There are many other features such as no need for manual input, real-time prediction, and easy maintenance.

	Demand forecasting by the Chaos Theory	Prediction by conventional method
Basic principle of prediction	Prediction by the Chaos Theory with non-linear data	Prediction by statistical approach with linear data
Basic prediction coverage time	1 hour	1 day
Method of hour-based prediction	Prediction at the intervals of 1 hour	Hour-based pattern applied to 1-day prediction
Method of day-based prediction	Every 1-hour prediction adds up until 24 hours	Prediction for each day
Adjustment for prediction	No need for tuning	Tuning is required at the time of starting. Another tuning is required when accuracy is lowered.

acquired within the monitoring and control system. Each time data are updated, the latest forecasting can be available based on the updated data. Even when the situation with water distribution is suddenly changed, a real-time forecasting system can be built so that follow-up forecasting can be made without delay. **Table 1** shows a comparison between chaotic demand forecasting by the Chaos Theory and a conventional statistical Prediction Method.

3 Supplied Water Consumption Volume and the Chaos Theory

It is generally believed that water consumption at a personal level or a household level is uncontrolled. In other words, each person consumes water at a desired time in a desired quantity. The use of water reflects how each consumer is using it, such as for drinking water, washing hands, cooking, or bathing. Simple changes in manner each person's "using" and "not using" are accumulated and this dictates the quantity of water distribution in a waterworks as a whole. Such characteristics in terms of quantity of water distribution are considered to form a so-called "complex systems." The complex systems mentioned here is defined as "the behavior of the integral part of the system is simple, but the behavior of the overall system is complex." The technology using the Chaos Theory excels in the application to predict complex systems. This is the reason why we can provide highly accurate forecasting for waterworks.

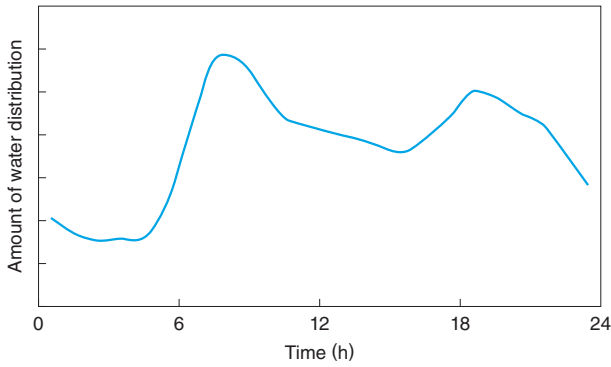


Fig. 2 Changes in Daily (24 hours) Water Distribution

The graph shows that there are big fluctuations in water distribution in one day. Changes differ every day, but water distribution becomes minimal from the early hours to early morning. It exhibits the curve with two peaks: in the morning and evening.

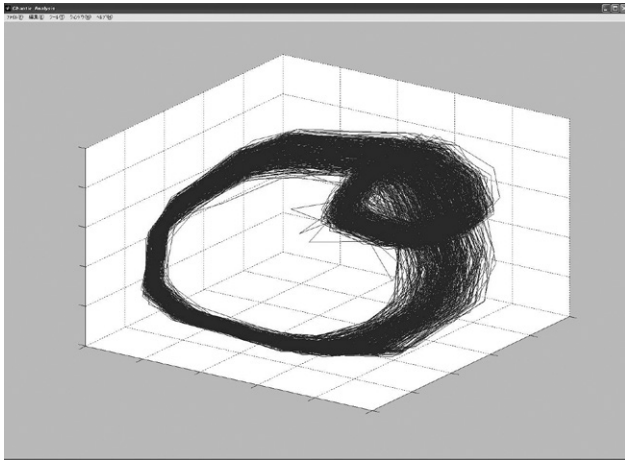


Fig. 3 Water Supply Data Embedded Dimension

The embedded water supply data exhibit unique trajectories called the “strange attractor” (a feature of the chaotic dynamical system).

When the water consumption volume is added up progressively and specifically, it equals the quantity of supplied water. In most water utilities, quantity of water consumed in an hour is defined as the unit-hour distributed amount and the accumulation of this amount in a day is recorded in a daily report for water distribution. This report is used as the basic data for water supply control in many cases. Fig. 2 shows changes in daily (24 hours) water distribution. There are great variations in water distribution throughout a day. The quantity of water distribution is non-linear data involving many changes.

To perform forecasting based on the Chaos Theory, actual distributed amount of data are converted into a status space where the Chaos Theory-based technology can be utilized, such an operation is called “embedding.” Fig. 3 shows the water supply

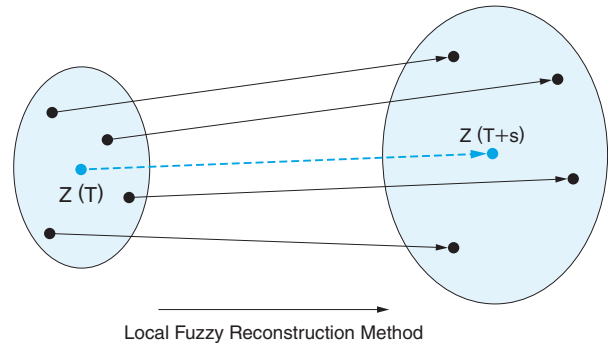


Fig. 4 Conceptual Diagram for Forecasting

Focusing attention to Point $Z (T)$ of the updated data on the strange attractor, the $Z (T + s)$ is obtained from the locus of proximity data of $Z (T)$ for the computation of demand forecasting. This computation method is called the “Local fuzzy Reconstruction Method.”

data embedded dimension. The embedded water supply data appears in a specific diagram called the “strange attractor” which is a characteristic of the chaotic system. The strange attractor shows the trajectory of data with chaotic characteristic in a cubic space. Its shape comes in a line complicatedly folded and accumulated, and looks like a twisted doughnut as a whole. The prediction result is obtained from these unique characteristics of the strange attractor through computation. Fig. 4 shows a conceptual diagram for forecasting computation. The prediction refers to an action to pursue data anticipated to arise in the future. Focus attention to Point $Z (T)$ where the newest water supply data closest to the near future are embedded in the strange attractor. The data staying in the vicinity of Point $Z (T)$ are already past data in actual time. Based on the trajectory identified on the strange attractor, computation is forwarded to establish another trajectory drawn by the fuzzy function along a temporal course from the latest to the future, $Z (T) \rightarrow Z (T + s)$. The obtained trajectory is then restored to the quantity of actual water distribution to define the result of computation for prediction. Such a method is called the “Local Fuzzy Reconstruction Method.”

4 Water Supply Automation System Using the Chaos Theory-Based Water Demand Forecasting Technology

The features of the Chaos Theory-based demand forecasting technology are that no manual input is required and real-time forecasting is possible. Utilizing these features, it is possible to establish a water supply automatic control system. The following is

the description of a water supply automation system.

Fig. 5 shows an excerpt model of waterworks system where water supply control is operated. Using this model, the basic function of water supply automation system is introduced below.

This model of waterworks is in the simplest configuration. A single system of a conveying pump is used to pump water up from a water purification plant to a water distribution basin located on a hillcock. From the water distribution basin, water is distributed to a single distribution area by gravity flow. Since the conveying pump is a speed controllable pump, the flow rate can be adjusted by rpm of the pump motor. The goal flow rate is controlled by an output from the water supply automation system.

Fig. 6 shows a screen of the water supply automation system. As described below, operation method of this system is very simple.

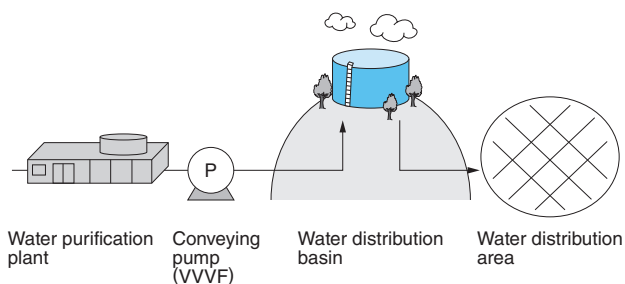


Fig. 5 Model of Waterworks

Water is distributed from a water purification plant to a water distribution basin with a help of a speed-variable conveying pump. From the water distribution basin, water is pumped up to a distribution area by gravity flow. These facilities are controlled by an automatic control system for water supply management.

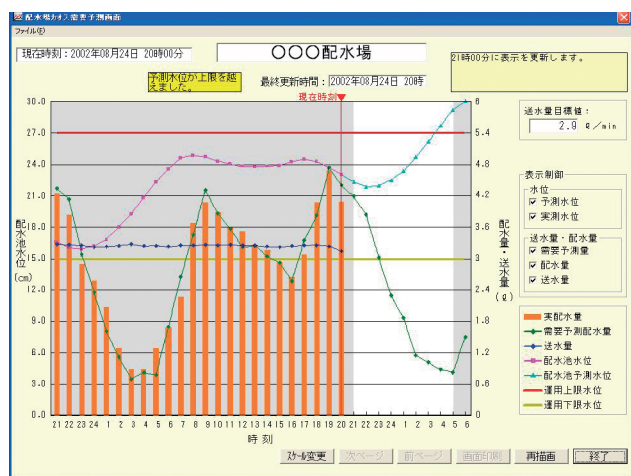


Fig. 6 Screen of the Water Supply Automation System

The PC screen of the water supply automation system adopts trend graphs. It is composed of 24 hours of the past data and 10 hours of the future forecasting data.

(1) Quantity of distributing water is predicted for each distribution area using the Chaotic Theory-based demand forecasting technology.

(2) Variations in water quantity are canceled by raising or lowering the water level in the water distribution basin.

(3) Processes of water transmission, purification, conveyance, and water intake are made based on a policy that operation is always performed for a constant supply of water.

The screen shown in Fig. 6 can display information about flow rate and water level. Display and non-display of data can be selected by switching over. For an explanation, all graphs in line and bar are displayed here. The horizontal axis is used for a time scale arranged to show the past data for 24 hours from the left side and the future data for 10 hours from the right side. This system predicts the future water level based on the result of real-time demand forecasting so that the water transmission rate can be adjusted if any deviation from the specified operating range is anticipated.

The water distribution rate actually achieved for 24 hours is indicated by bar graphs. The line graph drawn along the profile of bar graphs shows the anticipated water distribution rate. The line graph showing almost constant and stable values corresponds to the amount of distributed water. The line graph drawing a gently sloping curve in the upper part of the screen shows the water level in a water distribution basin and the section on the right side shows the predicted water level. Two lines interposing top and bottom of the water level denote the scope of system control. The water level cancels variations in the quantity of water distribution. It changes gently, yet is correctly accommodated within the scope of the system control.

When the predicted water level has exceeded the scope of the system control, the system is controlled to charge the target distributed water volume. Here, present water level is kept within the system control scope, but the predicted water level after 8 hours deviates from the upper limit of the system control scope. In such a case, the goal amount of distributed water is therefore slightly decreased so that actual water level does not deviate from the specified level. In this manner, even when the present situation seems to be stabilized, utilization of the predicted water distribution and water level can be used to take a remedial measure through the prediction of conditions in the future. As a result, violent

variations in water quality to be handled can be suppressed to a minimum and we can realize moderate and stable control.

5 Development of an Information Integration Type Chaos Theory-Based Demand Forecasting for Predictive Control of Waterworks Technology

Our Chaos Theory-based Demand Forecasting Technology and its applied automation system technology product-water supply introduced in this paper have been shipped to many water utilities in Japan. To support water supply operation and by working as an automatic control system, our product produced many positive results of savings: energy, electricity change and labor.

In order to realize further contribution, it is vital to increase forecasting accuracy. In particular, this is the case when interlinkage is needed among water purification plants as a result of the expansion of water service areas or when interconnection is made with the system having supply capacity limitation such as solar power or micro-grid system. Under such cases, a full day (24 hours) operation plan becomes important. In addition to high accuracy time-based forecasting inherent to the demand prediction based on the Chaos Theory, we studied the measurements to increase further such accuracy level for a full day (24 hours) operation plan.

With the recent progress of Information and Communications Technology (ICT), functions of monitoring and control system were improved. It realized the real-time collection of various information. Improvement of accuracy can be realized by linking with the Chaos Theory. Picking useful information commonly known as “big data,” we will work to increase the accuracy level by linking with the Chaos Theory.

The concept of development is described below.

- (1) The goal of development is the improvement of prediction accuracy; in particular, the accuracy of a full day (24 hours) prediction.
- (2) It can make the best use of features of demand forecasting by the Chaos Theory, such as no need for manual data input entry and auto-control capacity.
- (3) Utilizing the data collected by monitoring and control system, it actively promotes the interaction with Chaos Theory-based technology.

The information integration type Chaos Theory-based demand forecasting technology is outlined

below. The most noteworthy point in development is the extension of the chaos dimensions. Fig. 7 shows an enhanced image of fractal dimensions. In order to merge various information with the Chaos Theory-based technology, the fractal dimensions are enhanced. In this case, four basic fractal dimensions are added with three time series of information of integrated data: season, year, and holidays for example, to establish an enhanced image of a total of seven dimensions.

Together with original fractal dimensions, enhanced dimensions are also used so that a strange attractor can be rendered. The fractal dimensions, where the water distribution rate is embedded, are enhanced with three series of information of dimensions so that the selected strange attractor can be separated from all other strange attractors. Fig. 8 shows an image of strange attractor separated by

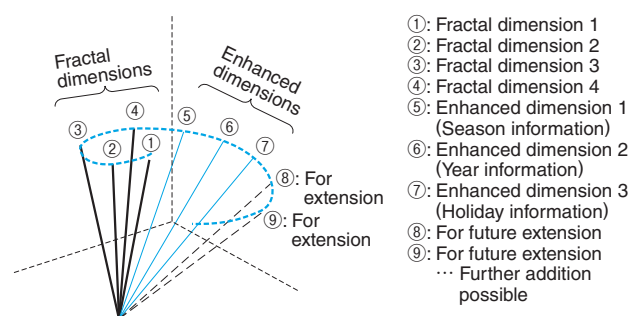


Fig. 7 Enhanced Image of Fractal Dimensions

The fractal dimensions embedded with water distribution data are added with three series of information: season, year, and holidays.

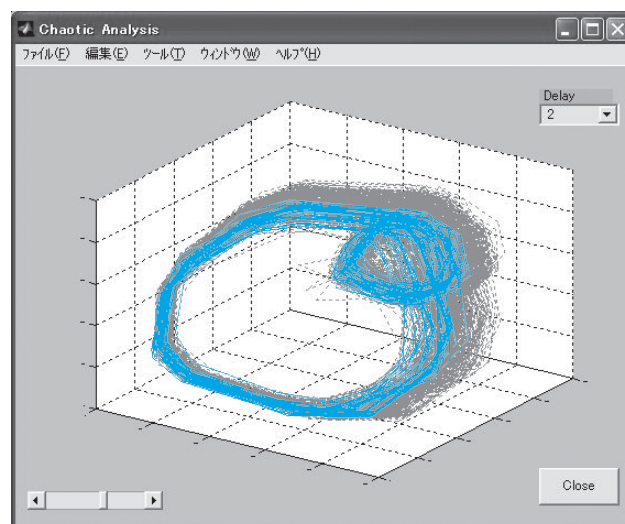


Fig. 8 Strange Attractor Separated by Enhanced Dimensions

Using the enhanced dimensions, a required strange reactor is selected and separated from all other strange reactors.

the above approach. When selecting proximate data out of an overall data set, prediction accuracy can be raised by increasing the selective probability of the strange attractor separated with a help of enhanced dimensions.

Even in basic demand forecasting by the Chaos Theory, the selection is made reflected by the information of season, year, holidays, etc., which is originally contained in the dynamics of chaotic behavior. In an event when a relatively long time of prediction is conducted, however, the function of selecting from a strange attractor which characterizes a deterministic chaotic system is not always sufficient and may result in a large margin of error. As a solution, we embedded a necessary amount of information as enhanced dimensions. In so doing, we improved prediction accuracy.

In the case of an actual selection, a fuzzy function is used for flexible computation. For this reason, the boundary line between separated data is gentle and moderate, and there is no definite separation as illustrated. By taking advantage of the merit of algorithm in selecting proper data out of the strange attractor, it reflects information in order to make a better selection.

In order to confirm the function of an information integration type Chaos Theory-based demand forecasting, we verified its prediction accuracy using actual water distribution rate. For the comparison, we used a basic demand forecasting using the Chaos Theory for the evaluation based on the total amount of water distribution for a full day (24 hours). Data for water distribution were obtained from three water utilities. Although data acquisition time is different from each other, data gathered for about 3 years were used to produce strange attractors and evaluation was based on the comparison of the prediction and followed one year of actual data. Daily prediction accuracy is determined by the expression below. The absolute values for one year of daily prediction accuracy are put into an annual average that is used for the verification.

$$\frac{(\text{Actual water distribution} - \text{Predicted water distribution})}{\text{Actual water distribution}} \times 100 (\%)$$

Fig. 9 shows improvement of prediction accuracy using an information integration type Chaos Theory-based demand forecasting. Prediction accuracy showed improvement in all of the three cases and the improvement rate is 5% to 11%. Although these figures may look small, it shows such an effect

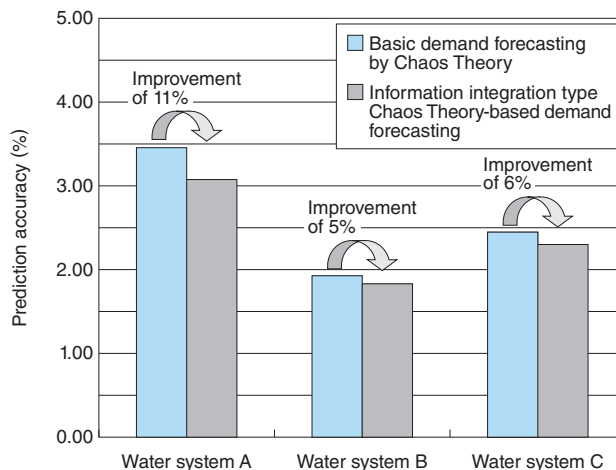


Fig. 9 Improvement of Prediction Accuracy using Information Integration Type Chaos Theory-Based Demand Forecasting for Predictive Control of Waterworks

Using actual water distribution data, the effect of prediction accuracy improvement was verified for the newly developed information integration type Chaos Theory-based demand forecasting. The rate of improvement is around 5% to 11%, and this effect can be perceived in all three cases.

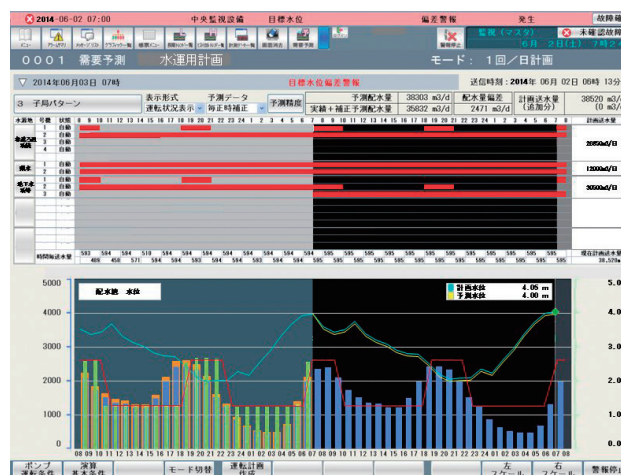


Fig. 10 Screen of Water Supply Control Plan by Information Integration Type Chaos Theory-Based Demand Forecasting for Predictive Control of Waterworks

Data Type Demand forecasting by the Chaos Theory Prediction An example of water supply control planning is shown. This plan utilized the information integration type Chaos Theory-based demand forecasting. Since prediction accuracy is improved from a short term to a long term forecasting, future prediction data can be extended to 24 hours as a standard setting.

of improvement is already available as a result of simply adding three series of information such as season, year, and holidays in this verification. The basic demand forecasting by the Chaos Theory is highly accurate.

Fig. 10 shows an example of a PC screen of a water supply control plan by an information integra-

tion type Chaos Theory-based demand forecasting. Since a full day (24 hours) prediction accuracy is improved, the standard prediction time has been doubled from 12 hours to 24 hours. Since the control function has been improved, a command output of a target of distributed water level can be made to the local remote terminal unit and functions of an operation plan like pump operation schedules can be established. These functions make the long-term planning easier which is required for a recent widening waterworks network. This enables making operation planning easier in co-operation with various facilities distributed in a wide area of waterworks. Starting from a level of an efficient control of a single facility or a single system, such effective operation can be extended to a level that is applicable to an overall interlinking scale of waterworks and interactive systems.

6 Postscript

This paper introduced the development of the information integration type Chaos Theory-based demand forecasting to realize advanced water supply control for efficient operation of water supply

system. We improved prediction accuracy by focusing our attention on the “big data” collected in the monitoring system, and we worked on data relating to the distributed water volume and flexibly embedded such data into the fractal dimensions by the Chaos Theory to improve prediction accuracy.

Japanese waterworks maintains the world top level in terms of stable water supply and its safety in drinking tap water. However, they face the many future challenges, such as issues from a declining population, securing the functions of facilities that are under the period necessary for renovation, succession of knowledge and expertise of experienced staff after their retirements, and countermeasures against disasters. All of these challenges are important to maintain the safety and stability of water supply systems. Drawing on our many experiences centering on electrical facilities, monitoring and control systems, and facility management, we contribute to realizing better water supply systems by integrating all information in our newly released water supply automation system.

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