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Design of Predictive Control Strategies for the Optimisation of Drinking Water Network in Thiruvananthapuram City

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***Abstract*—Drinking Water Management in Thiruvananthapuram city is a subject of increasing concern due to the improper operation of pumps and valves. Drinking Water Network (DWN) is managed centrally using telemetry systems which provide real time hydraulic variables at key locations. Over the past few years, Predictive Control Strategy has proven to be one of the most effective and accepted control strategies for large fluid systems. Control Oriented modelling based on the hydrological / hydraulic based variables of the network is the essential step in the implementation of Predictive Control in DWN. This modelling approach is easily calibrated online using data from telemetry system and embedded in an optimization problem to achieve the objectives. A control oriented model of Kerala Water Authority (KWA) in Thiruvananthapuram City is constructed using MATLAB and demand of drinking water for a time period of 24 hours is analysed and controlled by means of Predictive Algorithm and local controller.**

I INTRODUCTION

DWN Management in Thiruvananthapuram city is a subject of increasing concern. Limited water resources, unstructured conservation, sustainable policies and infrastructure complexities for meeting consumer demands make drinking water management a challenging control problem. Because of the improper pumping from reservoirs and unplanned operation of valves, there is a complex scenario in DWN of Thiruvananthapuram City by means of 50 % wastage of water and availability of drinking water is below 50 %. DWN is managed using telemetry and telecontrol systems which provide real-time pressure and flow of drinking water at key locations within the network. The use of optimal control for managing water supply systems helps KWA to achieve energy efficiency, minimization of loss and environmental protection. Optimal control concepts to water systems requires the development of control oriented dynamic model, which is based on the hydrological / hydraulic based variables of the network includes the representation of pressurized pipes, water tanks at different elevations, pumping stations and valves managing water flow and pressure.

Decision support system [1] – [4] based on hydrological model effectively contribute the optimal management of DWN by computing control strategies ahead of time. Predictive and optimal control techniques allow the authority to establish priorities among different control objectives, wherever these cannot be achieved simultaneously [5] - [11]. By using Predictive Control in the DWN of Thiruvananthapuram City, optimal performance according to the given set of control objectives and predefined performance indices is achieved. Figure 1 shows a conceptual scheme for a hierarchical structure considered on the control of networks related to the DWN.

Fig. 1: Hierarchical Structure of DWN

Control Oriented modeling is the essential step in the implementation of Model Predictive Control (MPC) in DWN. This model is simple, speedy, flexible and scalable to expand and / or modify the network. This modeling approach is easily calibrated online using data from telemetry system and embedded in an optimization problem [1] & [2] to achieve the objectives. For this, a control oriented model of KWA in Thiruvananthapuram City is constructed using MATLAB. Based on the water demand system, demand of drinking water for a time period of 24 hours is analyzed and controlled by means of MPC.

II MODELLING OF DWN IN THIRUVANANTHAPURAM CITY

There is a complex DWN in Thiruvananthapuram city with two water sources namely Aruvikkara and Thirumala, many routes, many nodes and many interconnected links. A detailed diagram of the DWN is shown in Figure 2. From the DWN diagram of Thiruvananthapuram City, a particular portion is taken as the modelling sample. The selection of a simple and better control oriented hydrological model from the existing infrastructure is the first step.

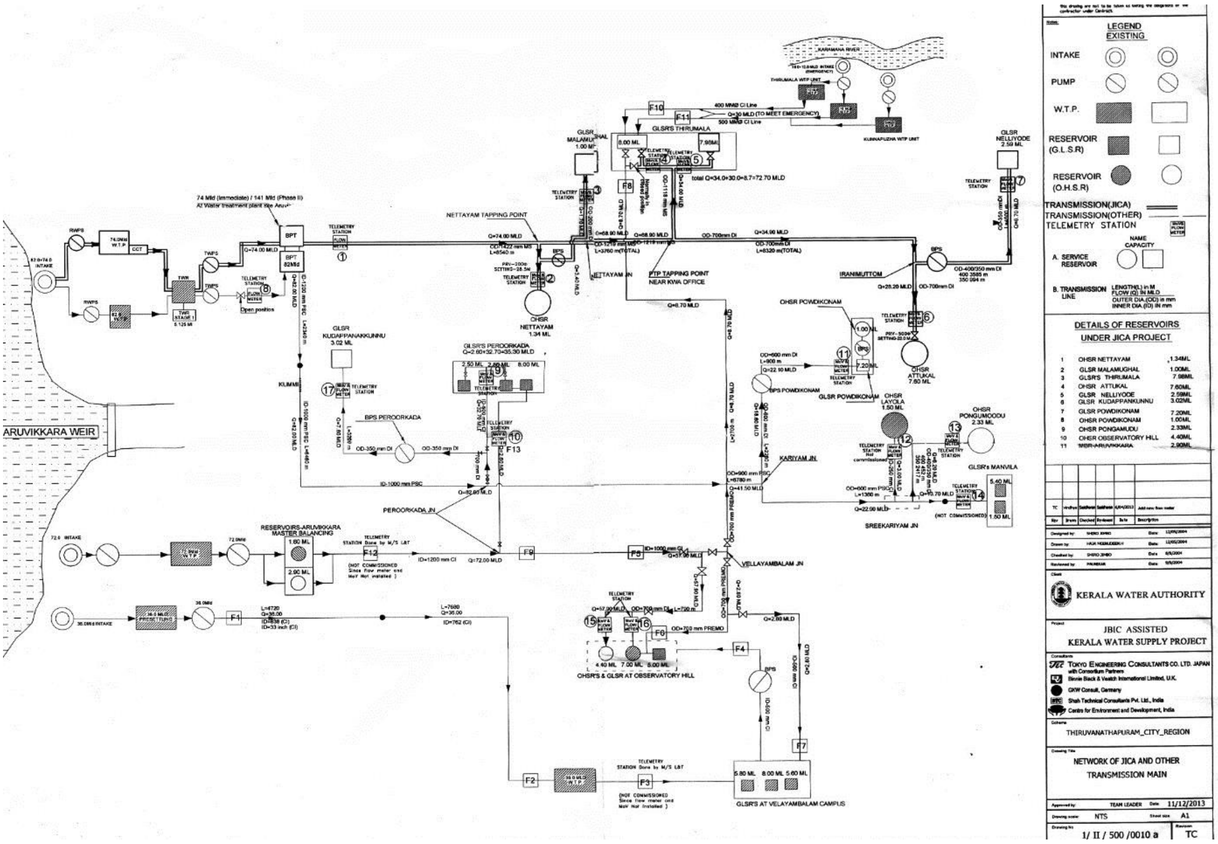

Fig. 2: Drinking Water Network in Thiruvananthapuram City

In the DWN model, Aruvikkara Dam is considered as the only water source of the model. Interconnected links between various water sources are eliminated. Japan International Corporation Agency (JICA) Project pipeline is only taken as water flow network, as telemetry systems for the online measurement and calibration of data is available only in JICA System. Water treatment plants and pumping stations are together taken as Pumping Stations. Overhead Tanks and Ground Level reservoirs are considered as the part of demand sector. Nodes and other links are represented as usage only. A demand sector represents the water demand of the network users of a certain physical area. It is considered as a measured disturbance of the system at a given time instant. The demand is anticipated by forecasting algorithms [5] - [9], which are integrated within the Model Predictive Control (MPC) closed loop architecture. This algorithm typically uses a two level scheme composed of a time-series model to represent the daily aggregate flow values and a set of different daily flow demand patterns according to the day type to cater for different consumption. Regarding the daily demand forecast, the corresponding flow model is built on the basis of an integrated time series modeling approach [1] & [2].

DESIGN OF HYDROLOGICAL MODEL

It is assumed that there is always a minimum level of water to cater the demand for whole year. The advantage of selecting single water storage as the source is that the analysis and performance of the model is truly dependent on the pressure applied from the pumping station at the source. Such a water source is easily represented in MATLAB as Constant Head Tank. Pressurized pipes are the medium through which the drinking water from the source to pumping stations and pumping stations to destinations is reached. Pumping stations are considered at each destination for catering the demand of drinking water by means of proper pumping pressure which comprises of a reservoir and pump house. Water flow through the pressurized pipes from the source is collected in the ground level reservoirs of the pumping stations and pump houses associated with these reservoirs are pumping the stored water of the reservoir to the destinations according to the proper management from the centralized control room. The basic structure of the model of the pump house in MATLAB is shown in Figure 3.

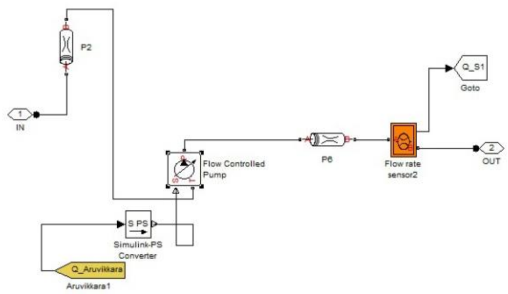

Fig. 3: Model of Pump House

The operation of the pump house is managed by means of flow controlled pump. The stored water in the reservoir is fed to the inlet of the flow controlled pump and pumping parameters are decided by the output of the PI controller from the centralised control room. Based on the input from the control room, pumping is managed by the speed of pump and by adjusting the actuators. Major components of a pump house is the Flow controlled pump and the Flow rate sensor. The drinking water pumped from the pumping stations at the water source is collected at the huge ground level reservoirs at the secondary pumping stations.

Consumption of DWN is analysed in terms of usage and loss components. Loss of drinking water network at these locations is predefined by KWA in terms of the difference between pumping water quantity and metered drinking water. This difference is directly considered as loss which may be due to theft and wastage of water through pipe breakage and improper pumping of water at pump houses. It is assumed that the loss of DWN is only the water loss due to breakage of pipes and improper pumping at pump houses. Overhead Water storage at the secondary distribution area and distribution area under direct pumping stations and secondary pumping stations are together considered as usage pattern at the destinations.Such a usage pattern is modelled in MATLAB as shown in Figure 4.

The lost drinking water is also measured in the same way of usage pattern by means of a constant head tank and the flow sensor associated with this for feeding back to the

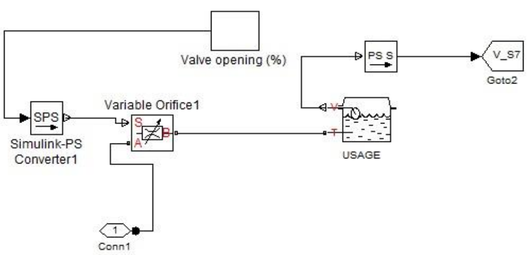

Fig. 4: Usage Model

central control room for recordical purpose. Loss model modelled in MATLAB is in Figure 5.

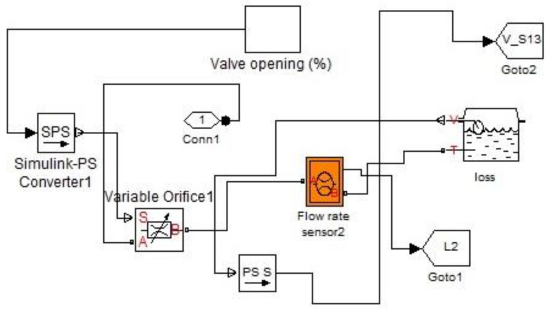

Fig. 5: Loss Model

DESIGN OF CONTROL STRATEGY

Predictive control is an advanced method in control strategy of dynamic models. The main advantage of predictive control [5] - [11] is the fact that it allows the current timeslot to be optimized, while keeping future timeslots in account. This is achieved by optimizing a finite time-horizon and has the ability to anticipate future events and to take control actions accordingly. Predictive Control is universally implemented as a digital control for achieving faster response with specially designed analog circuitry. Predictive Control uses a control algorithm that uses an internal dynamic model of the process, which optimizes the output based on the predefined demand model of the same network.

The model with predictive control strategy is generally intended to represent the behaviour of complex dynamical systems. Though the simple models are well managed by generic PI or PID Controllers, it is very difficult for them to manage large time delays and higher order dynamics of the complex nonlinear systems. Hence the predictive control algorithm is needed to provide adequate control in this case. Though there are various predictive control techniques, prediction by ANN [12] - [15] is proved as a best fit solution for large complex systems like DWN of Thiruvananthapuram city. The goal of supervised ANN algorithm is to find a function that best maps a set of inputs to its correct output. Back propagation algorithm works on backward propagation of errors and is a common method of training ANN used in conjunction with gradient descent optimization method.

There are different ANN tools available in MATLAB in which Elman back propagation network block is taken as the best fit ANN algorithm for the prediction of water demand. Elman Back Propagation Networks are Simple Recurrent Networks (SRNs) in symbolic time-series prediction, frequently trained with gradient descent based learning algorithms. Elman Back Propagation is implemented as a reinforcement learning scheme for getting better results than traditional back propagation tools [15]. Network simulations validate the result and found that the learning behaviors of Elman BP results in satisfactory output against the expected output.

An ANN prediction tool has been generated with Elman back propagation algorithm within permissible tolerances and the prediction of demand in drinking water at each demand sector is done in this. ANN predicts demand of drinking water easily and quickly, which gives satisfactory results with successful prediction rate of over 99%, compared with conventional methods.

III DEMAND ANALYSIS

Aruvikkara dam is taken as the source of the model and five demand sectors namely Nettayam, Malamugal, Attukal, Nelliyodu and Thirumala are taken as the demand sectors based on simplicity and the availability of telemetry systems. Daily usage of drinking water at the demand sectors are as shown in Table1, which reveals the primary consumption details of the demand sectors under improper and unplanned operation of pumping stations to meet the demand. Though there is different pumping strategy for different days, it is assumed as the existing management of drinking water is in the same way as mentioned in Table 1 , which are taken as the reference point. By analyzing the pumping volume of drinking water and volume of billed drinking water, the wastage of drinking water was predetermined by the authorities. Such predetermined values are considered as loss in the secondary water distribution area as mentioned in the Table 1. It is

TABLE 1: DAILY CONSUMPTION PATTERN

Location	Aruvikkara	Nettayam	Malamugal	Attukal	Nelliyodu	Thirumala
Flow Rate in m^3/s	0.85	0.04	0.02	0.32	0.08	0.39
Total Consumption in m^3 (for 24 Hrs)	73440	3456	1728	27648	6912	33696
Loss in %		20	30	60	40	50
Loss in m^3		691.2	518.4	16588.8	2764.8	16848

understood from the table that almost 50 % of the pumped drinking water is considered as wastage.

TIME SERIES DEMAND MODEL

Time series demand estimation is the most essential factor in the design of a predictive controlling mechanism. Though the minute wise demand at these locations are available in the central control room, 24 hour time span of a day is conveniently taken as four time slots for easiness and better control. The time slots for fixing the demand pattern are 5 AM to 10 AM, 10 AM to 5 PM, 5 PM to 10 PM and 10 PM to 5 AM. The selection of these time slots is on the basis of almost similar hourly usage patterns of the Day. The 24 Hr time horizon of the day is converted to 240 points, where each Hour corresponds to 10 points and morning 5 AM is taken as the initialization point of zero. Hourly demand pattern of the Day in each selected demand sectors is expressed in water flow in m^3/s as shown in Table 2.

TABLE 2 : DEMAND OF WATER

Time	Aruvikkara	Nettayam	Malamugal	Attukal	Nelliyodu	Thirumala
05 AM – 10 AM (0-50)	0.86	0.04	0.02	0.38	0.09	0.33
10 AM – 05 PM (50-120)	0.50	0.03	0.01	0.28	0.05	0.13
05 PM- 10 PM (120-170)	0.63	0.05	0.02	0.21	0.08	0.27
10 PM – 05 AM (170-240)	0.07	0.01	0.01	0.02	0.01	0.02

Predictive control mechanism is going to be the vital part to meet the objectives. The advantage of predictive control strategies over conventional controlling methods is that the same predictive algorithm with unchanged dynamic model is used for any scenario by making minimum changes. This advantage is effectively utilized by creating consumption details of demand sectors under different scenarios [9] like working day, holidays, hot day, rainy day, village area, urban area etc. For the sake of simplicity, we are taking the consumption pattern of drinking water under two common scenarios like working day and holiday.

By keeping the same time slots, Day type of the day is varied under the scenario of working day or holiday. Working day is represented by “0” Day type and holiday is represented by “1” day type. Based on this concept, Demand of Drinking Water is estimated at each demand sectors shown in Table 3.

TABLE 3: TIME SERIES DEMAND MODEL

Location			Flow in m^3/s					
Sl.No	Time Span	Day Type	Nettayam	Malamugal	Attukal	Nelliyodu	Thirumala	Aruvikkara
1	5 AM to 10 AM	0	0.04	0.02	0.38	0.09	0.33	0.86
2	5 AM to 10 AM	1	0.02	0.02	0.10	0.10	0.20	0.44
3	10 AM to 5 PM	0	0.03	0.01	0.28	0.05	0.13	0.50
4	10 AM to 5 PM	1	0.07	0.03	0.35	0.07	0.15	0.67
5	5 PM to 10 PM	0	0.05	0.02	0.21	0.38	0.27	0.63
6	5 PM to 10 PM	1	0.04	0.03	0.12	0.15	0.22	0.56
7	10 PM to 6 AM	0	0.01	0.01	0.02	0.01	0.02	0.07
8	10 PM to 6 AM	1	0.01	0.01	0.02	0.02	0.02	0.08

IV OPERATION OF THE MODEL

The hydrological model of the DWN at Thiruvananthapuram city is constructed in MATLAB based on the various design factors of such a complex nonlinear model as shown in the Figure 6.

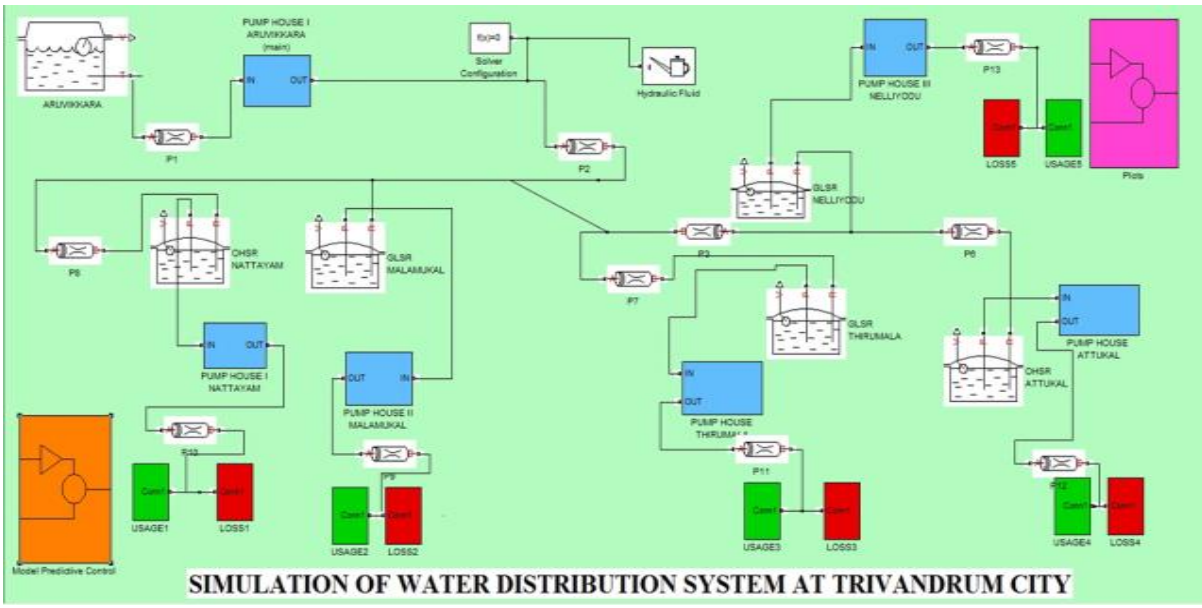

Fig. 6: Hydrological Model

The stored water in the Aruvikkara dam is pumped from the Pump House associated with it. Operation of the pump house is controlled by the Central control room through the telemetry network. The water is flowing from the source to reservoirs of demand sectors through the highly pressurised resistive pipes. The operation of all local pump houses associated with the reservoir is also controlled remotely and automatically by the central control room. The pumped water from the pumping stations of the local demand sectors are consumed in terms of usage block and loss block. The loss block is designed by incorporating the pre estimated loss factor at each demand sectors for analysing the wastage of water in the network. The basic online information like volume of reservoirs and volume of water & water flow maintained at each pump houses are measured and stored in the servers of the central control room. Decisions for the proper operation and management of the DWN of the entire city are controlled by this facility.

PREDICTIVE MECHANISM

The predictive algorithm using Elman Back propagation is created on the basis of demand pattern at each demand sector. Available two scenarios of working days and holidays in Thiruvananthapuram city is taken for consideration. The estimated demand of drinking water at each selected demand sector and estimated demand at source are fed to the ANN algorithm on the basis of considered as given in Table 3. On the basis of the detailed analysis on different results against the expected results, number of iterations is fixed as 1500 and Expected error is fixed as 0.0000001 for better results. Number of neurons in the network is fixed as 20 and number of layers is fixed as 3 for better and faster result. Training details of different scenarios in the consumption of drinking water is easily implemented in the prediction algorithm by changing minimum variables with respect to the scenario.

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Output of the of algorithm is plotted against the expected values and predicted output for each demand sectors subjected to different scenarios are directly fed back to the local control stations of the pump house as the

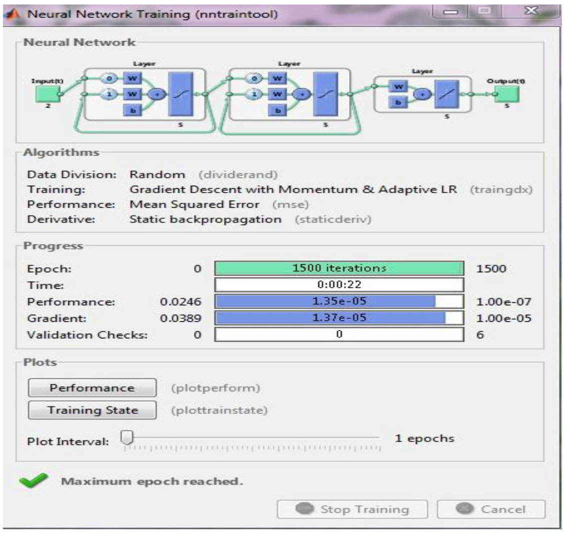

Fig 7: ANN Training Tool

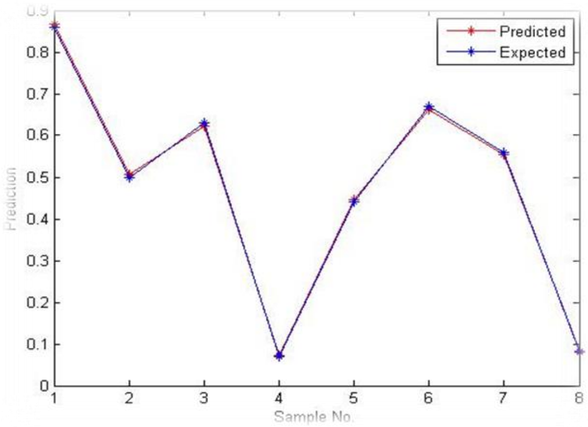

Fig 8: Output of the ANN Algorithm

reference signals to the PI controllers of the concerned demand sector. The graphical representation of the training tool used in the algorithm and graphical results are shown in Figure 7 and Figure 8. On analysis of the training tool, it is observed that only 22 seconds is the training time required for arriving at an optimum result with 1500 Nos. of iterations with better performance and minimum error. The output of the algorithm is shown in Figure 8 as eight points under four time spans with two scenarios. The predicted values in Y Axis against first four points in X-Axis are the predicted output of drinking water at source pumping station at Aruvikkara on working days and whereas the predicted values in Y axis against last four points of X-axis are the predicted demand of drinking water at source pumping station at Aruvikkara on Holidays. The predicted demand of various demand sectors at various time spans by the algorithm are as shown in the Table 4 and Table 5.

CONTROLLING METHODOLOGY

ANN Prediction is used to provide predicted data to the Controller. Demand at local pumping stations and Aruvikkara Dam is fed to the Prediction System and predicted values are fed as reference to PI controller. There are 6 Nos of PI controllers set up at the local pumping stations at the source and destinations for effective and smooth controlling action. Online water flow output at the local pumping stations and the predicted output of the predictive algorithm are fed to the controller. Output of the PI controller is fed to the flow controlled pump at the pump house and accordingly water flow is adjusted at the local pump house to provide adequate drinking water supply at

TABLE 4: PREDICTION OF DEMAND IN WORKING DAYS

Working Days - Predicted Demand in m^3/s			
5 AM – 10 AM	10 AM – 5 PM	5 PM – 10 PM	10 PM – 5 AM
0.0464	0.0367	0.0370	0.0058
0.0234	0.0217	0.0205	0.0136
0.3786	0.3171	0.2338	0.0248
0.0877	0.0800	0.0759	0.0281
0.3306	0.1383	0.2799	0.0973

TABLE 5: PREDICTION OF DEMAND IN HOLIDAYS

Holidays - Predicted Demand in m^3/s			
5 AM – 10 AM	10 AM – 5 PM	5 PM – 10 PM	10 PM – 5 AM
0.0337	0.0594	0.0344	0.0104
0.0182	0.0225	0.0182	0.0153
0.1062	0.3520	0.1125	0.0199
0.1241	0.0748	0.1223	0.0195
0.2117	0.1492	0.2087	0.0203

the demand sectors. The block diagram of the local control system at the source and destinations are shown in Figure 9.

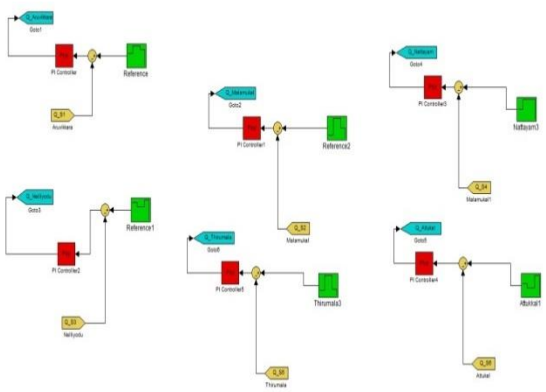

Fig. 9: Local PI controller

V RESULT

On analysis of the closed loop performance of the model value of proportional gain and integral gains are adjusted to get an accurate result. By fixing proportional gain K_p as 1 and the Integral gain K_i as 10 of the PI controller, a better result is obtained. Two different scenarios are tested; the demand of drinking water at the selected demand sectors for working days and holidays. Separate time series model was predicted for both scenario and fed to the common ANN algorithm. By selecting the desired output patterns for the both scenario, consumption pattern of five demand sectors are obtained in MATLAB for the working days and holidays as shown in Figure 10 and Figure 11 respectively.

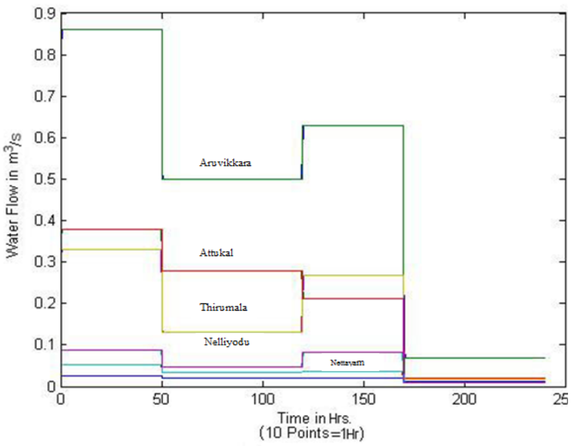

Fig 10: Demand during Working days

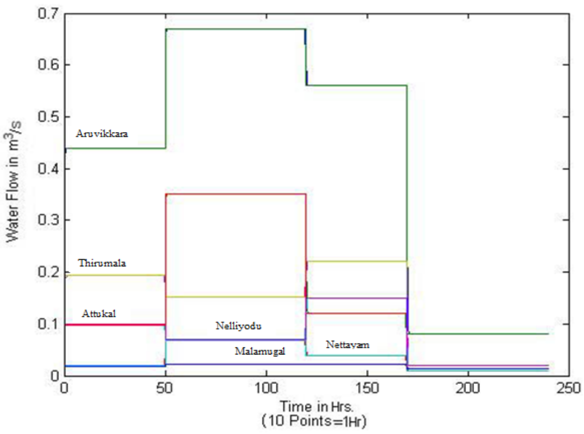

Fig 11: Demand during Holidays

On analysis of the results, it is understood that the closed loop operation is carried out correctly according to the time series pattern given to the algorithm. Entire operation of pump house is smoothened by the local controlling action of the PI controller which in turn connected to the central control room for feeding the predicted output. For analyzing the loss factor at all selected demand sectors and for proving the wastage of drinking water is reduced by the predictive design of DWN in Thiruvananthapuram city, Loss pattern at demand sectors for working days is only considered for comparison and the simulated output of MATLAB is shown in Figure 12.

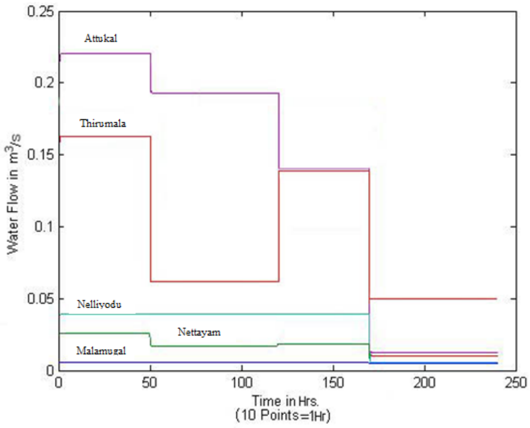

Fig 12: Loss during Working days

VI CONCLUSION

A control oriented model of KWA in Thiruvananthapuram City is created using SimHydraulics in MATLAB. Time Series Demand Matrix of five selected demand sectors is formulated based on four time slabs and nature of day. Based on the Time series model, predicted values are calculated using ANN Back Propagation Algorithm. Predicted output of the ANN Network is fed to the local PI controller of the pumping stations of individual demand sector. Based on the controlling action of the PI Controller, this Model shows that 98 % of the water demand is met at all demand sectors. On analysis of the loss pattern during working days, it is observed that the wastage of drinking water is reduced to 30 %.

In view of the analysis of results, Predictive Control has proven as a successful control strategy of drinking water management for achieving optimal performance by means of catering customer needs and regulatory needs at reduced cost. Availability and wastage details of drinking water at the selected demand sectors are shown in Table 6.

TABLE 6: AVAILABILITY AND WASTAGE OF DRINKING WATER

Location	Nettayam	Malamugal	Attukal	Nelliyodu	Thirumala
Availability	98%	98%	98%	98%	98%
Loss in m^3	486	322	10128	2162	8642

REFERENCES

[1] C. Ocampo-Martinez. Puig, V, Quevedo. J, “Application of Predictive Control strategies to the management of complex networks in urban water cycle”, in *Control Systems, IEEE (Volume: 33, Issue: 1)*, pp.15-41, 2013.

[2] C. Ocampo-Martinez, D. Barcelli, V. Puig, and A. Bemporad, “Hierarchical and decentralised model predictive control of drinking water networks: Application to the Barcelona case study,” *IET Control Theory Applications., vol. 6, no. 1*, pp. 62–71, 2012.

[3] J. Rawlings and D. Mayne, “Model Predictive Control: Theory and Design” *Madison, WI: Nob Hill*, 2009.

[4] Karl J Astrom, Bjorn Wittenmark , “Adaptive Control” *Second edition*.

[5] Cembrano, G. Wells, J. Quevedo, R. Perez, and R. Argelaguet, “Optimal control of a water distribution network in a supervisory control system,” in *Control Engineering Practice., vol. 8, no. 10*, pp. 1177–1188, 2000.

[6] Alessandro Casavola, Emanuele Garone, Francesco Tedesco, “ Preprints on Distributed Reference Management Strategies for Networked Water Distribution Systems” in *18th IFAC World Congress Milano (Italy) August 28 - September 2*, 2011.

[7] Puig, C. Ocampo-Martinez, J. Romera, J.Quevedo, P. Rodriguez, S. de Campos, R.R. Negenborn, “Technical Report on Model Predictive Control of Combined Irrigation and Water Supply Systems: Application to the Guadiana River” *in Networking, Sensing and Control (ICNSC), 9th IEEE International Conference*, pp. 85-90, 2012.

[8] Cong Cong Sun, Vicenc Puig and Gabriela Cembrano “Technical Report on Multi-layer Model Predictive Control of Regional Water Networks: Application to the Catalunya Case Study”. *The Spanish research project WATMAN (DPI2009-13744) of the Science and Technology Ministry and the DGR of Generalitat de Catalunya (SAC group Ref. 2009/SGR/1491), the AGAUR by an FI grant and by EFFINET grant FP7-ICT- 2012-318556 of the European Commission*, in *Decision and Control (CDC), 2013 IEEE 52nd Annual Conference* ., pp.7095-7100, 2012.

[9] Daniele Bernardini and Alberto Bemporad “Scenario-based Model Predictive Control of Stochastic Constrained Linear Systems” *Decision and Control, 2009 held jointly with the 2009 28th Chinese Control Conference. CDC/CCC 2009. Proceedings of the 48th IEEE Conference.*, pp.15-18, 2009.

[10] Rodrigo Toro, Carlos Ocampo-Martınez, Filip Logist, Jan Van Impe, Vicen¸c Puig “Tuning of Predictive Controllers for Drinking Water Networked Systems” *Preprints of the 18th IFAC World Congress Milano (Italy) August 28, September 2*, 2011.

[11] Rudy R. Negenborn, Peter-Jules van Overloop, and Bart De Schutter “Technical Report on Coordinated Distributed Model Predictive Reach Control of Irrigation Canals**”**, *Proceedings of the European Control Conference 2009, Budapest, Hungary,* pp. 1420–1425, Aug. 2009.

[12] Chen Li-an, *“Prediction for Magnitude of Short Circuit Current in Power Distribution System Based on ANN”* in *International Symposium on Computer Science and Society*, pp.130-13., 2011.

[13] Dr.L.S.Madhavan, P.Prasanna, Thenmozhi Varman, R. Dhanuskodi, S.Arumugam. “*ANN Prediction Tool for ReHeater and SuperHeater Sprays in Boiler Performance*” in *Electronics Computer Technology (ICECT 2011),* pp.335-337, 2011.

[14] L. Lahoucine-Abaih, Dr.A. Van Bennekom, Dr. M Fathi *“Development of an ANN for the Prediction of Heat Treatment Temperatures for Martensitic Stainless Steels”* in *Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium* pp. 100-105. 2007.

[15] B. Phaneendra Babu, JVS Srinivas, B.Vikranth, Dr.P.Premchand. “*Fault Diagnosis in multi-level Inverter System using Adaptive Back Propagation Neural Network*” in *India Conference, 2008 (INDICON 2008).* Pp.494-498., 2008.