

## REAL TIME CONTROL OF WATER SYSTEMS

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**Abstract.** The evolution of digital computer control of water supply, distribution and disposal is presented. Explanations of the difference in intensity of the use of computer control in water and electrical systems are given. The main control problems of water distribution are presented in mathematical and non-mathematical terms. Early attempts of the real time solution of the network equations and actual installation of digital control of water supply systems are described. The use of self-tuning control technique as an alternative to the computer aided control of water systems, commonly employed in actual installations, is suggested.

The water disposal control problem and several actual installations with different degrees of automation are briefly treated.

**Keywords.** Water distribution. Sewer system. Computer control. Large scale systems. Data acquisition.

### INTRODUCTION

As it occurs in many services today, in the water supply, distribution, treatment and waste water disposal services, the digital computer presence is being felt. However, in comparison with other utilities, such as the electrical utilities, the use of the digital computer as a direct control device is rather limited. While the number of digital control centers of electrical systems have grown enormously in recent years (Dy Liacco, 1978), there are only a few of such center devoted to water works controls.

Even though there has been a considerable activity in the field of real time forecasting and control of water resources (Wood, 1980), this paper will be devoted only to the urban water systems.

New technologies are adopted because a) are attractive from the benefit-cost point of view and for b) give the possibility of attacking unsolved problems with them.

Only recently both reason are becoming clear in the water industry as it will be detailed later.

The digital computers entered the urban water scene through the billing, accounting and administrative doors. Soon, they were being used in helping in the design of system expansions. Later, extended to simulation of operations and only recently, as a control tool (Caves and Earl, 1979).

Water supply systems in medium to large cities were operating rather satisfactorily in the fifties. System expansions and enhancementes were made through civil engineerings works and in agreement with the

times, without energy saving in mind. The systems were designed and built for easy operation.

To increase the reliability of the water distribution networks "circuits" were built in such a way as to guarantee water supply in the event of a single pipe failure. In some cities this decision have reduced the controllability of the networks.

The energy crisis of the seventies changed the criteria. Energy bill savings became the targets and economical operations were sought. Cities grew out of hand and distribution, all of a sudden, became a complex problem. Underground water was needed and its integrity was closely watched (Alexander 1976). Then, and only then, the digital computer control for water supply and distribution began.

The operation of sewer systems were handled with conventional controls, and even manually, until some twelve years ago. When antipollution laws throughout the world required the maintanance of a water quality it was needed that the sewerage had to be treated before discharging it into rivers, lakes or sea. It was demonstrated that with digital computer control the installed water treatment capacity can be more effectively used and major works investments can be reduced (Field, 1982).

In México, a real time digital computer control program for its drainage system has been started and the first phase, the data acquisition system, is fully operational (Guerrero-Villalobos, 1982).

In Fig. 1, the main components of the water cycle in a block diagram form are presented.

The rest of the paper is divided in two parts; in the first the water supply and distribution system computer control problems and practices will be presented. In the second, the sewer systems will be discussed.

#### WATER SUPPLY AND DISTRIBUTION

There are many similarities between the supply of water and the supply of electrical energy, but there is a basic difference that explains why the digital control had been used so much in the latter and so little in the former: water can be stored, either in large city reservoirs or in individual home storages, for later use.

The time scale of the two problems are widely different; while in the electrical industry the Automatic Generation Control function is performed every 4 to 10 seconds (de Mello, 1973) the valve manipulation is done every 10 minutes to several hours, making in many instances the manual or conventional control appropriate.

In places where there is enough water the immediate goal is to provide domestic water, under normal conditions, with enough pressure (typically from 4 to 9 atm.). In some countries like the USA there should be enough water for emergencies such as fires.

When there is a water shortage, like it occurs in many fast growing cities like in Mexico, the aim is to evenly distributed the water among the population.

For the operation it should be decided what primary sources (springs, wells, ponds, lakes and rivers) should be exploited; what pumps should be turned on; what should be the valves openings, etc, to guarantee the appropriate quality of the service guarding the integrity of the ground water and reducing the costs.

In the decade of the sixties, when computers were batch processing oriented, there were several ambitious attempts to use them in the control loop. Many of these efforts fell short of their expectation and produced a not very positive reactions among potential users. (Shamir, 1981).

On the other hand, there has been very little communication between the developers of similar systems. Also, the number of technical papers dealing with actual installations has been very small. These factors have prevented the diffusion of digital systems applications to water distribution systems.

#### Evolution of network control

In the Fig. 2 three degrees of automation in water networks are presented. Only in very rare cases systems have evolved in a different fashion. At first, the supervisory control is installed and digital technology is used only to monitor the network. All decisions

are made by the operator. In this stage most of the transducers and actuators are installed making simpler the development of later stages.

At the second stage, the computer is used as an aid in the decision making process. Data is transferred to it automatically by the SCADA (Supervisory Control and Data Acquisition System) and the operator request simulations and/or evaluation of tentative control strategies.

Only at the third stage is where the computer is a real "real time" device.

The city of Dallas is a typical example of the evolution of automation in water supply systems, this evolution is shown in table 1.

| YEAR  | FUNCTION  |
|-------|---|
| 1950  | All pumps were manned. Communication was made by telephone. Every hour the operators reported to a central station. |
| 1960  | Telemetry was introduced, but operations were manned.   |
| 1970  | Telecontrol started.  |
| 1975  | Digital Computers were used to process data and presented it in a meaningful way to the central station operator.   |
| 1980  | The digital computer was used as an aid to evaluate alternative operations.   |
| 1985? | Close loop digital control  |

TABLE 1. Automation Function Evolution.

#### Network analysis and simulation

The heart of the problem in water distribution control is the solution of the network equations. These are a set of equations that relate flows and pressures at different nodes. Typical systems have hundreds of pipes and nodes, and solving the equations might be a formidable task.

The equations that relate the variables  $Q_{ij}$ , the flow in pipe joining nodes  $i$  and  $j$ ,  $h_i$ , the pressure at node  $i$  and  $D_i$ , the flow outside the network are: (Canales, 1979).

#### Continuity at nodes

$$\sum_{j \in \Gamma(i)} Q_{ij} + D_i = 0 \quad i = 1, \dots, n \quad (1)$$

#### Losses in pipes

$$K_{ij} Q_{ij} |Q_{ij}|^{\alpha_{ij}-1} = h_i - h_j \quad i \in \Gamma(j) \quad \forall j \quad (2)$$

Terminal elements

$$F(h_i, D_i, x_i) = 0 \quad i = 1, \dots, n \quad (3)$$

where  $\Gamma(j)$  are the set of nodes connected to node  $j$  by a pipe,  $n$  the number of nodes of the network

$x_i$  is a state variable associated with node  $i$   
 $a_{ij}$  and  $K_{ij}$  parameters associated to the  $i, j$  pipe.

There are several types of terminal elements. Some of them are:

Constant node demand

$$D_i = D_o$$

Constant head

$$h_i = H_o$$

Free discharge

$$D_i = \begin{cases} k_i (h_i - h_{ei})^{1/2} & \text{if } h_i > h_{ei} \\ 0 & \text{otherwise} \end{cases}$$

Pumps

$$\beta_{i1} D_i^2 + \beta_{i2} D_i + \beta_{i3} - h_i = 0$$

Storage tank

$$D_i = f(x_i - h_i)$$

$$\frac{dx}{dt} = g(D_i - D_o)$$

Associated with the equations (1) - (3) there are several problems that have to be solved in real time to have digital close loop control.

D-H Given the demand  $D_i$  at every node and the head at a reference node, find  $h_i$  in all other nodes

$H_p - H$  Given  $h_i$  at some nodes and supplementary hypothesis (e.g., proportional load at nodes, that is  $D_i = k_i D_o$ ), find  $h_i$  at the rest of the nodes.

C -  $H_D$  Given an initial state, find control settings (valve positions, on pumps) such that a desired head profile  $H_D$  is obtained.

An early result

In the early seventies, one of the first studies to look into the applications of real time digital control techniques to typical water distribution networks was sponsored (De Moyer et al, 1975).

The posed problem consisted in the following: using the measured pressure at some nodes of a network, take the pressure of a specific

node to a fixed value by manipulating pumps and valves.

In order to test the feasibility of the results, a mathematical model to simulate the network was developed. Due to the limited core memory, a relaxation method (Hardy-Cross) was used to solve the D-H problem. The inverse problem was solved using the algorithm depicted in Fig. 3. This way, the estimation of the demand was made.

To solve the control problem very rudimentary search techniques were used.

By the middle of the seventies several efficient computer codes to simulate water distribution systems were available. (Cesario, 1980).

Most of the algorithms used Newton like iterative methods. However, the difference in acceptability was due to the capacity of effective man-machine interface.

Actual installationsHonolulu

A digital computer automated system was put into operation in the first half of the last decade in Honolulu. Demographic growth of Oahu island after World War II made it necessary to use additional water sources. Local wells were put into operation and were inexpensive, but overexploitation might lead to sea water intrusion.

Storage and main pipe systems did not grow according to demand. The least expensive solution was a more intelligent use of available resources (Alexander, 1976).

The main automatic control functions were:

- a) Supply water to customers within prescribed pressure limits.
- b) Monitoring system operation and alarm detection
- c) Management water resources
- d) Minimize pumping costs.

The automatic control actions are based on dynamic simulations. Every half hour the computing system, based on partial information (pressure at few points), makes an estimation of the actual demand and analyzes the effect of 8 possible control actions. The operator chooses the best.

Denver

(Colorado USA), a system operates around a simulation program WATSIM developed at Systems Control (Rao and Seitle, 1975). As in Honolulu the operator simulates several actions and chooses the one he considers the best.

St. Gallen and Zurich

(Switzerland), Computer based automated systems with the major functions oriented

toward the control of the water supply were installed last decade. Under normal conditions pumping stations are controlled automatically taking into account levels, future demands and electricity costs.

Many more cities, that are lenghtly to mention, do have digital supervisory control.

#### Self Tuning Control for a Water-Distribution System

Most of the water used in Mexico City is brought from remote wells and rivers. Because of undersupply, those sources are exploited to capacity and for practical purposes they can be considered of constant flow. Water is stored in large tanks located around the city. Distribution is done by gravity and can be changed only through very complex valve manipulations. Because of water shortage, domiciliary tanks are used to store water whenever the pressure is high enough.

Schemes, either for simulation or control, used in other cities do not apply because of the different type of end terminal elements. New techniques had to be found. A simulation model was built.

In Fig. 4 the evolution of municipal tank levels and in the Fig. 5 the domiciliary tank levels are shown.

For control purposes a self tuning technique was applied to the network to evenly distribute water among users. The controller had the task of identification and control.

In the Fig. 6 a network with similar structure of Mexico's is presented. The idea is to operate the valves to raise the pressure of individual nodes, one at the time, and at the same time identify the parameters of the terminal devices. A linearize relation between input (valve positions) and outputs (node pressures) are obtained in every observation period. (Hernández, 1981).

The results are shown in Fig. 7.

#### WATER DISPOSAL

The combined sewer operation was used for the first time in England after the well known Broads Street epidemic in 1854. Sewer systems until then were meant for storm water run-off only. People were ordered to discharge the sanitary waters into the sewer systems, in order to secure public health.

In the 1960 a great concern about the pollution of the waters became a big issue. Laws and international agreements were signed and a intense campaign to reduce pollution started. The municipal water disposal offices were asked to treat the water and discharge it into lakes, rivers and sea only when a certain quality was obtained.

It was believed that the answer was to undo what the british started more than a century before: to separate the combined sewer into storm-run off and sanitary and process only the latter.

Soon it was found that storm run-off water was in itself a source of stream pollution and that it had to be treated also, so the initial investment to separate the sewers services was not enough.

When the combined sewers systems were decided upon, then for peak loads the capacity of the treatment plant had to be large and too expensive. However, if the load could be leveled significant cost reductions could be realized.

The storage of the storm run-off couldn't be in only one place, it had to be distributed, either the piping system could be used or ad-hoc storage had to be built.

#### Some system in operation.

In table 2 some of the computerized sewer systems in the United States are presented, and they will be commented briefly (Brueck et.al, 1981).

|                     | DATA LOGGING | SCADA            | AUTOMATIC |
|---------------------|--------------|------------------|-----------|
| Seattle, Washington | 1971         | 1971             | 1974      |
| Detroit, Mich.      | 1968         | (1968)<br>ANALOG | --        |
| San Francisco, Ca.  | 1970         | --               | --        |
| Cleveland, Ohio     | 1972         | --               | 1974      |
| Minneapolis, MN     | 1968         | 1968-1976        | --        |
| Lima, Ohio          | 1979         | 1979             | 1980      |

TABLE 2. Computerized sewer systems in the U.S.A.

#### Seattle, Washington.

This was the first system with a real time digital control. The project CATAD (Computer Augmented Treatment and Disposal System) was started in 1966, and the purpose was to use the piping system as storage in order to maximize the water treated before dumping it into the sea.

The run-off water is pumped from some parts to other in the piping system, depending on the storage capacity. In Fig. 8 a schematic diagram of the system is shown.

The data acquisition system was operational in 1971 after having two contractors to develop the software. The problem then was that at time the project started there were not available event driven computers.

After three years of collecting data, then the system was run on a completed automated fashion, and currently is going through some modernization of equipment.

In Detroit, San Francisco, Victoria (B. C. Canada) and Minneapolis have a data acquisition systems, and are operated manually with the same ideas as in Seattle.

#### Lima, Ohio. (Brueck, 1981)

This is one of the most modern systems in operation. The reasons that move the city authorities to automated operation were economical. Separated sewers systems were too expensive.

In Fig. 9 there's an schematic of the sewer system. Water is stored temporarily and released gradually to the treatment plant, with the following priority system:

- a) Avoid in system flooding
- b) Avoid river overflow:
  - b.1 Dewater system prior to rain fall event
  - b.2 Increase treatment at plant
  - b.3 Maxime storage systems capacity
- c) Reduce gate operations.

The main difficulties found in the development of the automated system were: lack of dynamic performance data, the non linear relationship between sewer levels and system storage capacity and tuning.

A simulation model was used to supply the overall dynamic behaviour. The implementation phase was initially manual and only after sufficient data was collected, was put into operation in the automatic mode.

A computer was needed because appropriate decisions could not be made with only local information and even if it were centralized it was too difficult to process by humans. With the successful operation of the system it was confirmed that sewer systems real time digital computer control is feasible and practical.

#### Mexico.

Mexico city is located in a closed valley, no rivers for discharge are available. Few years ago, the city authorities ask national research institutions to examine how computers can be used to control water flooding, one of the major problems of the city. At this point in time, water quality release is not an issue. Looking at the problem it was early learned that there was a complete lack of data. Obviously, the real dynamic

behavior of the system could not be assesed. The logical step was to develop an automatic data gathering system. Special effort was made to built such a system with the own country technology. The automated rain gage network and alarm system was built and is in operation (Cuerrero-Villalobos, 1982).

The next two steps are:

- a) To predict sewer levels
- b) To control them

#### CONCLUSIONS

It is clear, from previous descriptions, that most of the schemes used in Real Time have been developed for specific systems and there is a lack of unifying concepts and practices.

Very few experts in real time digital control have participated in the system development and there is a lot to be done in this field; there are robust and proved ways to control some large scale systems from where operation of water networks might benefit. Is up to control engineers to make it happen.

#### Acknowledgments.

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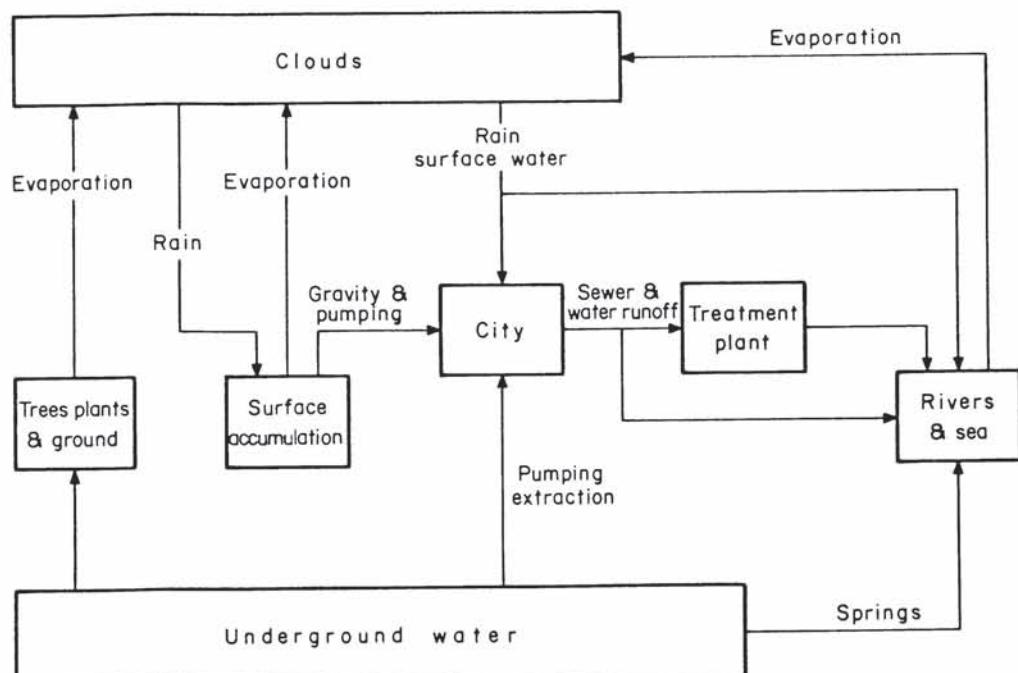


Fig 1 Block diagram of water cycles

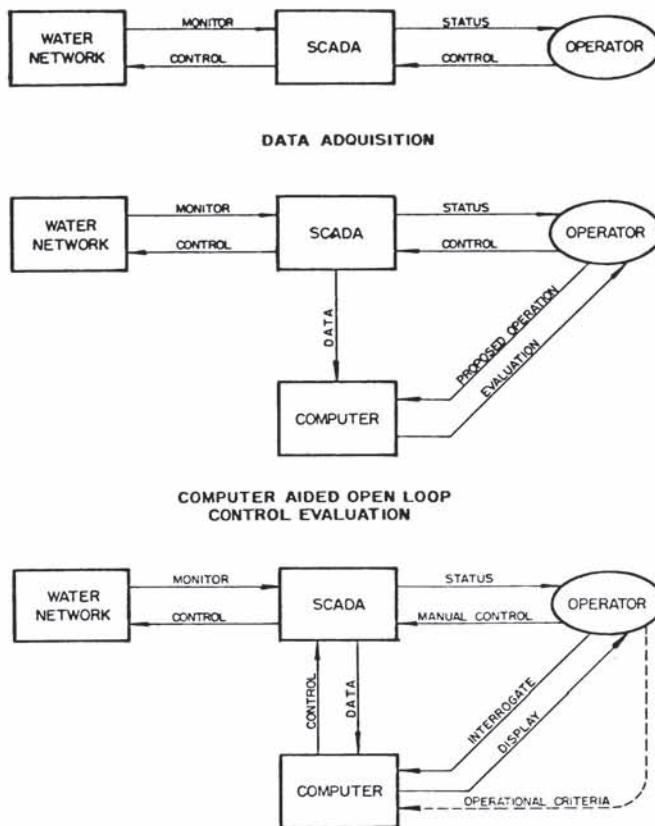


FIG 2 CLOSED LOOP COMPUTER CONTROL

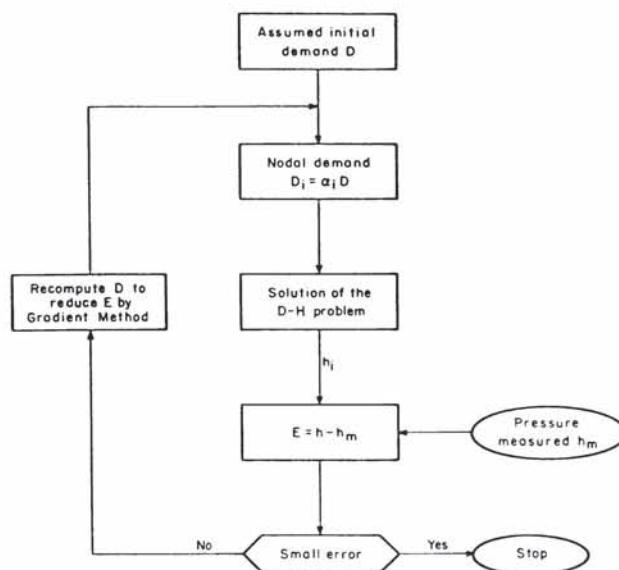


Fig 3 Solution of the inverse problem

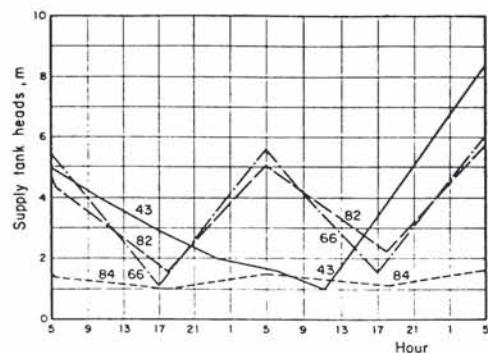


Fig 4 Water stored variation in supply tanks

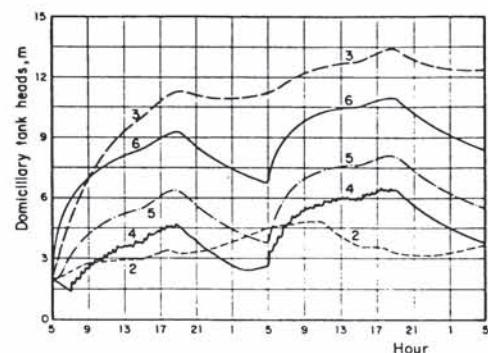


Fig 5 Water stored variation in domiciliary tanks

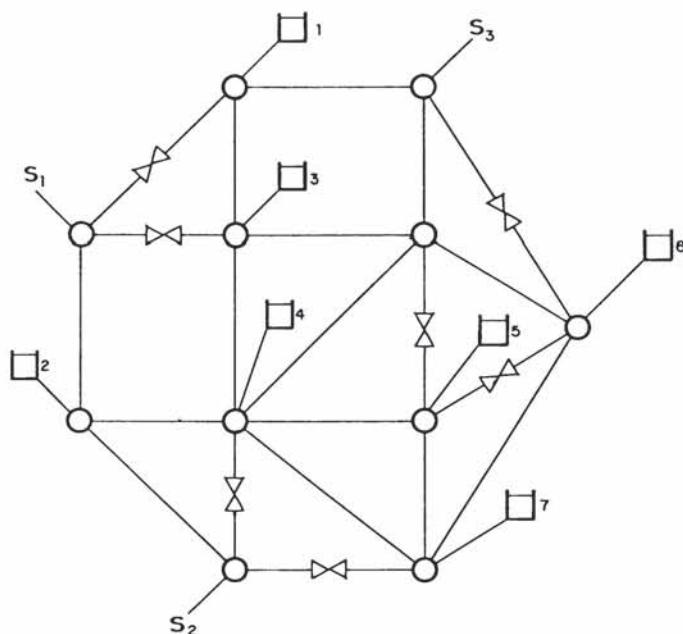


FIG 6 NETWORK FOR SELF TUNING CONTROL

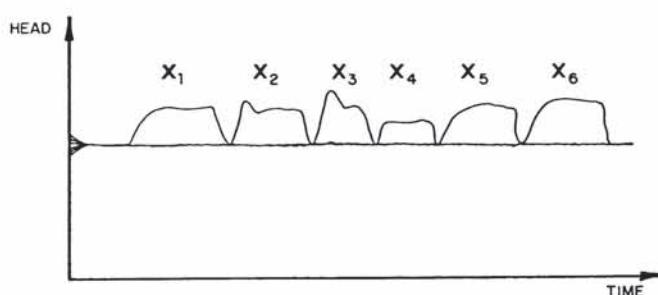


FIG 7 SELF TUNING CONTROL RESULTS

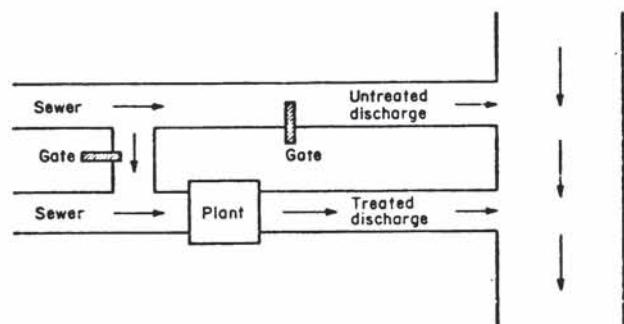


Fig 8 Discharge control

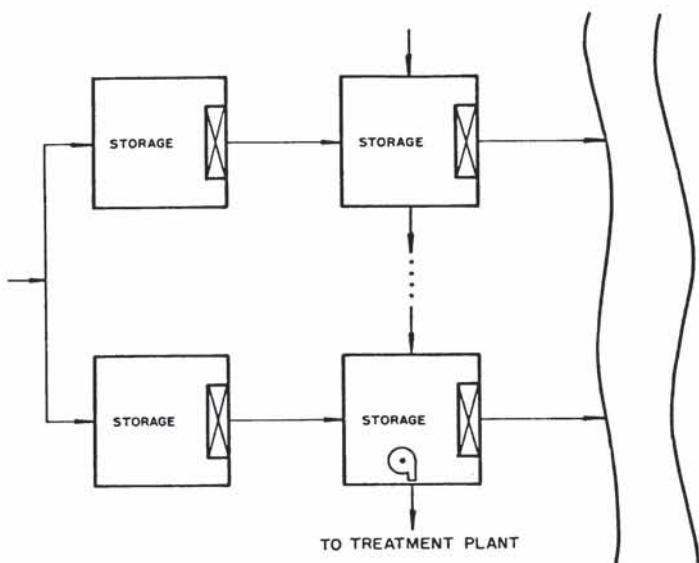


FIG 9 LIMA, OHIO STORM WATER MANAGEMENT SYSTEM