On-line Condition Assessment and Control of Water Distribution and Gas Pipeline Networks

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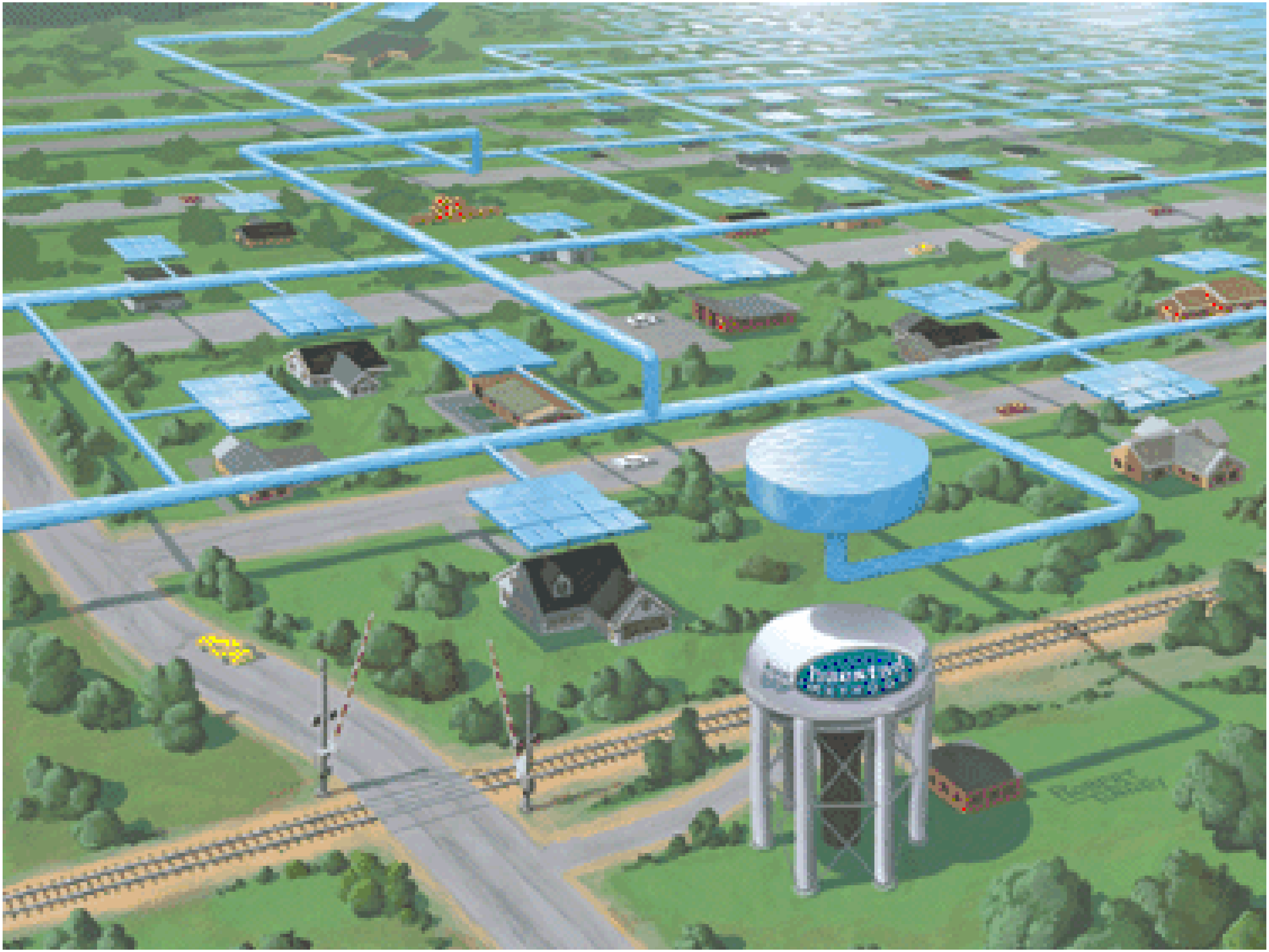


INTRODUCTION

- Water distribution networks - pipes, tanks, reservoirs, pumps, and valves.
- Water scarcity – need for increasing the efficiency and reliability of supply in these networks.
  - Leads to the studies on
    - Monitoring
    - Management and control

INTRODUCTION

- **Natural gas to be transported from producing regions to consumption regions.**

- **The biggest problem with the safe operation of the oil and natural gas pipelines is development of rupture leaks.**

- **Delay in detecting leaks leads to loss of property and human life in fire hazards.**

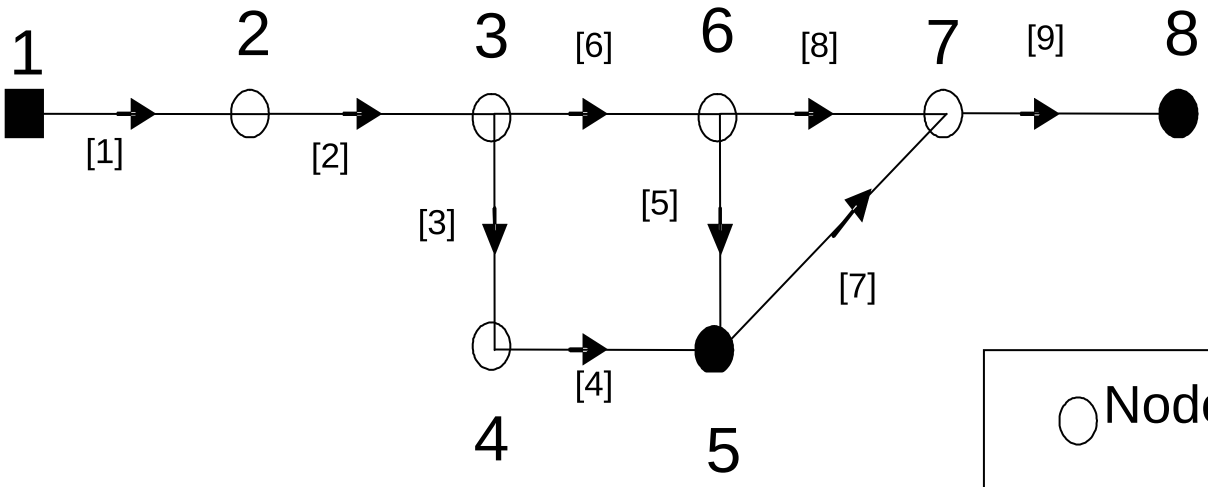
INTRODUCTION

- **LDS can be classified as Software based automatic leak detection systems and field investigative leak detection systems.**

- **SCADA based LDS is inexpensive and continuously monitors gas pipelines.**

Problems with existing Methods

▪ Hardware based techniques:	Can detect small leaks, but expensive
▪ Software based techniques:	Cannot detect small leaks, but inexpensive
▪ Inverse Transient methods:	Computationally intensive, not suitable for on-line app.
▪ Frequency analysis methods:	Require suspension of normal operations Not tested for complex networks
▪ Most of the methods:	Developed for WDN and not for gas pipelines



○ Node without demand

● Delivery node

■ Sourcenode

Fig. 1: schematic of network

SIMULATION

Given

Pipe Characteristics

Source Pressure {function of time)

Demands {function of time}

Gas Composition {function of time}

Determine

Pressures & Flow rates

at all the points in the system

HOW DO WE DO THIS?

Continuity & Momentum Eqs.

For a Pipe Inclined at an Angle

$$\frac{\partial M}{\partial x} + (A/c^2)\frac{\partial p}{\partial t} = 0$$

$$\frac{\partial p}{\partial x} + (g\sin\theta)p/c^2 + \lambda c^2 M\left|M\right|/(2DA^2 p) + \frac{1}{A}\frac{\partial M}{\partial t} = 0$$

Continuity Equation at a junction

Pressure Equality at a Junction

Solve the PDEs

- Appropriate Numerical Method (FD / FV)
- For Specified Boundary Conditions

(Specify Temporal
Pressure Variation at Source
& Demand Variation)

WHAT IS THE PROBLEM ?

FD Methods:

- **Time consuming !**
- **Not Suitable for On-Line Applications (Leak Detection)**

LEAK DETECTION

- **Assume a leak location & corresponding leak magnitude**
- **Run the FD model for the above using pressure at source node and demand variation (Leak is treated as demand!)**
- **Obtain Simulated pressures and flows at all the desired points where measurements are available**

LEAK DETECTION (Contd.)

- Determine the RMS error between measured & simulated pressures & flows
- Solve the Optimization problem for leak magnitude & location such that the RMS error is minimized
- This involves thousands of calls to the simulation code
- Too much CPU time !!! (2 hours for a 1000 s run of one simulation, DT = 1 s)
- Measurement noise is not factored into the methodology

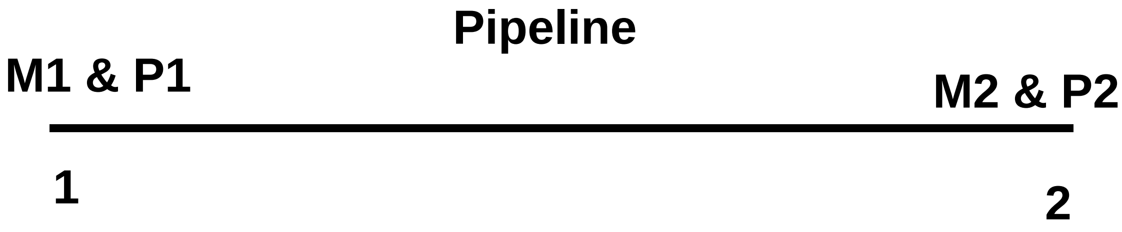
STATE ESTIMATION

- All we need for simulation: Pressure variation at source nodes and Demand variation at demand nodes
- But we may have more measurements than this
- All the above come with measurement noise

STATE ESTIMATION (Contd.)

- **Which measurements shall I consider in simulations ?**
- **How do I know that the considered measurements are noise free?**
- **State estimation reconciles all the measured data and gives out the expected (mean) state of the system which satisfies the governing equations**
- **Absolutely important in leak detection via hypothesis testing**

WHAT IS A TRANSFER FUNCTION MODEL?



Pipeline

M1 & P1

M2 & P2

1

2

Transfer functions relate M1 & P2 at any instant to M2 & P1 at that instant & Past values of M2 and P1

Using an approximation of Governing Equations

There is no need to discretize the pipeline as in FD methods

- **Linearize governing equations**
- **Analytical solution in Laplace domain**
- **Get transfer functions in Laplace domain**
- **Take inverse Laplace in time domain**

Down stream pressure equation in time domain

$$\Delta p_2(N*T_s)=\sum_{i=1}^{N}\left[k_1*e^{-(N-i)*\frac{T_s}{T}}*(1-e^{-\frac{T_s}{T}})*\Delta p_1(i*T_s)\right]+$$

$$\sum_{i=1}^{N}\left[-k_2*e^{-(N-i)*\frac{T_s}{T}}*(1-e^{-\frac{T_s}{T}})*\Delta M_2(i*T_s)\right]-$$

$$\left[\frac{-k_2*T_2}{T}*(1-e^{-\frac{T_s}{T}})\left[\sum_{i=1}^{N}\Delta M_2(i*T_s)*e^{-(N-i)*\frac{T_s}{T}}\right]+\frac{k_2T_2}{T}*\Delta M_2(N*T_s)\right]$$

(11)

Upstream flow equation in time domain

$$\Delta M_1(N*T_s) = \sum_{i=1}^{N}\left[e^{-(N-i)*\frac{T_s}{T}} *(1-e^{-\frac{T_s}{T}})*\Delta M_2(i*T_s)\right]+$$

$$\left[-\frac{\mathrm{T}_1}{\mathrm{T}}*(1-e^{-\frac{T_s}{T}})*\left[\sum_{i=1}^{N}\Delta p_1(i*T_s)*e^{-(N-i)*\frac{T_s}{T}}\right]\right]$$

$$+\frac{\mathrm{T}_1}{\mathrm{T}}*\Delta p_1(N*T_s)$$

(12)

By expanding Transfer functions

$$F_{P2,P1} = k_1 \frac{1}{1+Ts}$$

$$F_{M1,P1} = \frac{T_1 s}{1+Ts}$$

$$F_{M1,M2} = \frac{1}{1+Ts}$$

$$F_{P2,M2} = -k_2 \frac{(1+T_2 s)}{1+Ts}$$

$$k_1 = e^{\Psi}$$

$$k_2 = e^{\Psi/2} \frac{\lambda L}{DA} \bar{u} \left(1 + \frac{1}{24}\Psi^2\right)$$

$$T = e^{\Psi/2} \frac{\lambda L^2 \bar{u}}{2D\bar{c}^2} \left(1 - \frac{1}{6}\Psi + \frac{1}{24}\Psi^2\right)$$

$$T_1 = e^{\Psi/2} \frac{AL}{\bar{c}^2} \left(1 + \frac{1}{24}\Psi^2\right)$$

$$T_2 = \frac{D}{\lambda \left|\bar{u}\right|} + \frac{1}{6}\left(\frac{\lambda L^2 \left|\bar{u}\right|}{D\bar{c}^2} \frac{1}{1 + \frac{\Psi^2}{24}}\right)$$

$$\Psi = \frac{\lambda L}{2D} \frac{\bar{u}\left|\bar{u}\right|}{\bar{c}^2} - \frac{gL \sin\theta}{\bar{c}^2}$$

Complete discrete model in the time domain for the entire network:

Combine above Eqs.(11) and (12) for all the pipe elements with

Continuity equation and pressure equilibrium equations at the junctions

Continuity equation and pressure drop equation at valves

Continuity equation and equations describing compressor operation.

Formulation of the State Estimation Problem

Resulting system of equations for the entire network: Linear

$$Ax + Bu = 0 \qquad (13)$$

vector *x:* **All measured variables (corresponding to time instants *(N-n)T* to *NT*,**

vector *u:* **All unmeasured variables (corresponding to time instants *(N-n)T* to *NT*).**

The matrices *A* and *B* depend on the pipe parameters, sampling period, compressibility factor and friction factor.

Matrices *A* and *B* are time dependent

The best estimates of variables *x* and *u*, for a given set of measurements *y* for the variables *x*, can be obtained by solving the following weighted least squares estimation problem

Minimize $$(y-x)^T Q^{-1} (y-x)$$

Subject to $$Ax + Bu = 0$$

- **Matrix *Q* is the covariance matrix of errors in measurement**
- **Standard reconciliation problem**
- **Crowe's Projection Matrix technique**

Obtain the state estimate for the current time instant *NT* in a recursive manner by utilizing the estimates obtained for all the previous times

The constraint Eq. (13) is re-cast as given below.

$$\overline{A}\overline{x} + \overline{B}\overline{u} = c$$

where $\overline{x}\ ,\ \overline{u}$

Measured and unmeasured variables corresponding to the current time instant *NT*

and $\overline{A}\ ,\ \overline{B}$

are the corresponding sub-matrices of *A* and *B*.

Vector *c* : *W*eighted sum of the estimated flows and pressures at the previous time

Just enough variables are specified

Solution: objective function value = 0

simulation problem

- More measurements (specifications) than the minimum required to solve the problem are given:

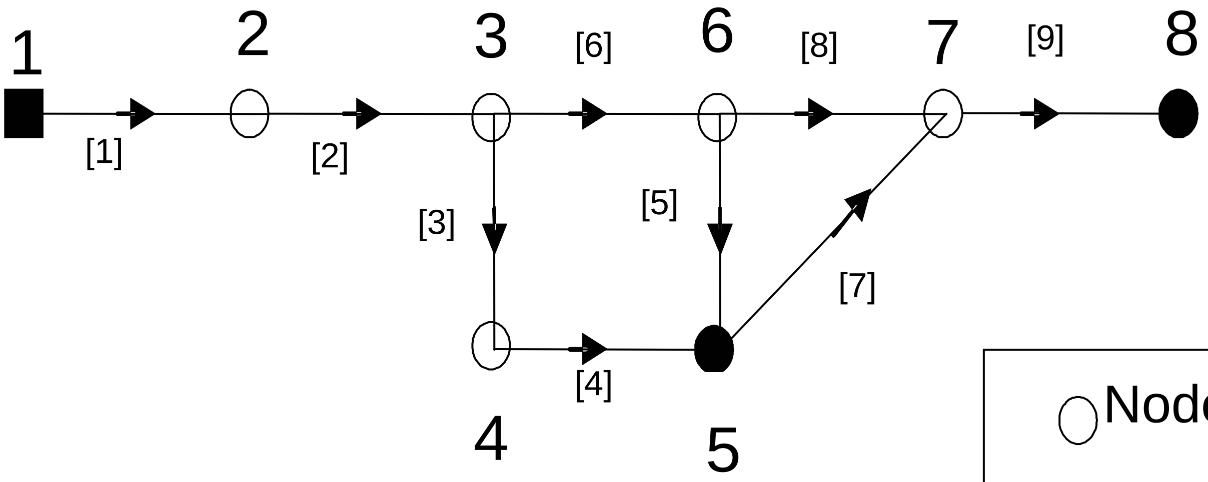
Formulation gives a best fit solution

Takes into account the inaccuracies

state estimation

RESULTS AND DISCUSSION

- **Second order MacCormack explicit FD method is used to validate the proposed TF model.**
- **Network (fig. 1) consists of 8 nodes and 9 pipe elements**
- **Slow transient caused by variation of demand at one of the demand node is simulated with Bench mark model (FD model) and proposed model**



- ○ Node without demand
- ● Delivery node
- ■ Sourcenode

Fig. 1: schematic of network

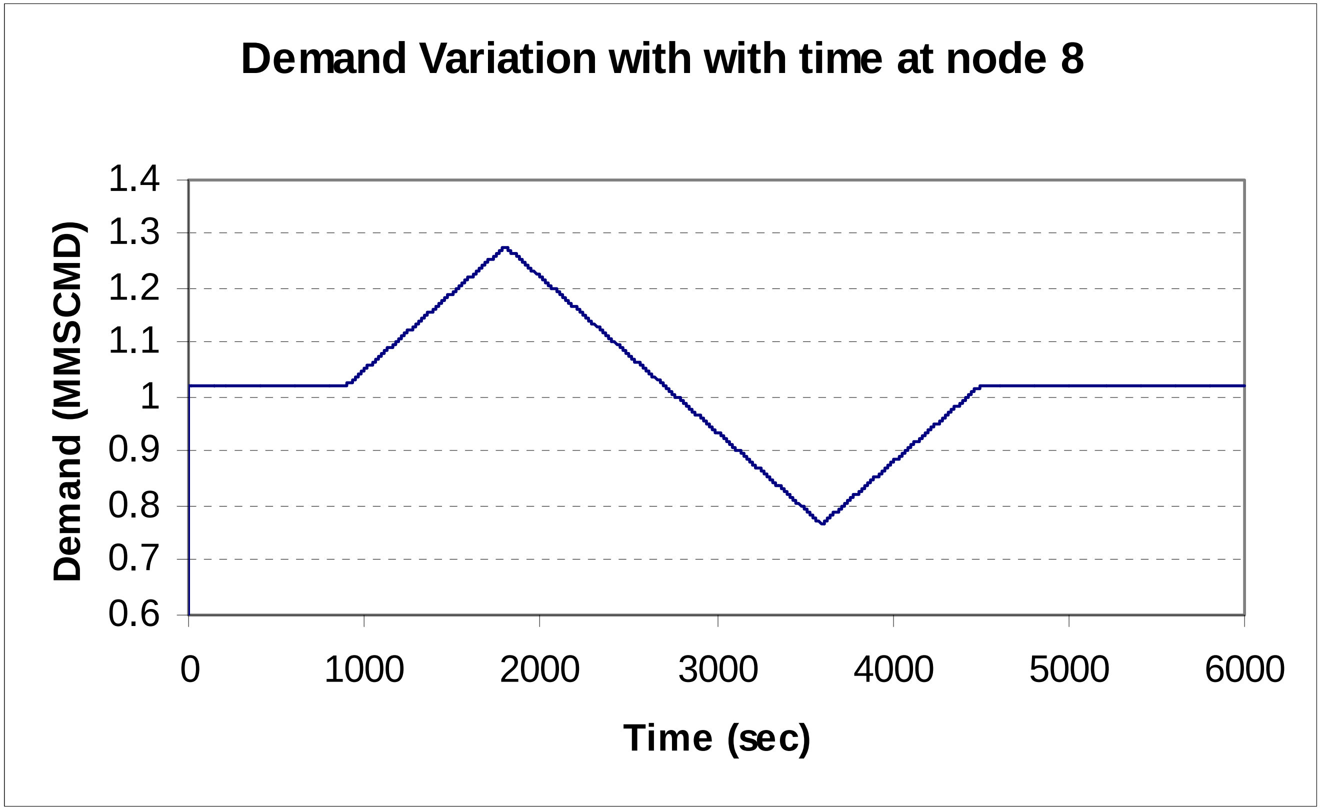
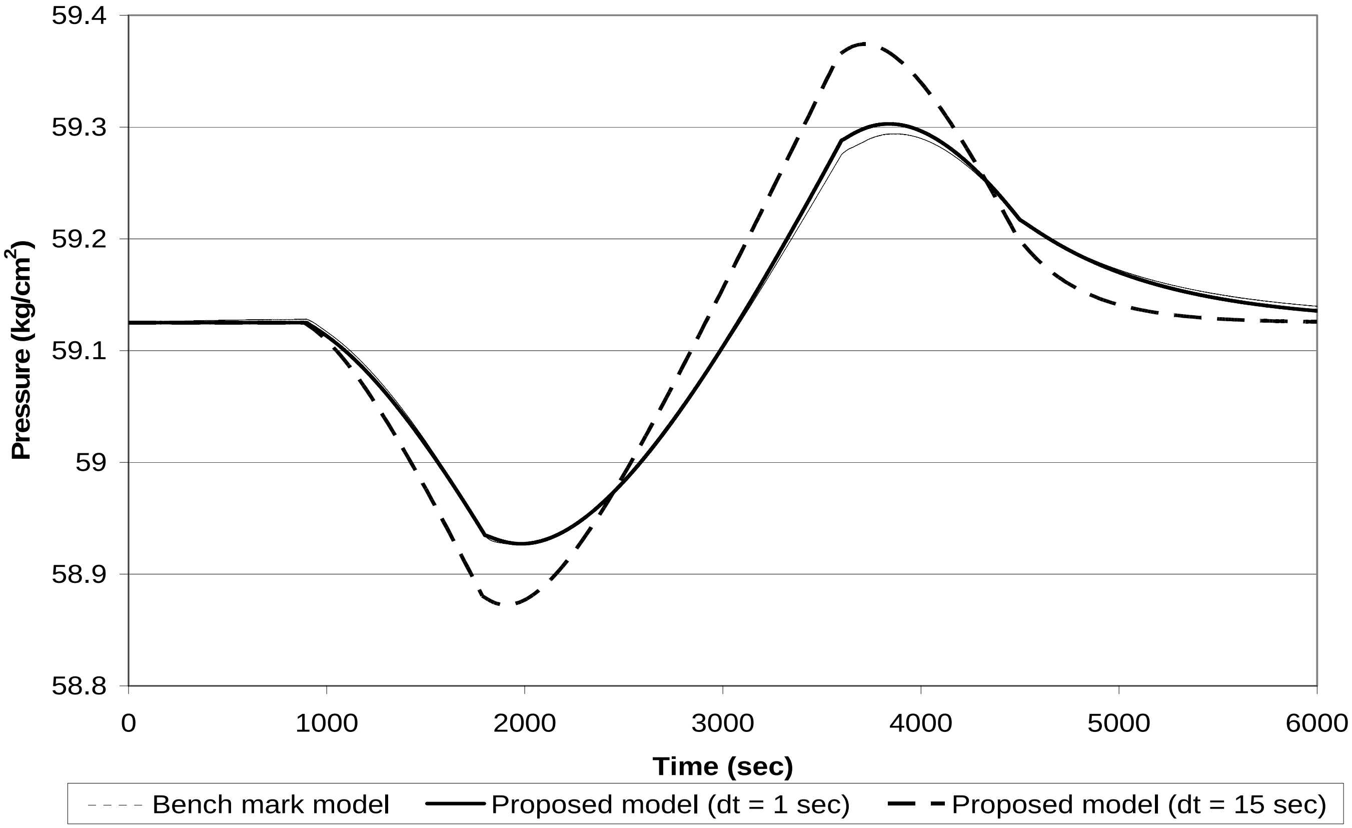


Fig. 2 Specified Demand variation at node 8

RESULTS AND DISCUSSION – DYNAMIC SIMULATION



Comparison of pressure at node 8

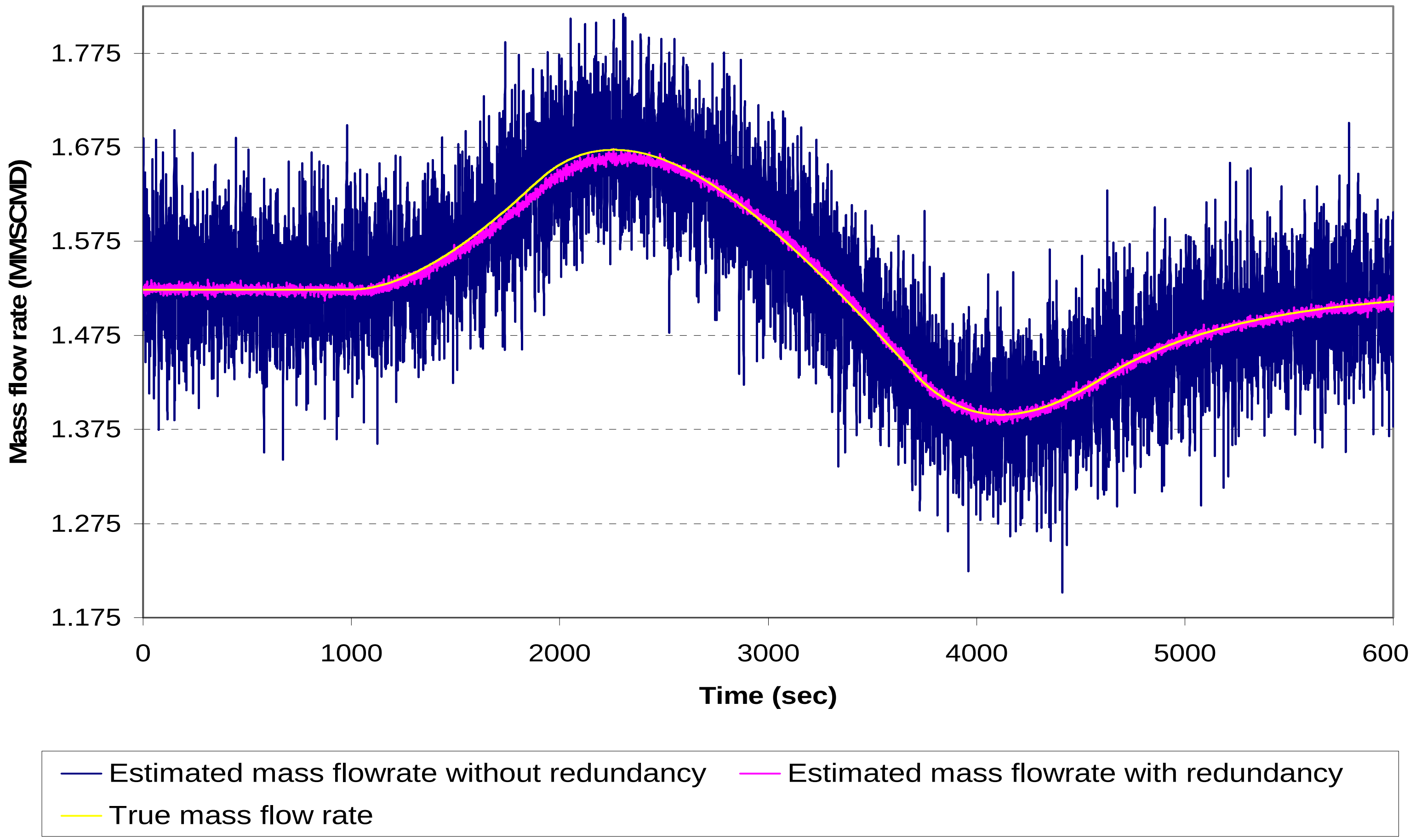


Fig. 12: True and estimated mass flow rates at node 1: Case-2

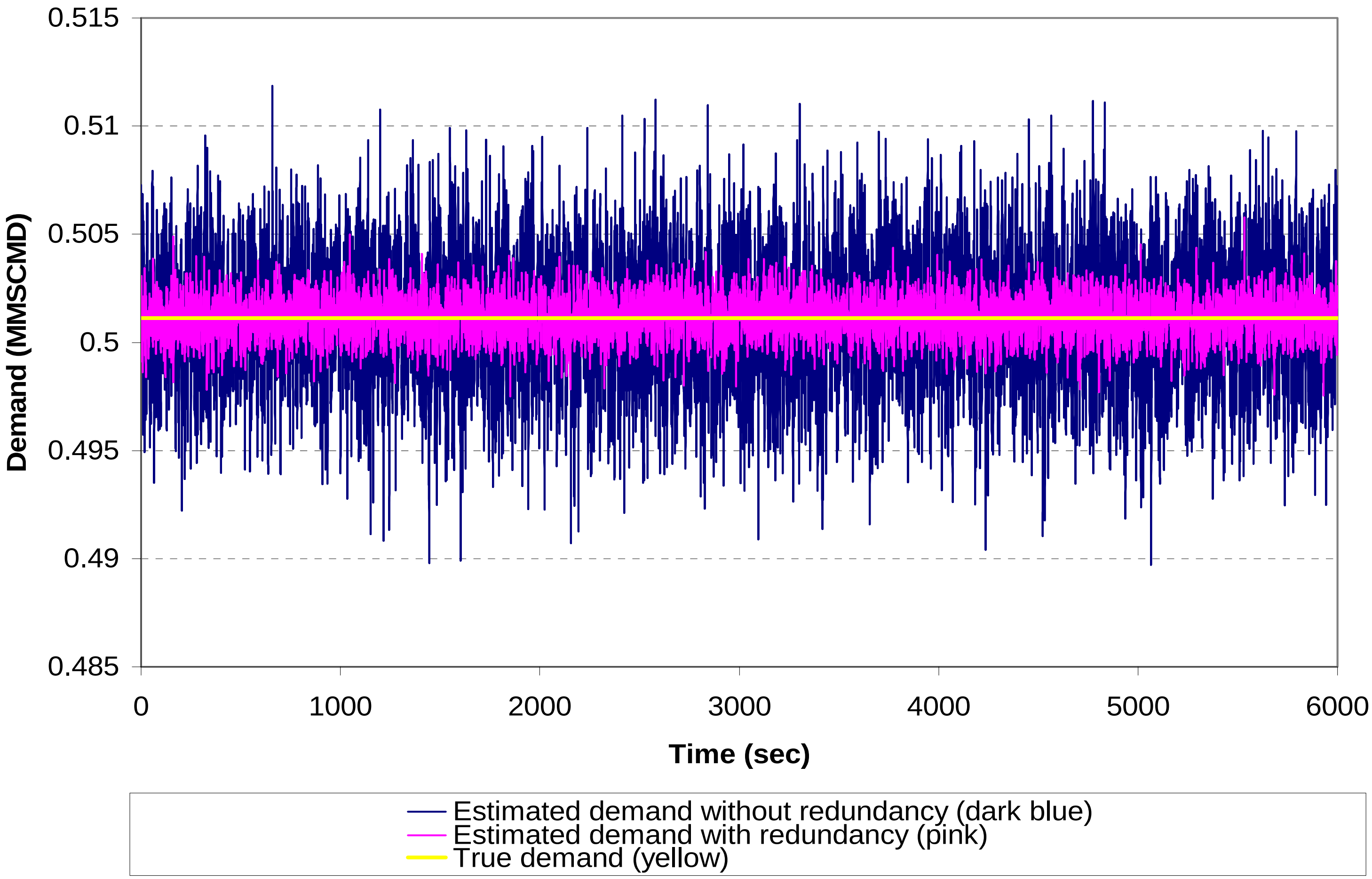


Fig. 14: True and estimated demands at node 5: Case – 2

Table 5: Reduction in RMS error with increased redundancy

Variable	Just specified with noise	Redundant Measurements with noise
P1	**0.01000**	**0.00492**
F1	**0.05489**	**0.000106**
P2	**0.02480**	**0.01868**
F2	**0.004563**	**0.000188**
P3	**0.02521**	**0.01837**
P4	**0.02394**	**0.01709**
F4	**0.001087**	**0.000123**
P5	**0.02393**	**0.01703**
D5	**0.00313**	**0.001**
P6	**0.02444**	**0.01752**
P7	**0.02365**	**0.01682**
P8	**0.02116**	**0.01462**

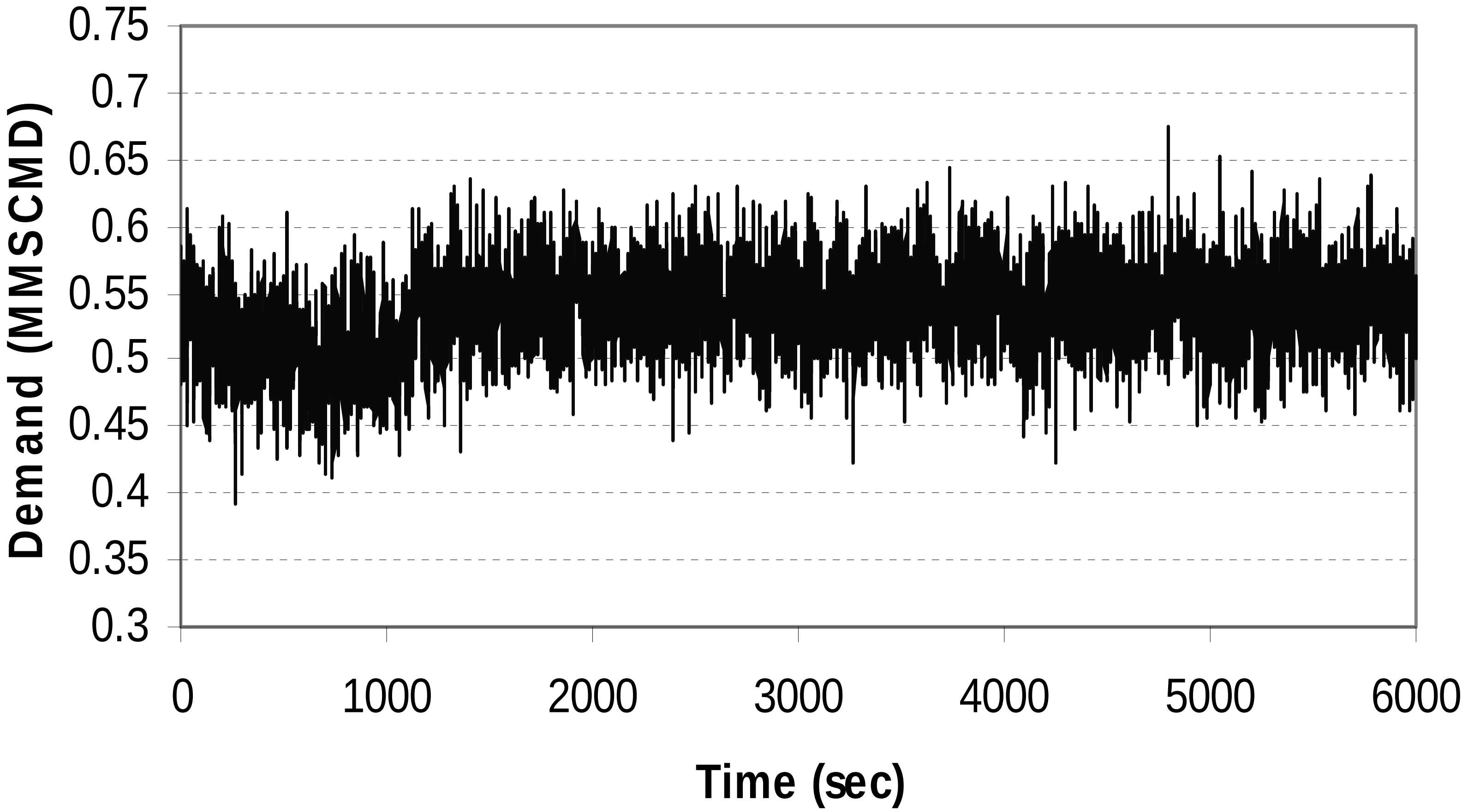


Fig. 17 Estimation of unknown demand at Node 5

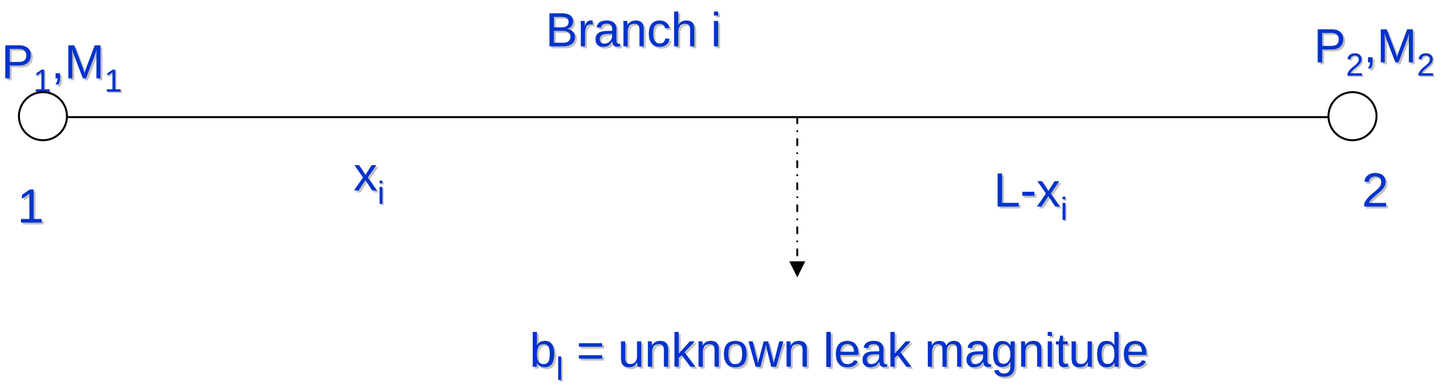
CONCLUSIONS – STATE ESTIMATION

- Test problems on the example network indicated that the proposed method is 25 times faster than the explicit finite-difference approach.
- It was also demonstrated that the proposed approach can be used to estimate unknown demands.
- The above features, coupled with the computational efficiency, make the approach ideally suited for on-line leak detection and identification.

LEAK DETECTION METHODOLOGY

- In order to detect a leak online, we will call state estimator at each sampling time instant.
- ObjFunction > Threshold => possible leak
- We will hypothesize a leak in every branch of the pipeline network and determine best fit D_L, X_L based on measurements [t, t+WT] in each branch.
- The hypothesis that best fits the data among all the hypotheses then determines the branch, location and magnitude of the leak

LEAK DETECTION METHODOLOGY


Branch i

P_1,M_1

P_2,M_2

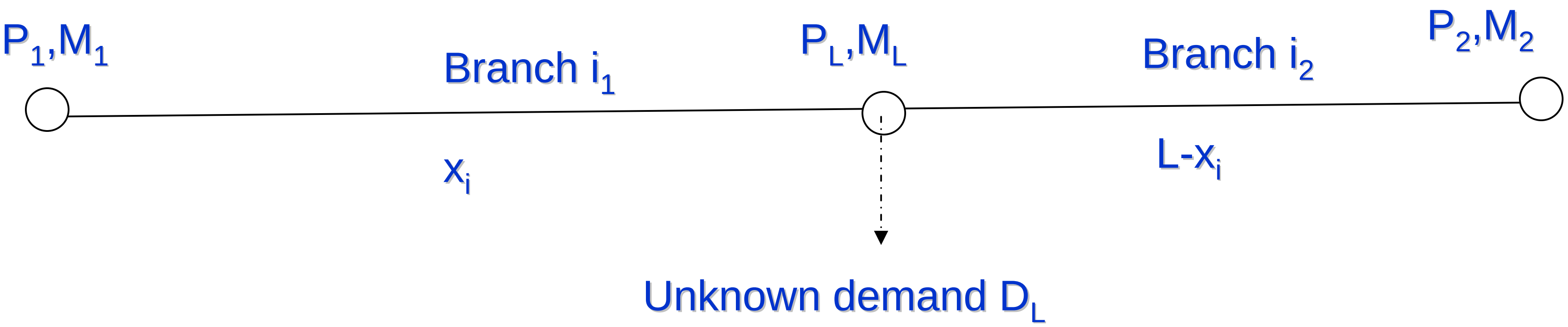
1

x_i

$L-x_i$

2

b_l = unknown leak magnitude


P_1,M_1

Branch i_1

P_L,M_L

Branch i_2

P_2,M_2

x_i

$L-x_i$

Unknown demand D_L

Leak pipe model

LEAK DETECTION METHODOLOGY

Leak detection hypothesis – optimization problem

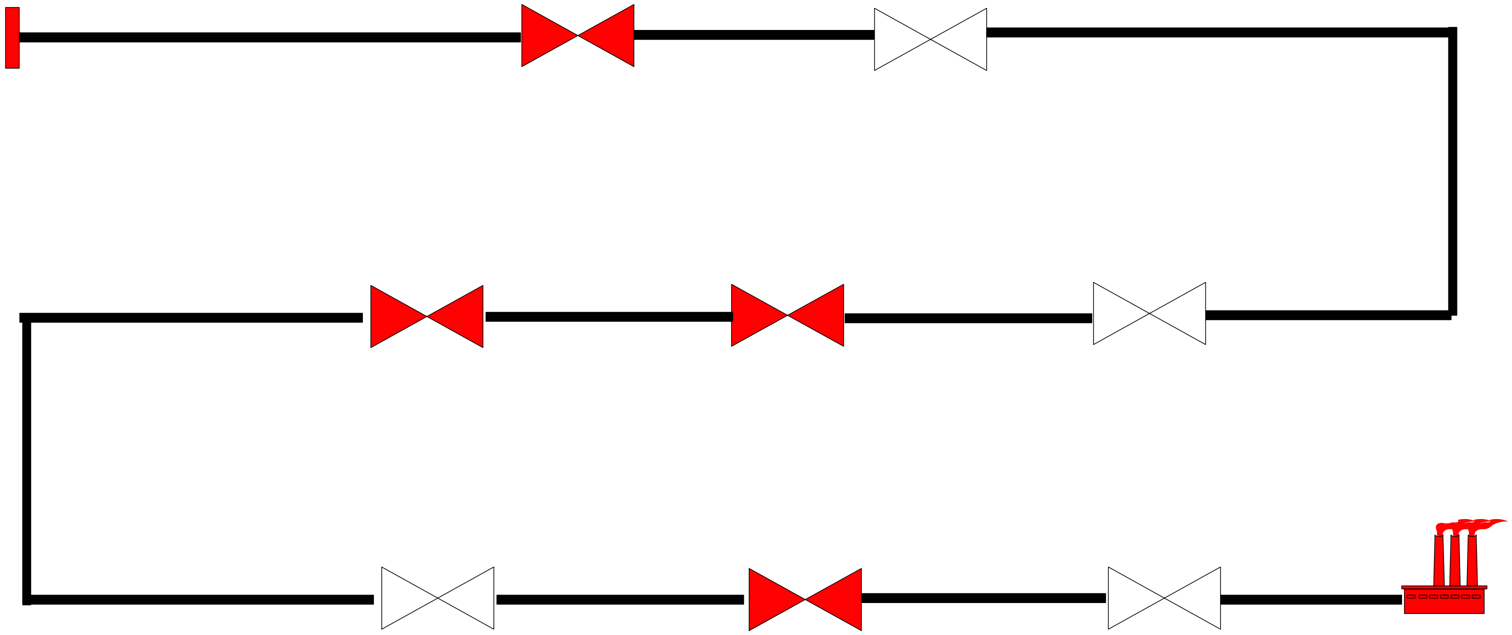
$$\underset{m,u}{\mathrm{Min}} \quad (\overline{y} - \overline{m})^T \, \overline{Q}^{-1} (\overline{y} - \overline{m})$$

$$Subjected \ \ to$$

$$\overline{A}\overline{m} + \overline{B}\overline{u} = c$$

The D_L is unknown and it is part of u vector

RESULTS AND DISCUSSION - LEAK DETECTION USING SIMULATIONS



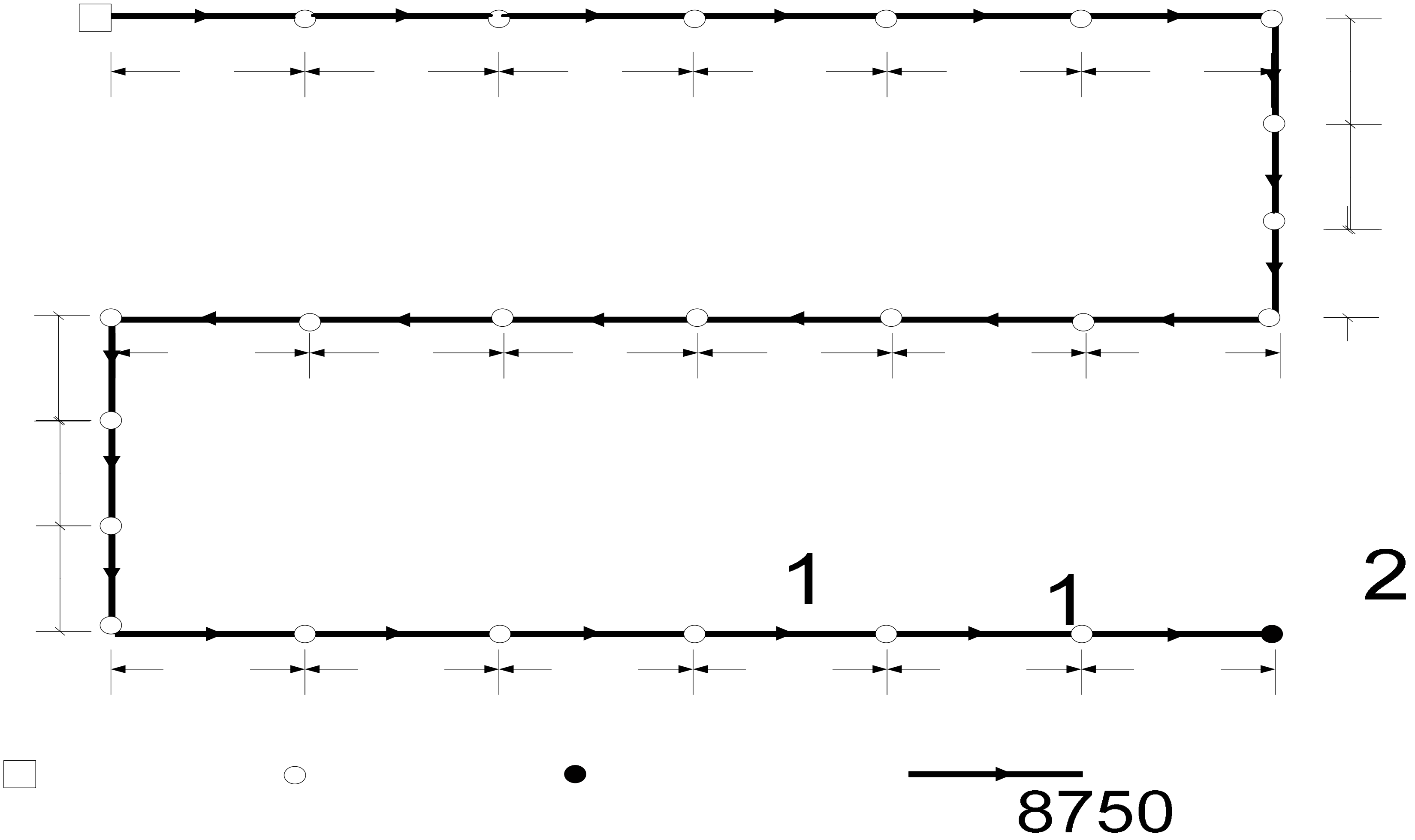
hypothetical series pipeline

RESULTS AND DISCUSSION - LEAK DETECTION USING SIMULATIONS

Available instrumentation:

- Pressure and flow measurements are available at both the ends.
- Intermediate pressure measurements are available at SV-1, SV-4, SV-5 and SV-7.
- Total six pressure measurements and two mass flow measurements.
- This is the basic instrumentation level considered for leak detection simulations but additional pressure measurements added to improve the leak isolation efficiency.

RESULTS AND DISCUSSION - LEAK DETECTION USING SIMULATIONS



Discretized form of hypothetical series pipeline

RESULTS AND DISCUSSION - LEAK DETECTION USING SIMULATIONS

- Natural gas composition used is: CH_4 93.42, N_2 0.12, CO_2 2.36, C_2H_6 1.76, Propane 1.35, i-Butane 0.31, n-Butane 0.32, i-Pentane 0.01, n-Pentane 0.08, n-Hexane 0.01.
- Dynamic Viscosity of the natural gas was taken as 0.0000125 N s m^{-2}.
- Boundary conditions for the transient test:
- P1 (Pressure at node-1) = 45.0 kg/cm^2;
- Normal demand at consumption node is 60500 SCMH but is a function of time to create unsteady flow conditions;

RESULTS AND DISCUSSION - LEAK DETECTION USING SIMULATIONS

CATEGORIES OF TESTS

S. No	Test Description
Category-1	Without noise + existing instrumentation
Category-2	With noise + existing instrumentation
Category-3	With noise + filter (80% weightage to past data) + existing instrumentation
Category-4	With noise + filter (90% weightage to past data) + existing instrumentation
Category-5	With noise + no filter + additional ten PT's to existing instrumentation
Category-6	With noise + no filter + PT at every node

RESULTS AND DISCUSSION - LEAK DETECTION USING SIMULATIONS

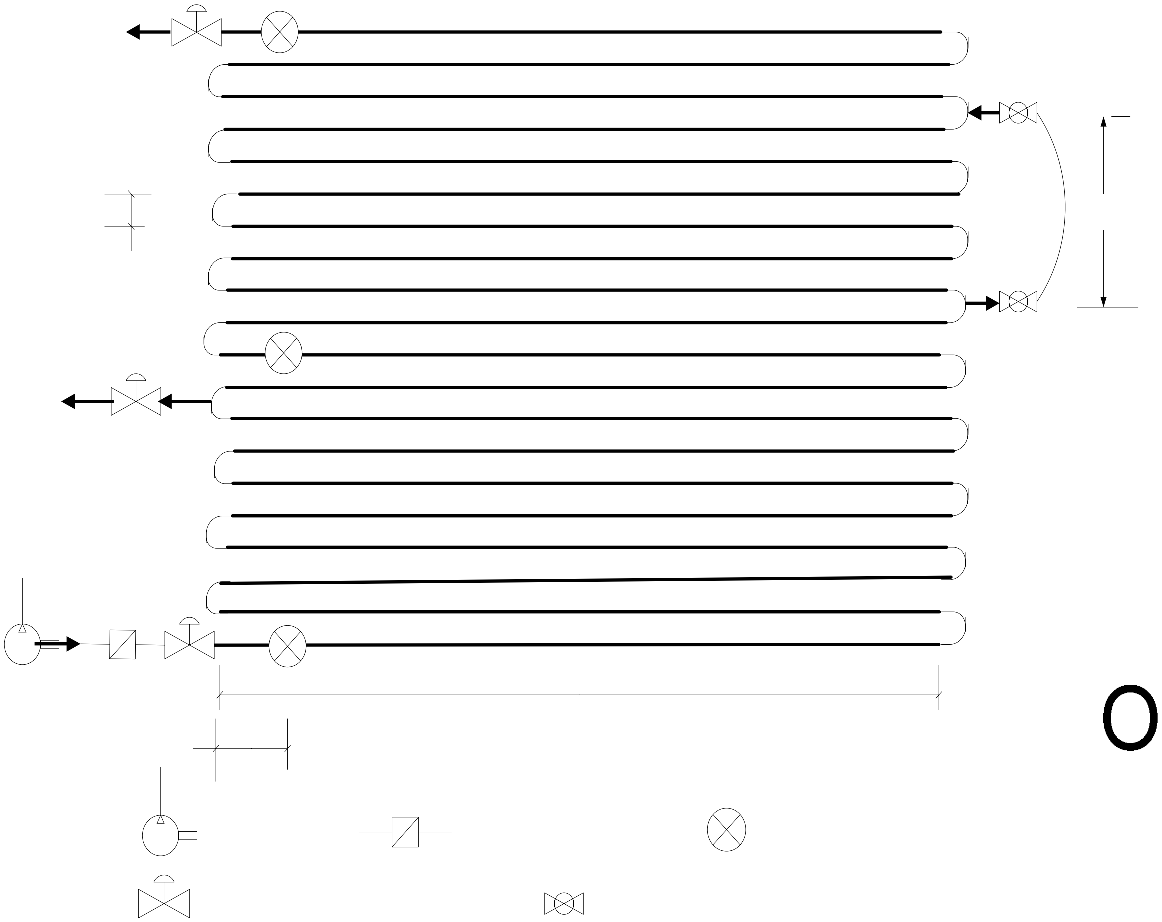
Improvement in the leak detection results with extra nineteen pressure measurements added to the existing instrumentation

S. No	Leak location (km)	Estimated leak location	Error in leak location	Magnitude of leak tested	Estimated leak magnitude	% error in estimated leak magnitude	Delay in leak detection time (sec)
		(km)	(km)	(SCMH)	(SCMH)		
1	53.73	52.84	0.89	1210	1596.3	31.9	175
2	53.73	53.21	0.52	3025	2735.3	9.6	52
3	53.73	53.97	0.24	6050	6193.8	2.4	21
4	103.06	102.15	0.91	1210	1393.6	15.2	180
5	103.06	103.83	0.77	3025	3472.5	14.8	49
6	103.06	103.56	0.5	6050	6310.1	4.3	18
7	195.5	192.61	2.89	1210	1020.7	15.7	128
8	195.5	194.56	0.94	3025	2723.9	10	33
9	195.5	195.08	0.42	6050	6123.7	1.2	15

CONCLUSIONS - LEAK DETECTION USING SIMULATIONS

- Proposed methodology is validated for 2%, 5% and 10% leaks using a series pipeline and a pipeline network.
- Accuracy of the proposed method decreases when measurement noise is present.
- Results for a total of 66 numerical runs indicated that the proposed methodology works very well if noise level in the measured data is low. In case of noisy data, the proposed method performs well if there is a sufficient redundancy in the measurements.

RESULTS AND DISCUSSION - LEAK DETECTION USING LAB EXPERIMENTS



Out flow

Experimental setup

RESULTS AND DISCUSSION - LEAK DETECTION USING LAB EXPERIMENTS

Validation of proposed leak detection methodology using laboratory experimental data

Flow rate (SLPM)	Time of Leak (sec)		Leak Location from inlet end (m)		Leak Magnitude (SLPM)		Pipeline configuration
	Actual	Estimated	Actual	Estimated	Actual	Estimated	
150	200	206.3	49.68	45.94	6.0	6.34	Series
200	200	203.6	74.68	75.05	9.0	9.72	Series
250	200	201.5	99.68	100.42	12.0	12.13	Series
250	200	204.4	24.68	30.92	6.0	7.38	Series
150	200	227.2	49.68	56.9	6.0	4.83	Network
200	200	203.8	74.68	75.06	9.0	10.05	Network
250	200	203.5	99.68	103.04	12.0	13.02	Network
250	200	206.9	24.68	26.71	6.0	7.65	Network

CONCLUSIONS – LAB EXPERIMENTS

- A total of 72 experiments were conducted by changing initial flow rate, leak location, leak magnitude, and network configuration (series and network).
- In series pipeline, the error in the magnitude estimation was less than 10% in 65% of the cases and the error in the magnitude estimation was less than 15% in 78% of the cases. Maximum error in estimation (31%) occurred in one test.
- The proposed method located the leak within 3 m (2.5% error based on the total length of the pipe) from its actual location of occurrence in most of the cases (32 out of 36 tests). (series pipeline)
- The estimated leak location was within 3 m (2.5% error based on the total length of the pipe) from its actual location of occurrence in 17 out of 36 cases. (network)
- The magnitude error in the estimation was less than 10% in 50% of the cases. The magnitude error in the estimation was less than 15% in 72% of the cases. (network)

RESULTS AND DISCUSSION – FIELD LEAK DETECTION TESTS

- The leak detection and identification method was implemented on-line on the LANCO pipeline, owned and operated by the GAIL (India) Ltd.
- The pipeline is used to supply natural gas from Tatipaka to the LANCO power plant at Kondapalli.
- The existing instrumentation consists of six pressure sensors one each at Tatipaka, Dindi (SV-1), Mortha (SV-4), Tadepalligudem (SV-5), Koppaka (SV-7) and Kondapalli, a gas chromotograph at Kondapalli, mass flow meters at Kondapalli and Tatipaka, and temperature sensors at Kondapalli and Tatipaka.

RESULTS AND DISCUSSION – FIELD LEAK DETECTION TESTS

Hypothetical Series pipeline system

Pipeline characteristics:

Length = 204.7 km

Diameter = 0.443 m (ID)

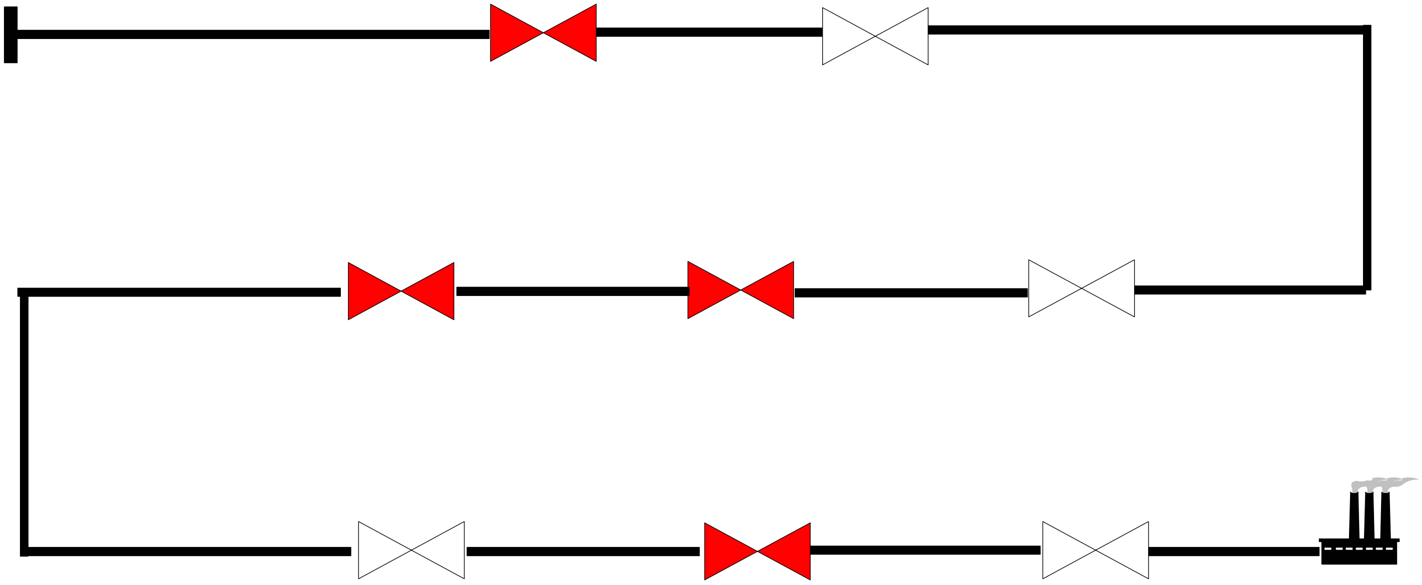
Roughness = 250 microns

Natural gas is flowing through the system

Average temperature = 302 K

Flow measurements sampling interval = 10 seconds

RESULTS AND DISCUSSION – FIELD LEAK DETECTION TESTS



Schematic of LANCO pipeline

RESULTS AND DISCUSSION – FIELD LEAK DETECTION TESTS

Validation of the proposed leak detection methodology using field tests

Field Test No.	Time of Leak		Leak Location from Tatipaka (km)		Estimated Leak Magnitude (% of total flow)
	Actual	Estimated	Actual	Estimated	
1	10.20 AM	10:20 AM	61.9	63.6	1.5
2	6:25 PM	6:49 PM	139.0	162.1	10
3	7:07 PM	7:31 PM	139.0	113.4	3
4	12:55 PM	1:07 PM	61.9	66.0	10
5	6:06 PM	6:35 PM	139.0	125.1	6
6	1:51 PM	1:58 PM	17.5	4.67	3

Objectives

- Overall objective - develop techniques for monitoring and control of water distribution networks.
- The specific goals are to
    - Monitor the health of the pipes by online estimation of pipe roughness coefficient
    - Develop an online control strategy for optimal operation of water distribution network
    - Validate the developed methods through simulation of large scale networks

State Estimation

- State estimation – estimate flows, pressure, outflows from noisy measurements.
  - Nonlinear constrained optimization problem
- Objective

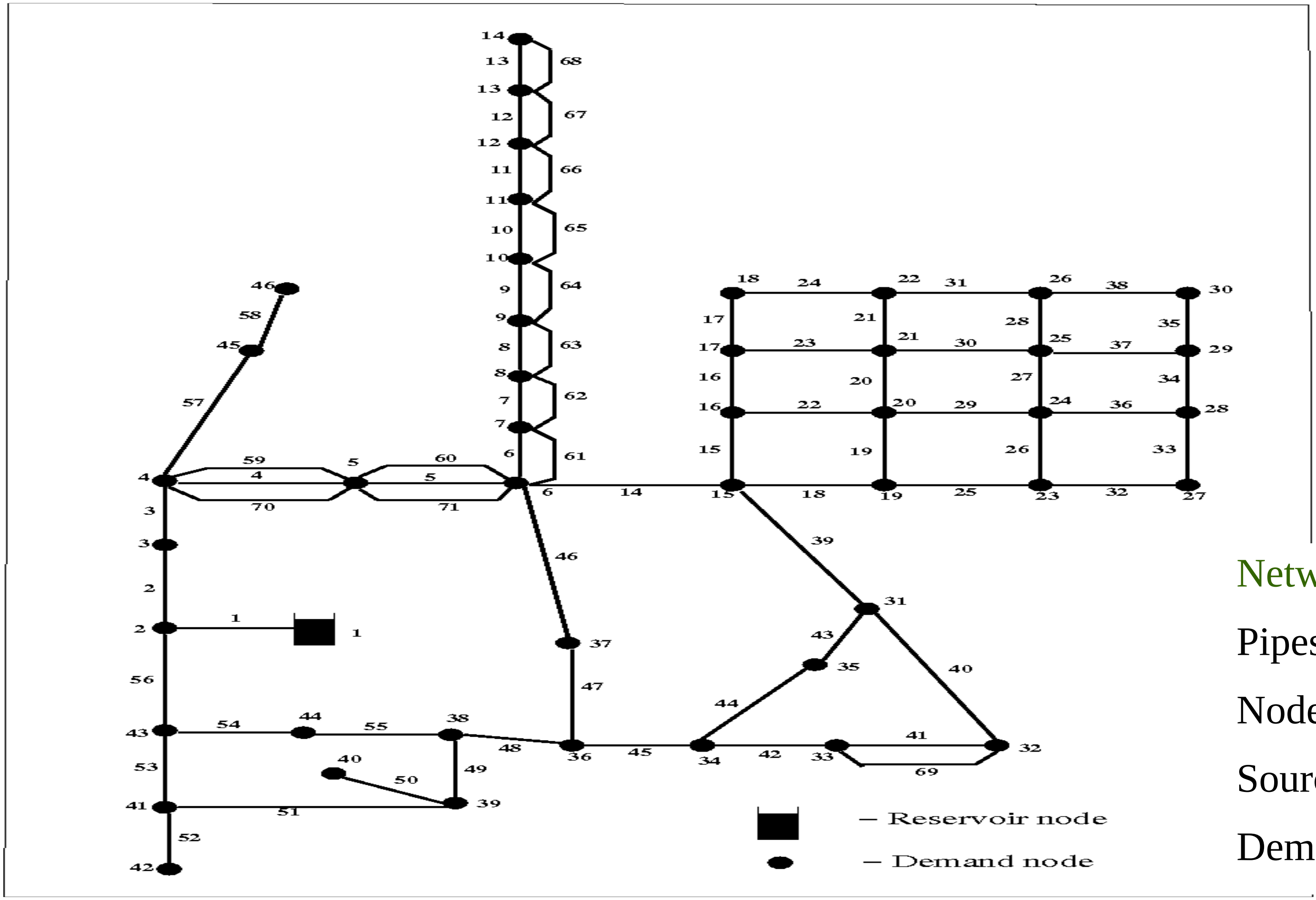
$$\phi = Min\left(\tilde{Y}-\hat{Y}\right)^T \sum^{-1}\left(\tilde{Y}-\hat{Y}\right)$$

- Constraints
  - **Continuity (flow balance) equation at each node**
  - **Loop equations that relate the pressure drop variables**
  - **Correlation for energy losses due to friction (Hazen- Williams correlation is used here)**

Methodology

- Derive reduced optimization problem using graph theoretic concepts
- Reduced number of constraints is equal to number of independent loops
- Reduced optimization problem is then solved using Successive Quadratic Programming technique
- Gradient of objective function and reduced constraints are derived analytically

Schematic diagram of Tiruppur network



Network Details

Pipes = 71

Nodes = 46

Source Node = 1

Demand node = 45

Case Studies – Tiruppur network

Case	Measured variables			Noise (Yes/No)
	Flows in pipes	Pressures at nodes	Demand at nodes	
1	-	1	All 45 nodes	No
2	-	1	All 45 nodes	Yes
3	1 to 12	1	All 45 nodes	Yes
4	1 to 12	1, 35 to 46	All 45 nodes	Yes

% error less than	% pipes (flow)		
	Case-2	Case-3	Case-4
0.1	15	21	26
0.5	48	65	68
1.0	77	77	88
2.0	94	94	95
5.0	100	100	100

Unknown Demand Estimation

Case	Demand unknown at nodes	Actual demand, (m^3/s)	Estimated demand (m^3/s)	% Error
5	3	0.00373	0.00423	13.4
6	3	0.00373	0.00433	16.1
	16	0.00126	0.0012	5.2
7	3	0.00373	0.00432	15.7
	16	0.00126	0.00118	6.3
	19	0.00051	0.00052	3.6
	27	0.00297	0.00298	0.2

Parameter Estimation in WDN

- **Given measurements flows, pressures and outflows estimate pipe roughness coefficients**
- **State estimation is extended to perform combined state and parameter estimation**
- **Step-1: Reduce number of parameters by grouping pipes**
  - **K-means clustering algorithm used to group pipes based on pipe diameter and age**
- **Step-2: Estimate states and reduced set of pipe coefficients**
  - **Graph theoretic reduction procedure extended**

Case studies for parameter estimation

Pipe No’s	**Cases- 8,9 and 10**	**Case - 11**
1-5, 56	120	60
10-23, 29-33, 57-69	120	90
6-9, 24-28, 34-55, 70, 71	120	120

Measurements for different cases

Case	Measured variables			Noise (Yes/No)
	Flows in pipes	Pressures at nodes	Demand at nodes	
8	1-5	1, 23-26	All 45 nodes	Yes
9	1-15	1, 23-32	All 45 nodes	Yes
10	1-24	1, 23-32	All 45 nodes	Yes
11	1-24	1, 23-32	All 45 nodes	Yes

For cases 8,9,10 and 11– noise added 1% of the true value

Comparison of actual and estimated HWC

Pipe No's	Actual HWC	Case-8		Case-9		Case-10	
		Estimated HWC	Error %	Estimated HWC	Error %	Estimated HWC	Error %
1-5,56	120	111.85	6.79	112.24	6.46	114.84	4.3
10-23,29-33,57-69	120	130	8.33	115.16	4.03	130	8.33
6-9,24-28, 34-55, 70,71	120	76.48	36.26	109.02	9.15	125.51	4.59

Case-11	Pipe No's	Actual HWC	Estimated HWC	Error %
	1-5, 56	60	64.38	7.30
	10-23, 29-33, 57-69	90	106.85	18.72
	6-9, 24-28, 34-55, 70, 71	120	130	8.33

Control of water distribution network

- **Control objective**
  - **Equitable distribution of water**
- **Manipulated variables -**
  - **valve openings - continuous valves**
- **Solution strategy – Model predictive control**

Control problem formulation

Objective

$$\min_{u_k \ldots u_{k+M-1}} \quad f = \sum_{i=1}^{N_d} \sum_{j=1}^{P} \left(d_{i,k+j}^{sp} - \hat{d}_{i,k+j} - \hat{d}_k^{pmm} \right)^2$$

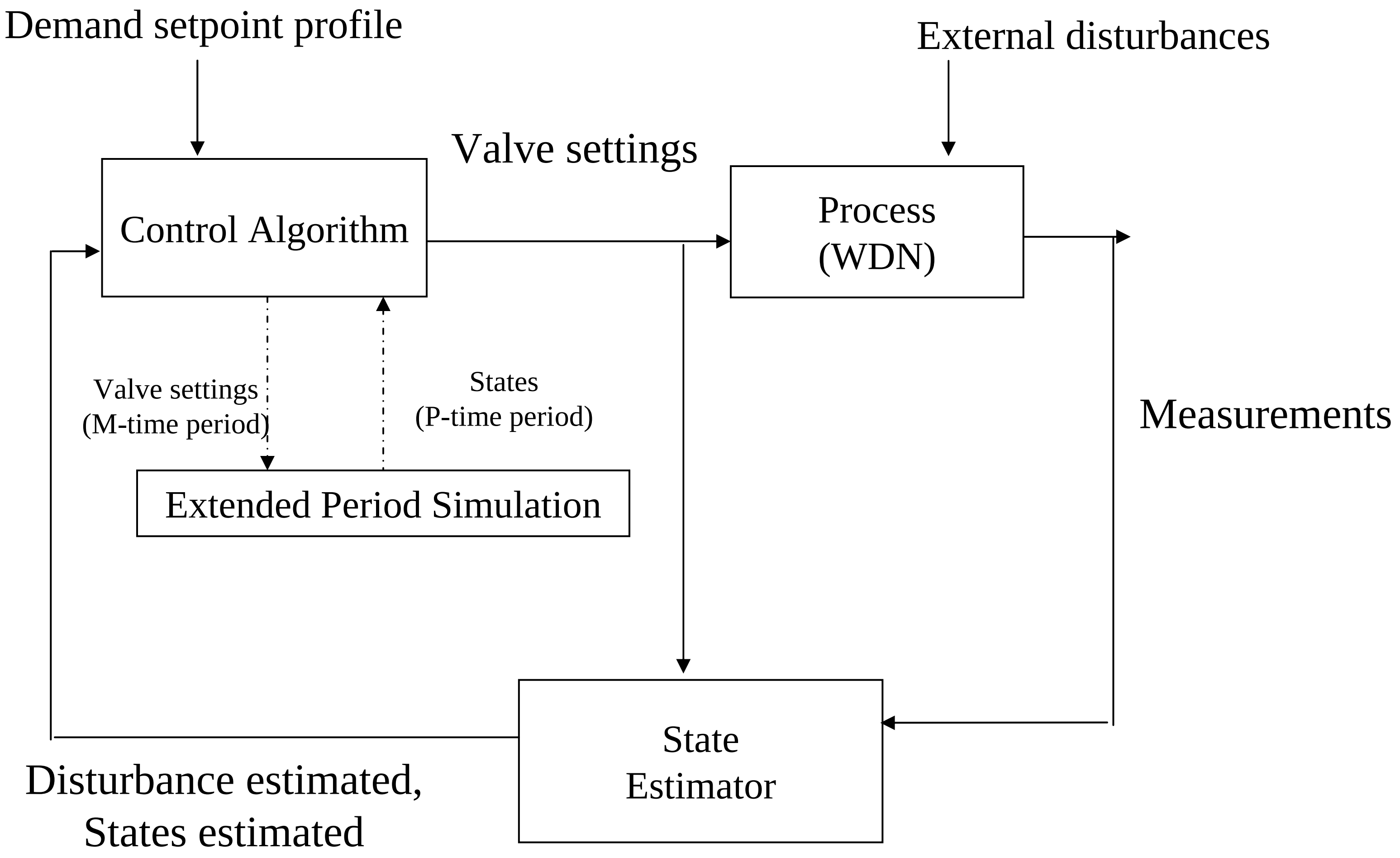
$$\hat{d}_k^{pmm} = \tilde{d}_k - \hat{d}_k$$

Inferential Scheme $$\hat{d}_k^{pmm} = \hat{d}_{k|k-1} - \hat{d}_{k|k}$$

Constraints

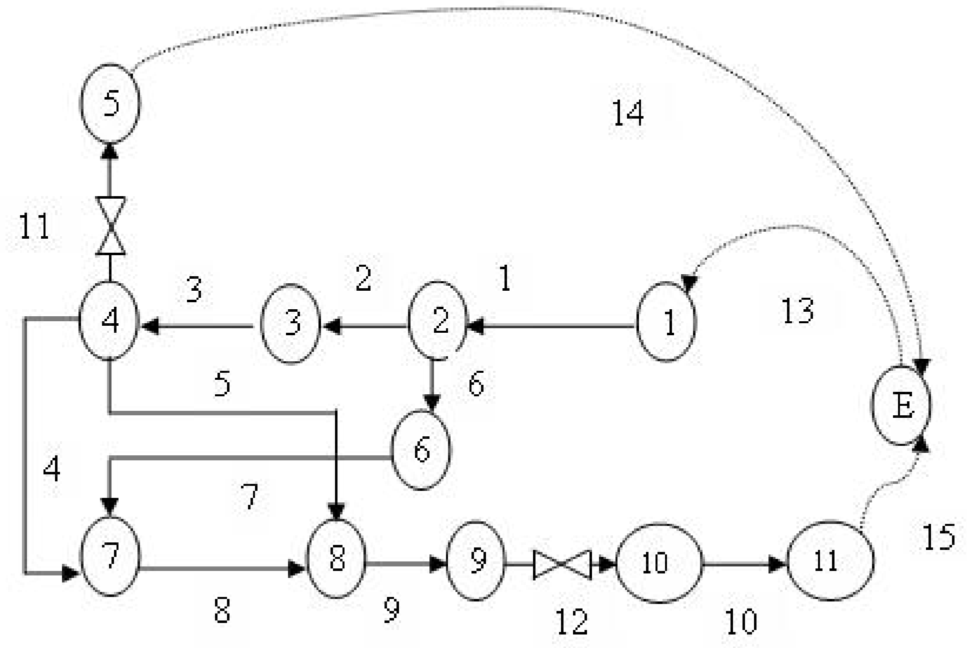
$$\left.\begin{array}{l}\text{▪}0 < \text{U} < 1 \text{ for continuous valves}\\ \text{▪Loop constraints}\\ \text{▪Minimum pressure specifications}\end{array}\right\} \text{ for P time periods}$$

Control strategy – Flow chart



Modular implementation in C interfaced with FORTRAN optimizer

Sample network with only continuous valves



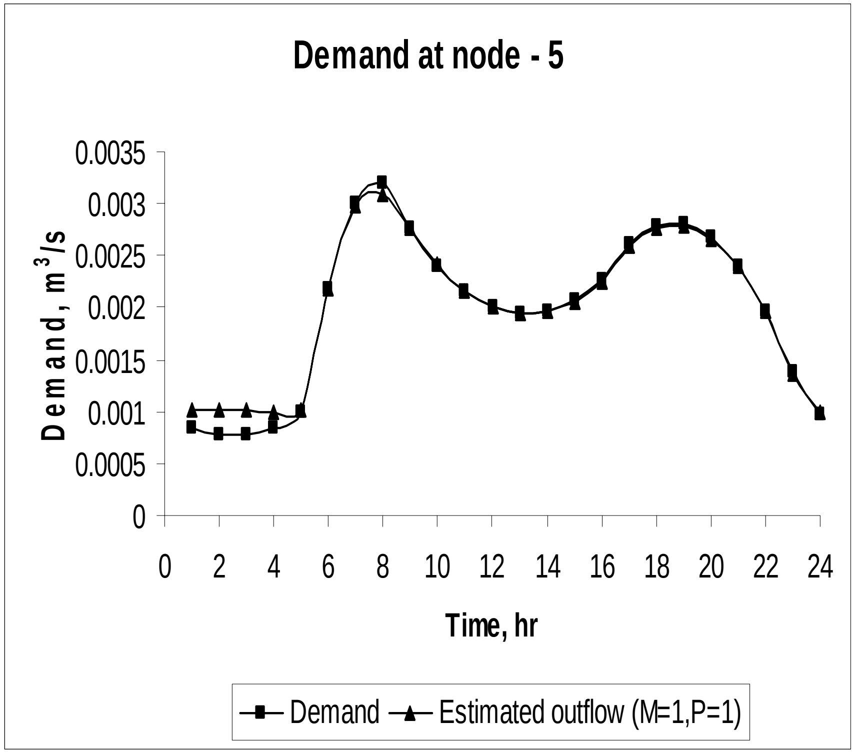
Case studies

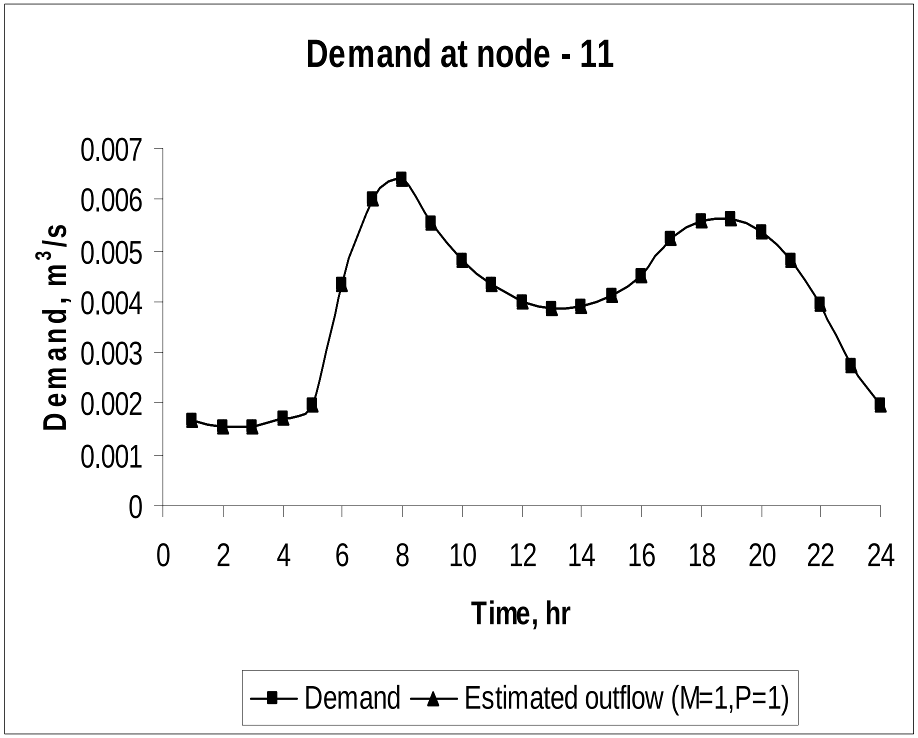
Case	Water available in reservoir
1	Sufficient
2	Insufficient

Continuous valves = 11 and 12

Demand nodes = 5 and 11

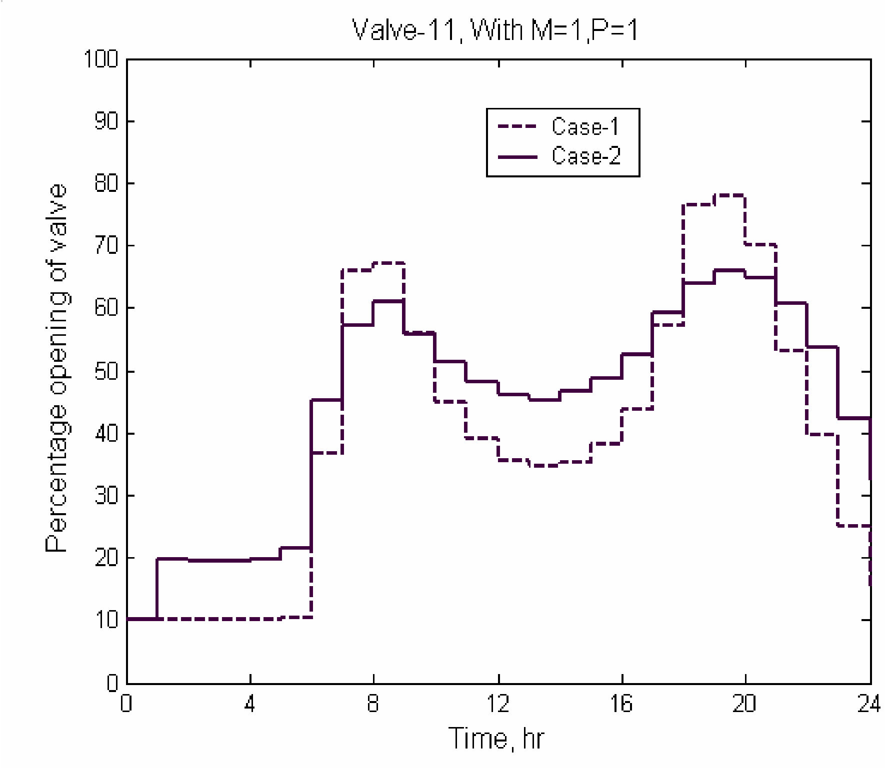
Case- 1: Control algorithm results

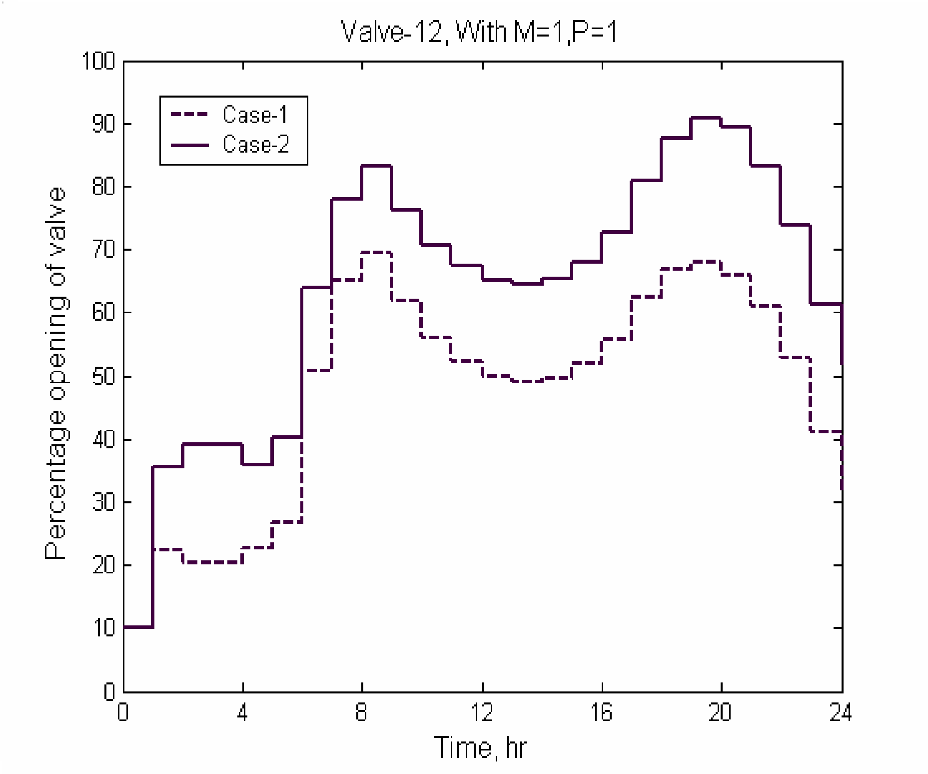




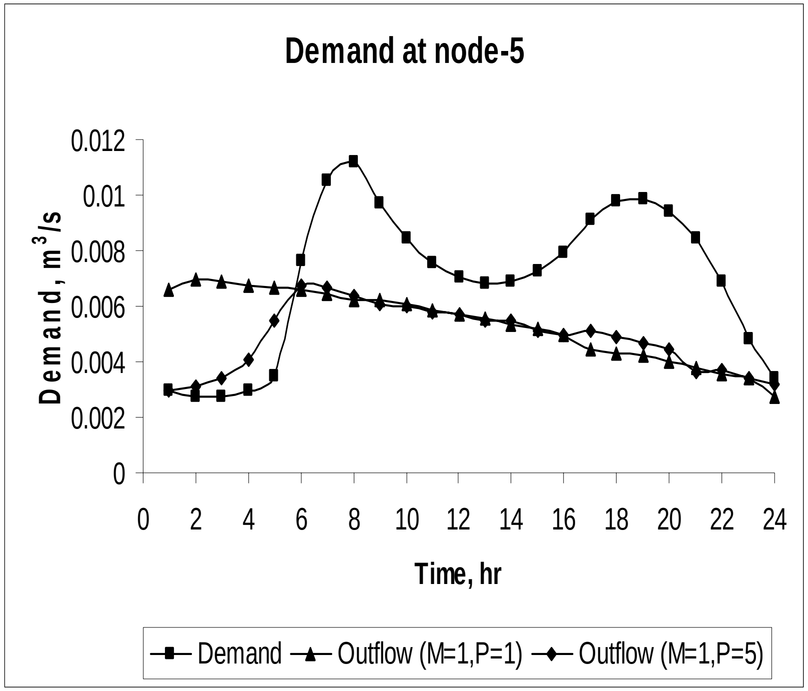
Demand at nodes are met since sufficient water available

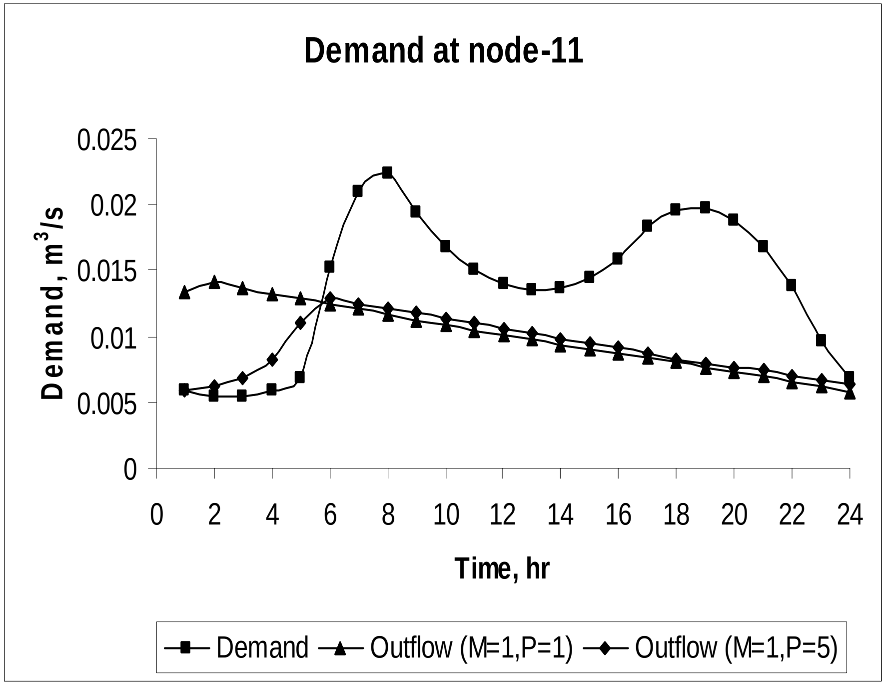
Case- 1: Control algorithm results





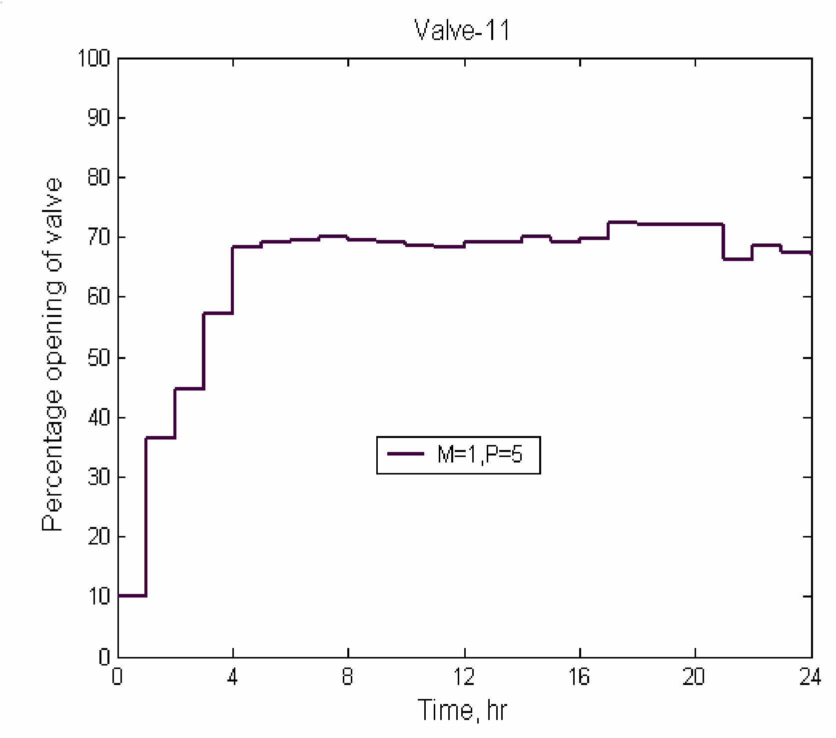
Case- 2: Control algorithm results

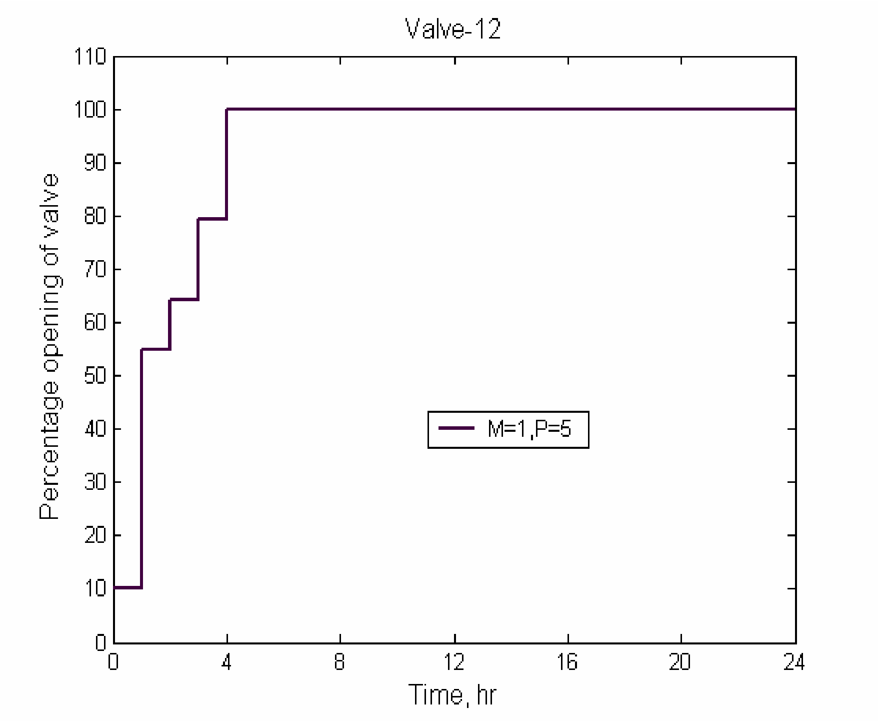


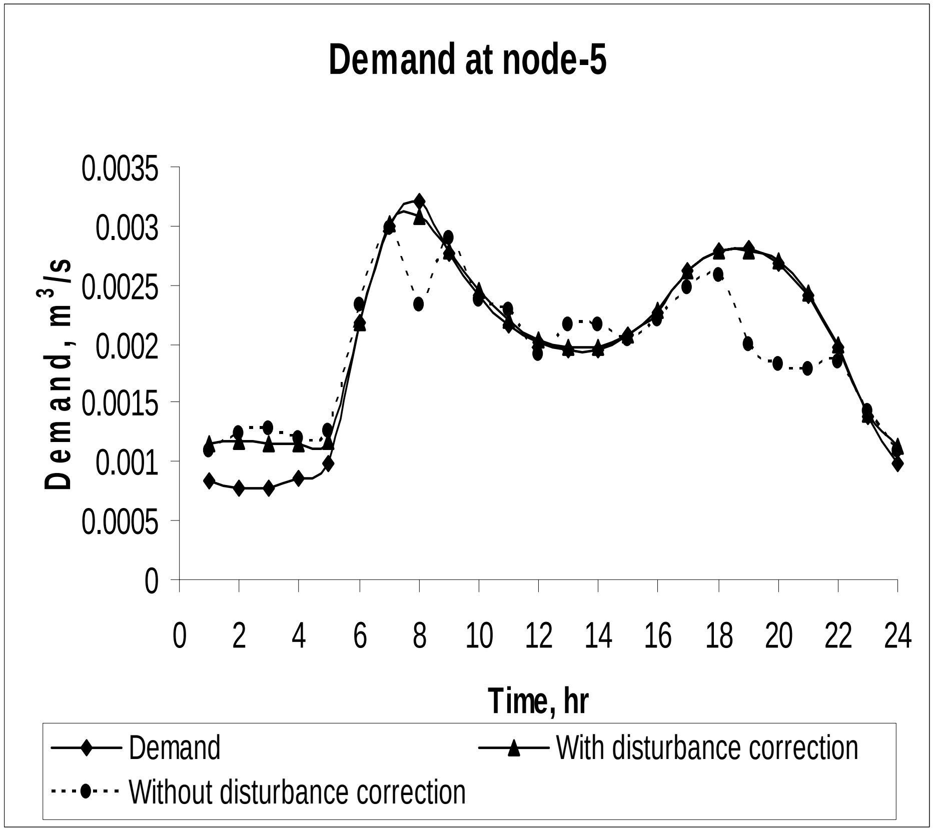


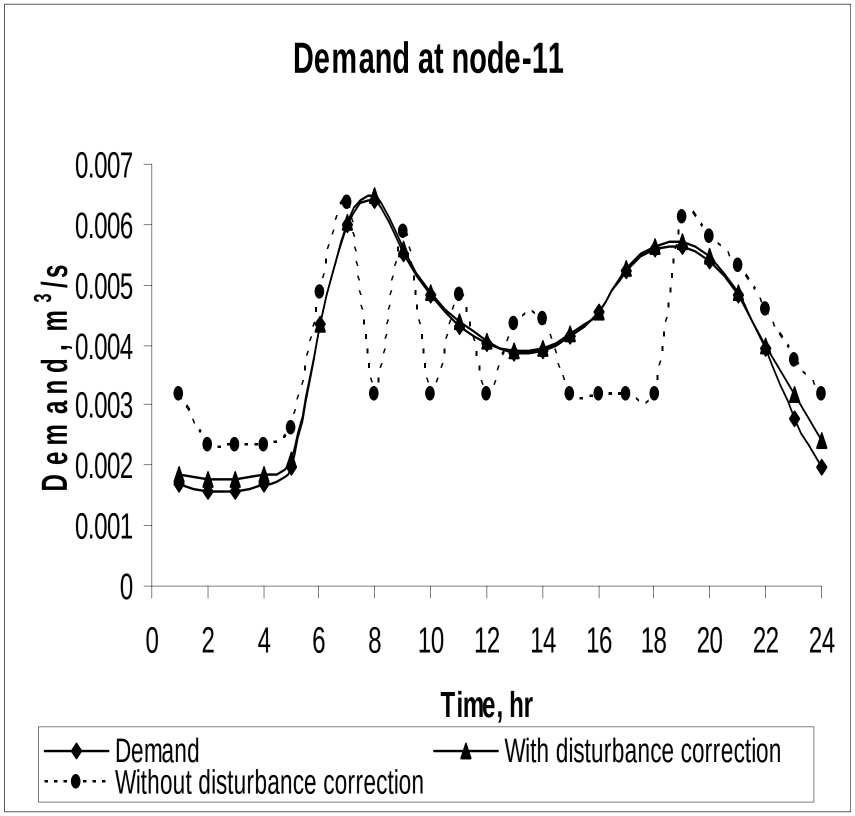
Demand at nodes are not met since sufficient water is not available

Case- 2: Control algorithm results






Demand at node-5
0.0035
0.003
0.0025
0.002
0.0015
0.001
0.0005
0
Demand, m3/s
0
2
4
6
8
10
12
14
16
18
20
22
24
Time, hr
Demand
With disturbance correction
Without disturbance correction


Demand at node-11
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Demand, m3/s
0
2
4
6
8
10
12
14
16
18
20
22
24
Time, hr
Demand
With disturbance correction
Without disturbance correction

Thank You..