AAiT

Addis Ababa
Institute of Technology
School of Civil and
Environmental Engineering

Water Distribution Modelling
Lecture By Fiseha Behulu (PhD)

Lecture-3:
The Modeling Theory

Prepared By

Fiseha Behulu, AAiT

2020

Contents of the Course

1. **Components of Water Supply**
2. **Basic Principles of Pipe Flow (Hydraulics)**
3. **The Modeling Theory**
4. Model Calibration
5. Optimization in WDS
6. Water Hammer Theory
7. Water Supply Project Design (Application of Tools)

The Mopics

- The Modeling Theory
  - Introduction
  - What is a model
  - Why do we model a system
  - Conceptualization of a Model
- The modeling process
  - Key elements of a model
  - Methods for network Analysis
  - Fundamental Concepts
- Review of Principles, Methods, Models and Practices

Introduction

- In our previous lectures, we have covered Water Distribution Network analysis methods based on hydraulic principles. Now let's move from Network Analysis to Modeling.

- Model-based simulation is a method for mathematically approximating the behavior of real water distribution systems.

- Understanding of the mathematical principles involved are the key for a successful modeling.

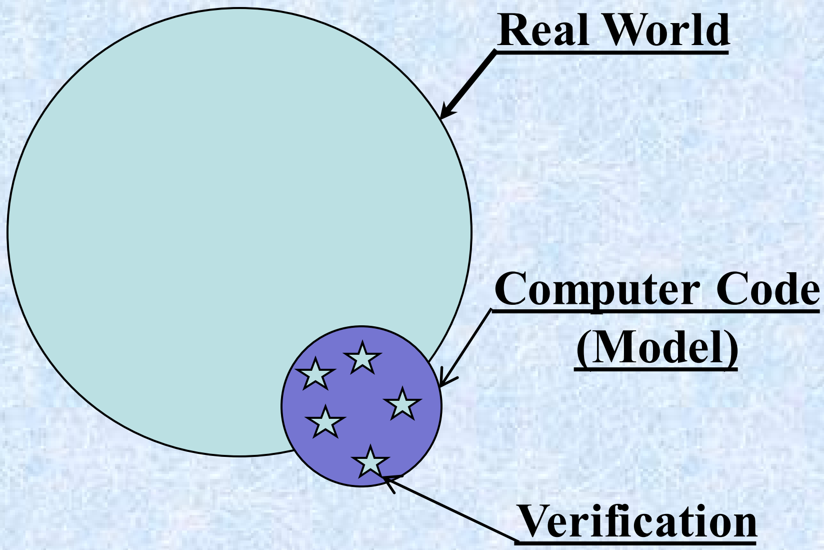
- Therefore review of pipe flow hydraulics and network modeling software are quite essential

The Modeling Concept

- **What is a model?**

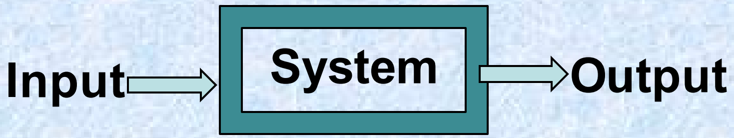
  Various definition exists

  - A model is a simplified representation of a complex system.
  - A model is any device that represents an approximation of a field situation
  - A model is a computer code filled up with variables and parameters of specific system



- **Why do we model a system?**

To replace reality, enabling measuring and experimenting in a cheap and quick way, when real experiments are impossible, too expensive or too time-consuming (Eppink, 1993)*



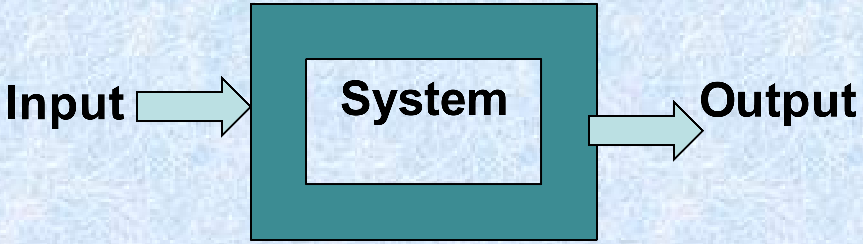
*Processes and models in erosion and soil and water conservation

The Modeling Concept

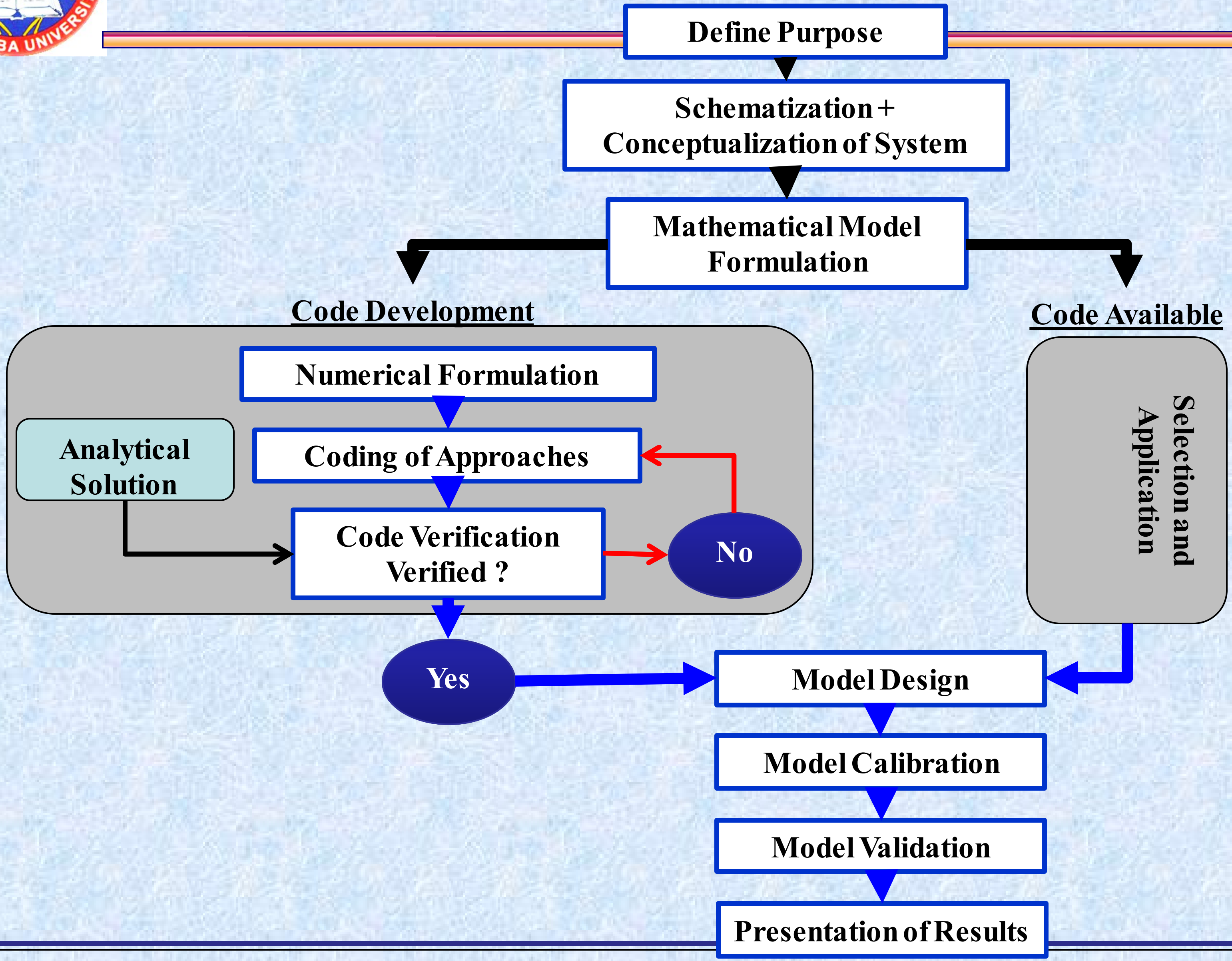
- **Why do we model a system?**

To replace reality, enabling measuring and experimenting in a cheap and quick way, when real experiments are impossible, too expensive or too time-consuming (Eppink, 1993)*

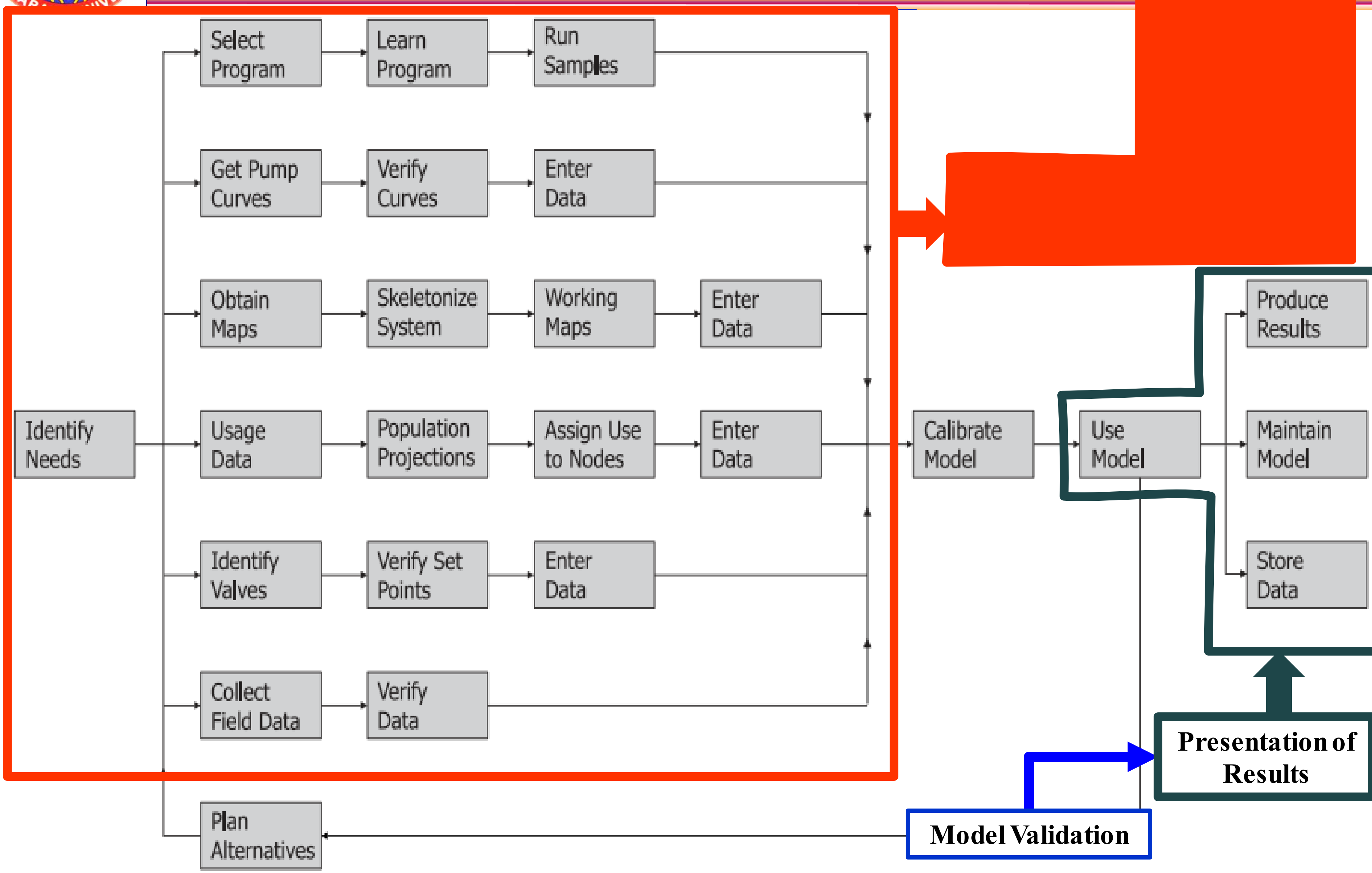
*Processes and models in erosion and soil and water conservation



The Modeling Concept…

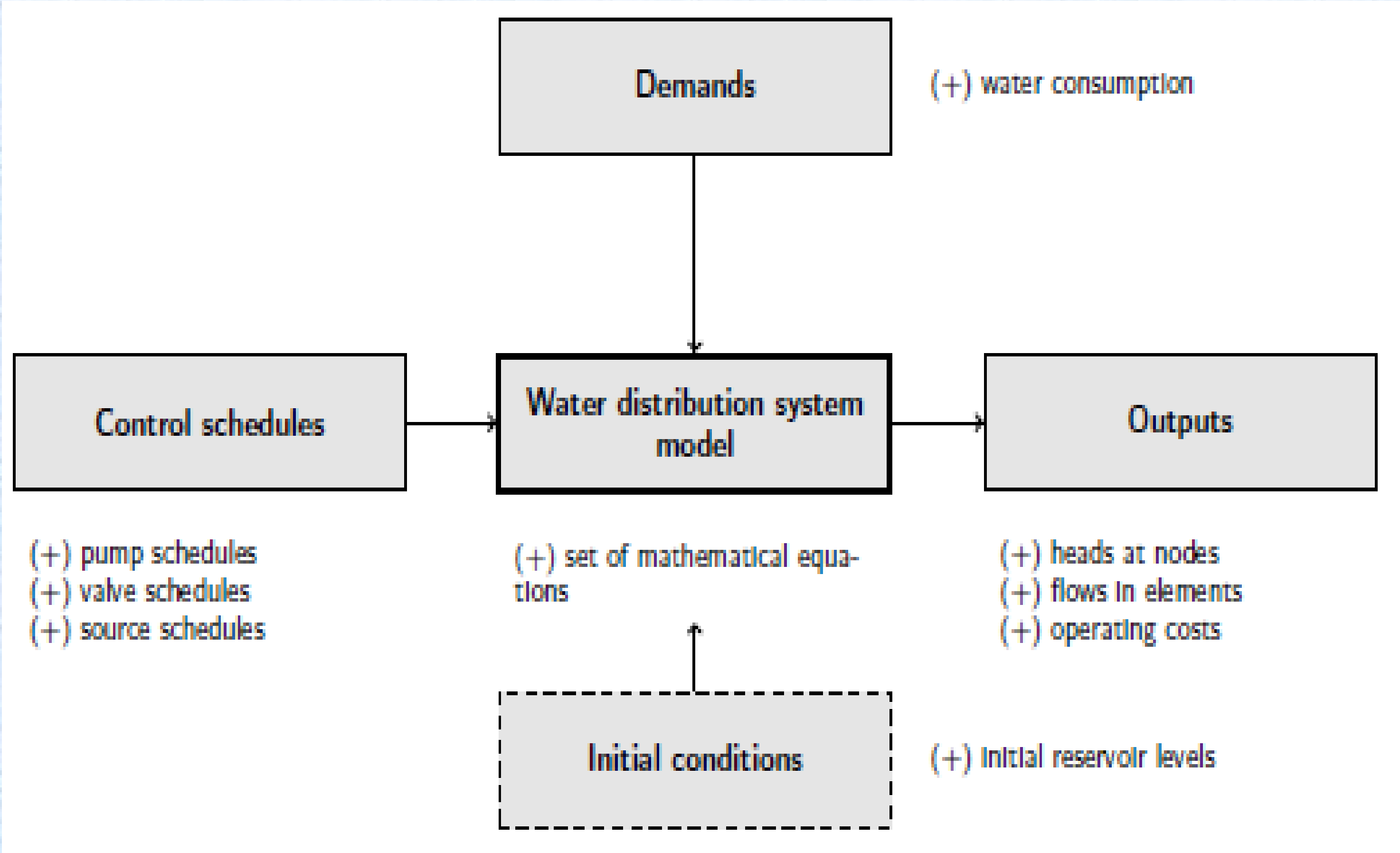


The Modeling Concept…



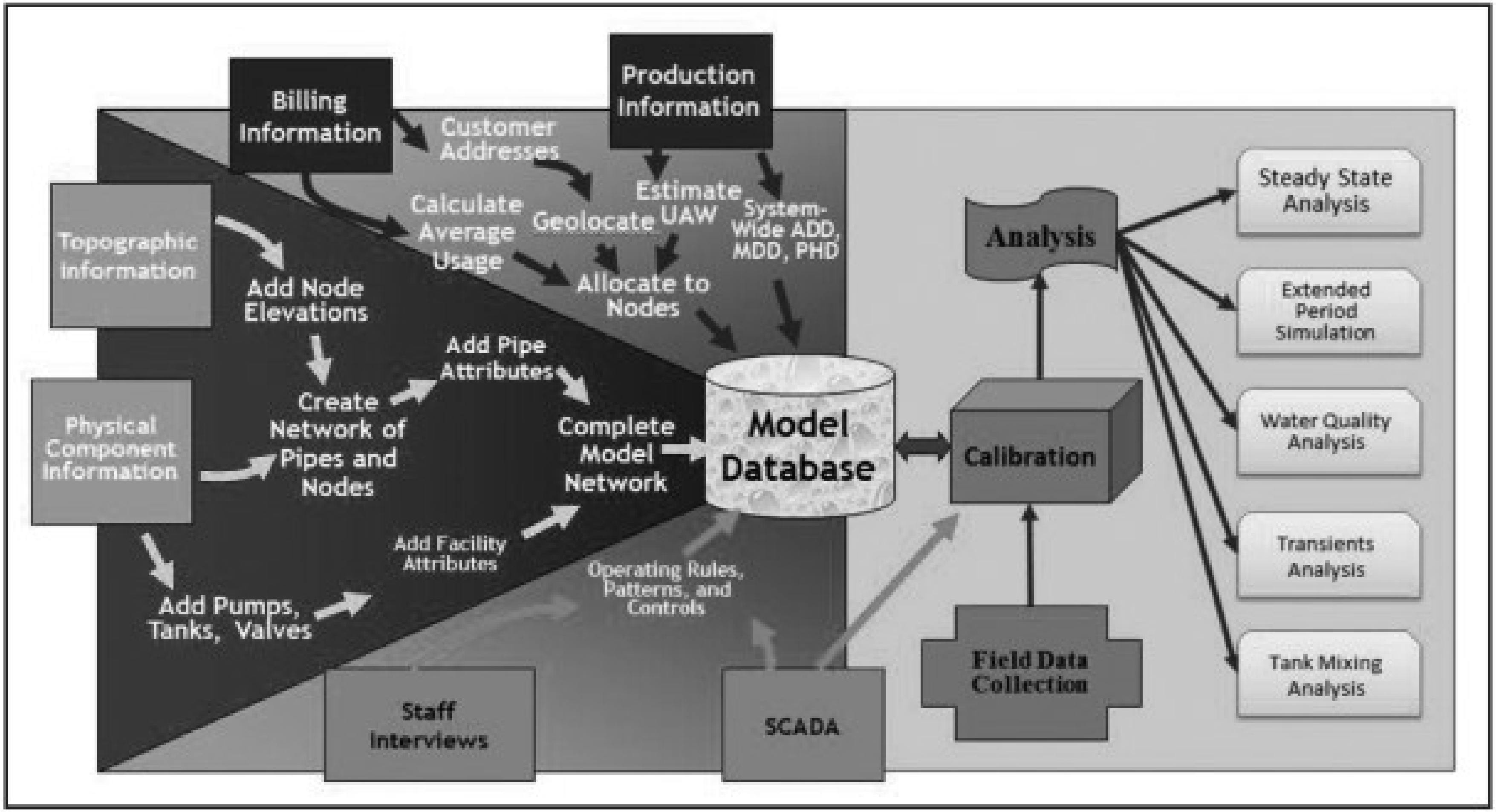
The Modeling Concept…

- From Network Analysis to Modeling



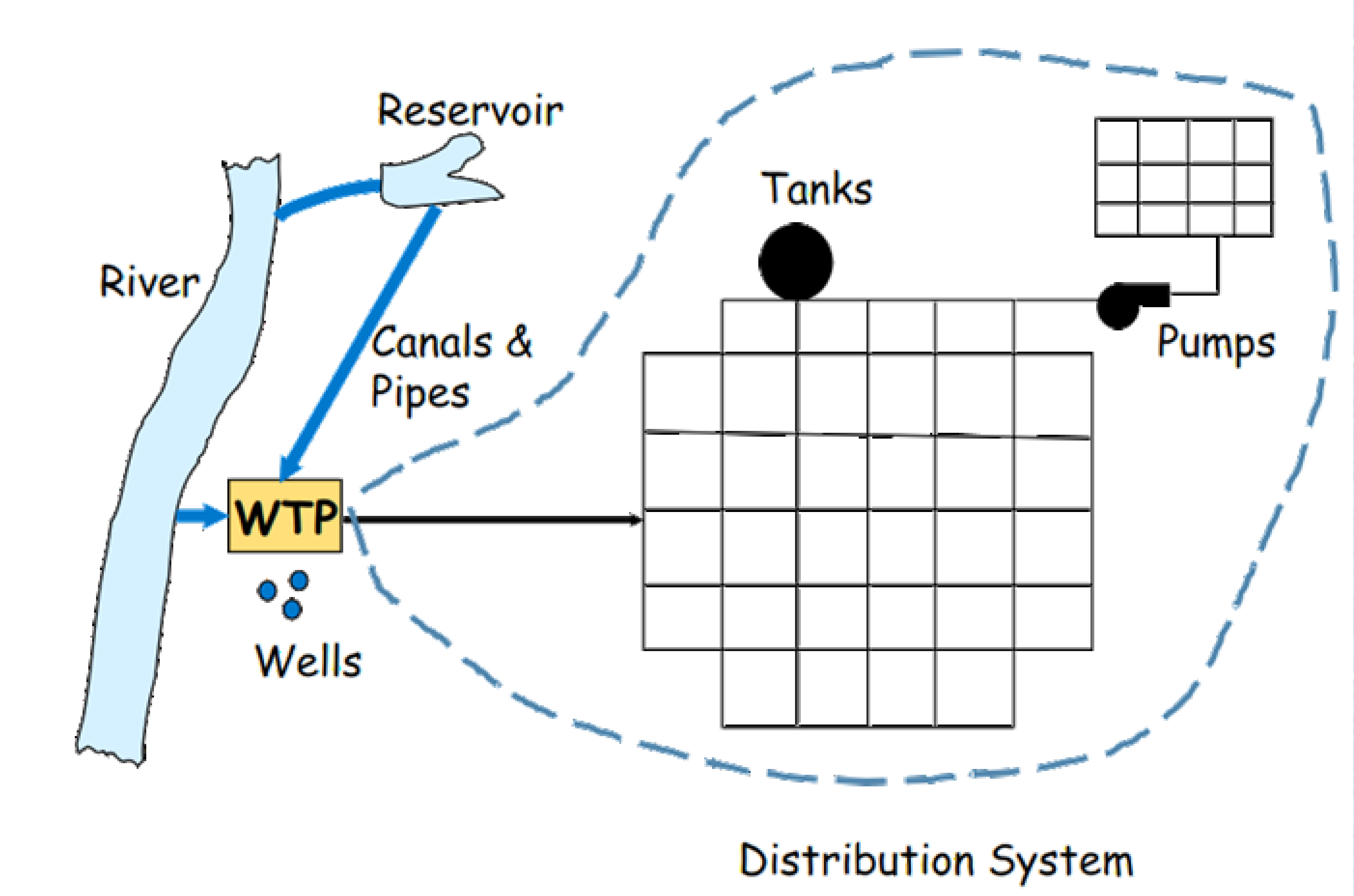
The Modeling Concept…

- The process from model build to analysis



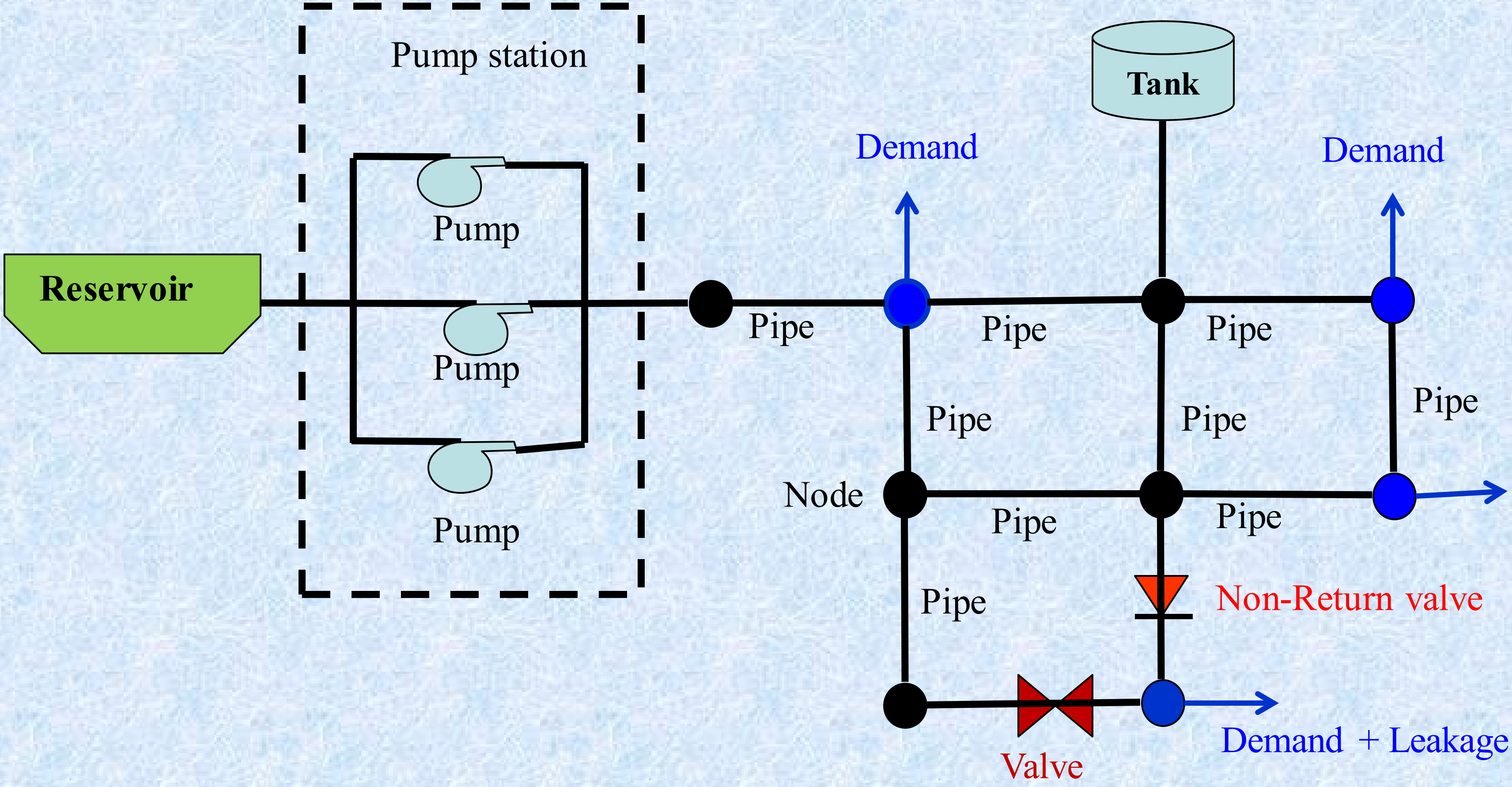
The Modeling Concept
(Water Distribution Systems and Model)

- Elements of a water distribution system (WDS)



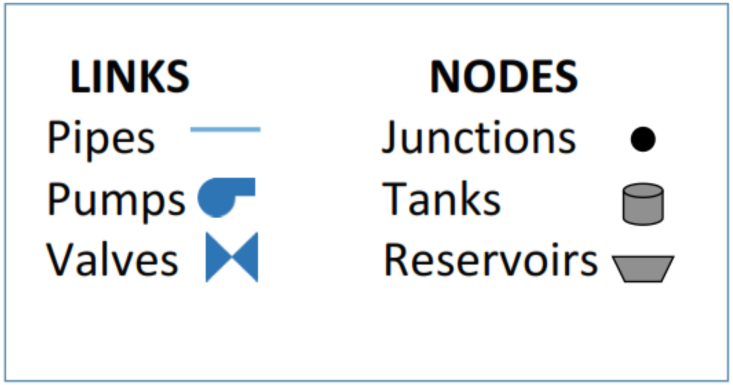
The Modeling Concept
(Water Distribution Systems and Model)

- Elements of a water distribution network model (*Representation of WDS)*

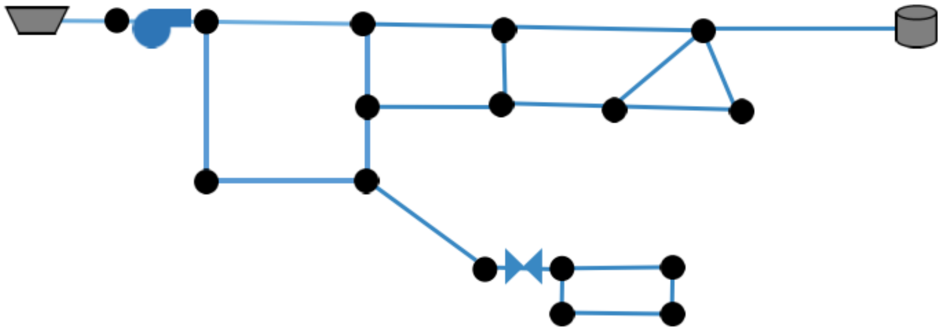


The Modeling Concept
(Water Distribution Systems and Model)

- Elements of a water distribution network model (*Representation of WDS)*



- Links and nodes are generic names.
- Pipes, pumps, junctions, tanks, etc. are specific types of links and nodes.
- A link connects two nodes
- The specified direction of a link depends on the specific type of link.

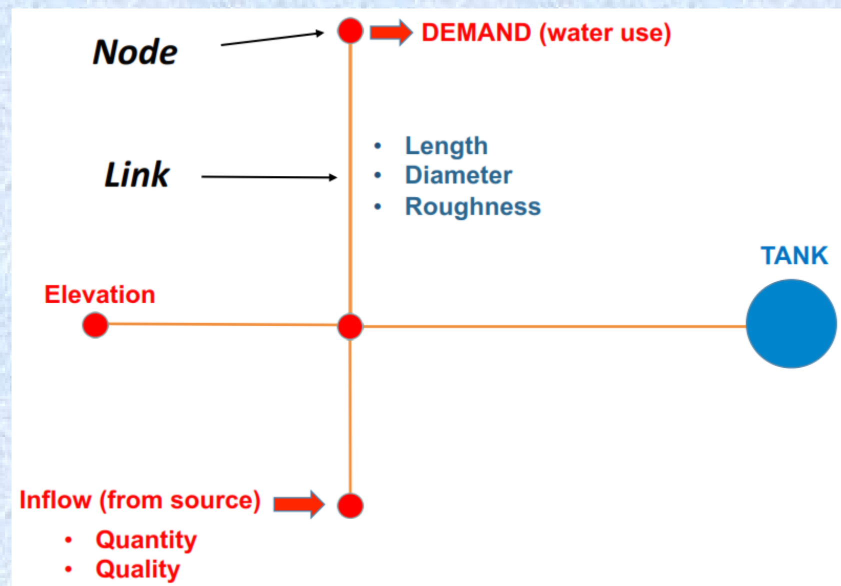


- Water Distribution System- Defined

  - A collection of pipes, tanks, pumps, valves, control systems and other appurtenances that together are used to move water from a water source or treatment plant to individual water users





The Modeling Concept
(Water Distribution Systems and Model)

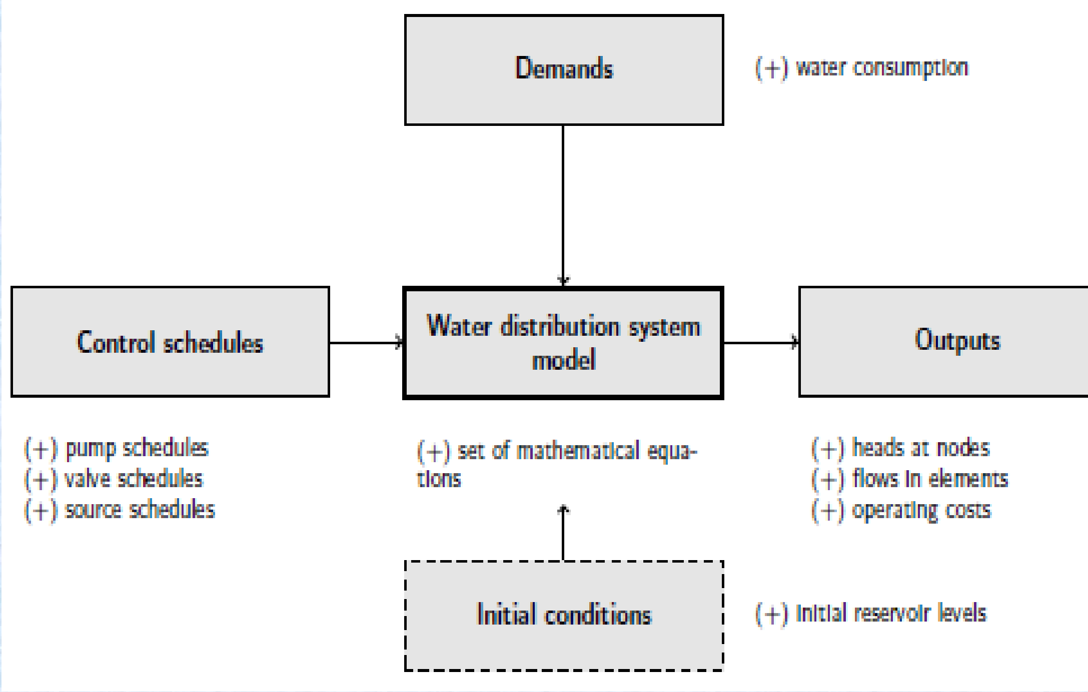
- What is a water Distribution System Hydraulic Model?

  - It is a computer program (software)
  - It takes **as input:**
    - Pipe network layout
    - Water demand (consumption)
    - Information on system operation

  - It provides **as output**
    - Flows and pressures (heads) in the network
      - Steady-state: at a single point in time
      - Extended period simulation: at each time step

Methods for Network Analysis

- Demand allocation
- Network configuration
- Control system
- The model equations
- Decisions to be made



Fundamentals

Elements	Type	Modeling Purpose
Tank(variable head)	Node	Stores excess water within the system and releases that water at times of high demand
Reservoir (forced head)	Node	Provides water to the system
Junction	Node	Removes(demand) or adds water to the system
Pipe	Link	Conveys water from one node to other
Pump	Link	Raise hydraulic grade
Control valve	Link	Regulates flow or pressure

Problems that could be analyzed with the help of modeling (Pilipovic, 2004)

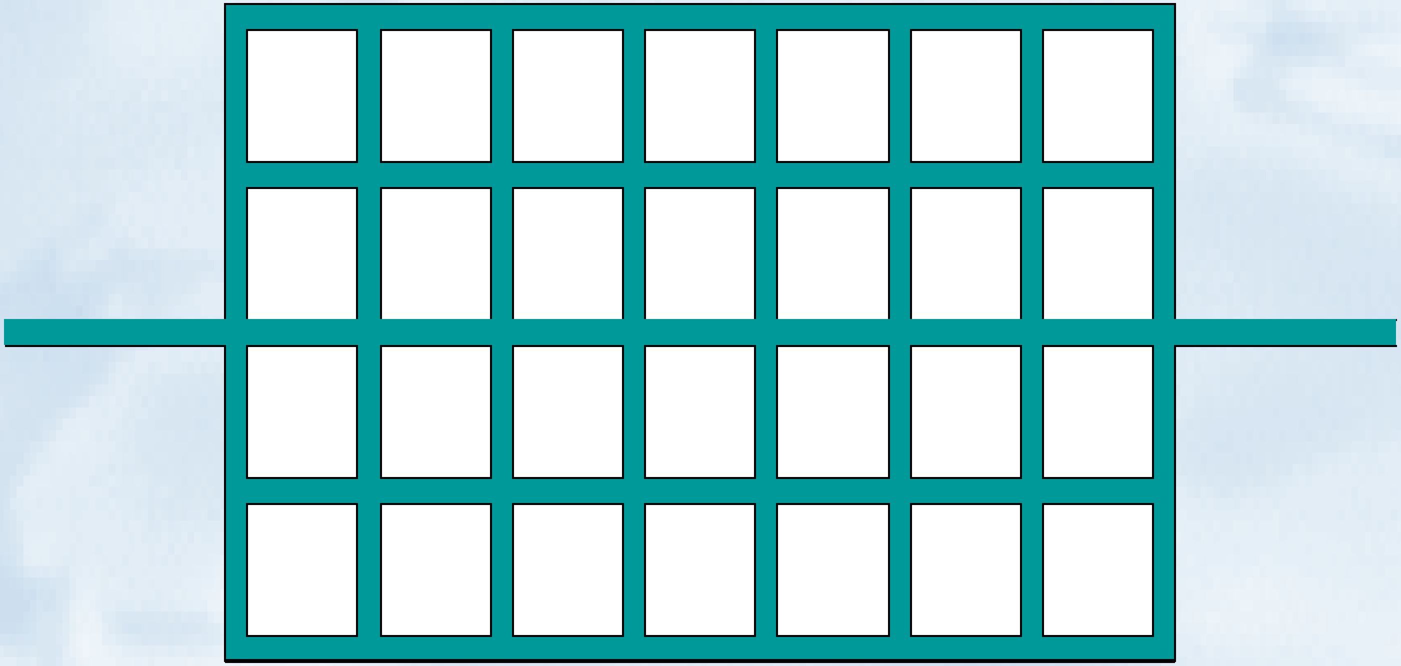
Domain	Possible problem
Operational management	Developing and understanding of how the system operates. Training water system operators. Assessing the level of service. Assessing the carrying capacity of the existing system. Assessing the efficiency of current operational management policy. Assessing levels of pressures at critical points within the system. Identifying and resolving operational anomalies. Low pressure or high pressure fluctuation problems. Low fire flow at hydrants - if it is different from expected capacity. Daily operational use - shutting down a section of the system due to major breaks. Power outage impact on pump stations. Sizing control points subsystem metering, control valves PRV, PSV, FCV. Sizing sprinkler systems fire service and other. Assessing the available range of pressure at customer connections. Real time control of the system.

Problems that could be analyzed with the help of modeling (Pilipovic, 2004)

Planning	Identifying the impact of future population growth on the existing system. Identifying the impact of major new industrial or commercial developments on the existing system. Identifying key bottlenecks in current and future systems. Designing the reinforcement to the existing system to meet future demand. Designing the new distribution system. Optimizing the capital works programs. Assessing the new resource option. Assessing the effects of rehabilitation techniques. Leak control reducing losses by lowering maximum pressure. Demand management reducing the pressure related demand by lowering service pressure. Sizing elements of the system to meet fire service requirements in existing and future systems. Assessing the value and design of distribution monitoring systems. Contingency planning.

Problems that could be analyzed with the help of modeling (Pilipovic, 2004)

Legislative	Assessing levels of service, regulatory levels of service reporting, and options for future planning based on community consultations. Maintaining water quality within predefined regulated values. Assessing the financial contribution required for new developments. Water and pressure requirements for fire fighting purposes.
Water quality	Disinfectant residual assessments. Substance tracking, determination of age of water, water blending from various sources. Analysing water quality contamination events.



Network Modelling :

Review of Principles, Methods, Models and Practices

Modelling Water Distribution Networks

- Fundamental Principles
- Methods for network analysis
- Network configuration
- Demand allocation
- Pressure zoning
- A brief review of modelling tools
- The modelling process
- Modeling in WaterCAD
- Integrated decision making approach in WDM
- Real time WDS management
- Current research trends

Review of Models

- Public Domain
  - EPANET
  - Branch
  - Loop
- Commercial
  - Aquis
  - H20 map
  - KYPipe
  - WaterCAD, WaterGEMS etc

Review of Models- Issue

- Data management
- Graphic user interface
- Reporting
- Simulation dimension
  - Hydraulic analysis
  - Water quality analysis
  - Steady state and extended period simulation
  - System optimization
  - Scenario building and management

Review of Models…

WaterCAD V8i

- Wide range of functionality
- Flexibility in data archiving and profiling
- Hydraulic and water quality analysis
- Steady state and extended simulation
- Integration with AutoCAD and GIS
- Optimization and scenario management

Review of Models…

WaterGEMS V8i

- Wide range of functionality
- Flexibility in data archiving and profiling
- Hydraulic and water quality analysis
- Steady state and extended simulation
- Integration with AutoCAD and GIS
- Optimization and scenario management
- Geospatial integration

Branch

- Branch is public domain optimization software in which program is developed to design the branched water distribution networks. Branch software takes certain parameters like elevation data, pipe lengths, coefficient of friction and demand of nodes as inputs over the cost as function. The output is optimized length and diameters of pipes so that overall cost of network is the least one.

Review of Models…

DisNet

- DisNet (2014) is powerful and efficient water distribution software and offers great simplicity in building water distribution networks. Key strengths of DisNet include its simplicity and appealing user interface with maximum accuracy in output with optimum input details. Along with design of water distribution, DisNet is used in the modeling of stream hydrology, generation of unit hydrographs and establishing interrelationships between them. DisNet is integrated with CAD as its inbuilt management tool and used in modeling different types of water distributions networks for different topographical conditions .

EPANET

- EPANET (2014) is public domain software which can be efficiently used to design any sort of network. It provides variety of advantages like water quality analysis, extended period simulation, residual chlorine calculations for disinfection, etc. It can also be used to renovate or restore the existing water supply systems. It is available as public domain softwares with the relative nomenclature as EPANET 2.0, EPANET 2d-2w .

HydraulicCAD

- HydrauliCAD (2014) is AutoCAD based water distribution software integrated with EPANET hydraulic analysis program. Fundamental understanding serves the purpose of building hydraulic model with it. HydrauliCAD possesses a feature of building query for addition and editing of different hydraulic parameters like head-loss, pressure, flow of distribution networks. HydrauliCAD provides inbuilt pipe catalogue comprises of detailed information about pipe material, classes and sizes.

Review of Models…

HydraulicCAD

- Along with water distribution HydrauliCAD is also used for fire-flow analysis. HydrauliCAD is versatile software used by the modelers, field professionals and engineers .

WATSYS

- WATSYS (2014) is water distribution simulation and modeling software based on Geographical Information System (GIS). WATSYS is efficiently used for designing new water distribution as well as for up-gradation of existing distribution network. WATSYS uses EPANET program as basis for water distribution and water quality analysis scenarios. WATSYS is easily integrated with AutoCAD to use CAD based drawings to develop and build hydraulic networks.

- WATSYS comprises of features like color-coded plans for making colorful visualizations of pressure, elevations and flows at different nodes, easy importing and exporting data files, in-built pipe catalogue, etc. WATSYS is efficiently used for simulation and modeling variety types of distribution networks .

KYPipe

- Pipe2014 is the recent version of KYPipe hydraulic modeling software package which has a strong computational algorithm for the fluids essentially water. Pipe2014 can be used for the designing and selection of pumps, valves, tanks as well as pipes. It also includes the features like sizing of pipes and optimization of pump operations. Pipe2014 provides a very interactive and user friendly interface which offers extensive flexibility to users for the designing and optimization of distribution networks.

KYPipe

- Pipe2014 is compatible to integrate with GIS and variety of formats of images used for designing distribution networks .

Synergi Water

- is hydraulic modeling and simulation software package with the strong database management used for increasing the efficiency of existing distribution network as well as in the design and development of the newer one. Synergi Water provides the variety of advantages over other public domain softwares, as it provides versatile environment of tools for detailed and comprehensive modeling, performs speedy and accurate analysis of extremely large systems comprising of more than one hectar system

Review of Models…

Synergi Water …

components, water quality modeling and designing of complex systems with proper arrangements of pump, valves and tanks. Its integrity with the GIS and SCADA is extremely flexible which makes the remote operations simple and trouble free .

H2Onet

- H2Onet and H2Omap (2015) are commercial soft wares which are integrated with the GIS and used for design, analysis and optimization of different types of water distribution networks. It is advantageous for leakage detection and assessment, analysis of fire-flow and hydrant, cost optimization, etc. The most important feature which makes this software stand-out includes programmed and automated online SCADA interface. Its integration with GIS software provides different vector and raster tools which supports wide range of spatial analysis, sampling, planning, evaluation and assessment of existing as well as newly developed water supply system

HYDROFLO3

- HYDROFLO3 (2015) is advanced version of HYDROFLO series and used to design variety of the distribution systems includes pumped flow, gravity fow, flow through pipes as well as open channel flows. HYDROFLO3 offers advantages of easy conversions between Metric and SI units, calibration and validation of existing networks, easy addition and editing of hydraulic parameters of entire distribution network.

Review of Models…

HYDROFLO3…

HYDROFLO3 provides a unique feature as Pump base used for the calculation of pump hydraulic characteristics required in forced flow systems. Along with water distribution networks HYDROFLO3 is used for simulation of treatment plants, chemical dosing systems, industrial applications, fireflow analysis, etc. It is comprehensive software package used to design variety of distribution networks with strong data management capacity [14].

Others

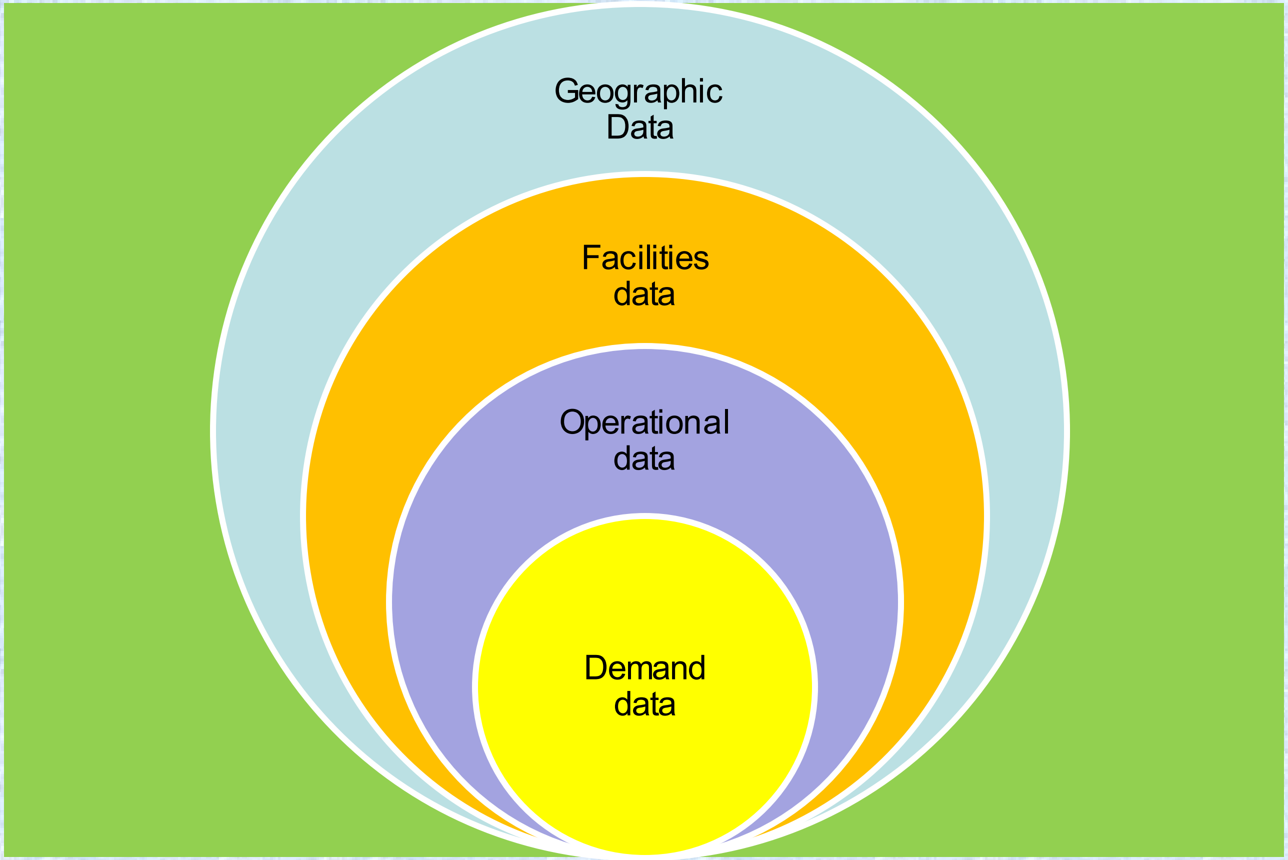
- Apart from these softwares large number of other hydraulic modeling and optimization softwares are available in the market which essentially include Archimede, Cross, Eraclito, Helix delta-Q, Netis, OptiDesigner, Wadiso SA, etc

The Modeling Process

- Preparing the Model
  - System characterization
  - Source data of the network
  - Degree of detail
  - Degree of accuracy
  - Skeletonization

The Modeling Process-(Preparing the Model)

- System Characterization



The Modeling Process-
(Preparing the Model)

❑ System Characterization

- Identify and collect geographic data
- Establish inventory of existing facilities
- Review system operating records and interview staff
- Review water consumption records
- Develop water demand
- Establish background information for power management and operational improvement program

The Modeling Process-
(Preparing the Model)

Sources of network data

- Paper data
- Electronic data
- Physical inspection

Degree of Detail

- Intended purpose of the model (e.g. long range planning, leakage control, water quality modeling)
- Sources:
  - Paper data
  - Electronic data
  - Physical inspection

The Modeling Process- (Preparing the Model)

- **Degree of Accuracy**
  - Distribution system's sensitivity
  - Sensitivity analysis

- **Skeletonization**
  - Modeling simplicity
  - Purpose of the model (e.g. transmission main design, master planning studies, small distribution systems, water quality analysis, etc.)
  - Scenario management capabilities

Summary of Model Formulation Step

Determine Purpose of the Model and Simulation Process

↓

Establish Inventory of Existing Facilities and Data Sources

↓

Review Operating Records and Interview Operations Staff

↓

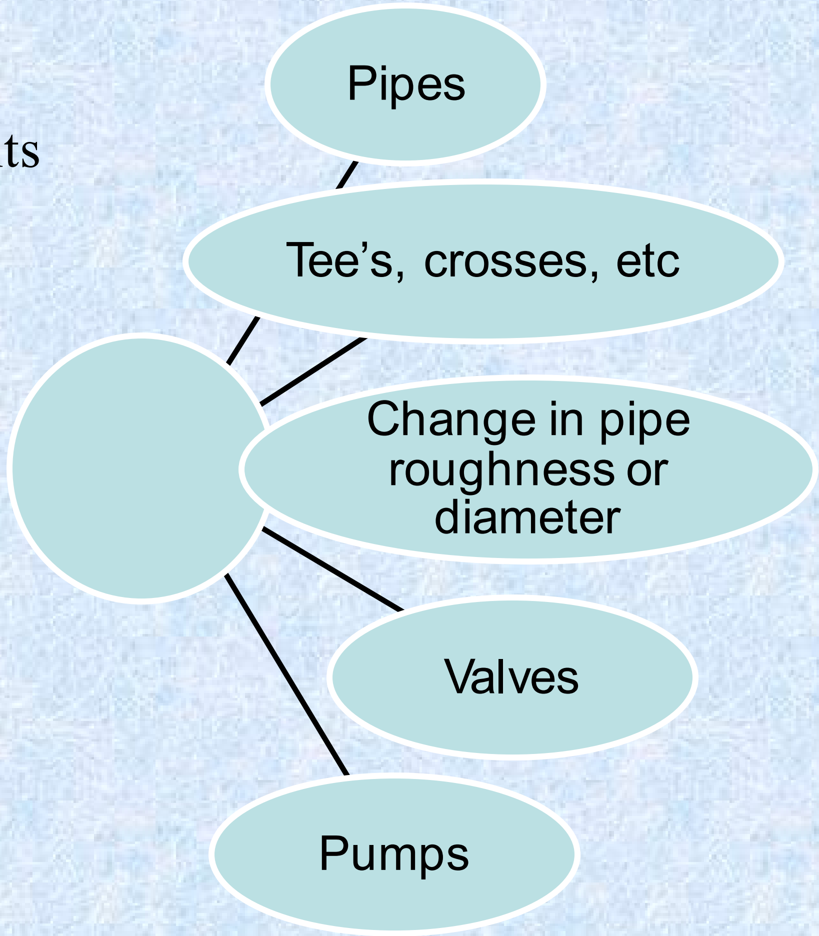
Review Consumption Records and Develop System Demand Curves and Determine Critical Demand Conditions

↓

Develop the Hydraulic Model , Calibrate Model, Validate Model

The Modeling Process-(Model Setup)

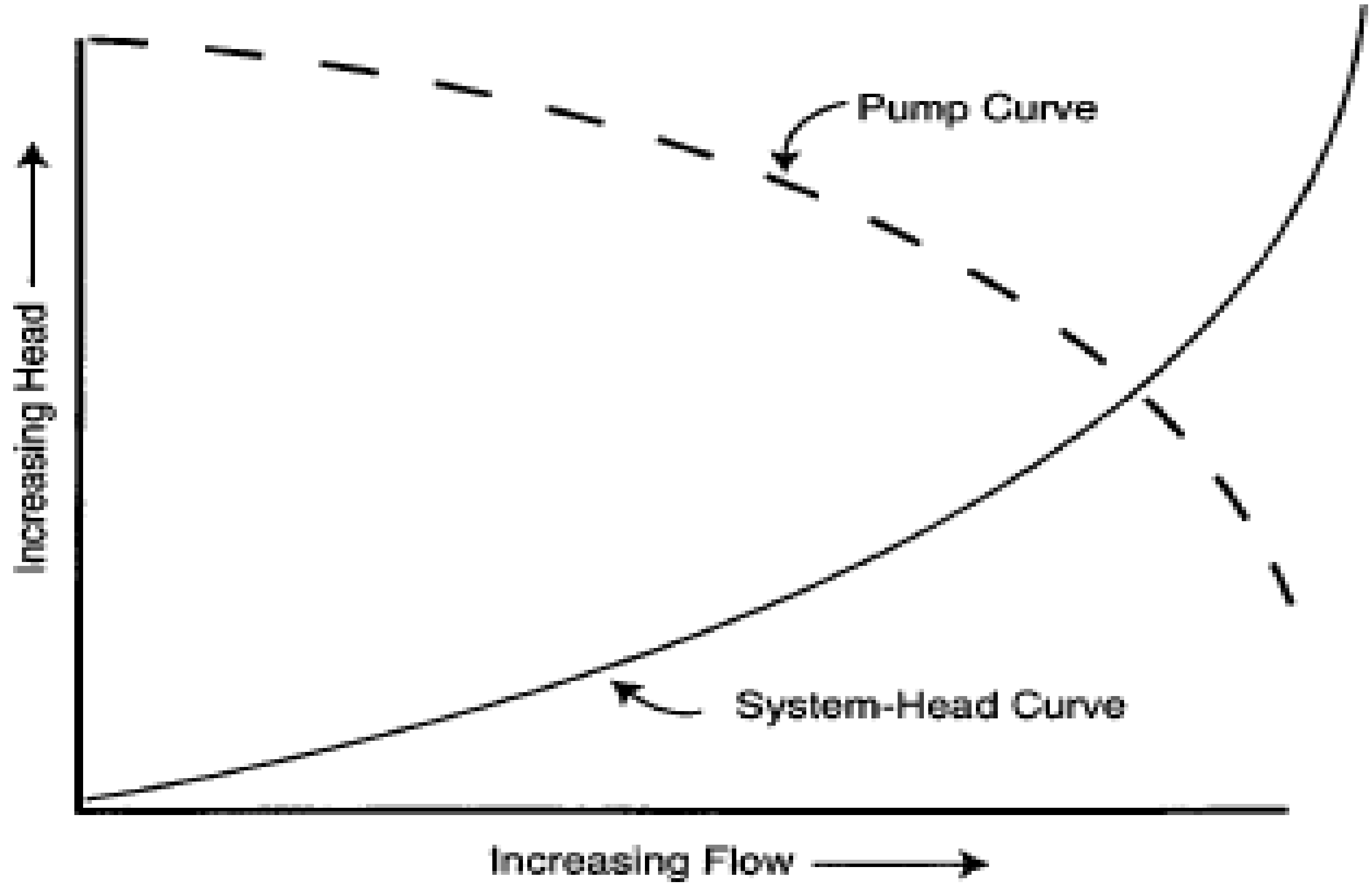
- **Nodal Data**
  - Node end points



The Modeling Process-
(Model Setup)

- **Elevation Data**
  - Two categories
    - Control elevations
    - Ground elevations
- **Facilities data**
  - Data on nodes, ground elevations, pipe etc.
  - Pipes (material properties, length, diameter, roughness)
  - Pumps (Characteristics curves)
  - Valves (manual isolation valves, check valves, automatic control valves)

The Modeling Process-
(Model SetuP)



Pump curve

The Modeling Process-
(valves)

Modeling valves

- Manual isolation valves – generally not modelled
- Check valves –
  - if in front of pumps do not bother about it.
  - However in the distribution system – then modelled as a valve link or pipe link specified with one directional flow.
- Automatic control valves (1. pressure reducing valves 2. pressure sustaining valves 3. altitude valves 4. flow control valves 5. Vacuum breaking valves)

The Modeling Process- (Model SetuP)

- **Pressure Reducing valves -** detect pressure on the downstream end of the valve and will throttle if necessary to ensure that the downstream pressure does not exceed a set value. They are used in the distribution system where there is a substantial drop in topographical elevation-without the PRV, excessive pressures develop in the customer residences. When multiple PRVs service a single area, potential exists for the valves to work against each other, creating pressure waves as they try to reduce the operating pressures. Setting the pressure points to a slightly different grade line, making one of the valves predominate, sometimes alleviates this problem

The Modeling Process-(valves)

- **Pressure sustaining valves -** measure the pressure on the upstream end of the valve and throttle to maintain a setback pressure in the system. They are often used on long transmission mains that terminate at a large reservoir. The reservoir feed can then be regulated to ensure that customers serviced along the main have adequate supply pressure.

The Modeling Process- (valves)

- **Altitude valves -** are used in conjunction with reservoirs to automate the filling cycle of the reservoir. A level sensor opens and closes the altitude valves based on two (high and low) level set points. Altitude valves are either fully open or fully closed, so they can impose a large demand on a water distribution network when they open for this reason, they are often used in conjunction with pressure-sustaining valves that throttle flow.

The Modeling Process-(valves)

- **Vacuum breaker valves -** are used to prevent back siphonage when a partial vacuum pulls non potable liquids back into the supply line. The valve consists of a check valve operated by water flow and a vent to the atmosphere. When flow is forward, the valve lifts and shuts off the air vent. When flow stops or reverses, the valve drops to close the water supply entry and open an air vent.

The Modeling Process-(valves)

- **Flow control valves -** Flow control valves are pressure-regulating valves installed to regulate the flow of water. Throttling the flow of water requires special valve designs that are durable over a long period of time. Butterfly and needle valves are commonly used to control flow in water systems in different applications.

The Modeling Process-
(Model Setup)

- **Storage Tanks and Reservoirs -** Storage tanks include both elevated and ground level storage facilities that supply water via gravity or via a pump station. Water levels in tanks fluctuate with system demand. Tank capacities, tank geometry, operating ranges, and control valves are important model inputs.

The Modeling Process- (Model Setup)

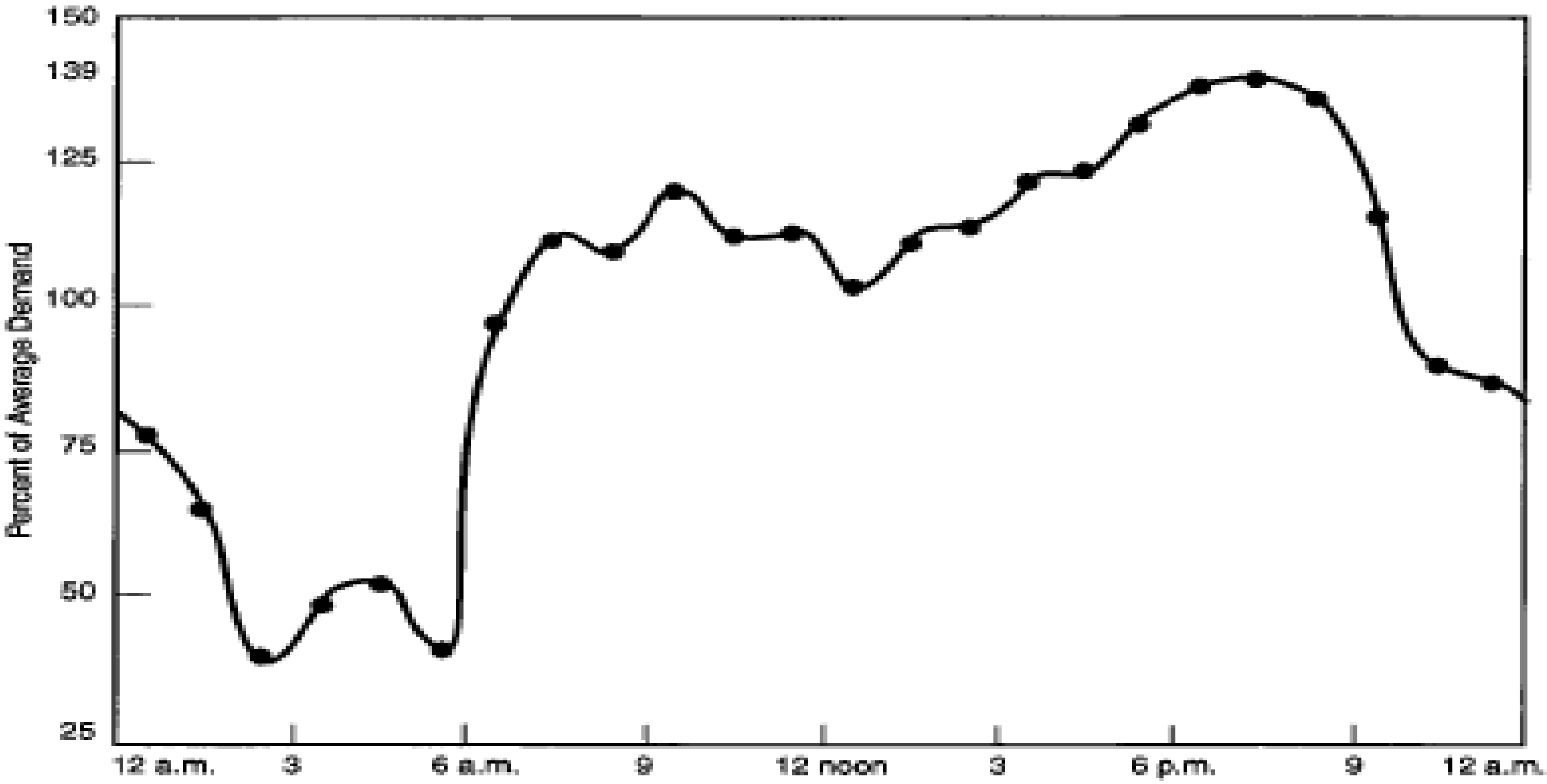
For steady state analysis, much of this data is not included in the model but is required for use in interpreting and evaluating model results. In extended-time-period simulations, tank data is modeled so that water level fluctuations can be calculated and the altitude valves modeled correctly .

Most software programs require specification of the operating range, as well as geometric information, such as volume versus water level for each tank

The Modeling Process-
(Model Setup)

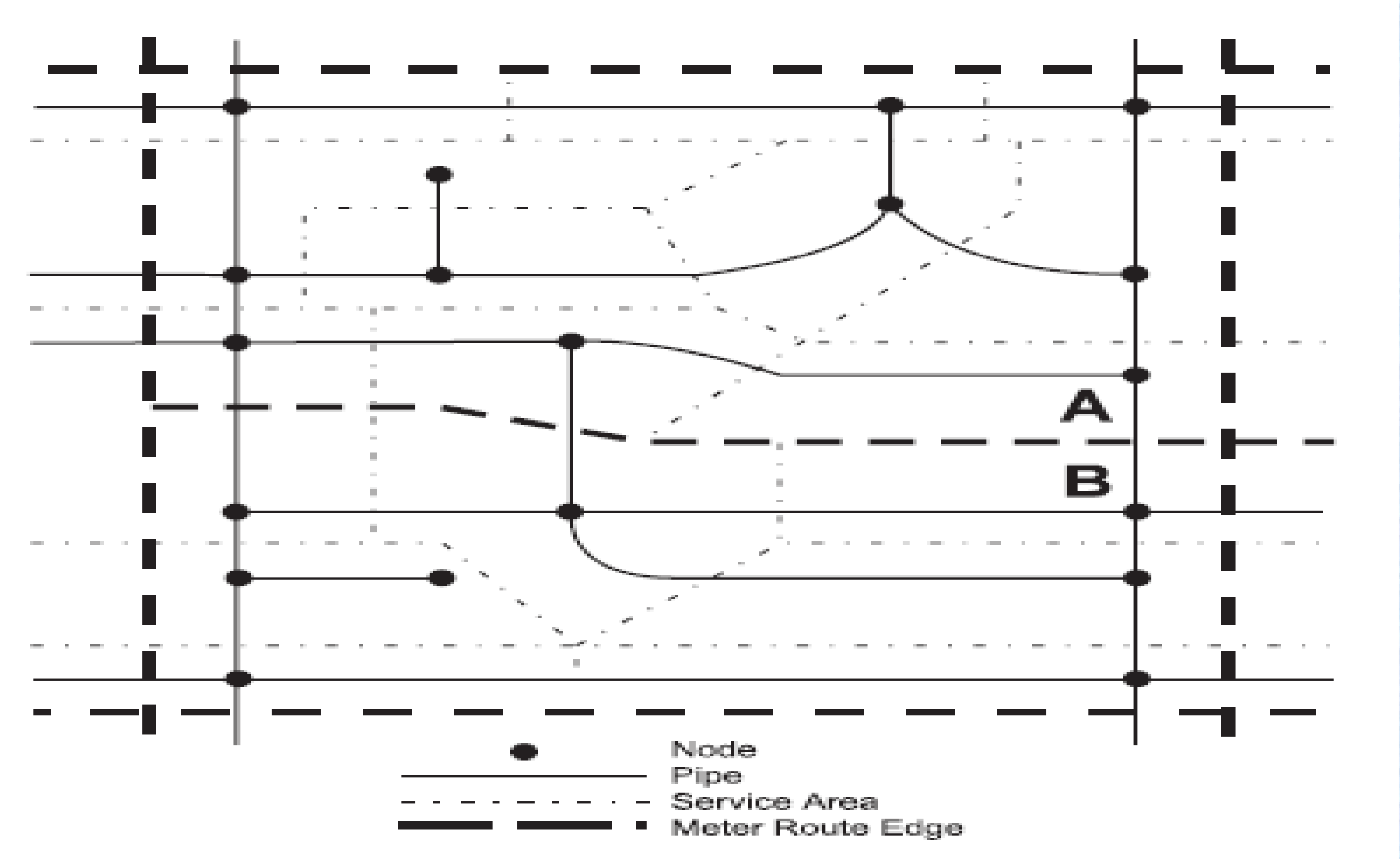
- Demand Data
  - Determine demands (chapter 2)
  - Allocate demands in the model
  - Adjust demands to develop factors to convert from average day demands to the demands at the conditions that are to be modeled

The Modeling Process-(Model Setup)



Diurnal curve

The Modeling Process- (Model Setup)



The Modeling Process- (Model Setup)

Facility/Equipment	Operation Data Required
Reservoirs	• Water elevations (i.e., dead storage, overflow) • Inflow/outflow rates
Pumps	• Pump status (on/off) • Pump speed (variable speed only) • Flow rate and head
Pressure-Regulating Valves	• Upstream pressure • Downstream pressure • Valve position and setting
Flow Control Valves	• Valve position • Flow rate through valve • Downstream pressure
Node Pressures	• Any pressure data collected at pressure-monitoring stations in the distribution system
Pipe Flows	• Any in-line flow data measured in the distribution system (includes wholesale supply locations or zone boundary meters)

The Modeling Process- (Model Calibration)

- Flow measurements
  - Planning field tests
  - Flow measurements
  - Meter calibration
  - C-factor tests
  - Diurnal demands
  - Hydraulic gradient tests
  - HGL tests
  - Fire flow tests

The Modeling Process- (Model Calibration)

- Hydraulic Testing
  - Major control points
  - Flow monitoring is done at all inlets and outlets
  - Reservoir levels, pump station flows, and pump station pressures provide valuable information during fire flow tests.

The Modeling Process- (Model Calibration)

- Flow measurements
  - Flow measurements are an integral part of meter tests, C-factor tests, diurnal demand measurements, pump tests, and fire-flow tests. Flow-measuring equipment in water supply includes hydrant pitot gauges, pitot tubes, master meters, and portable magnetic meters.

The Modeling Process-
(Model Calibration)

- C- Factor tests
  - Measuring C-factors for each and every pipe is usually not practical; therefore, assumptions are made based on a sample of C-factor measurements. The sampling includes all combinations of pipe sizes and materials, and also old and new pipes. Larger pipes tend to have higher coefficients. If there are unlined cast iron pipes in the system, they should definitely be included in the sample, as C-factors vary widely from less than 25 to over 100, depending on the pipe age and water quality.

The Modeling Process- (Model Calibration)

- C- Factor tests
  - It is important to take C-factor measurements near sources where treatment processes have coated the inside of pipes.

The Modeling Process- (Model Calibration)

- Diurnal demand measurements
  - Diurnal demand is the variation in water demand over a 24-hr period
  - Knowledge of diurnal demand provides information on demand peaks, determines peaking factors, as well as the distribution of demand over time.
  - Diurnal demand measurements also allow the user to easily check for leakage. Excluding industrial use, a minimum demand flow rate over 50 percent of the average flow rate indicates the likelihood of leakage

The Modeling Process-(Model Calibration)

- Pump Tests
  - Data from pump tests are entered into the model for simulating hydraulic performance and for calculating energy costs. Input data based strictly on design curves introduces significant errors, as true performance is sometimes quite different from design parameters caused by worn impellers, undocumented equipment changes, or trimming of impellers.

The Modeling Process-(Model Calibration)

- Pump Tests
  - Knowledge of diurnal demand provides information on demand peaks, determines peaking factors, as well as the distribution of demand over time. Diurnal demand measurements also allow the user to easily check for leakage. Excluding industrial use, a minimum demand flow rate over 50 percent of the average flow rate indicates the likelihood of leakage
  - Tests usually include normal conditions, design conditions, induced flow, throttled flow, etc.

The Modeling Process- (Model Calibration)

Hydraulic Gradient Tests

- Hydraulic gradient tests consist of taking simultaneous flow and pressure measurements at intervals along a pipe path, under the condition of steady flow. In large systems, the tests follow trunk mains between plants, tanks, and pump stations
- In small systems, the tests follow pipes from sources to flowing hydrants at key locations. Pressure measurements are taken at plants, on the inlet and outlet of pump stations, at tanks and major pipe intersections, and where pipe diameters transition. At key pipe sections, the flow rate is measured.

The Modeling Process-
(Model Calibration)

- Fire Flow Tests
  - Fire flow tests are used to determine friction factors in pipes near hydrants. These tests consist of simultaneously taking flow and pressure measurements at selected locations. These simple tests are an inexpensive way of checking a model against measured values..

The Modeling Process- (Model Calibration)

- Other Tests
  - Some models require conducting other types of tests. Modeling pressure-reducing valves requires accurate downstream pressure measurements at known elevations. Pressure and flow measurements are useful in modeling other types of control valves. Pressure and tank level measurements are necessary for checking the accuracy of data from water plant charts and SCADA systems

The Modeling Process-(Simulation/caliberation)

- Steady state
- Extended period simulation
- Transient simulation

The Modeling Process- (Simulation/caliberation)

- **Steady state**
  - A steady-state model simulation predicts behavior in a water distribution system during a hypothetical condition where the effects of all changes in the operation and demands of the system have stopped. Steady-state analysis is sometimes compared with taking a snapshot picture of the distribution system.

The Modeling Process-(Simulation/calibration)

- **Steady state calibration:** trial and error approach and/or automatic.
- Fine-tuning a model means correcting errors and adjusting the data to within .reasonable limits. Examples of errors that are in the data include incorrect pipe sizes or interconnections that do not exist. Adjustments to the data usually involve demand distribution, friction coefficients, and controls, such as pump curves. Unreasonable adjustments, such as changing C-factors to 25 for lined pipes, may force models to match measurements without finding underlying problems, such as closed valves.

The Modeling Process-(Simulation/calibration)

- Manual method prohibitive for large networks. Genetic algorithm way out.
- The need for calibration arises because of uncertainties and assumptions in the data. Assumptions include Hazen-Williams coefficients, skeletonization, pump performance, and demand loading (Cruickshank and Long).

The Modeling Process-(Simulation/calibration)

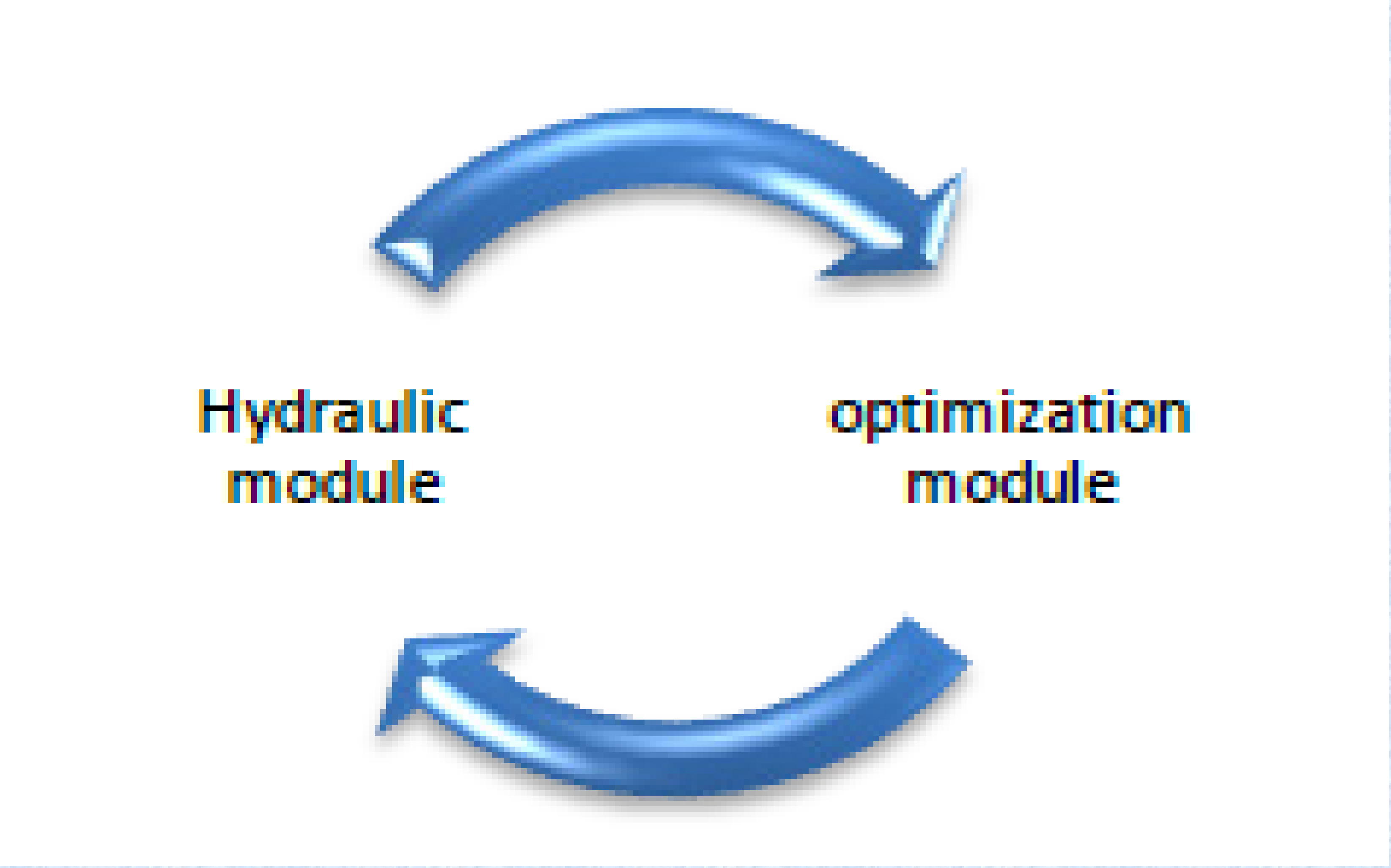
Table 4-1 Typical model scenarios

Purpose of the Analysis	Recommended Steady-State Demand Scenario
Studies of normal operation	Maximum day
Production and pumping requirements	Maximum day
Design—small systems	Maximum day plus fire flow
Design—large systems	Maximum hour of maximum day
Tank filling capabilities	Minimum hour of maximum day
System reliability during emergency or planned shutdown	Condition when the emergency or shutdown is likely to occur
Model calibration	Condition during time when measurements were collected

Advanced Design Procedures

- The design process as a function of a number of competing objectives.
- Optimal solution

Advanced Design Procedures



Advanced Design Procedures

- **Objectives of**
  - the hydraulic model should be framed
  - optimization model should be framed.

- **The optimization model**
  - estimates the cost of the network and settles with the least cost satisfying all the constraints.
  - The network cost is calculated as the sum of the pipe costs where pipe costs are expressed in terms of cost per unit length. Total network cost is computed as follows:

$$C = \sum c_k(D_k) \cdot L_k \qquad (9)$$

where, $c_k(D_k)$ = cost per unit length of the k^{th} pipe with diameter D_k,

L_k = length of the k^{th} pipe.

Advanced Design Procedures

- The optimization module keeps on checking the combination of pipe diameters satisfying the head conditions and resulting in the least cost of the network.

Research Trends

- Real time modeling for system operation
- Integrated optimization –hydraulic modeling