Energy Recovery from Water Distribution Systems

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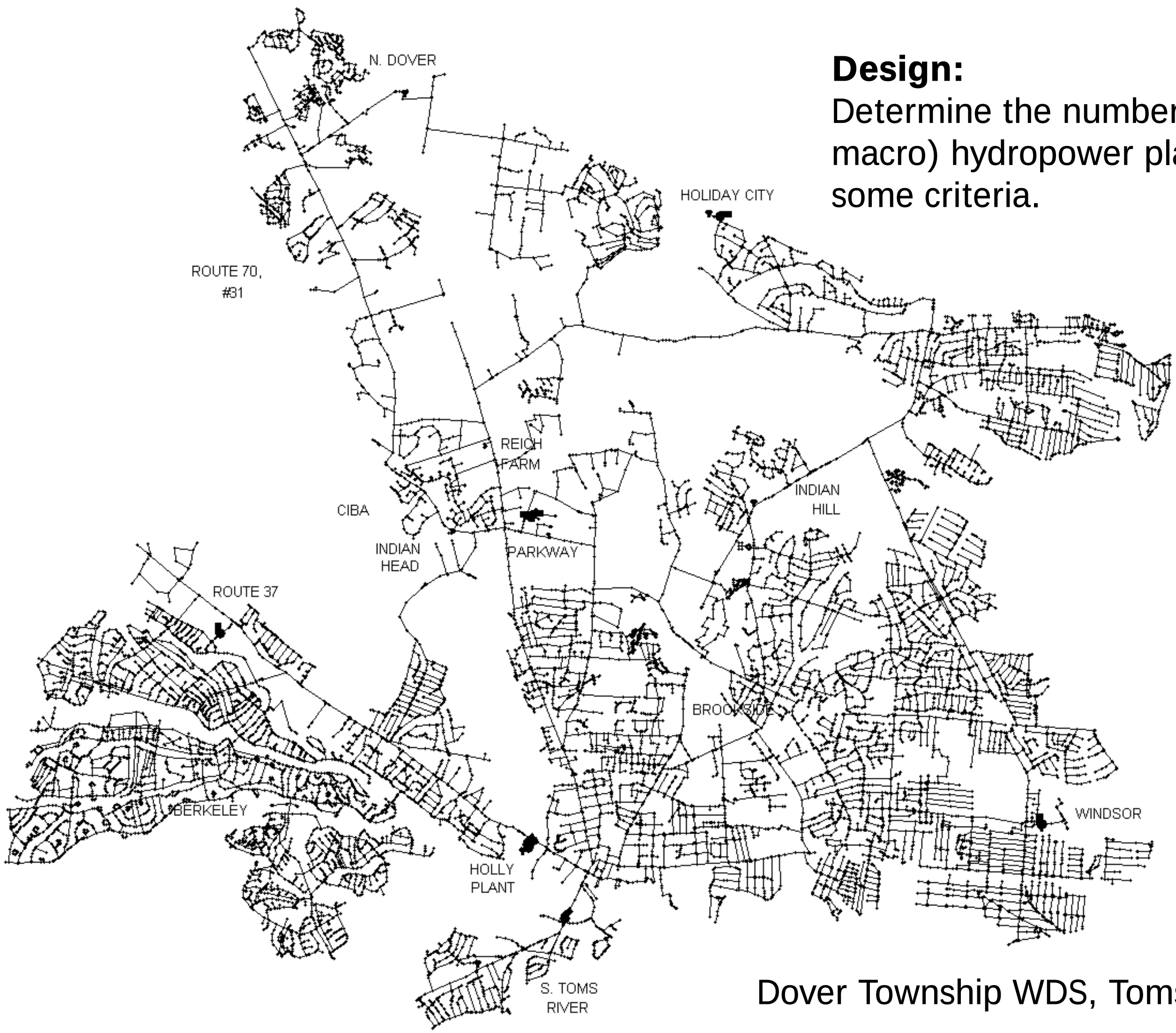
Outline

- Problem definition.
- Pipe flow review, water distribution systems (constraints, problems and solutions).
- Examples from literature.
- Summary of literature and tentative solution method.
- Preliminary analysis of Dover Township WDS.

Problem definition

- Optimum design of an energy recovery system for water distribution networks.

Design:
Determine the number, location and capacity of micro (or macro) hydropower plants in the network by optimizing some criteria.



Dover Township WDS, Toms River, NJ

Pipe flow review

Total head (or energy) defines EGL: $H = z + \dfrac{p}{\gamma} + \dfrac{V^2}{2g}$

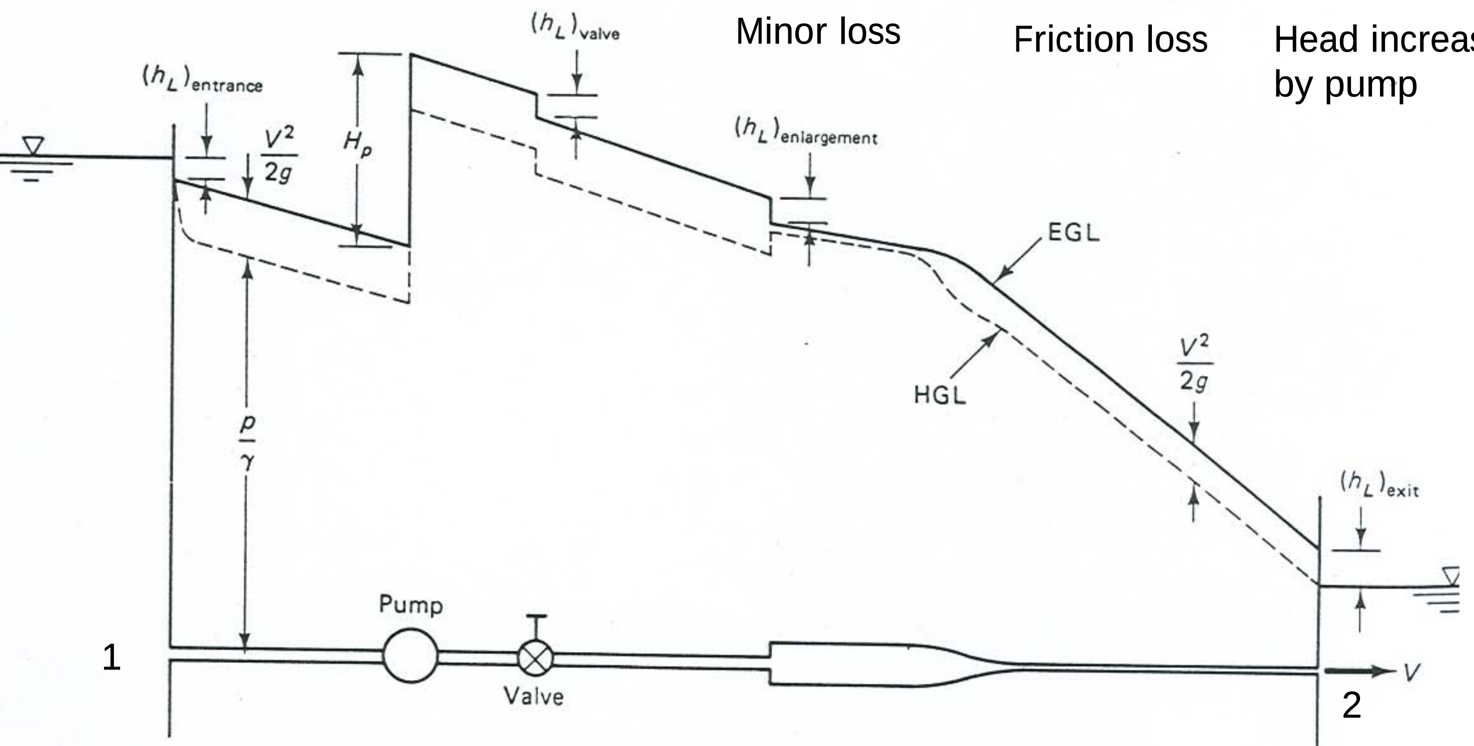
Energy equation: $$H_1 + \sum H_P = H_2 + \sum h_L + \sum h_f + \sum H_T$$

$h_L = K\dfrac{V^2}{2g}$ Minor loss

$h_f = f\dfrac{L}{D}\dfrac{V^2}{2g}$ Friction loss

$H_P = \dfrac{\eta_P P_P}{\gamma Q}$ Head increase by pump

$H_T = \dfrac{P_T}{\eta_T \gamma Q}$ Head loss at turbine



Hydraulic grade line (HGL) and energy grade line (EGL) for a piping system.

WDS constraints

- The pressure head throughout the WDS should be within minimum and maximum permissible limits to eliminate potential damages to the pipeline.
- The demand flows should always be satisfied.

Major problem in a WDS

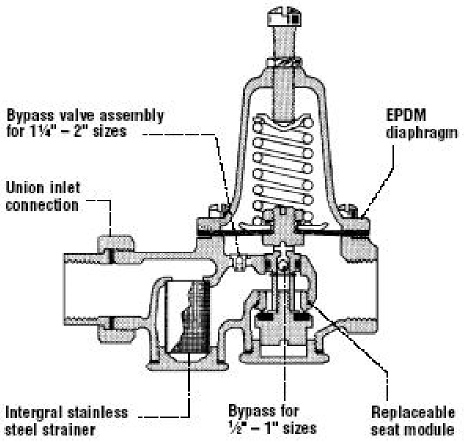
- Excessive pressure heads are the major problems in WDS.

- Excessive pressure may cause:
  - damage to the pipeline,
  - leakage

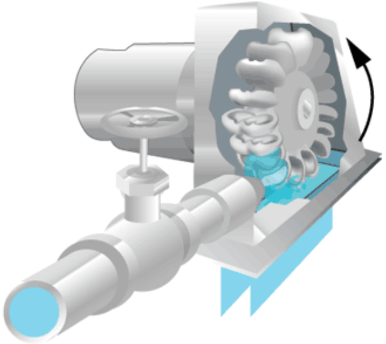
- Thus, excessive pressures should be minimized while customer demands are ensured to be satisfied at all times.

Solution of excessive pressure problem

- Classical solution:
  - Pressure reducing valves (PRVs)



- New solutions:
  - Turbines,
  - Pumps as turbines (PATs)



Property	PRV	Turbine	PAT
Energy recovery	No	Yes	Yes
Efficiency	NA	High	Low
Installation cost	Lowest	High	Low

Examples from literature

- Afshar, A., F. Benjemaa, et al. (1990). "OPTIMIZATION OF HYDROPOWER PLANT INTEGRATION IN WATER-SUPPLY SYSTEM." Journal of Water Resources Planning and Management-Asce **116(5): 665-675.**

- Ramos, H., D. Covas, et al. (2005). Available energy assessment in water supply systems. XXXI IAHR Congress. Seoul, Korea.

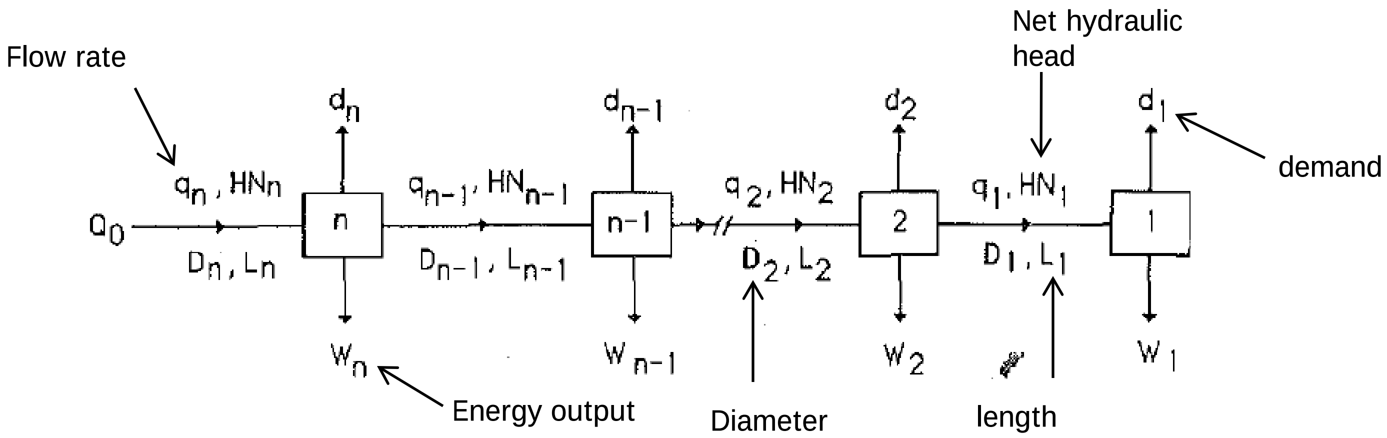
- Giugni, M., N. Fontana, et al. (2009). Energy saving policy in water distribution networks. International Conference on Renewable Energies and Power Quality (ICREPQ'09). Valencia, Spain.

- Liberatore, S. and G. M. Sechi (2009). "Location and Calibration of Valves in Water Distribution Networks Using a Scatter-Search Meta-heuristic Approach." Water Resources Management **23(8): 1479-1495.**

Examples from literature (1)

- Afshar, A., F. Benjemaa, et al. (1990). "OPTIMIZATION OF HYDROPOWER PLANT INTEGRATION IN WATER-SUPPLY SYSTEM." Journal of Water Resources Planning and Management-Asce **116(5): 665-675.**

  - They optimized the number, locations, capacities and conduit diameters of hydropower plants along a main supply pipe.



  - They used dynamic programming model for this optimization.

Examples from literature (1)

- Afshar, A., F. Benjemaa, et al. (1990). "OPTIMIZATION OF HYDROPOWER PLANT INTEGRATION IN WATER-SUPPLY SYSTEM." Journal of Water Resources Planning and Management-Asce **116(5): 665-675.**

  - The objective is to maximize the net annual benefits associated with the water transmission and hydropower system while satisfying some conditions and constraints.

$$f_k(q_k, P_{k+1}) = \max_{(HN_k, D_k)} \{B_k(q_k, HN_k) + C_w q_k - [C(D_k)L_k - C_0(QD_k, HD_k)]F(r,t) - OM_k + f_{k-1}(q_{k-1}, P_k)\}$$

- $B_k(q_k, HN_k)$: Annual hydropower revenue
- $C_w q_k$: Price of water delivered
- $C(D_k)L_k$: Cost for conduit k
- $C_0(QD_k, HD_k)$: Cost for hydropower plant
- $F(r,t)$: Capital recovery factor
- OM_k: Operation and maintenance cost

subject to

$$q_k = d_1 + d_2 + \ldots + d_k$$

$$H_{\min} \leq HN_k \leq H_{\max}$$

$$P_{\min} \leq P_k \leq P_{\max}$$

$$D_{\min} \leq D_k \leq D_{\max}$$

Examples from literature (2)

- Ramos, H., D. Covas, et al. (2005). Available energy assessment in water supply systems. XXXI IAHR Congress. Seoul, Korea.
  - They showed experimentally that PRVs and PATs have similar behaviors for steady state flows and some differences under transient conditions.
  - They observed that although in some cases PATs perform better in pressure regulation, in other cases a mixed solution of PATs and PRVs is recommended.
  - They proposed an optimization method to minimize pressure and the number of PRVs in the network.

Pressure calculated at node i for instant t

$$\text{Optimize} \quad f(p_i, nv)\Big|_{t=1}^{T} = nv_t \Big/ \left\{ \sum_{i=1}^{N} \left[\frac{\left(P_{cal,i,t} - P_{\min}\right)}{P_{\min}} \right]^2 * nv_t + nv_t \right\}^2 \Bigg|_{t=1}^{T}$$

#of time steps

#of PRVs calculated for instant t

s.t. $P_{cal,i,t} > P_{min}$ and $nv_t < N_p$

Examples from literature (3)

- Giugni, M., N. Fontana, et al. (2009). Energy saving policy in water distribution networks. International Conference on Renewable Energies and Power Quality (ICREPQ'09). Valencia, Spain.

  - A simulation model based on a Genetic Algorithm is used to locate PRVs and optimize water system performance.
  - PRVs are substituted by PATs for renewable energy production.
  - PAT installation resulted in a similar leakage reduction as PRVs.
  - Economic analysis shows significant profits from energy production.

Examples from literature (4)

- Liberatore, S. and G. M. Sechi (2009). "Location and Calibration of Valves in Water Distribution Networks Using a Scatter-Search Meta-heuristic Approach." Water Resources Management **23(8): 1479-1495.**

  - Pressure reference method is used to identify the locations of PRVs.

  - Meta-Heuristic Scatter search method is used for optimal calibration of the valves.

$$\min \ OF = \gamma_1 OF_1 + \gamma_2 OF_2$$

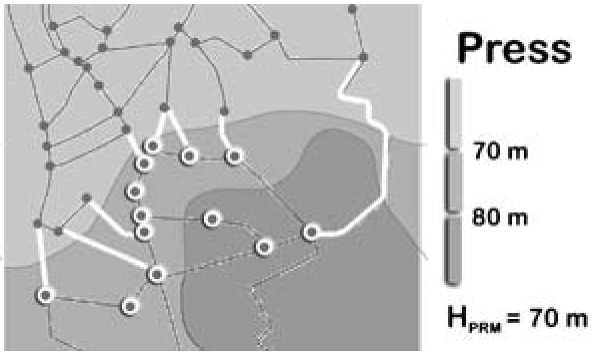
$$OF_1 = \sum_{d=1,K} \sum_{i=1,N} \left| c_i \left(H_{i,d} - H_{\max} \right)^2 \right|_{H_{i,d} > H_{\max}}$$

← Penalty for excess pressures Summed over demand patterns d and nodes i

$$OF_2 = \sum_{j=1,nv} f\left(H_j^*, D_j \right)$$

↖ Total Cost function for the PRVs which have calibrated head loss of H* installed on a pipe with diameter D.

Pressure reference method:



Summary of literature (1)

General considerations

- Excess pressures are the main concern among hydraulic engineers.
- Energy recovery has secondary importance.
- The objective functions consider the pressure in the network (except Afshar, et.al (1990)) and installation costs.
- First, locations of PRVs are determined, then replacement with a turbine (or PAT) is considered.

Tentative suggested solution method (1)

- This study would focus on energy recovery from existing WDS.
- However, pressures in the WDS are still important and appear as constraints in the model together with .
- The objective would be to maximize the net economic benefit which should be greater than a threshold to be feasible.
- This optimization model is similar to the model developed by Afshar, A., F. Benjemaa, et al. (1990) in terms of the decision variables and constraints.
- However, the application will be different.
  - They limited the solution space to the supply main pipe. We can search the complete WDS or we can apply Pressure reference method (Liberatore, S. and G. M. Sechi (2009).
  - They used dynamic programming. We can use Genetic Algorithms.

$$f_k(q_k, P_{k+1}) = \max_{(HN_k, D_k)} \{B_k(q_k, HN_k) + C_w q_k - [C(D_k)L_k - C_0(QD_k, HD_k)]F(r,t) - OM_k + f_{k-1}(q_{k-1}, P_k)\}$$

Annual hydropower revenue

Price of water delivered

Cost for conduit k

Cost for hydropower plant

Capital recovery factor

Operation and maintenance cost

subject to

$$q_k = d_1 + d_2 + \ldots + d_k$$

$$H_{\min} \leq HN_k \leq H_{\max}$$

$$P_{\min} \leq P_k \leq P_{\max}$$

$$D_{\min} \leq D_k \leq D_{\max}$$

Tentative suggested solution method (2)

- Objective Function

$f\left(n_T, X, C\right)$: total income from energy recovery - total cost of the system (installation, operation and maintenance)

- Decision variables:

n_T: number of hydropower plants to be installed.

X: location vector of size $n_T \times 1$ (indicating the pipes where a hydropower plant is to be installed).

C: capacity vector of size $n_T \times 1$ (indicating the capacity (in Watts) of each hydropower plant).

- Optimization

$$Maximize\ \ f\left(n_T, X, C\right)$$

$$s.t.$$

$P_{min} \leq p_i \leq P_{max}$ $\forall i$, where i indicates the node ID.

$q_j \geq d_j$ $\forall j$, where j indicates the demand node ID, q and d are available flow rate and demand.

$$f\left(n_T, X, C\right) \geq BenefitThreshold$$

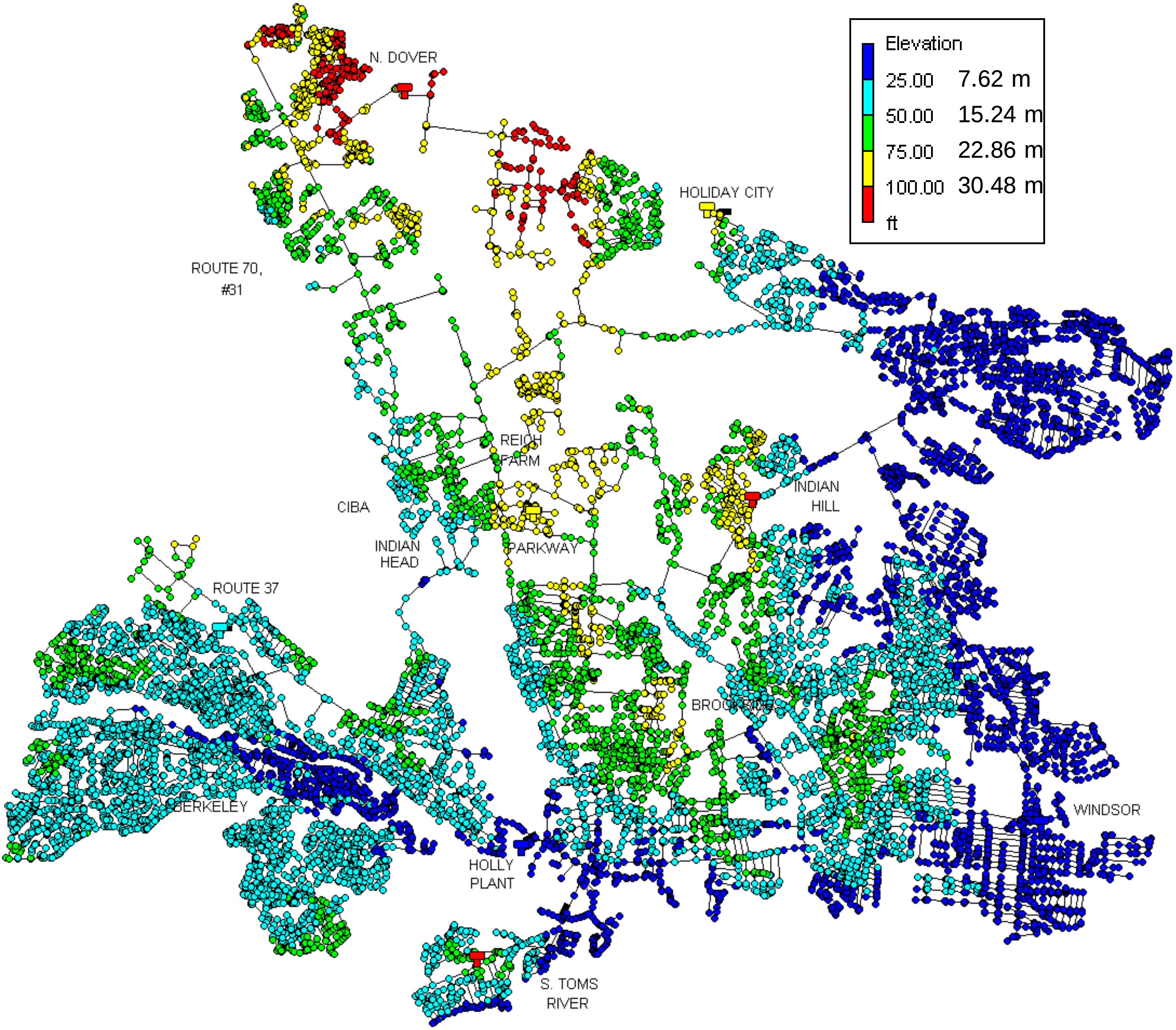
Summary of literature (2)

Specific considerations about Dover Township WDS

- According to Ramos, H., D. Covas, et al. (2005), high topographic gradients are favorable to adopt energy recovery using turbines (or PATs).
- Giugni, M., N. Fontana, et al. (2009) sets a minimum pressure head of 25 m since there are 6 storey buildings in the WDS area.
- If the distribution network is organized in urban districts, district method which involves inserting valves (as a consequence turbines for energy recovery) in all district supply pipes can be applied (Alonso et al., 2000).

Dover Township WDS

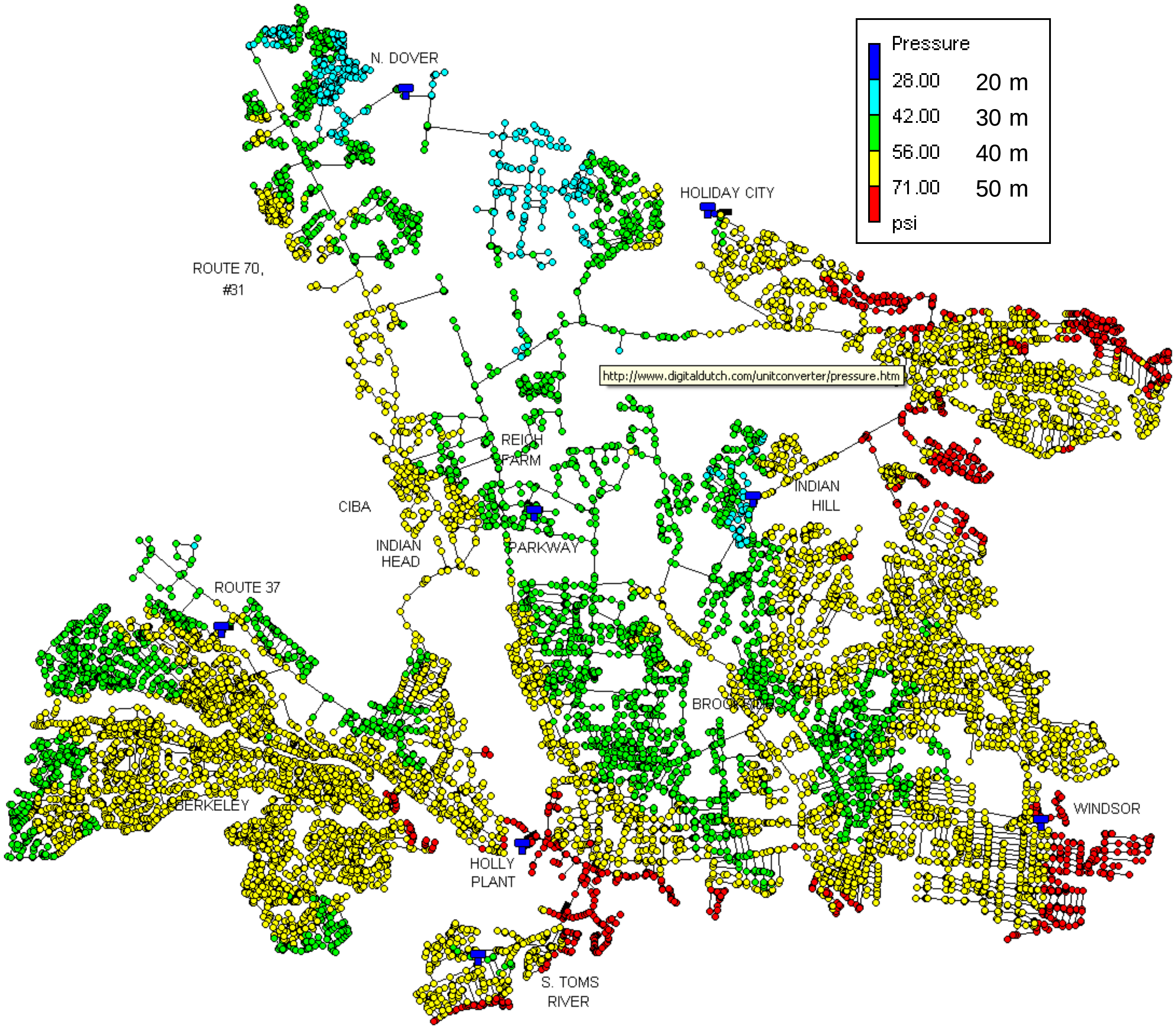
Preliminary Analysis: Elevations



- Topographic gradients are not very high.
- There are 12 pumps.
- No valves.
- Districts are observable

Dover Township WDS

Preliminary Analysis: Pressures



- In general, pressures are higher than 25 m
- No high buildings are seen in satellite photos.

Thank you…