Effect of GIS-Based Demand Allocation on Water Distribution System Modeling

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Mathematical modeling has been used for more than 60 years to analyze flow in water distribution system networks since the concept was proposed by Cross in 1963. Using computers for conducting analyses of flow in pipe networks originated in the early 1960s and was greatly expanded during the ensuing decade with the advent of enhanced solution algorithms and the implementation of modeling techniques for devices such as pumps and valves.

In the late 1970s, single-time-period simulations were advanced to extended period simulations with techniques developed by Rao and Bree (1977). Hydraulic models can be used to analyze systems where demand and operating conditions are static or is time varying. The former type of model is a 'steady-state' model, and the latter is referred to as an 'extended period simulation' or EPS model. In this analysis, EPS mode was utilized.

Water demand is the driving force behind the hydraulic dynamics of water distribution systems. It is therefore critical to accurately represent demands in hydraulic systems.

The most common method of loading a water distribution model involves the spatial allocation of demands. Most water distribution hydraulic software leverage the spatial analysis abilities of GIS software and use source data types such as geocoded billing meter records, water production data, census tracts, land use zoning, traffic analysis zones, meter routes, and demand density information.

The objective of this article is twofold:

1. Compare water demands projected using population information, land use, and customer billing records.
2. Evaluate and discuss the effect of demand allocation techniques on water distribution system modeling.

Methodology

The first steps in evaluating a water distribution system are to derive existing and future demands and to develop the hydraulic model. The water demands are then allocated to the model nodes, with applicable peaking factors, and diurnal water use patterns applied. The model is then used to determine system improvements needed to correct existing and projected future deficiencies.

Water Demand Projection

The main purpose of water demand projection in the water master planning process is to identify sufficient water supply to meet the projected aggregated demand curve. The projection of water demand through ultimate build-out provides a series of supply targets that must be met in the years to come. The establishment of existing and projected future demands is an early and critical step, and a miscalculation can derail the entire master planning process.

Demands have many uses besides distribution system modeling, including supply planning and setting treatment plant and transmission main capacities; therefore, it is important that demands are consistent with accepted water use characteristics and available data and that they undergo a thorough review process.

In this analysis, water demands were estimated using three methods: population projections, land use information, and water production records.

Water Demand Projection Using Population Projections

Developing a comprehensive water system hydraulic model begins with evaluating the area's historical population trends and projected growth patterns. To predict water demands accurately, it is necessary to determine the magnitude, direction, and characteristics of population growth.

An analysis of population and customer class within the service area of the city of Olathe, Kansas, was conducted to provide a population estimate for 2005. The city's population grew from 64,900 in 1990 to 107,523 in 2005, an increase of about 66 percent.

In order to derive projected water demand from projections of population, the average amount of per-capita water usage in the city was determined. Such water usage is commonly measured in gallons per capita per day (gpcd). The per-capita demand was estimated using the average day water production for a specific year and the population for that year. Table 1 shows the per-capita demands from the city's 2000 master plan report, as well as those from more-recent years.

The per-capita demands indicate that

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Table 1: Per Capita Water Usage

Year	Water Area Population	Water Production (mgd)		Per Capita Usage (gpd/person)
		Average Day Demand	Maximum Day Demand	
1980	37,258	5.10	9.03	137
1985	50,365	5.54	9.90	110
1990	64,900	7.20	13.6	111
1995	73,975	9.02	15.8	122
2000	92,572	12.13	23.3	131
2001	97,753	12.02	23.0	123
2002	99,226	13.59	25.0	137
2003	101,426	13.39	27.11	132
2004	103,657	11.92	19.4	115
			Average	124

Table 2: Existing Land-Use Characteristics

Land-Use Designation	Existing Development (acre)	Average Water Demand Coefficient (gpm/acre)	Demand (gpm)
Low Density Residential	8,433	0.75	6,325
Medium Density Residential	751	0.85	638
High Density Residential	698	1.00	698
Retail/ Commercial	722	0.80	578
Industrial/ Business Park	385	0.85	327
Heavy Industrial	399	0.90	359
Office/ Public	1344	0.10	134
Park	1317	0.10	132
Right-of-Way	3,821	0.00	0
Total	**17,870**		**9,191**

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although usage is usually around 120 to 126 gpcd, it can reach values as high as 131 to 137 gpcd. Using an average per-capita consumption of 124 gpcd and 2005 population of 107,523, an average day demand of 13.33 million gallons per day (mgd) was estimated for the year 2005.

Land Use-Based Water Demand Projections

To estimate current and future demands from land use information, acreages of land use type, accurate historic water use patterns, and water use records are necessary. The city's 2005 land use plan was used to categorize Olathe into nine land use types, which are defined in Table 2.

The estimated acreage for each land use type and average water demand coefficients are also summarized in Table 2. The acreage for each land use type was measured in actual developable acreage, which is the total acreage reduced by major undevelopable areas such as open space, streets rights-of-way, and interstate right-of-way.

The water demand by each land use category was calculated by multiplying the gross developable acres by the projected water demand factors. The water demand factors were obtained from Olathe's 2005 Water Master Plan Update Draft Report. The factors were estimated by matching derived demands to actual consumption and production using an iterative process, starting with assumed water use factors (by acre and land use type), then comparing results to actual records. The water use factors were adjusted until a match was obtained between the derived and actual records.

Total water usage at designated discrete points of demand on the water system was determined for the purpose of system design. This was accomplished by dividing the city into sub areas whose total demand was assumed to be located at a designated point within each sub area.

The sub areas were then further divided into the various land use categories, based on the land use plan. By applying the unit demand factors from Table 2, the total demand for each sub area was developed. The total demand by land use designation is summarized in Table 2.

Water Demand Projection Using Customer Billing Records

Metered use data are actual meter readings that are read approximately every month or bimonthly. These data typically do not contain spatial data other than a billing address, which may or may not be the same as the service address. These addresses can be converted to a location using GIS geocoding tools to approximate the meter locations.

Summary customer billing reports for 2003 through 2005 were obtained from the city. The data list totaled monthly billed water use by meter size and customer category. An analysis of the data shows that the institutional, commercial, and industrial uses are stabilized. As the city develops toward saturation, this commercial and industrial usage is expected to remain the same.

Water usage by customer category is shown graphically in Figure 1. By computing the average percent total of water usage, it can be seen that the majority of the water demand comes from the residential sector. "Other" is the metered water that does not fall under any of these categories.

The 2003-2005 consumption data obtained from customer billing records were totaled for various categories of users. The water consumption subtotals were then adjusted to account for unmetered water use and water losses such as leakages, and the results were aggregated to determine total water demand projections for the city. Based on this method, a total water demand of 13.2 mgd was projected for 2005.

Water production reports also were received from the city for the years 1995 through 2005. The water production reports include monthly information on raw water pumping from the water supply sources, finished water pumping at the treatment plants, and metered city usage. Actual finished water produced in 2005 was extracted from these records to validate water demands estimated from the three independent databases. Figure 2 compares water demands estimated from the three databases.

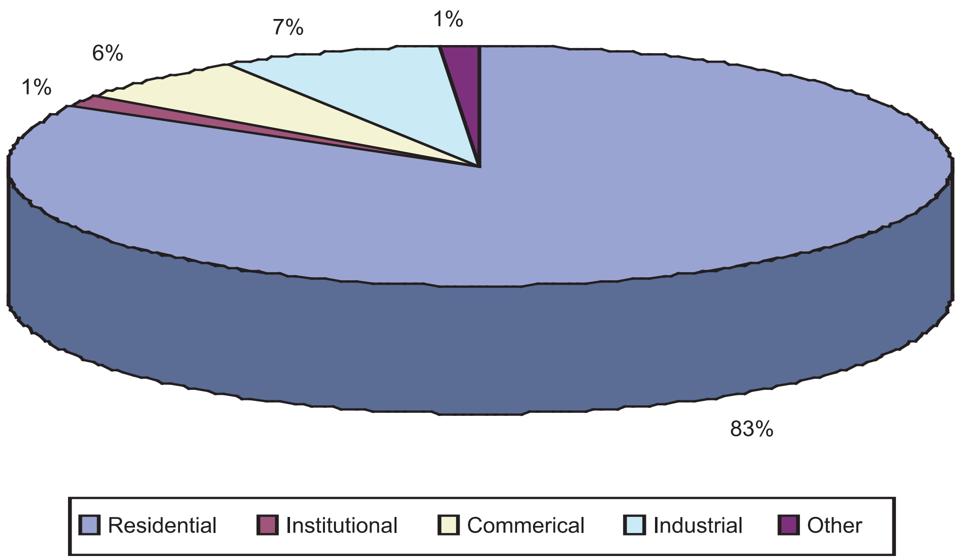

Figure 1: Demand by Customer Category (2003 - 2005)

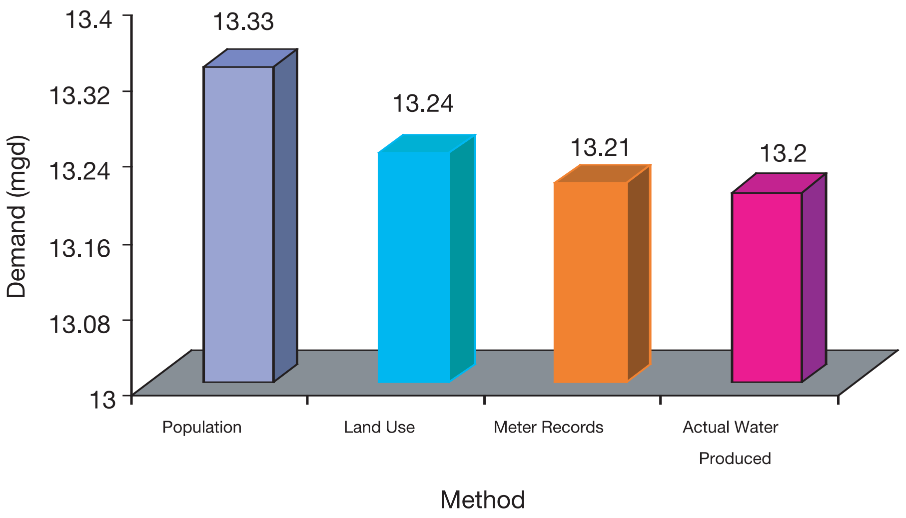

Figure 2: Comparison of Water Demands

Demand Allocation

The spatial distribution of water consumption throughout the hydraulic network model is the key element of water distribution modeling. Water demands must therefore be accurately distributed geographically to properly represent and simulate the water system. Spatial distribution of water consumption in a hydraulic network model is generally referred to as demand allocation.

Demand allocation methods have evolved to meet challenging water utility needs. The methods used to allocate existing and future water demands have become increasingly sophisticated. These methods incorporate improved data sources, including GIS, metered water use, and SCADA data, and link to advanced hydraulic modeling software.

The data sources used for determining and allocating demands are large and complex, and GIS software is needed to refine the data, define relationships between data sources, and perform demand calculations. In this analysis, Excel™ and ArcView™ software were used in the examples referred to in this paper. This software enables links between one another and has the ability to import and export data in a variety of formats.

GIS and other sophisticated tools bring an unprecedented speed, accuracy, and flexibility for calculating, distributing, and managing consumption data in hydraulic network models. The three demand allocation methods evaluated in this analysis are discussed in the following paragraphs.

Uniform Nodal Demand Method

In the uniform nodal demand method, population projections by census information and per-capita water use were used to distribute water demands uniformly to the model nodes. The demands developed in the previous section were distributed over the pipe junctions, or nodes, in the computer distribution system model.

The simplest way to distribute demands is to divide the total demand by the number of nodes and apply the same demand to each node; however, with some additional information, it was possible to create a much more accurate demand distribution, based on the following items:

- The largest water customers.
- The population distribution in the city of Olathe.
- The distribution of growth in the Olathe service area.
- Region-route records.

The demands for large users were applied to the nodes in the distribution system model that was nearest to the meter location of the customer. The sum of the

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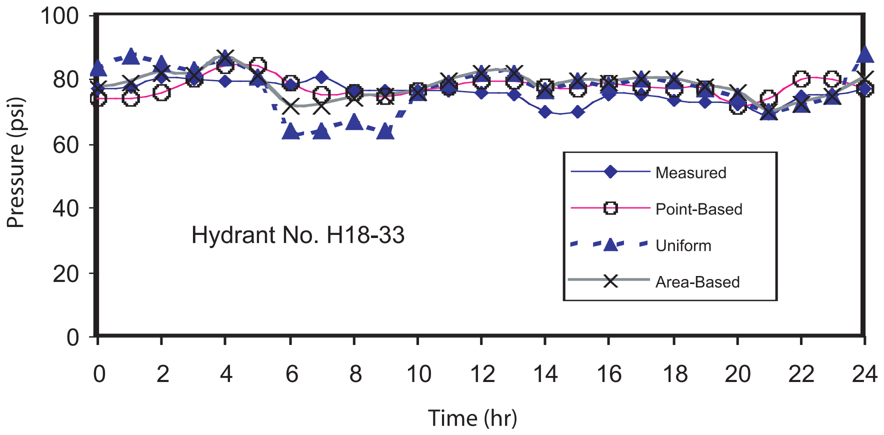


Figure 3: Pressure Comparison at Hydrant No. H18-33

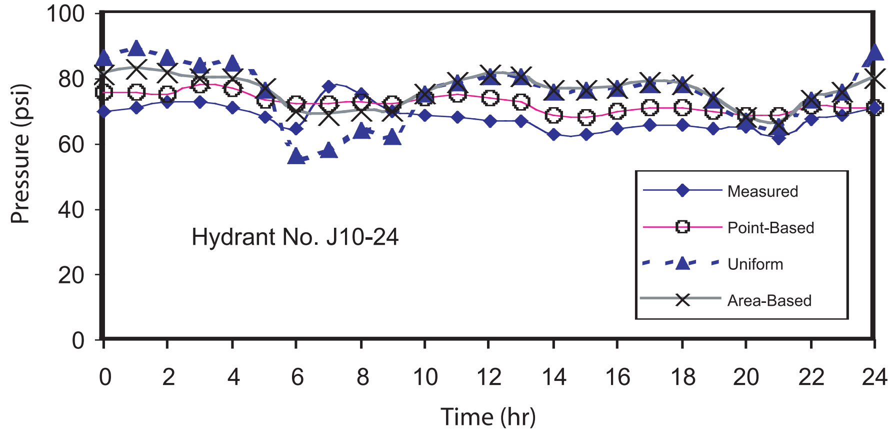


Figure 4: Pressure Comparison at Hydrant No. J10-24

Figure 5: Uniform Nodal Demand Pressure Contours

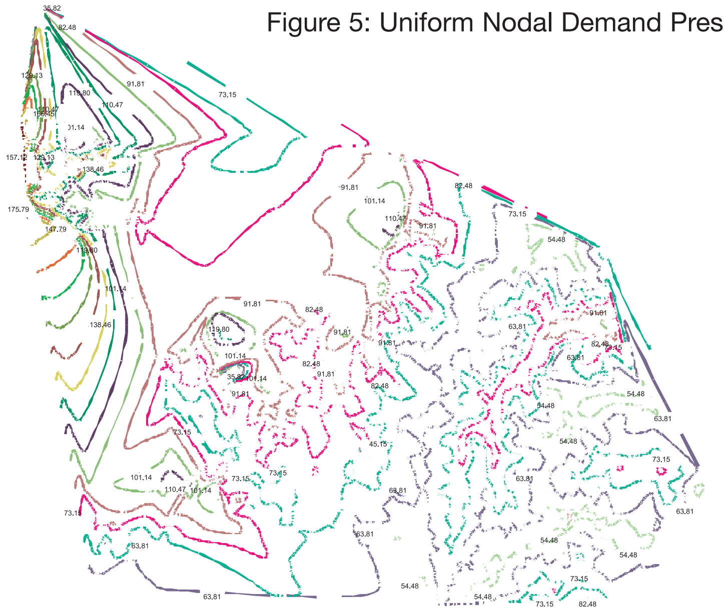


Figure 6: Area Based Pressure Contours

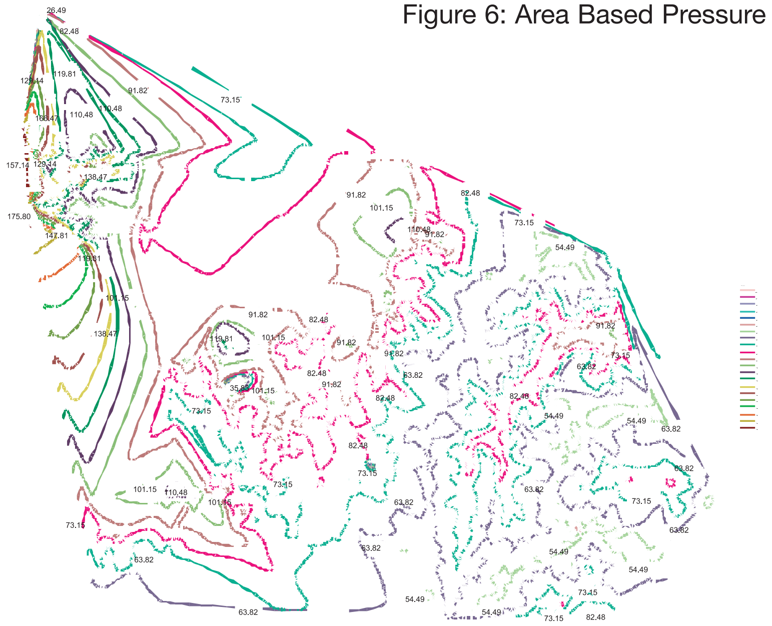
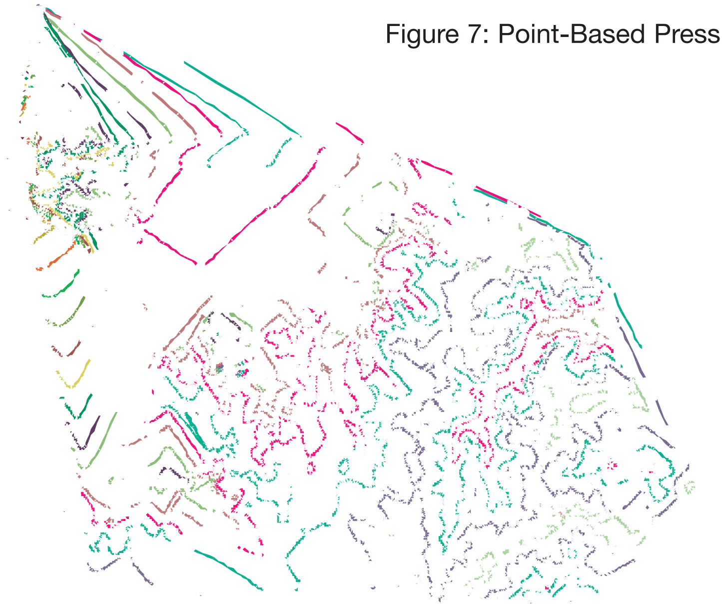


Figure 7: Point-Based Pressure Contours



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demands of these large water users were then subtracted from the total projected average day demand, and the remaining demand was distributed to the rest of the nodes.

The distribution of the remaining demand, not including the large water users, is in accordance with region-route records. The proportion of the total average day demand was calculated for each region-route. After the total usage of the large water customers was subtracted from the appropriate region-route, the proportion of the remaining average day demand was then calculated for each region-route. Exporting the model node data to ARCView, the demand proportions by region-route were distributed amongst the nodes. Certain model nodes, such as those defining pump stations and standpipes, and those along major transmission mains, were excluded from the demand distribution.

Area Methods

Area methods use areas as the basis of the demand distribution. Water demands are derived from land use types that are specified in land use maps. The areas are broken down into sub areas for allocation to model nodes by intersecting them with pressure zone boundaries, grids, or customized nodal influence areas. A nodal influence area is an area drawn around each demand node, and all demands generated within that area are assigned to that node.

For area-based methods, additional area GIS coverage is needed to differentiate existing from vacant areas. This coverage is also intersected with the other area coverages for existing and future demands to be calculated and assigned to the model nodes. GIS tools are used to intersect area coverages and recalculate acres and population for each new sub area.

A land use-based method was used for the city's 2005 model update. Demand at each node was calculated based on a direct spatial intersection between land use polygons or demand categorization polygons and demand area coverage or service area polygons. Actual water use and meter locations were used for the top 20 users.

Point-Based Methods

Point-based methods are used when actual meter locations are known or can be obtained cost effectively. This method uses actual historical demand by meter, adjusted to match the accepted existing base demands. It uses the ArcView "spatial join" function to assign each meter to the closest demand model node. For areas nearing build-out, this method significantly reduces the uncertainty of predicting demands, since demands are estimated for the remaining vacant and undeveloped parcels.

Meter use data was geocoded and address matched to parcel data to obtain a 95 percent match of its 37,500 services. Water use for the remaining 5 percent unmatched metered services was assigned by user type to unmatched developed parcels.

Although it was not feasible to individually check every meter read, general checks were made, including an individual check of each of the top 25 users. This data also provided insights into future land use water uses by determining average water use by street or neighborhood and identifying water use trends. These water use characteristics can be applied to future development areas and can be allowed to vary from unit uses in more established areas.

The demand at each node was determined by identifying and summing all the customers or meters in its associated demand area polygon.

Pressure Data

Telogers were used to collect pressure data at 20 locations in the distribution system. The data from the tests were gathered at one-minute sampling intervals, therefore, the pressure graphs show transients or "spikes" in the data. To use the measured pressure data as a reference for evaluation, the data were averaged over one-hour time periods—the smallest time step for which the water distribution system model is valid. From this point, all pressure data will be referenced to the one-hour average values of the measured pressure data.

Analysis of pressure data from both tests indicates that pressures throughout the water distribution system generally range from a minimum of approximately 40 pounds per square inch (psi) to a maximum of about 108 psi.

Results

The results of the EPS calibration are summarized in Figures 3 and 4 (page 17), which show simulated pressures versus recorded data for the 24-hour period at two hydrant locations. Figures 5 through 7 also compare average pressure contours for the three demand allocation methods. Unlike the hourly pressure distribution shown in Figures 3 and 4, the average pressure contours do not show significant variations.

Error Statistics

In an effort to assess the overall quality and reliability of the demand allocation methods, analyses were conducted using error statistics. Because measured data were collected in terms of pressure at the test hydrant locations, analysis of error statistics will be presented in terms of measured and simulated pressures.

The error statistic used for the analyses, referred to as "mean absolute pressure difference (∂p)," is defined as the mean of the absolute value of the difference between measured pressure values and simulated pressure values in psi over the 24-hour duration. This error statistic is defined mathematically as:

$$\partial p = \frac{\sum_{i=1}^{N} |P_{mi} - P_{si}|}{N}$$

where:
∂p = mean absolute pressure difference (psi)
N = number of hourly measurements
Pmi = measured pressure at hour i (psi)
Psi = simulated pressure at hour i (psi)
$|P_{mi}-P_{si}|$ = the absolute value of pressure difference (psi)

Figure 8 shows a summary of the error statistics generated for each demand allocation method. In this study, the point-based demand allocation method provided a mean pressure difference improvement of five to seven psi over area-based and uniform demand allocation methods.

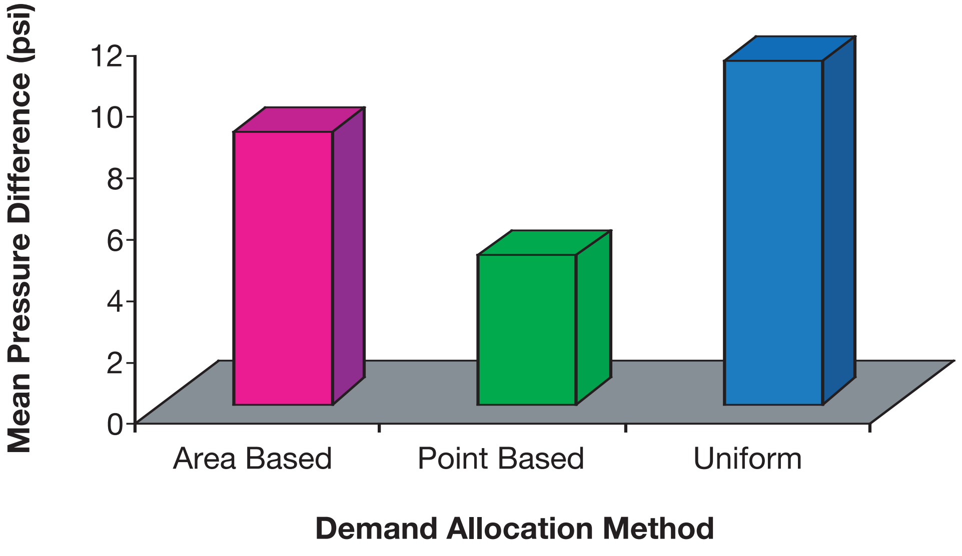

Figure 8: Comparison of Error Statistics

Discussion & Conclusion

Database and GIS software provide tools to combine the different large databases and GIS coverages into a single application for queries and updates of the demand allocation. The demand database documents demand calculations and assumptions and provide a direct link from those calculations to the hydraulic model.

The best method for a specific system depends on the quality and type of data, agency preferences and past methods, planned uses, and the available budget. Ideally, these details have been specified in a project's scope of work. Typically, a modeling effort is started with less than ideal data, but, with creative solutions, it fills the gaps and provides a demand allocation representative of current conditions and future projections.

Area methods for demand allocation apply when there is no meter or parcel-specific water use data available. Population or land use areas provide the distribution, or spatial component, of the demands.

Accurate meter billing data with address information makes a point-based method feasible for existing demand allocation. Significant time savings and improved accuracy are results of preexisting locational data, including GPS meters or a location field in the meter database.

Future demand allocations typically use the area method because future demands are usually based on population or vacant area projections. Area methods require population, land use, and aerial photos to confirm current vacant status and future development potential.

References

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