LOCATING OPTIMAL WATER QUALITY MONITORING LOCATIONS USING DEMAND COVERAGE INDEX METHOD

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ABSTRACT

Locating Optimal Water Quality Monitoring Locations Using

Demand Coverage Index Method

Jeffrey Scott Brake

Water quality regulations are always expanding especially in the field of water quality monitoring; however, threats to our water distribution systems still remain. Components of water distribution systems are susceptible to intentional and accidental contamination; therefore, they represent highly vulnerable aspects of our infrastructure.

An analysis was performed on a city in California with a population of 30,000 to 40,000 residents. The analysis is performed to determine the optimal locations of monitoring stations throughout the water distribution system. The method presented by Liu and colleagues (Liu et al, 2012) selects the optimal monitoring locations for the virtual California city using the Demand Coverage Index (DCI) method. In order to study small scale systems which are typically more vulnerable to tampering, the method attempts to use the virtual city to show the effectiveness of the DCI method and how it can be implemented on smaller water distribution systems (WDS).

The analysis results lay out a number of monitoring stations that should be used to prevent a large scale contamination event from occurring. The number of monitoring stations will vary depending on funding for water infrastructure and coverage requirements. The results represent an outline for improving the effectiveness of the monitoring capabilities in the WDS. The monitoring stations increase the resilience of the WDS from potential terrorist sabotage and mitigate potential outbreaks due to microorganisms, pipeline leaks, or hazardous chemicals entering the WDS.

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ACRONYMS AND ABBREVIATIONS

ADCR	Accumulation of Demand Coverage Ranking
AOP	Advanced Oxidation Process
ASCE	American Society of Civil Engineers
AWWA	American Water Works Association
Cc	Coverage Criterion
cVOC	Carcinogenic Volatile Organic Compound
CWA	Clean Water Act
DBP	Disinfection Byproducts
DBPR	Disinfection Byproducts Rule
DC	Demand Coverage
DCI	Demand Coverage Index
DWS	Drinking Water Strategy
EPA	Environmental Protection Agency
FBI	Federal Bureau of Investigations
FBRR	Filter Backwash Recycling Rule
GPM	Gallons per Minute
HAA	Haloacetic Acid
IESWTR	Interim Enhanced Surface Water Treatment Rule
ISAC	Information Sharing and Analysis Center
GWUDI	Groundwater Under the Direct Influence of surface water
LT1	Long Term 1 enhanced surface water treatment rule
LT2	Long Term 2 enhanced surface water treatment rule
MCL	Maximum Contaminant Level
MCLG	Maximum Contaminant Level Goal
MRDL	Maximum Residual Disinfectant Level
MS	Monitoring Station
NCDCR	Normalized Cumulative Demand Coverage Ranking
NPDES	National Pollutant Discharge Elimination System
PRV	Pressure Reducing Valve
SDWA	Safe Drinking Water Act
SRF	State Revolving Loan Fund
SWTR	Surface Water Treatment Rule
TCR	Total Coliform Rule
TDC	Total Demand Coverage
THM	Trihalomethanes
TOC	Total Organic Carbon
TTHM	Total Trihalomethanes
WDS	Water Distribution System
WIFIA	Water Infrastructure Finance Innovations Authority
UV	Ultraviolet
UIC	Underground Injection Control

1. PROBLEM STATEMENT

Water quality monitoring is a constant concern in water distribution systems, especially with increasing threats of terrorism and a crumbling water infrastructure. This is made obvious with the Homeland Security Presidential Directive 7 and the Bioterrorism Preparedness Act of 2002 which heightened alertness about protecting critical water infrastructure and the need to harden the overall system. Quality of intake water and application of treatment technologies are difficult aspects of distribution systems, but when contamination and the threat of a terrorist attack are possible scenarios, water quality monitoring throughout the system is essential. Security is also vital but difficult to maintain because of the vast areas these systems cover and how vital clean drinking water is. Monitoring is not possible everywhere due to limited resources; hence optimal, or efficient, locations of sensors and monitoring stations are necessary to screen the water for contaminations and discrepancies.

Data concerning water distribution networks, including the population a system serves, physical characteristics, and security, are extremely difficult to obtain due to obvious security concerns. However, Brumbelow (Brumbelow et al, 2007) proposed using a virtual city to analyze and obtain realistic water distribution data. This virtual city is an optimal solution because realistic world data can be used for various threat or disaster scenarios to create security or relief plans.

For the current study, a water distribution system was obtained for a 30,000 to 40,000 resident community. This is a real system in California but for protection of the operators and users, the community will only be referred to as “the CITY” in this study. This system was modelled and analyzed in a previous Master of Science thesis (Johnson,

2012), where a heuristic method was used to solve for the optimal locations for monitoring stations. The method counted the number of contamination detections a particular node obtained when the storage tanks were contaminated. The nodes with the highest number of detections are considered the optimal locations. Another, more complex, method presented by Liu (Liu et al., 2012) will be used in this study to analyze the WDS to compare results and discuss the validity and accuracy of both methods.

The method used in this study is called the Demand Coverage Index (DCI) method and it differs from the heuristic method since it takes into consideration the impact of the temporal distribution of the system as the demand is changing throughout a given day. The method begins with a steady state analysis of the WDS. A trace analysis is then then conducted to determine the fraction of water that contributes to the water distribution system and a water fraction matrix is created. Using a coverage criterion, a coverage matrix and then a demand coverage matrix are created to determine the demand coverage index at each node. Finally, maximizing the demand coverage index gives the most optimal locations for the monitoring stations. The same analysis is then performed for several extended period simulations to represent a more realistic analysis of the WDS.

1.1 Other Methods

The heuristic method used in the previous study on the same WDS was introduced by Chastain (Chastain, 2004). The method counts the times a node detects a contamination event when a particular source node is injected with contaminant. The previous thesis (Johnson, 2012) used the tanks as injection sites to determine the locations of the monitoring stations.

Another method that Liu and colleagues discuss is the Demand Coverage (DC) method presented by Lee and Deininger (Lee et al., 1992). This method is based on the notion that sampling at an upstream location will give information about the water at a downstream location. Then, it maximizes the coverage of water with the minimum number of monitoring stations. Lee and Deininger (Lee et al., 1992) optimize this problem using an integer programming method but a variety of methods can be used. For example, Kumar et al (Kumar et al., 1997), used a heuristic based algorithm, Al-Zahrani and Moied (Al-Zahrani et al., 2001) used a genetic algorithm, and Tryby and Uber (Tryby et al., 2001) used a mixed integer linear programming model to use water age to determine how representative a sample may be. All these alternatives are derived from the Demand Coverage method.

The DC method differs from the DCI method because it ignores how the different time periods will affect the representativeness of a node. This could lead to problems calculating the demand coverage and therefore change the location of the monitoring stations. An example of how these two methods differ can be seen in Table 10 in the Methodology section.

2. WATER SYSTEM EXAMINATION

2.1 Drinking Water Infrastructure

The problem of monitoring the water distribution system is compounded by the deteriorating water infrastructure. The water systems are declining at an alarming rate where frequently the pipes are over 100 years old and significantly past their design lives. According to the 2013 Report Card for Drinking Water (Drinking Water, 2013) by the American Society of Civil Engineers (ASCE), the drinking water infrastructure receives a D+ grade. This rating is unacceptable for a first world country that relies heavily on water distribution systems to supply water to citizens. The U.S. has over 170,000 public drinking water systems and 54,000 are community water systems serving over 264 million people. Approximately 240,000 water mains break per year in the U.S. causing major damage and interruption to roadways, structures, fire control, and transportation.

The main reason for the large number of main pipe ruptures is the difficulty in examining the pipes because they are buried underground and it would be financially unrealistic to examine every pipe. Communities are using analysis tools to determine the worst-condition pipes which should be replaced or repaired first. Another reason for the poor infrastructure is the lack of funding and the additional costs due to requirements set forth by regulations such as the Safe Drinking Water Act (SDWA). These regulations force communities to improve their systems while providing insufficient funding to accomplish this. According to the Environmental Protection Agency (EPA), an investment of $335 billion would be needed to update and repair our failing infrastructure (Figure 1). This investment is likely to be much higher taking into account population growth especially if the U.S. waits years to take action.

SYSTEM SIZE AND TYPE	NEED
LARGE COMMUNITY WATER SYSTEMS SERVING 100,000 OR MORE PERSONS	$116.3 BILLION
MEDIUM COMMUNITY WATER SYSTEMS SERVING 3,301 TO 100,000 PERSONS	$145.1 BILLION
SMALL COMMUNITY WATER SYSTEMS SERVING 3,300 AND FEWER PERSONS	$59.4 BILLION
NONPROFIT COMMUNITY WATER SYSTEMS	$4.1 BILLION
TOTAL STATE NEEDS	$324.9 BILLION
NATIVE AMERICAN AND ALASKAN NATIVE VILLAGE WATER SYSTEMS	$2.9 BILLION
COSTS ASSOCIATED WITH PROPOSED AND ADOPTED SAFE DRINKING WATER ACT RULES	$7 BILLION
TOTAL NATIONAL NEEDS	$334.8 BILLION

Source: Environmental Protection Agency, 2007 Drinking Water Infrastructure Needs Survey and Assessment (In Billions of 2007 Dollars)

Figure 1: EPA Estimate of 20-yr Water Investment to Update WDS (Drinking Water, 2013)

In order to improve the drinking water infrastructure, significant changes will have to occur. The options presented in the report card by ASCE (Drinking Water, 2013) are as follows:

1. Increase public knowledge of the actual cost of water. Raising knowledge of the need for water infrastructure and the associated costs will show people that the current water rates are unrealistic for providing clean, reliable water. Higher water rates are required to help improve the drinking water infrastructure.

2. Bolster the State Revolving Loan Fund (SRF) program. This can be done by reauthorizing more federal funding over the coming years. Figure 2 shows funding for 2008-2012.

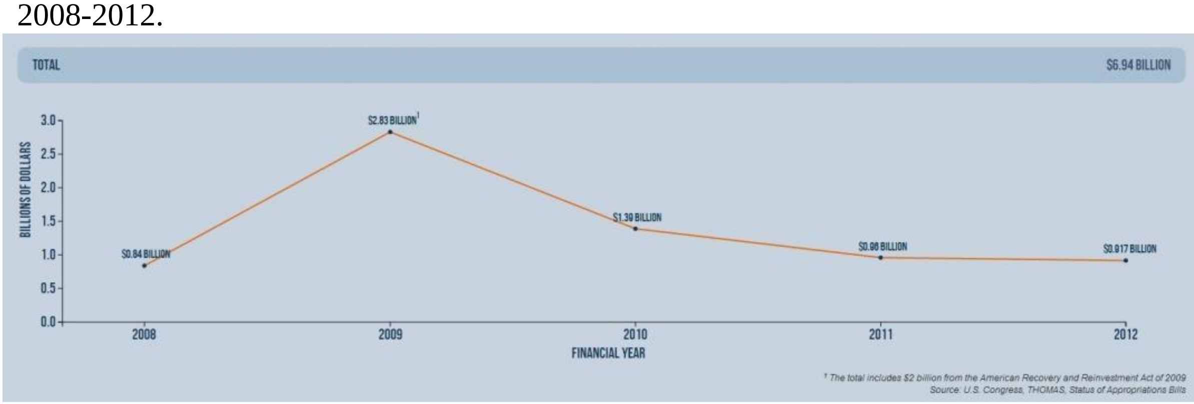

Figure 2: State Revolving Loan Fund for 2008-2012 (Drinking Water, 2013)

3. Suspend state caps on private activity bonds for water infrastructure. This could bring an estimated $6-7 billion annually to be used to rebuild and improve the current infrastructure.

4. Assess the possibility of a Water Infrastructure Finance Innovations Authority (WIFIA). The WIFIA would use funds loaned from the U.S. Treasury to support water projects. Eventually, the loans would be paid back to WIFIA and then the Treasury.

5. Create a federal Water Infrastructure Trust Fund. The Trust Fund would help finance infrastructure projects under the Clean Water Act (CWA) and SDWA.

2.1.1 Solution to Aging Pipes

An innovative solution to the aging pipes is the Aqua-Pipe. The Aqua-Pipe is a trenchless technology used in drinking water systems to reline water main pipes. It is 20-40% less expensive than traditional rehabilitation, causes less impacts to residents because roads do not need to be excavated and repaved (Figure 4), requires no future maintenance, and it can be used under bridges and highways without requiring large excavations. Figure 3 is a cross section of the layers of the Aqua Pipe and Figure 5 shows the final product in place. The new pipes are corrosion resistant and increase the life of the pipe without compromising flow pressure or capacity.

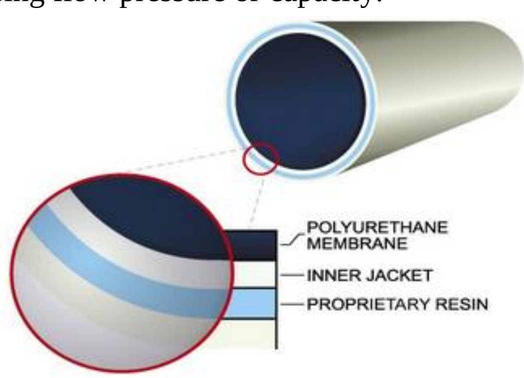

Figure 3: Cross Section of Aqua Pipe (Home, 2015)

Figure 4: Impact on Residents due to Installation (Bright, 2010)

Figure 5: Before and After Rehabilitation (Home, 2015)

Installing this system is significantly easier to accomplish because access pits are only needed at the ends of the section as opposed to digging up the whole pipeline (Figure 6). The new pipe material is then pulled through the pipe and is cured in place with hot water. This process works along bends and under bridges as well. Figure 5 shows a pair of photos of the pipe before and after rehabilitation. This innovative new technology reduces costs associated with replacing water infrastructure and reduces the time required to fix urgent water mains which if ruptured, can cost huge amounts of money to repair surrounding roads and buildings. The Aqua-Pipe would be an ideal solution to the deteriorating pipe network by helping utility workers fix potential weaknesses in the system and put in place monitoring stations to ensure a steady, reliable water supply for future generations.

Figure 6: Installation Process (Bright, 2010)

2.2 Hardening

Water system hardening is the process of protecting a system by reducing possible weaknesses or vulnerabilities. It continues to be an important aspect of water resources as threats of intentional sabotage or contamination rise, regulations expand to include more contaminants and stricter guidelines, and technology advances. For water distribution systems, hardening means protecting vulnerable locations from tampering (i.e. treatment plants, storage tanks, etc.) and reducing the risk of microorganisms contaminating the water supply.

Updated in 2007, the Key Features to achieve system hardening were developed by the EPA to "enhance resiliency and promote continuity of service, regardless of the exact type of hazard or adverse effect a utility might experience (Water: Key Features, 2014)." The Key features are as follows:

1. Integrate protective concepts into organizational culture, leadership, and daily operations.

Protection must be a daily routine supported by senior leadership who are receptive to employees that may observe suspicious activities or may have concerns about potential problems. Well informed leadership is a key aspect of this feature. Leaders are encouraged to stay up to date with advances in security and threat information while working collaboratively with employees to ensure a safe environment.

2. Identify and support protective program priorities, resources, and utility-specific measures.

Continuous focus on protective programs requires resources and investments such as time and effort from managers. Resources should be allocated to the utilities at the most risk and these resources should be used to determine specific protective program needs. Metrics should be used to evaluate performance of the protective programs so adjustments can be made. Self-assessment and progress measurements are vital metrics that should be evaluated regularly.

3. Employ protocols for detection of contamination.

An overall contamination warning system is made up of monitoring water quality, sampling and analysis, enhanced security, and monitoring customer complaints. These aspects help to reduce the public health risk associated with potential contamination events.

4. Assess risks and review vulnerability assessments.

Due to the ever changing threats to water systems, utilities should continually update and review their vulnerability assessments in order to stay up to date on potential susceptibilities and possible consequences.

5. Establish facility and information access controls.

Restrictions should be made to utilities to limit access to authorized users only and controls should be established to detect unauthorized intrusions by physical and cyber threats. Examples of these controls include fences, motion detectors, security patrol, changing access codes regularly, inventorying keys, maintaining firewalls, and denying remote access to data networks.

6. Incorporate resiliency concepts into physical infrastructure.

Utilities should be designed with plans that contribute to overall protection of the utility while also designing for effective daily operations that ensure the safety of workers.

7. Prepare, test and update emergency response, recovery and business continuity plans.

The plans should constantly be updated to manage the evolving threats that utilities face. These plans should involve emergency services in the larger community and utilities should test these plans frequently to ensure preparedness of the community in the event of an emergency.

8. Form partnerships with peers and interdependent sectors.

Building relationships with emergency services and managers of critical infrastructure, such as the power sector, will help people work together to manage an emergency effectively with a minimal interruption of service.

9. Develop and implement internal and external communication strategies.

Utilities should increase awareness of employees, customers, and the general public about response plans. This is accomplished through regular communications about developing strategies. Websites, social media, and annual reports can be great ways to keep all stakeholders informed.

10. Monitor incidents and threat level information.

Systems that analyze threat information should be developed by utilities so proper procedures can be followed based on the threat level. Collaboration with local law enforcement as well as the Federal Bureau of Investigations (FBI) is essential.

The vital characteristics of the Key Features are consistency and flexibility among all utilities, regardless of size, type of source water, treatment capacity, budget, etc. The Key Features will help ensure that all utilities are working toward protecting critical drinking water supplies and that those supplies are monitored to mitigate risks to public health.

2.3 Water Distribution System Components

2.3.1 Water Sources

Drinking water sources are provided by public utilities, commercial entities, communities, or individuals and are supplied through a distribution system consisting of pumps and pipes. These water sources can be categorized into groundwater, surface water, ground water under the direct influence of surface water (GWUDI), and brackish water.

2.3.1.1 Groundwater

Groundwater is water in all the voids within a geologic layer of fractured rock or soil. The sources of this groundwater are confined aquifers, unconfined aquifers including perched water tables, and leaky, or semiconfined aquifers. A confined aquifer is where impermeable strata covers groundwater so it is under more than atmospheric pressure as demonstrated by Figure 7. An unconfined aquifer (Figure 8) is where the water table fluctuates depending on recharge, human use, and permeability. A perched water table is an unconfined aquifer where water has been trapped by impermeable strata due to the rise and fall of the water table as seen in Figure 8. Figure 9 is a sketch of a leaky aquifer, or semiconfined aquifer. This is the most common type and is where a semiconfining, or semipervious layer, has a permeable strata on top or underneath it.

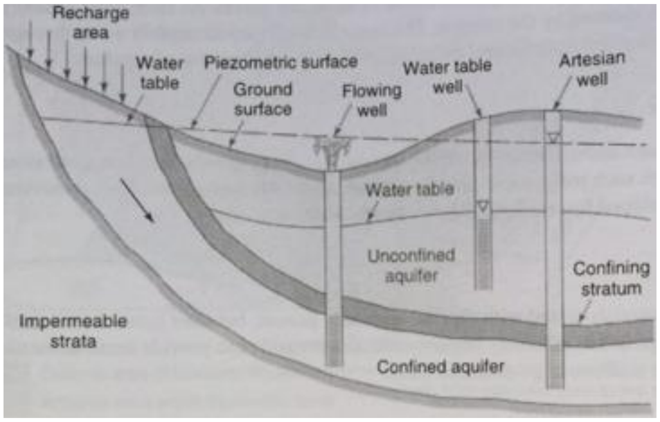

Figure 7: Sketch of Confined and Unconfined Aquifers (Todd et al., 2005)

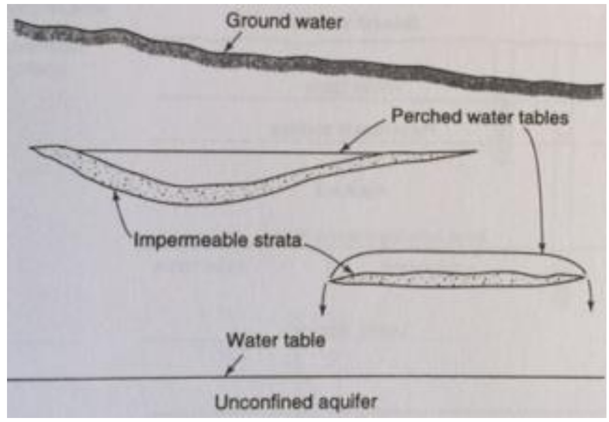

Figure 8: Sketch of Unconfined Aquifer with Perched Water Tables (Todd et al., 2005)

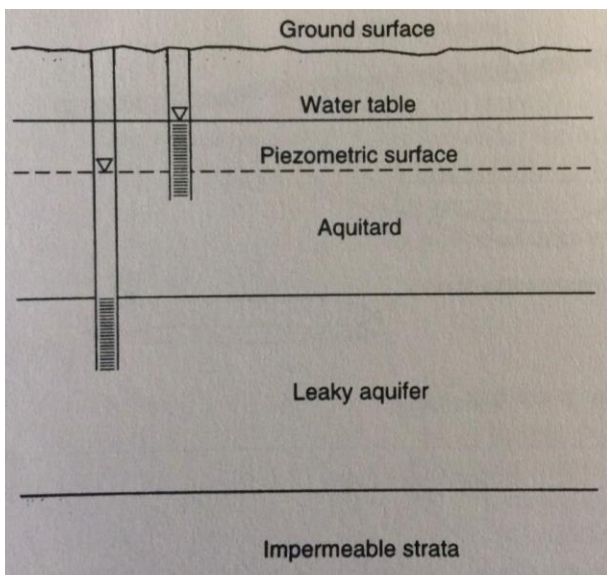

Figure 9: Sketch of Semiconfined, or Leaky Aquifer (Groundwater Hydrology, Todd et al., 2005)

In the unconfined aquifer, natural recharge is the primary means for groundwater to be replenished because rain can percolate through the soil strata. Natural recharge can occur from precipitation, lakes, rivers, snow, and reservoirs. However, in confined aquifers, natural recharge is limited because of a confining stratum so many times artificial recharge is used by pumping water back into the confining aquifer.

The primary uses of groundwater are irrigation, industries, municipalities, and rural homes. This water is desirable because of availability, good water quality, and the low cost of extraction. The water quality is the primary reason groundwater is preferred to surface water. Infiltration and percolation through the soil strata filter the water and remove some contaminants so less, if any, filtration is required. However, groundwater can be contaminated if nearby sites spill waste or improperly dispose of chemicals. Tests are initially performed at sites to ensure good water quality and monitoring protects from future contamination.

2.3.1.2 Surface Water

Surface water consists of streams, rivers, lakes, wetlands, and the ocean which rain water tends to collect in. The water quality of this water is typically poor especially in urban environments because the runoff collects chemicals that cars or garbage leave behind. The water that is collected must be handled according to the Surface Water Treatment Rule discussed in Section VI, Water Rules and Regulations, in this chapter. This includes removing harmful contaminants through disinfection and filtration while monitoring to ensure water quality standards are met.

2.3.1.3 Groundwater Under the Direct Influence of Surface Water (GWUDI)

GWUDI is a groundwater source that receives direct surface water recharge. Examples include some springs, shallow wells near surface water, and basins that allow water to percolate through the soil into groundwater sources. This category was created because the water is potentially contaminated with pathogens from the surface water which are not typically in true groundwater. This water must be treated according to the surface water treatment rules presented in Section VI, Water Rules and Regulations.

2.3.1.4 Brackish Water

Brackish water contains more salt than fresh water but less than sea water. Examples are estuaries, mangroves, deltas, brackish seas (i.e. Baltic Sea), and brackish lakes. This water must be desalinized before it can be used by humans which makes it a less common source of water and a significantly more expensive option. Saltwater intrusion can create brackish water in coastal communities if too much water is pumped from the aquifer. This can compromise a community's water supply so monitoring should be performed regularly to protect residents near the coast. If brackish water is detected, various treatment options or preventative measures will have to be considered to limit the saltwater intrusion.

2.3.2 Treatment Plants

Water and wastewater treatment plants ensure that water is treated and cleaned for use, such as drinking, recreational, and industrial needs. Water treatment plants treat source water and groundwater to ensure the safety of public drinking water and wastewater treatment plants ensure only treated water is pumped back into the

environment. There is a wide variety of treatment options depending on the quality of water and thorough sampling is required to determine which method is most viable. Treatment options include chlorine disinfection, ozone disinfection, ultraviolet (UV) disinfection, advanced oxidation process (AOP), and many more.

2.3.3 Distribution Network

A water distribution network is composed of many parts that are interconnected in order to ensure the delivery of clean drinking water. Typically a water treatment plant receives water from a source such as a lake, river, reservoir, or groundwater. The water is treated and pumped through main transmission lines to large scale industrial users, storage reservoirs, or other water users. Water is conveyed from the storage reservoirs to the public through distribution mains and domestic lines. The network uses a looped system to distribute the water to ensure a certain level of redundancy in case of an event that disrupts part of the water distribution network.

2.4 Redundancy

Water distribution systems are built with a certain level of redundancy in order to operate normally during times of interruption. Such interruptions include maintenance, power outages, pump failures, intentional attacks, pipe failures, etc. The redundancy can be observed in a WDS with backup power generators, additional pumps, looped networks, etc.

Redundancy can be achieved through the basic design of the distribution network, branched vs looped networks. Branched networks (Figure 10) are less expensive but do not provide service to customers if a pipe failure were to occur. Looped networks (Figure

11) are preferred because even if a pipe failure were to occur, the water can be redirected to continually provide services. Figure 10 shows a scenario where a pipe failure has occurred in a branched network and three customers are without service. In contrast, Figure 11 shows a similar looped network with a pipe failure but no customers are affected. The benefits of a looped network and the idea of redundancy are easily seen by the continued service to all customers in Figure 11. The redundancy of the WDS is very important as it ensures consumer service even if a failure were to occur somewhere in the system.

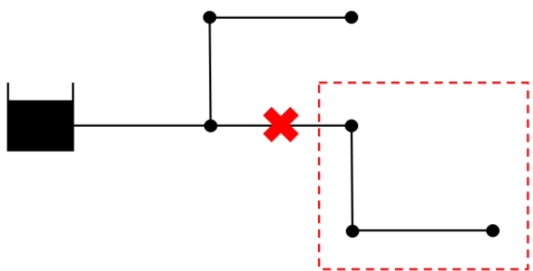

Figure 10: Schematic of Branched Network

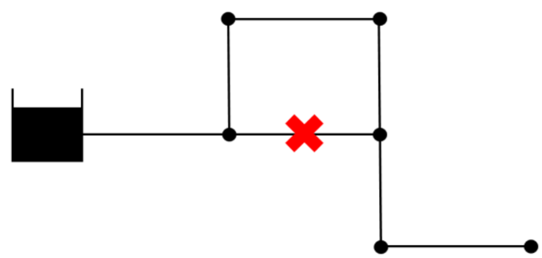

Figure 11: Schematic of Looped Network

2.5 System Residual

With the implementation of the Surface Water Treatment Rule of 1989, a disinfectant residual must be maintained throughout the water distribution system after primary disinfection. This residual is typically referred to as secondary disinfection. The reasons for this residual are to inactive microorganisms, indicate imbalances in the system, and control biofilm build up. Two problems with residuals are certain microbial pathogens are resilient, *Cryptosporidium*, and residuals can react with naturally occurring materials to form byproducts, trihalomethanes and haloacetic acids. The main secondary disinfectants are free chlorine, chloramines, and chlorine dioxide. Other secondary

disinfectants that are being investigated include copper combined with hydrogen peroxide, silver combined with hydrogen peroxide, anodic oxidation, and potassium permanganate and ozone combined with hydrogen peroxide. Regulations regarding secondary disinfectants are presented in Table 1.

Free chlorine is the most common secondary disinfectant in the U.S. due to its effectiveness and long lasting residual. Free chlorine is used less with systems whose source waters have high concentrations of total organic carbons and bromide. Also, due to the potential for DBP formation, the distribution system residual may not exceed 4 mg/L of Cl_2 due to the disinfection byproducts (DBPs) rule. Chloramines are less common and control taste and odor. The main attractions of chloramines are that they produce lower concentrations of DBPs and they are more stable than free chlorines. The distribution system residual may also not exceed 4 mg/L of Cl_2. Chlorine dioxide is even less common and used mainly in small systems. This is due to the residual not lasting as long in the system which makes their use in large systems unrealistic. A problem with chlorine dioxide is that it breaks down into chlorite which is a DBP with a maximum contaminant level (MCL) of 1 mg/L. The distribution system residual may not exceed 0.8 mg/L due to the DBPs rule. Cryptosporidium and some other viruses are resistant to these residuals so other methods of treatment are necessary especially if the source water has a high concentration.

Table 1: Regulations for Secondary Disinfectant Residual (HDR)

Regulation	Effective	Secondary Disinfection Elements
Surface Water Treatment Rule (SWTR)	1990	• For all systems using surface water or groundwater under the influence of surface water for supply, a detectable disinfectant residual must be maintained within the distribution system in at least 95% of the samples collected (or heterotrophic bacteria counts must be less than or equal to 500 cfu/ml as an equivalent) and at least 0.2 mg/L concentration of residual disinfectant (free or combined) entering the distribution system must be maintained. • Monitoring must be conducted throughout the distribution system at same time and locations as those used for total coliform monitoring and continuously at entry point.
Total Coliform Rule (TCR)	1990	• TCR does not require disinfectant residuals or monitoring for disinfectant residuals. • TCR lists disinfectant residual as a Best Available Technology for compliance with total coliform Maximum Contaminant Level (MCL).
Stage 1 Disinfectant/Disinfection By-Products Rule (Stage 1 DBPR)	2002	• Establishes Maximum Disinfectant Residual Levels (MRDLs) of 4.0 mg/L as Cl_2 for chlorine, 4.0 mg/L as Cl_2 for chloramine, and 0.8 mg/L for chlorine dioxide. The DBPR also lowers the MCL for total trihalomethanes (TTHMS) from 0.10 mg/L (established in THM Rule) to 0.080 mg/L, and sets new MCLs for haloacetic acids (HAA_5) (0.060 mg/L), chlorite (1.0 mg/L), and bromate (0.010 mg/L). System may use SWTR disinfectant residual monitoring results to determine MRDL compliance. • Monitoring must be conducted throughout the distribution system at same time and locations as those used for total coliform monitoring and continuously at entry point

2.6 Water Rules and Regulations

This section presents rules and regulations that increase the safety of the public drinking water systems throughout the US. These rules are created and implemented by the EPA in order to provide cleaner drinking water by reducing the risk of microbial contaminants in the WDS.

2.6.1 Clean Water Act

The Clean Water Act (CWA) was passed through Congress in 1972. This act is a significant change of the Federal Water Pollution Control Act of 1948. The purpose was to provide a regulating structure for discharge of pollutants and for quality standards of waters in the United States. The act forbade the discharge pollutants from a point source, such as a pipe or ditch, into navigable waters without a National Pollutant Discharge Elimination System (NPDES) permit. In addition, the act helps to get funding the construction of sewage treatment plants due to new wastewater standards that the EPA implemented with the CWA.

2.6.2 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) of 1974 was created to protect drinking water and its sources as well as to regulate the nation's public drinking water supply. The SDWA is the main federal law that safeguards water quality. Threats to the system include animal and human waste, pesticides, improperly disposed of chemicals, and naturally occurring substances. The EPA set national health-based standards for drinking water quality that applies to all 160,000+ public water systems in the US. These standards protect drinking water from contaminants and other threats. This does not apply to private wells that serve less than 25 people. An amendment in 1996 changed the focus

of the SDWA from treatment of the water to increasing laws relating to funding for system improvements, source water protections, and public information. These components greatly increase the protection of drinking water by ensuring the quality from source to tap. Another important aspect of the SDWA is the underground injection control (UIC) program which regulates injection wells that put liquid into the ground for storage or disposal purposes.

2.6.3 Surface Water Treatment Rules

In order to further increase the safety of drinking water supplies, the EPA created the surface water treatment rules (SWTR) in conjunction with the disinfectants and disinfectants byproducts rules. All these rules were developed to decrease the presence of microbial contaminants in the water and reduce the risk posed by disinfectants and disinfectant byproducts (DBPs). Figure 11 shows the progression of rules relating to limiting DBPs. Presented below are the five SWTRs with a brief description of each.

a. Surface Water Treatment Rule of 1989

b. Interim Enhanced Surface Water Treatment Rule of 1998

c. Filter Backwash Recycling Rule of 2001

d. Long Term 1 Enhanced Surface Water Treatment Rule of 2002

e. Long Term 2 Enhanced Surface Water Treatment Rule of 2006

2.6.3.1 Surface Water Treatment Rule of 1989

The SWTR of 1989 requires microbial contaminants to be removed through filtration and disinfection in surface water and groundwater under the direct influence of surface water (GWUDI). The rule is intended to decrease public health risk to contaminants such as viruses, *Giardia lamblia,* and *Legionella* by setting maximum contaminant level goals (MCLGs) at zero mg/L. The goals are set at zero because the

presence of the contaminants at source waters and the health risks associated with exposure. The rule specifies that treatment should be adequate to reduce source water concentration of *Giardia lamblia* by 99.9% (3 log removal) and viruses by 99.99% (4 log removal). The SWTR determines filtration systems performance by measuring turbidity and requiring a disinfectant residual to be maintained throughout the water system at a detectable level. The most common residual disinfectant is chlorine but chlorine may interact with some naturally-occurring materials to create byproducts which could be a hazard to the health of users. Another important part of the SWTR is the absence of any control for *Cryptosporidium,* which has a high resilience to chorine disinfection.

2.6.3.2 Interim Enhanced Surface Water Treatment Rule of 1998

The Interim Enhanced Surface Water Treatment Rule (IESWTR) of 1998 improves public health protection by reducing the risk of microbial contaminants, in particular, *Cryptosporidium* and disinfection byproducts. Cryptosporidium is an important contaminant because of its resistance to chlorine disinfection combined with its adverse health effects. The IESWTR requires a lower turbidity standard which improves filtration performance. It also only applies to systems serving greater than 10,000 people with surface water sources or groundwater under the direct influence of surface water.

2.6.3.3 Filter Backwash Recycling Rule of 2001

The Filter Backwash Recycling Rule (FBRR) requires the filter backwash water from treatment plants to be recycled. This backwash must be filtered through all processes of filtration and monitoring data must be sent to the state. The FBRR is employed to reduce the presence of microbial contaminants in public drinking water systems.

2.6.3.4 Long Term 1 Enhanced Surface Water Treatment Rule of 2002

Long Term 1 Enhanced Surface Water Treatment Rule (LT1) expands the IESWTR to water systems serving less than 10,000 people. It increases control of microbial pathogens, such as Cryptosporidium, and addresses additional concerns with disinfection byproducts. These controls include improving filtration requirements and requiring systems to determine microbial inactivation. The latter requirement is used for microbial protection of systems that make changes to avoid disinfection byproducts.

2.6.3.5. Long Term 2 Enhanced Surface Water Treatment Rule of 2006

Long Term 2 Enhanced Surface Water Treatment Rule (LT2) specifies additional treatment for Cryptosporidium and other microbial contaminants if significant levels are found at the source waters. This applies to surface water or GWUDI systems. In addition, the LT2SWTR reduces potential risk from disinfection byproducts by implementing rules that address the cost/benefit of certain pathogens and DBPs.

2.6.4 Drinking Water Strategy

The Drinking Water Strategy (DWS) was developed in 2010 by the EPA to further increase protection of drinking water from contaminants as well as to promote speedy and cost-effective new technologies. The DWS has 4 goals as described below:

The first goal is to address contaminants in groups as opposed to individually. This promotes a cost and time effective means to protect water supplies. Grouping contaminants like this allows facilities to improve treatment methods more efficiently by protecting against a greater number of contaminants more easily.

The second goal is to promote new drinking water technologies that will protect against a wider variety of contaminants. The Water Technology Innovation Cluster was created to develop, test, and market these new technologies.

The third goal is to use laws to ensure our drinking water is protected. A list of over 130 chemicals was compiled due to their potential harmful effects to the endocrine system. This list allows for screening of these chemicals to determine their concentrations in water sources and determine if additional testing is necessary.

The last goal is to allow for shared access to public water systems monitoring data between the EPA and states. This will increase the use of advanced information technologies and will allow states, industry, and consumers to obtain information about drinking water quality and performance. The sharing of data will also enhance review of drinking water health issues without further information collecting problems.

2.7 Contaminants and Monitoring

2.7.1 Contaminants of Concern

The National Public Drinking Water Regulations have standards for limiting contaminants in drinking water. Contaminants that may endanger public safety are being continuously updated to ensure the safety of drinking water systems. There are several types of contaminants that may put public health at risk and they include microorganisms, disinfection byproducts, disinfectants, inorganic chemicals, and organic chemicals. Table 2 provides an abbreviated list of the microorganisms that are monitored and their maximum contaminant level goals (MCLG). A complete list of the contaminants of concern is located in Appendix B.

Cryptosporidium is particularly important to examine because of its resistance to chlorine disinfection and history of outbreaks. The most notable outbreak was in Milwaukee, Wisconsin in 1993 where more than 400,000 people became ill due to the contaminated drinking water. This contaminated drinking water was linked back to the city water supply system. The outbreak along with the several other incidents involving Cryptosporidium around the world has prompted new regulations and monitoring standards. For more information on the regulations, view section VI of Chapter 2, Water Rules and Regulations.

Table 2: Abbreviated Version of Microorganisms of Concern (Drinking Water)

Microorganisms				
Contaminant	**MCLG[1] (MG/L)[2]**	**MCL or TT[1] (MG/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Cryptosporidium	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Giardia lamblia	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Viruses (enteric)	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Legionella	zero	TT[3]	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems

2.7.2 Monitoring

The EPA must remain vigilant against all threats to water supplies and this is accomplished through monitoring water quality. Water quality monitoring includes sampling and analysis to determine water constituents and current conditions. These constituents include pollutants that are introduced by humans (oils, pesticides, metals, microorganisms, etc) and naturally occurring constituents (dissolved oxygen, bacteria, nutrients, etc). According to the EPA, there are 4 reasons to monitor water quality.

1. Determine if the water is meeting designated usage guidelines. These uses include fishing, swimming, and drinking. Pollutants must be monitored to ensure that they do not exceed certain thresholds.

2. Identify specific pollutants and their sources. This allows the EPA to determine responsible parties if pollutants are introduced into water sources.

3. Access trends in long term monitoring. This helps determine if water sources are changing due to human involvement and aid in rehabilitating contaminated sources to natural conditions.

4. Screen for impairment. Monitoring provides an early warning system to users of the water so pollutants can be contained to mitigate risk to human health.

Due to the wide variety of contaminants, monitoring is performed by using sensors and instruments that are able to detect changes in baseline water quality. Some of the factors that the sensors measure are pH, total chlorine, total organic carbon (TOC), temperature, and turbidity. An important contribution to water quality monitoring is the development of network based detection systems in order to create a clearer overall picture of the WDS. In addition to this system, continuous sampling is being

implemented to replace sampling every day or every month. The cheap, commercially available sensors are typically between $5,000 to $10,000 (Hall, 2009), therefore it is reasonable to assume sensors that continuously monitor water quality and are networked together may be quite expensive. With new developments in technology and software, monitoring will become easier to implement and will continue to protect water supplies from a broad array of contaminants, both naturally occurring and man-made.

When designing a water quality monitoring program, an engineer must use the monitoring location to determine what pollutants will most likely be associated with that location. Table 4 shows several examples of sources along with associated pollutants. Also, volunteer water quality monitoring programs should be involved to ensure continuously uncontaminated water.

Table 3: Pollutants Associated with Certain Sources (Chapter 5)

Source	Common Associated Chemical Pollutants
Cropland	Turbidity, phosphorus, nitrates, temparature, total solids
Forestry harvest	Turbidity, temperature, total solids
Grazing land	Fecal bacteria, turbidity, phosphorus, nitrates, temperature
Industrial discharge	Temperature, conductivity, total solids, toxics, pH
Mining	pH, alkalinity, total dissolved solids
Septic systems	Fecal bacteria (i.e., Escherichia coli, enterococcis), nitrates, phosphorus, dissolved oxygen/biochemical oxygen demand, conductivity, temperature
Sewage treatment plants	Dissolved oxygen and biochemical oxygen demand, turbidity, conductivity, phosphorus, nitrates, fecal bacteria, temperature, total solids, pH
Construction	Turbidity, temperature, dissolved oxygen and biochemical oxygen demand, total solids, and toxics
Urban runoff	Turbidity, phosphorus, nitrates, temperature, conductivity, dissolved oxygen and biochemical oxygen demand

3. VULNERABILITY ANALYSIS

3.1 Vulnerability Categories

Analyzing various vulnerability categories is an important aspect of determining possible weaknesses and threats associated with the WDS. According to Haimes and colleagues (Haimes et al., 1998), the vulnerability categories are as follows.

3.1.1 Physical Threats

Physical threats to water facilities are physical damage to the water system. Facilities that are at risk include dams, levees, water and wastewater facilities, storage tanks, pipes, etc. These types of threats can be acts of terrorism or natural disasters.

Possible solutions to these physical threats are designing for natural disasters, fencing in vital areas, locking doors and gates, installing cameras, maintaining well lit areas, employee patrols, and using alarm systems. Other procedural controls can be implemented to deter threats such as changing access codes regularly, requiring identification cards, inventorying keys, and monitoring contractors and other temporary workers in the area. These are only a few of the solutions that could help to mitigate physical threats to critical water infrastructure.

3.1.2 Chemical and Biological Threats

Chemical and biological threats include both intentional and accidental contamination events that affect the water distribution system. These threats can be the most dangerous because if the contamination is not detected, thousands of people can be exposed to the harmful contaminants. Contamination events can include reservoir contamination, terrorists introducing harmful microorganisms, accidental over- or under-

dosing chemicals in the treatment process, and groundwater or surface water contamination.

3.1.3 Cyber Threats

Water facilities are at risk for cyber intrusion because of their use of industrial control systems and electronic networks. These systems monitor and control intakes, sewage collection, water and sewage treatment, effluent discharge, and other processes. In the event of a cyber-attack, a hacker may use chemicals to overdose or under dose, discharge untreated sewage, disrupt water distribution, or send tampered or false data to the operators. This can have serious consequences on users who may receive contaminated drinking water or swim in waters that have untreated sewage flowing in them.

Due to several recent cyber intrusions, a more detailed description of cyber security will be provided. These intrusions include threats that ended in physical damage, the centrifuges in Iran (Sanger, 2012) where hackers were able to send false data to the centrifuges in order to make them run faster and ultimately break. Another type of cyber intrusion is information theft such as the hack on Sony (Pepitone, 2015) where hackers were able to obtain extensive personal information about individuals in the company. In recent years, there have been several important measures to reduce cybersecurity risks. In 2008, the "Roadmap to Secure Control Systems in the Water Section" was developed to provide a 10-yr vision for water facility control systems to remain functional in the event of a cyber-attack. The document expresses the need for finding ways to detect, respond to, and mitigate consequences of attacks on the control systems. In response to this, the American Water Works Association (AWWA) developed guidelines that reduce the risk

of cyber-attack by identifying prioritized actions for water and wastewater facilities. Another measure is to promote information sharing through analysis centers, host monthly cyber threat briefings to always be informed on evolving threats, and have a Water Information Sharing and Analysis Center (ISAC) that receives reports on cyber incidents in order to relay the possible threats to facility operators.

Many techniques have been developed in recent years to ensure minimal consequences if a cyber-attack occur. The first is to employ manual overrides should critical systems be compromised. Also, storing water in the distribution system and having the capability to isolate certain systems from the Internet are important options that ensure facilities can stay operational during an attack. Another technique is for facilities to be custom designed which ensures that there are very few common processes or systems that hackers could use to spread out to multiple facilities and disrupt large water systems. Finally, chemicals cannot be remotely released and control systems do not allow operators to perform actions that may endanger containment.

Cybersecurity will always be an important topic but due to recent developments and safety procedures, it is unlikely that a cyber-attack will cause widespread contamination with adverse effects on public health or safety. However, an attack may cause a temporary disruption of normal operations in water and wastewater facilities.

For the research presented in this study, we examine the threat of intentional chemical or biological contamination in the distribution system because it is the most likely method that would be employed. This is due to the higher level of cyber security and the inherent difficulty in physically harming the water infrastructure to a level that would be significant and far reaching.

3.2 Points of Contamination

Water distribution systems are large systems covering many square miles so intentional and accidental contaminations are inherent. There are numerous points where contamination is likely and some of these are more susceptible than others. Chemical or biological contamination is the most serious because of the likeliness of intentional contamination and widespread distribution. The entry points of possible contamination are highlighted and briefly discussed below.

3.2.1 Water Treatment Plant

Treatment plants rely on surface water for large scale water systems and groundwater for smaller, community water systems. According to the EPA, about 68% of the population is served with water from surface water sources while about 32% of the population gets their water from groundwater sources. As discussed earlier, surface water is more easily contaminated than groundwater due to its ease of access. Contaminated surface or groundwater does not mean the population is at risk due to the strict treatment and monitoring guidelines set up by the EPA. The regulations ensure that source water will be properly treated and monitored in order to ensure the safety of the public. Even if no treatment is available for a specific contaminant, a treatment plant may shutdown to stop the spread of the contaminant.

3.2.2 Tanks and Reservoirs

For this research, tanks and reservoirs will be a primary target for an intentional contamination event because these are the easiest to access. This ease of access is due to their remote locations and limited security. Fencing may be the only line of defense for the tanks and there is an extensive challenge in constantly surveying the entire reservoir.

These systems are desirable as contamination sources because they could quickly affect a large population. Tanks receive water during low demand periods while delivering water during high periods which make high demand periods enticing times to contaminate.

3.2.3 Pump Stations

Pump stations are usually protected from tampering or sabotage by reinforced concrete, steel, and masonry wall construction with no standard windows. Occasionally some pumping equipment may be located in outside enclosures which increases the chances of tampering. However, these locations are not constantly monitored so outside access is still possible. If accessed, the shutdown or tampering of valves may cause significant problems throughout the system especially if contaminants are allowed to enter the system at these key locations.

3.2.4 Hydrants

Hydrants are easily accessible to people and the only current means of protection is hydrant locks which are aftermarket ad-ons. These locks are often only used in places that have experienced vandalism and are not used "preemptively over broader areas of the distributions system (Hydrant, 2011)." A possible solution is a check valve which blocks the backflow so contaminants cannot enter the system while allowing emergency services access to the hydrants for firefighting capabilities. Another difficult part of contaminating hydrants is having the proper equipment (portable tank, pump, and motor assembly) and not attracting unwanted attention which is difficult because the pumping would be loud and obvious to nearby people. The proximity of hydrants to largely populated areas is the main reason that this contamination issue is unlikely and will not be examined in this research.

4. METHODOLOGY

4.1 Terminology

4.1.1 Water Fraction

W(i,j) is the fraction of water that contributes to monitoring station i from node j.

An example water distribution network is shown in Figure 12. It shows node J3000 contributes 85% of its water to monitoring station J4000, therefore, W(J4000,J3000) = 0.85. It can be assumed that the water quality at J4000 is representative of the water quality at J3000 if W(i,j) is greater than the coverage criterion.

4.1.2 Coverage

Refers to whether the water quality at a particular node is representative of the source node. If the water fraction is greater than the coverage criterion then it is covered.

In Figure 12, node J4000 is a coverage of J3000 or node J4000 is covered by J3000.

4.1.3 Coverage Criterion

A pre-defined criterion to determine if the water quality at one node can represent the water quality at another.

In this study a coverage criterion of 0.50 is used. The W(J4000,J3000) is 0.85, meaning that node J4000 is representative of node J3000, or covered by J3000. If the water fraction were to be less than 0.50 than node J4000 is not representative of J3000. Since W(J5000, J3000) = 0.15, the water quality at J5000 cannot be representative of the water quality at J3000 because it is less than the coverage criterion.

4.1.4 Coverage Ratio

The ratio of demand covered by the selected monitoring stations to the total demand.

For example, say the set of monitoring stations covers a demand of 905 out of a total demand of 1000. The coverage ratio of the WDS is calculated to be 0.905 which means that 90.5% of the total demand is covered by the selected monitoring stations.

4.1.5 Demand Pattern

The usage demands at a single node combined with a demand multiplier that changes throughout a 24 hour cycle.

Figure 13-16 show the demand patterns used in this study. Demand pattern 2.0 will raise a nodes demand in the morning and at night to simulate peak hours of water use. While demand pattern 3.0 will raise the demand during the middle of the day (Figure 14).

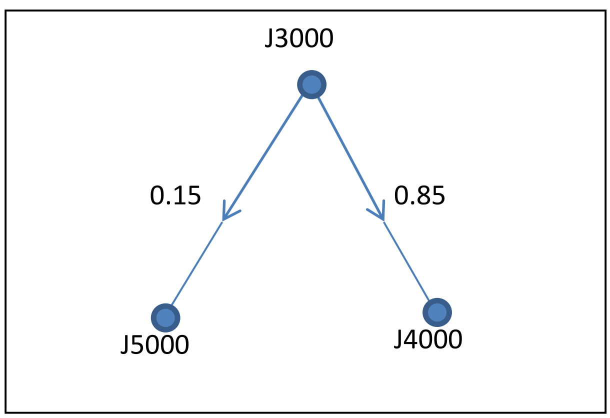

Figure 12: Example WDS

4.2 EPANET Theories

EPANET is the software utilized by WaterCAD for the analysis of the system response to various demands.

4.2.1 Advection Transport Theory

The principal transport mechanism throughout the system is advection while longitudinal dispersion is negligible under normal operating conditions. This means that a dissolved substance will travel at the same average velocity in the pipe as the surrounding fluid while reacting (growing or decaying) at a given rate. No mixing occurs between adjacent segments of water. This transport mechanism is expressed in the following equation:

$$\frac{\partial C_i}{\partial t} = -u_i \frac{\partial C_i}{\partial x} + r(C_i) \quad (1)$$

Where:

C_i	= Concentration (mass/volume) in pipe i	
u_i	= Flow velocity (length/time) in pipe i	
r	= Rate of reaction (mass/volume/time)	
t	= Time	
x	= Longitudinal distance in pipe i	

4.2.2 Junction Mixing Theory

The mixing of fluids at junctions that receive inflow from two or more pipes is assumed to be complete and instantaneous. Therefore, the concentration of a substance at the junction outflow is the flow-weighted sum of inflow concentrations. For a particular node k, the equation is:

$$C_{i|x=0} = \frac{\sum_{j\varepsilon I_k} Q_j C_{j|x=L_j} + Q_{k,ext} C_{k,ext}}{\sum_{j\varepsilon I_k} Q_j + Q_{k,ext}} \qquad (2)$$

Where:

- i = Link with flow leaving node k
- I_k = Set of links with flow into k
- L_j = Length of link j
- Q_j = Flow (volume/time) in link j
- $Q_{k,ext}$ = External source flow entering at node k
- $C_{k,ext}$ = Concentration of external flow entering at node k
- $C_{i|x=0}$ = Concentration at start of link i
- $C_{i|x=L}$ = Concentration at end of link i

4.2.3 Storage Mixing Theory

The contents of tanks, reservoirs, and other storage facilities are assumed to be completely mixed. This is a valid assumption because the tanks operate under fill-and-draw conditions with minimum momentum flux being conveyed to the inflow (Rossmand and Grayman, 1999). With this assumption, the contents of the tanks are a mixture of current contents and inflow water. Due to various reactions, however, the internal concentration may be changing. The equation that represents the mixing is:

$$\frac{\partial(V_s C_s)}{\partial t} = \sum_{I \varepsilon I_s} Q_i C_{i|x=L_i} - \sum_{j \varepsilon O_s} Q_j C_s + r(C_s) \quad (3)$$

Where: V_s = volume in storage at time t

C_s = concentration within the storage facility

I_s = set of links providing flow into facility

O_s = set of links withdrawing flow from facility

4.2.4 System of Equations

The following conditions are applied to equation 1-3 in order to solve for the concentration in each pipe as well as the concentration in each storage facility (tank or reservoir):

- initial conditions specifying C_i for all x in each pipe i and C_s in each storage facility s at t = 0
- boundary conditions specifying values for $C_{k,ext}$ and $Q_{k,ext}$ for all time t at each node k which has external mass inputs
- hydraulic conditions specifying the volume V_s in each storage facility s and the flow Q_i in each link i at all times t

4.2.5 Bulk Flow Reactions

These reactions occur between substances in the pipe or storage facility and the constituents in the water. For this study the bulk flow is assumed to be zero. This is a conservative approach because the study is assuming the contaminant does not degrade throughout the system but rather is primarily traveling by advection. Without degradation, the contaminant would have a higher concentration when humans consumed it so the analysis is for a worst case scenario.

4.2.6 Lagrangian Transport Algorithm

A Lagrangian time-based approach is used by EPANET to track discrete water parcels as they travel and mix together throughout the system. Due to the quick travel times within pipes, short water quality time steps (minutes) are used instead of the longer hydraulic time steps (hours).

4.3 Number of Optimal Monitoring Stations

The optimal number of monitoring stations is difficult to determine due to limits in funding and evolving threats to the WDS. The number of monitoring stations should be at least the same as the number of tanks, if economically feasible, but more would be recommended for complete coverage. The closest nodes to the tanks will detect contamination immediately before it spreads throughout the system so these would be the bare minimum of the monitoring locations. This results in at least seven monitoring stations for the CITY in this study.

However, if contamination occurred in another point of the distribution system or along the main transmission line then the optimal locations for monitoring stations would be different and there should be an increase in the number of nodes being monitored. This makes it difficult to determine the most vulnerable aspect of the system because it is an ever-evolving threat. The ultimate number of nodes should be dependent on economic feasibility as well as inherent risk to the distribution system. In this study, the best 15 monitoring locations in the WDS are determined because these will provide significant protection at a reasonable cost for a WDS serving 30,000 to 40,000 residents. The monitoring stations are listed in order of importance in case the CITY cannot afford all 15 but must purchase fewer due to insufficient funding.

4.4 Chosen Model Type

The WDS came with a wide variety of demand patterns. These help to determine if the temporal distribution affects the location of the optimal monitoring stations. Two types of demand patterns will be examined: steady state and unsteady state. The steady state analysis represents a baseline to determine if the changing temporal distribution affects the location of the best monitoring stations while unsteady state represents a more realistic examination of the WDS.

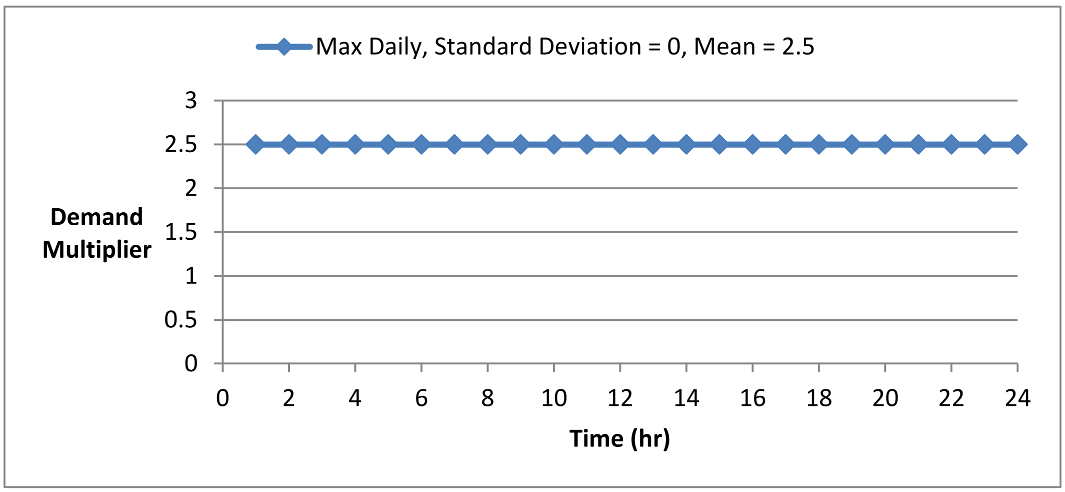

Figure 13: Max Daily Demand Pattern

Several models were developed for the CITY. Steady state and unsteady state hydraulics are used. For steady state, an average daily demand and max daily demand were available but only max daily demand will be used. Max daily demand is used in order to be conservative and assume the worst case scenario such as peak water use during a hot summer day (Figure 13). For unsteady state, patterns 2.0, 3.0, 4.0, 5.0, 6.0, & 7.0 will be used. These patterns have varying temporal distributions to simulate different

ways the water may be used in a given day. A more detailed description of the patterns can be seen in Figure 14-16.

The analysis disregards the nodes along the main transmission line because these are harder to contaminate and stations located throughout the distribution system would be more site specific.

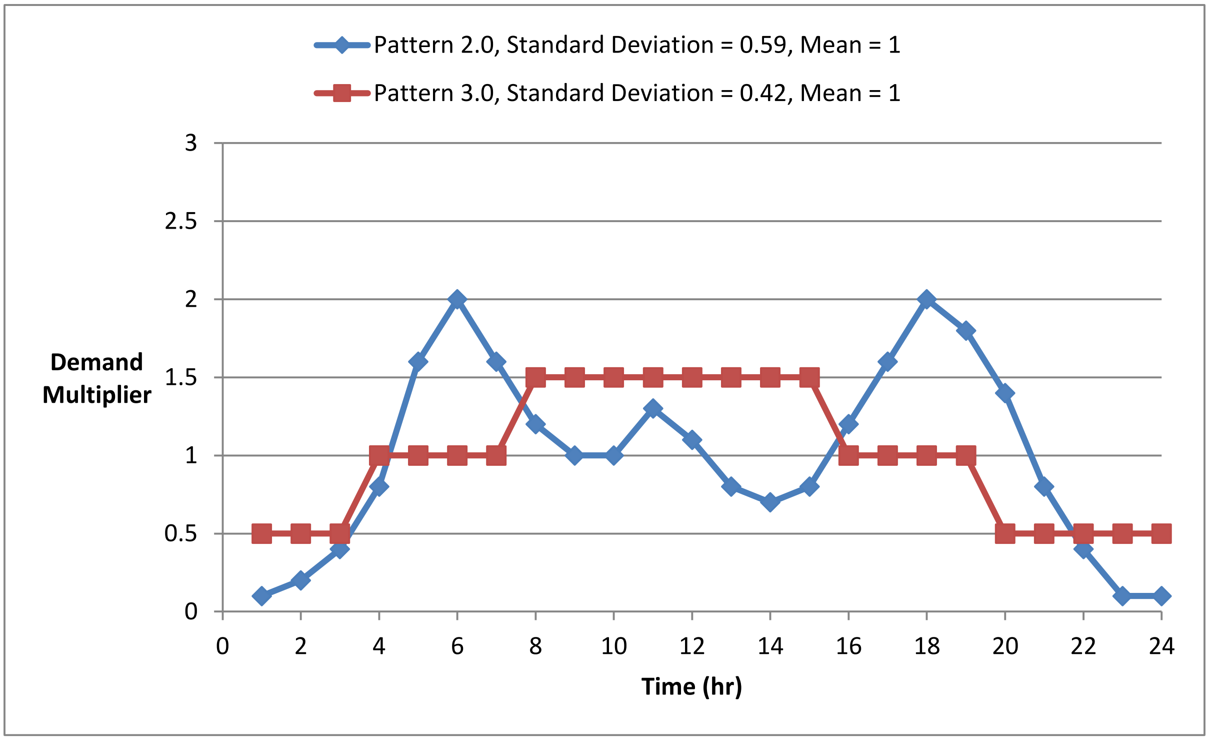

Figure 14: Demand Pattern 2.0 and 3.0

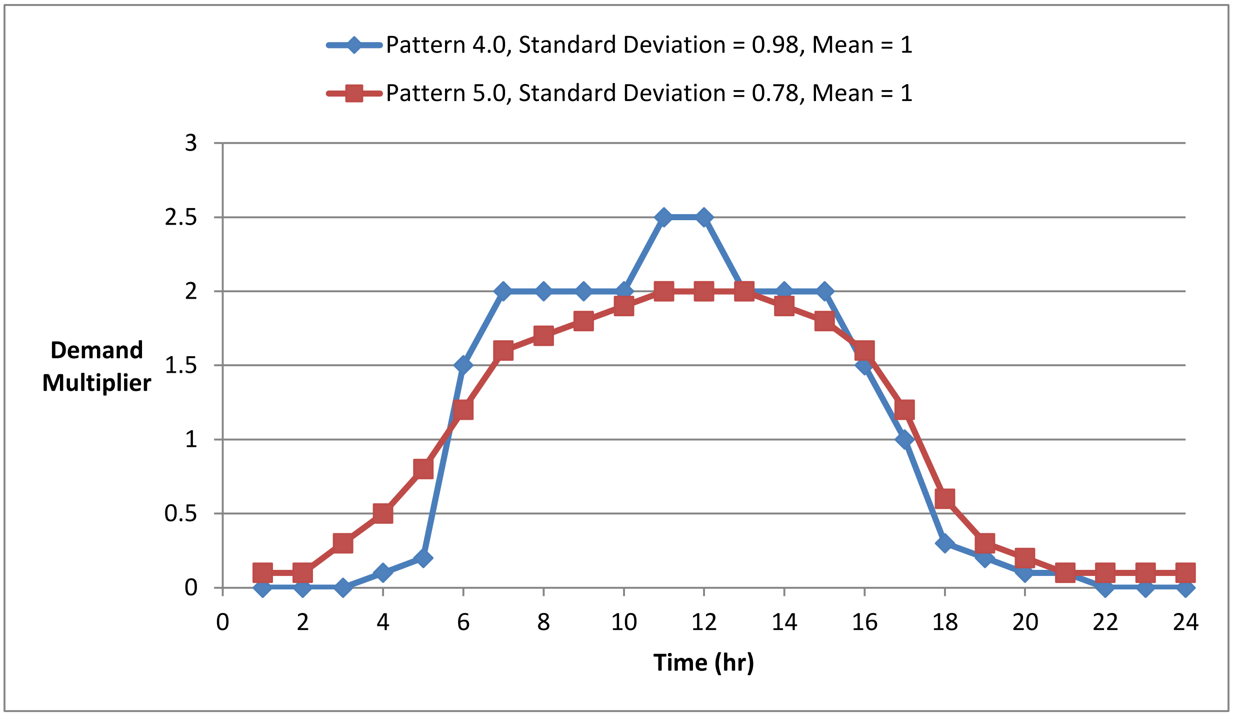

Figure 15: Demand Pattern 4.0 and 5.0

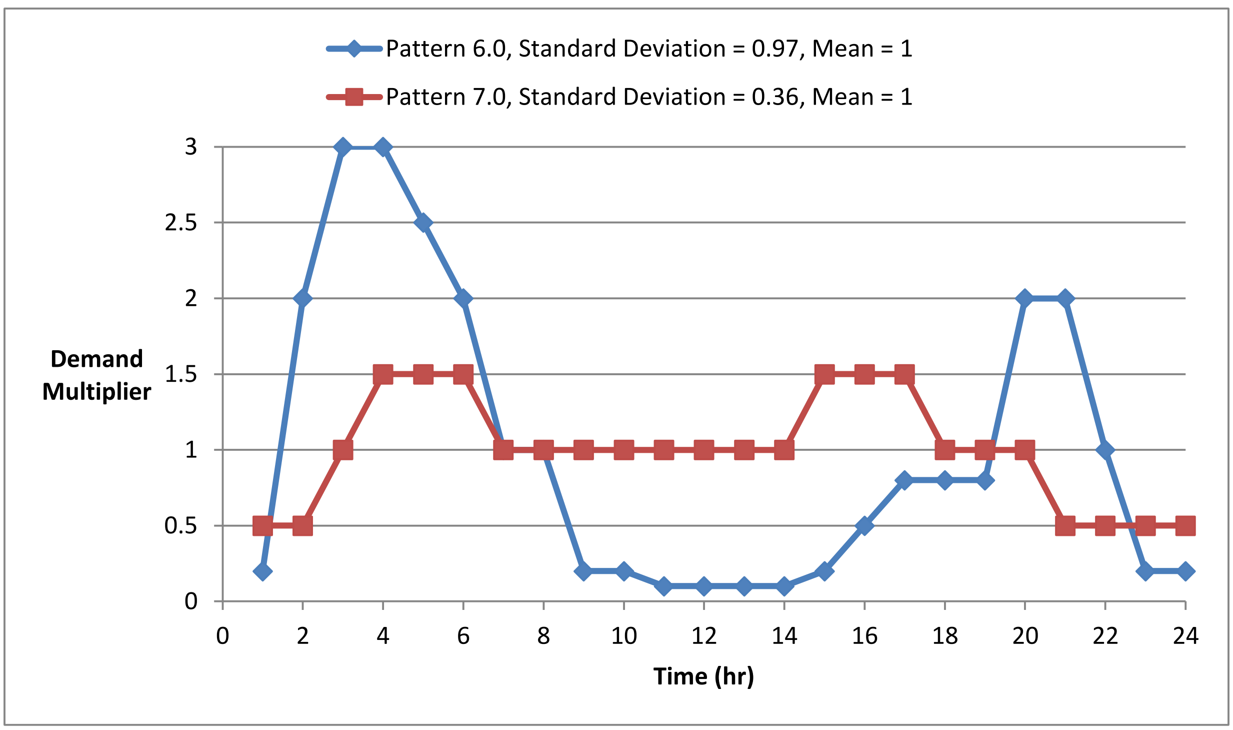

Figure 16: Demand Pattern 6.0 and 7.0

4.5 The "CITY" Examined

Description: The city serves 30,000 to 40,000 residents and will remain anonymous throughout the paper to protect the WDS, as well as the users and operators of the system. It contains 654 nodes, 619 in water distribution system and 35 in the main transmission line. There are 13 pressure reducing valves located throughout the main transmission line, as well as 10 tanks and 5 wells. Figure 17 shows all the various components of the WDS.

How it Works: The system starts at T-92, which we can assume is a water treatment plant or large reservoir, where the water begins flowing through the main transmission lines. This water enters the water distribution system through 13 pressure reducing valves (PRVs) and propagates throughout the network. Pressure reducing valves reduce a high pressure at the inlet to a lower, steadier pressure at the outlet. The PRV works automatically as the flow rate changes and inlet pressure varies. Water is stored in tanks and wells. The booster schedule in Table 4 shows when the tanks open their isolation valves to provide the system with water. A pump is used to pressurize the water to the current operating pressure. When the tank is closed off from the system, it does not contribute to the hydraulics. This water serves the community according to the booster schedule of the tanks. The remaining water in the main transmission lines exit the system through T-91 and T-93.

Table 4: Booster Schedule for Tanks

Tank #	Boost Days	Boost Times
1	Thursday, Sunday	5 am - 8 am
2	Tuesday, Saturday	5 am - 9 am
3	Thursday, Sunday	5 am - 9 am
4	Tuesday, Saturday	5 am - 9 am
5	Monday, Wednesday, Friday	4 am - 9 am
6	Monday, Wednesday, Friday	5 am - 4 pm
7	Monday, Wednesday, Friday	4 pm - 10 pm

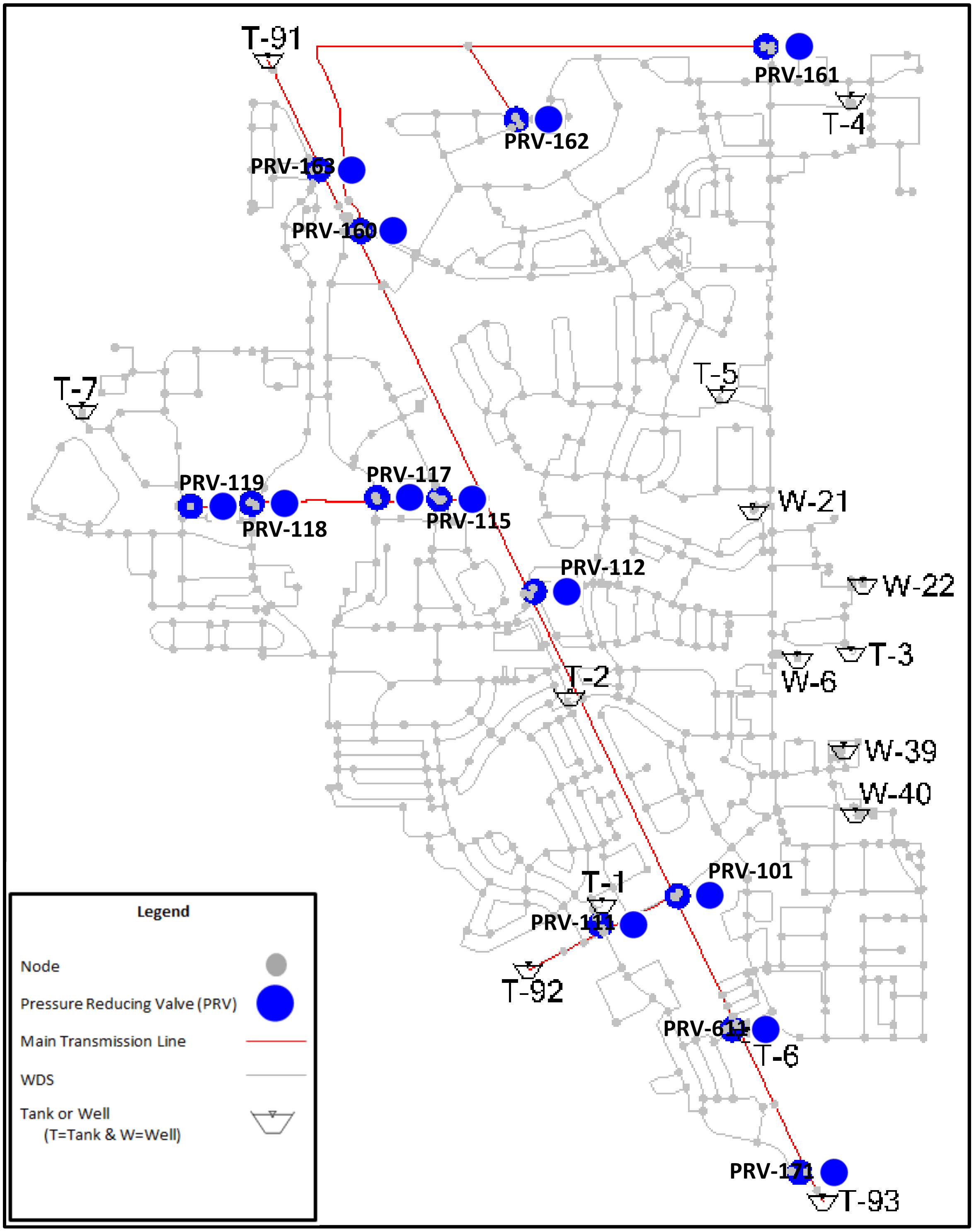

Figure 17: Water Distribution System of "the CITY"

4.6 Scenarios

4.6.1 Scenario 1: Steady State with Max Daily Demand and Cc=50%

Scenario 1 represents steady state conditions where demand and pump pattern are fixed. Under these conditions, a node's representativeness is constant because the system hydraulics do not change. The scenario does not accurately represent a real life scenario because the demand throughout a 24 hour duration typically fluctuates with people's changing water use. The coverage criterion is 50% for scenario 1-7.

4.6.2 Scenario 2-7: Extended Period Simulation with Cc=50% and Pattern 2.0, 3.0, 4.0, 5.0, 6.0, and 7.0

Scenarios 2-7 are more realistic analogs because water distribution systems run under extended periods of unsteady hydraulic conditions. The different patterns simulate varying seasons and alternate usage schedules. They are used to determine how temporal distribution may affect the optimal locations of the monitoring stations. A node's representativeness is more difficult to evaluate in these scenarios because they change with time, e.g. hourly. Important characteristics to examine with the demand patterns are the mean and standard deviations. All the means are 1.0 but the standard deviations vary considerably. This means that the temporal distribution fluctuates which may alter the demand coverage ratio of the monitoring stations. The higher the standard deviation, the more the node demand varies which can easily be seen in Figure 16 as one compares demand pattern 6.0 to 7.0. The standard deviations for pattern 6.0 and 7.0 are 0.97 and 0.36 respectively and pattern 6.0 clearly varies more than pattern 7.0.

4.6.3 Scenario 8: Max Daily Demand and Pattern 2.0 with Cc=25%, 50%, and 75%

This scenario demonstrates how the changing coverage criterion will affect the location and coverage ratio of monitoring stations for steady and unsteady state conditions. The coverage criterion is important to examine because if a contaminant is

highly concentrated and dangerous in small doses, then a lower coverage criterion may be used to locate potentially contaminated locations. Note that the coverage criterion does not affect the demand pattern.

4.6.4 Scenario 9: A Coverage Ratio of 95% is Desired Using Pattern 2.0

This scenario demonstrates a city requesting to have 95% coverage of their WDS. For this particular city, funds are not the limiting factor so coverage ratio is used. More monitoring stations can be afforded by some cities due to economics or growth and a 95% coverage ratio adequately protects a city from large outbreaks due to contaminants. The demand pattern 2.0 is used because it represents the most likely pattern of a city.

4.6.5 Scenario 10: Demand Coverage (DC) vs Demand Coverage Index (DCI) Methods

The last scenario examines how the demand coverage method compares to the demand coverage index method. The DC method has weaknesses we have already discussed but it is still instructive to examine how the two methods compare. Components to examine are order of the monitoring stations and the demand coverage ratio.

4.7 Summarization of Demand Coverage Index Methodology

This section will include a detailed description of the steps performed in this analysis as well as a simplified example of the steps required in the DCI method. The simplified example is in Table 10 and follows the exact methodology as the DCI method but with 5 nodes as opposed to 619 nodes. The exact process and equations necessary to calculate the DCI and other results can be seen in the steps preceding the example.

1. A trace analysis is employed for all nodes using EPANET 2.0 in WaterCAD to construct a water fraction matrix. The trace analysis uses a source, or trace, node to determine the percent of water contributing to all downstream nodes in the system. The trace analysis must be employed for every node and results will give an output for every hour since the water from the source node needs time to propagate through the system. Also, note a coverage criterion of 50% is used which means nodes with 50% or more water contributed to them by the source node can be assumed to represent the same water quality as that source node.

2. WaterCAD outputs are exported to excel. Refer to section VIII, Exporting WaterCAD Results to Excel, for a more detailed description and example. Table 5 shows the results of all trace analyses combined on a table for pattern 2.0 at hour 13. A similar table is created for each hour in the 24 hr duration. The rows in Table 5 represent the source nodes with the columns showing the percent of water contributing to that downstream node.

3. WaterCAD outputs are converted to a more usable form in excel with a coverage criterion of 50%. Since the results are in a percentage, the $C_c = 50$. If the $C_c \geq 50$, then the node is covered and it gets a value of 1 and nodes that are not covered are

given a 0. Doing this also allows for an easy calculation of results if one alters the coverage criterion as in scenario 8. The results with a coverage criterion of 50% for pattern 2.0 at hour 13 is seen in Table 6.

4. A steady state analysis or extended period simulation for hydraulic analyses is completed using WaterCAD for 7 demand patterns (max, patt 2.0, 3.0, 4.0, 5.0, 6.0, & 7.0).

5. WaterCAD outputs are exported to excel to be used with the water fraction matrix. The demand at each hour is multiplied by the water fraction matrix for that hour in order to obtain the demand coverage matrix. The total demand is also calculated for every node at every hour. Also, note that the demand coverage will be either the demand from the pattern at that particular hour or 0 depending on if it is covered or not. Table 7 is the demand coverage matrix after being exported to excel. The demand for demand pattern 2.0 can be seen by the orange highlighted section and the total demand for every node can be seen by the yellow highlighted section. A similar table will be created for every hour, 0-24.

6. All hours of demand coverage are combined on a single table and a demand coverage ranking of the demand coverage matrix is added. This allows for a better understanding of which nodes are temporally important throughout the 24 hour duration. Table 8 shows how this set of data is organized.

7. The total demand coverage index (DCI) is calculated by first determining the total demand coverage (TDC), accumulation of demand coverage ranking (ADCR), and normalized cumulative demand coverage ranking (NCDCR) for the full 24 hour duration. The TDC is the summation of all demand coverages for a single node. The ADCR is the

summation of the demand coverage rankings for a single node and is represented by the equation below. The NCDCR is calculated by dividing the ADCR by the minimum ADCR of all the nodes. The minimum for the figure below is 37 so for node J8205, the NCDCR is 1453/37=39.27. DCI is finally calculated for each node based on the below equations.

$$TDC = \sum_{k=0}^{k} DC_k \qquad ADCR = \sum_{k=0}^{k} DCR_k$$

$$NCDCR = \frac{TDC}{ADCR_{min}} \qquad DCI = \frac{TDC}{ADCR}$$

Note, Table 8 and 9 show hr 0-8 for simplification but hr 9-24 are also included. Add a ranking for the total DCI to determine the nodes with the highest DCI. Table 9 shows the completed results for the final step in the demand coverage index method.

The Demand Coverage Index method will now be observed in a simplified example which is seen in Table 10. The example has 4 demand patterns, each representing 6 hours for a total duration of 24 hours. It gives results for both the Demand Coverage method, where the total demand coverage (TDC) is maximized, as well as the Demand Coverage Index method, where the demand coverage index (DCI) is maximized.

The example shows a formatted results table after the trace and hydraulic analysis is exported to excel and reorganized. Therefore, the example shows a results table for step 6 and 7 and skips 1-5 because those involved exporting WaterCAD results and reformatting them into excel. The important information to examine in Table 10 is the results and how they are calculated and interpreted.

Based on the Demand Coverage method, the best location to put a node is node 3 because the total demand coverage is the highest, 105 units. However, this does not take into account the change in representativeness that occurs throughout the 24 hour time

period. Node 3 best reflects the water quality for the first 6 hrs as seen by the demand coverage ranking (DCR) of 1 for pattern 1 and node 4 best reflects the water quality for the remaining 18 hrs. Therefore, node 4 has a better representativeness than node 3 even though node 3 has a slightly higher TDC. The optimal location of the monitoring station should be node 4, not node 3, and this weakness in the DC method is due to the fact that it ignores the temporal distribution and only takes into account the demand covered. The Demand Coverage Index method is the best indicator to pinpoint the optimal locations based on the temporal distribution and the total demand covered by a monitoring station.

Table 5: Water Fraction Matrix for Pattern 2.0 at Hr 13

	A	BD	BE	BF	BG	BH	BI	BJ	BK
1		J8205	J8200	J8070	J8065	J8060	J8055	J8050	J8045
2	J8205	100	0	0	0	0	0	0	100
3	J8200	0	100	0	0	0	0	0	0
4	J8070	0	0	100	100	100	0	0	0
5	J8065	0	0	0	100	100	0	0	0
6	J8060	0	0	0	0	100	0	0	0
7	J8055	100	0	0	0	0	100	100	100
8	J8050	100	0	0	0	0	0	100	100
9	J8045	0	0	0	0	0	0	0	100
10	J8040	0	0	0	0	0	0	0	0
11	J8035	0	0	0	0	0	0	0	0
12	J8030	0	0	0	0	0	0	0	0
13	J8025	0	84.4	0	0	0	0	0	0
14	J8020	0	84.4	0	0	0	0	0	0

Table 6: Coverage of Pattern 2.0 at Hr 13

	A	BD	BE	BF	BG	BH	BI	BJ	BK
654	Cc=	J8205	J8200	J8070	J8065	J8060	J8055	J8050	J8045
655	50								
656	J8205	1	0	0	0	0	0	0	1
657	J8200	0	1	0	0	0	0	0	0
658	J8070	0	0	1	1	1	0	0	0
659	J8065	0	0	0	1	1	0	0	0
660	J8060	0	0	0	0	1	0	0	0
661	J8055	1	0	0	0	0	1	1	1
662	J8050	1	0	0	0	0	0	1	1
663	J8045	0	0	0	0	0	0	0	1
664	J8040	0	0	0	0	0	0	0	0
665	J8035	0	0	0	0	0	0	0	0
666	J8030	0	0	0	0	0	0	0	0
667	J8025	0	1	0	0	0	0	0	0
668	J8020	0	1	0	0	0	0	0	0
669	J8015	0	0	0	0	0	0	0	0
670	J8010	0	0	0	0	0	0	0	0
671	J8005	0	0	0	0	0	0	0	0

Table 7: Demand Coverage Matrix for Pattern 2.0 at Hr 13

	A	SX	SY	SZ	TA	TB	TC	TD	AAF
1308	Demand	52	18	40	20	8	8	31	
1310	MS	Nodes							
1311		J3930	J3925	J3920	J3915	J3910	J3905	J3900	Total
1312	J8205	52	18	40	20	8	8	31	548
1313	J8200	0	0	0	0	0	0	0	22
1314	J8070	0	0	0	0	0	0	0	153
1315	J8065	0	0	0	0	0	0	0	161
1316	J8060	0	0	0	0	0	0	0	161
1317	J8055	52	18	40	20	8	8	31	548
1318	J8050	52	18	40	20	8	8	31	548
1319	J8045	52	18	40	20	8	8	31	548
1320	J8040	0	0	0	0	0	0	0	0
1321	J8035	0	0	0	0	0	0	0	0
1322	J8030	0	0	0	0	0	0	0	22
1323	J8025	0	0	0	0	0	0	0	0
1324	J8020	0	0	0	0	0	0	0	0
1325	J8015	0	0	0	0	0	0	0	192
1326	J8010	0	0	0	0	0	0	0	192
1327	J8005	0	0	0	0	0	0	0	192
1355	J6061	0	0	0	0	0	0	0	160

Table 8: Demand Coverage Matrix for Pattern 2.0

	A	B	C	D	E	F	G	H	I	J
1		Hour	J8205	J8200	J8070	J8065	J8060	J8055	J8050	J8045
2	Demand Coverage	0	0	0	0	0	0	0	0	0
3		1	12	0	0	0	3	5	10	14
4		2	47	0	10	11	11	29	34	47
5		3	122	0	24	65	65	99	99	122
6		4	313	0	138	138	138	253	261	313
7		5	845	0	346	346	348	807	845	845
8		6	1071	18	431	435	435	1071	1071	1071
9		7	855	41	371	371	371	855	855	855
10		8	673	31	320	320	320	646	646	673
27	Rank	0	450	450	450	450	450	450	450	450
28		1	75	554	554	554	339	216	93	56
29		2	63	574	317	296	296	120	96	63
30		3	54	595	322	130	130	76	76	54
31		4	46	595	135	135	135	68	64	46
32		5	40	596	117	117	115	45	40	40
33		6	40	571	130	127	127	40	40	40
34		7	42	490	121	121	121	42	42	42
35		8	42	488	106	106	106	46	46	42

Table 9: Results Table for Pattern 2.0

	Hour	Nodes								
		J8205	J8200	J8070	J8065	J8060	J8055	J8050	J8045	J8040
Demand Coverage	0	0	0	0	0	0	0	0	0	0
	1	12	0	0	0	3	5	10	14	0
	2	47	0	10	11	11	29	34	47	0
	3	122	0	24	65	65	99	99	122	0
	4	313	0	138	138	138	253	261	313	0
	5	845	0	346	346	348	807	845	845	0
	6	1071	18	431	435	435	1071	1071	1071	0
	7	855	41	371	371	371	855	855	855	0
	8	673	31	320	320	320	646	646	673	0
Demand Coverage Ranking	0	450	450	450	450	450	450	450	450	450
	1	75	554	554	554	339	216	93	56	554
	2	63	574	317	296	296	120	96	63	574
	3	54	595	322	130	130	76	76	54	595
	4	46	595	135	135	135	68	64	46	595
	5	40	596	117	117	115	45	40	40	596
	6	40	571	130	127	127	40	40	40	601
	7	42	490	121	121	121	42	42	42	601
	8	42	488	106	106	106	46	46	42	601
Results	TDC	14131	256	5701	5755	5760	13958	14014	14133	0
	ADCR	1453	13680	4074	3844	3627	1704	1548	1434	14744
	NCDCR	39.27027	369.72973	110.1081	103.8919	98.02703	46.05405	41.83784	38.75676	398.4865
	DCI	359.8396	0.6923977	51.77639	55.39412	58.75931	303.0786	334.9599	364.659	0
	rank	41	572	126	120	115	46	44	40	607

Table 10: Example of Demand Coverage and Demand Coverage Index Methods

Patterns	Nodes				
	1	2	3	4	5
1	10 4	15 3	40 1	20 2	5 5
2	5 4	10 3	20 2	25 1	5 4
3	10 4	15 3	20 2	25 1	15 3
4	10 3	10 3	25 2	30 1	10 3
TDC	35	50	105	100	35
ADCR	15	12	7	5	15
NCDCR	3.0	2.4	1.4	1.0	3.0
DCI	2.33	4.17	15	20	2.33

Keys to Table 5:

40 → Demand Coverage (GPM)
1 → Demand Coverage Ranking

TDC: Total Demand Coverage
ADCR: Accumulated Demand Coverage Ranking
NCDCR: Normalized Cumulative Demand Coverage Ranking
DCI: Demand Coverage Index

4.8 Optimization Procedure

The results are optimized to maximize DCI with the minimum number of monitoring stations. The optimization procedure is meant to maximize coverage of the water distribution system with the minimum number of monitoring stations. Many different optimization methods have been utilized on the DCI method including an integer programming method (Lee and Deininger, 1992), a greedy heuristic based algorithm (Kumar et al, 1997), and a genetic algorithm (Al-Zahrani and Moied, 2001). This study uses a simple trial and error method where the total DCI of similarly covered nodes are compared to one another and the most optimal node is picked. The method is presented below:

1. Total DCI is calculated as DCI of source node plus DCI of nodes being covered by this source node. Table 12 shows the individual DCI as well as the total DCI of all source nodes.

2. The node with the highest total DCI is chosen to be a monitoring station but ensure that the same nodes are not covered by previous monitoring stations because a node cannot be covered twice. For example, in Table 11 the nodes covered by J8205 and J8050 are covered by J8055 in addition to an extra node (J8055) so nodes J8205 and J8050 are inferior monitoring stations and are represented by red numbers in Table 12. The red nodes represent nodes that are already covered by an upstream monitoring station.

If the potential monitoring station covers the same nodes, subtract these already covered nodes and calculate the new total DCI, or adjusted DCI, for that source node. There are

no adjusted DCIs in the top monitoring stations in Table 12 because the water distribution system is large enough that the coverage does not overlap.

3. Step 2 is repeated until the proper number of monitoring stations are determined.

Table 11: Comparison of Similarly Covered Source Nodes

Node	J8205	J8055	J8050
TDC	6722	6651	6659
ADCR	717 (2.8)	963 (3.7)	932 (3.6)
DCI	2438	1796	1858
Nodes Covered	8205	8205	8205
		8055	
		8050	8050
	8045	8045	8045
	5570	5570	5570
	4130	4130	4130
	4125	4125	4125
	4100	4100	4100
	4095	4095	4095
	4090	4090	4090
	4065	4065	4065
	4060	4060	4060
	4055	4055	4055
	4050	4050	4050
	4045	4045	4045
	4040	4040	4040
	4035	4035	4035
	4005	4005	4005
	4000	4000	4000
	3995	3995	3995
	3930	3930	3930
	3925	3925	3925
	3920	3920	3920
	3915	3915	3915
	3910	3910	3910
	3905	3905	3905
	3900	3900	3900
	3895	3895	3895
	3890	3890	3890
	3885	3885	3885
	3880	3880	3880
	3875	3875	3875
	3870	3870	3870

Table 12: Final Output for Optimization Procedure for Pattern 2.0

Monitoring Station #	Node	# of Nodes Covered	Individual DCI	Total DCI	Adjusted DCI
1	J3455	68	960.8	3969.7	
2	J3840	54	727.8	2953.2	
3	J5860	30	717.5	2900.4	
4	J8055	33	303.1	2681.2	
	J8050	32	335.0	2378.1	
5	J5875	46	654.0	2236.4	
	J8205	31	359.8	2043.2	
	J5820	39	462.3	1979.2	
	J5825	33	217.4	1804.5	
	J8045	30	364.7	1683.3	
6	J5325	29	643.0	1256.1	1253.9
7	J3000	30	298.0	1198.5	
8	J4520	32	300.4	1106.7	
9	J4030	26	284.6	1010.9	1001.2
10	J6005	13	502.6	702.9	646.2
	J3375	10	105.1	626.1	119.7
11	J5175	34	8.9	620.6	
	J5865	8	152.6	596.5	
	J4325	12	29.6	585.2	
	J4330	11	28.8	583.5	
	J5870	17	10.1	553.4	
	J5415	16	133.3	543.4	
	J5855	24	126.8	539.5	
12	J5085	18	298.2	496.1	496.0
13	J5475	27	251.8	469.7	393.0
	J5495	15	5.2	463.5	
	J5490	15	7.6	463.5	
	J4310	7	181.6	443.9	
14	J5845	23	122.8	406.8	388.6
	J4490	15	10.1	405.8	82.2
	J3170	22	73.6	400.0	64.8
15	J3210	14	71.6	398.7	380.4

4.9 Exporting WaterCAD Results to Excel

The trace percent and demand data from WaterCAD needs to be exported into an excel file in order to perform an analysis. The first step is to modify the flex table for the junctions to include trace percent and demand when performing the steady state or extended period simulations. This is done by using the edit feature at the top of the flex table. All categories should be removed in order to limit the amount of data being analyzed and to speed up the exporting process. The categories of importance are trace (%) when performing the trace analysis and demand (gpm) when performing the steady state or extended period simulation analysis. For the trace percent, all time steps are required to do a proper analysis. This is achieved at the top of the flextable by looking at the results options and selecting report all time steps. A report is generated but the format does not allow for proper analysis and must be exported to an excel file. Under file and export document, a few options are available to export the document but an excel file is the desired format. The WaterCAD output will look similar to Table 13.

In order to efficiently format the data, macros are necessary to rearrange the data into a useful form. Excel makes creating macros simple by selecting record macro under the developer tab and inputting a desired keystroke for that particular macro. The desired transferring of data is completed and then the stop macro button is selected. That macro will now occur every time the associated keystroke is pressed.

Table 13: WaterCAD Output for Trace % and Demand at Hour 12

Current Time: 12.000 hours	
Label	Trace (Calculated) (%)
J3445	59.7
J3440	21.4
J3435	53.9
J3430	0.0
J3425	3.4
J3420	71.8
J3415	71.9
J3410	71.8
J3405	73.2
J3400	72.0
J3395	71.8
J3390	100.0
J3385	81.8
J3380	71.8
J3375	71.8
J3370	71.8
J3365	71.8
J3360	71.8
J3355	0.0
J3350	0.0
J3340	0.0
J3338	0.0
J3335	0.0
J3330	0.0

Current Time: 12.000 hours	
Label	Demand (gpm)
J3445	10
J3440	1
J3435	4
J3430	17
J3425	9
J3420	1
J3415	22
J3410	14
J3405	12
J3400	4
J3395	2
J3390	47
J3385	17
J3380	3
J3375	14
J3370	5
J3365	6
J3360	10
J3355	3
J3350	6
J3340	4
J3338	8
J3335	4
J3330	4
J3325	8

An example macro is the trace analysis to water fraction matrix transformation. Table 14 is the WaterCAD output of a trace analysis for node J8205 after being exported to excel. The output contains the trace analysis for hour 0-24 but only hr 13 is seen in the table. This data needs to be arranged into a more accessible table; therefore, a macro will be used due to the large amounts of data and repetitious nature of the transformation. The macro takes the WaterCAD output arranged in columns and transforms them into rows

with each hour getting its own tab in excel. Each WaterCAD output is only for one node however so the macro has to be used 619 times. Table 15 shows the results of the macro after all nodes have been transferred. This is the water fraction matrix for hr 13 but one is created for each hour. The highlighted region of the tables show how the macro functions for hr 13.

Table 14: WaterCAD Output in Excel (Pre-Macro)

	A	B	C	D	E	F	G
1	**FlexTable: Junction Table (TanksTrace.wtg)**						
2	**Licensed for Academic Use Only**						
3							
9221	**Current Time: 13.000 hours**						
9222	Label		Trace (Calculated) (%)		Demand (gpm)		
9277	J8205		100.0		0		
9278	J8200		0.0		0		
9279	J8070		0.0		0		
9280	J8065		0.0		0		
9281	J8060		0.0		0		
9282	J8055		0.0		0		
9283	J8050		0.0		0		
9284	J8045		100.0		0		
9285	J8040		0.0		0		
9286	J8035		0.0		0		
9287	J8030		0.0		0		
9288	J8025		0.0		0		
9289	J8020		0.0		0		
9290	J8015		0.0		0		
9291	J8010		0.0		0		
9292	J8005		0.0		0		

Table 15: Water Fraction Matrix for Hr 13 (Post-Macro)

	A	BD	BE	BF	BG	BH	BI	BJ	BK
1		J8205	J8200	J8070	J8065	J8060	J8055	J8050	J8045
2	J8205	100	0	0	0	0	0	0	100
3	J8200	0	100	0	0	0	0	0	0
4	J8070	0	0	100	100	100	0	0	0
5	J8065	0	0	0	100	100	0	0	0
6	J8060	0	0	0	0	100	0	0	0
7	J8055	100	0	0	0	0	100	100	100
8	J8050	100	0	0	0	0	0	100	100
9	J8045	0	0	0	0	0	0	0	100
10	J8040	0	0	0	0	0	0	0	0
11	J8035	0	0	0	0	0	0	0	0
12	J8030	0	0	0	0	0	0	0	0
13	J8025	0	84.4	0	0	0	0	0	0
14	J8020	0	84.4	0	0	0	0	0	0

Problems that may occur with the macro are too much data to format and the data is automatically converted to text. The first problem is addressed by dividing the macro into several macros to reduce how much data is changed under a specific keystroke. The trace percent reformatting requires the use of 4 keystrokes to complete the macro. The text problem can be solved by changing all values formatted as text to numerical values by hand. The text values created problems because calculations cannot be done with the text data so the analysis can be temporarily delayed by this problem.

4.10 Summary and Discussion of Results

4.10.1 Scenario 1: Max Daily Demand

The results for scenario 1 and 2-7 will be presented together due to the many similarities.

4.10.2 Scenario 2-7 Demand Pattern 2.0, 3.0, 4.0, 5.0, 6.0, & 7.0

The optimal locations of the monitoring stations for max daily demand, demand pattern 2.0, 3.0, 4.0, 5.0, 6.0, & 7.0 are identical; however, the order of importance is slightly different for several of the patterns. This is only relevant if funding is limited and fewer than 15 monitoring stations will be built. Tables 16-22 give a detailed look at the monitoring stations and corresponding coverage ratio for the desired number of monitoring stations.

The result verifies that the temporal distribution of the different patterns does not affect the representativeness of a significant node. A monitoring station location will be the same regardless if the peak demand is in the middle of the day or if it peaks in the morning and at night. This is an ideal result because throughout a year, the demand pattern may change with seasons and varying usage schedule but this method shows that the location of the monitoring stations will remain the same and provide significant monitoring capabilities.

The coverage ratios vary from about 88% to 91% which means about 90% of the total network demand can be monitored depending on the demand pattern being used. This is an important result because if one demand pattern had a coverage ratio that is significantly less, then the monitoring stations would be significantly less effective for that day or season. This would be a huge weakness that could be exploited to disrupt or infect the whole system without detection. Depending on the funding available for a

30,000 to 40,000 resident city, the number of monitoring stations may differ and Figure 18 shows the results for the top 15 monitoring stations. Figure 19-21 show the individual coverage of these monitoring stations and Figure 22 shows the entire coverage from the 15 monitoring stations.

The 15 stations cover 455 nodes of the possible 619, which is 73.5% of the nodes. There appears to be a significant number of nodes that are not covered but many of the remaining nodes have a DCI of less than 5. Remember, none of the nodes are covered twice, but rather the higher ranked monitoring station will cover it and the other remaining nodes will not.

Table 16: Summary of Results Using the DCI Method and Max Daily Demand (Total DCI = 23351.5)

Number of MS	Optimal Locations of MS for **Max Daily Demand Pattern**	Total DCI	Coverage Ratio
1	3455	3643.1	0.1560
2	3455, 3840	6432.9	0.2755
3	3455, 3840, 5860	9117.1	0.3904
4	3455, 3840, 5860, 8055	11579.3	0.4959
5	3455, 3840, 5860, 8055, 5875	13614.3	0.5830
6	3455, 3840, 5860, 8055, 5875, 5325	14823.7	0.6348
7	3455, 3840, 5860, 8055, 5875, 5325, 3000	15956.1	0.6833
8	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520	17003.7	0.7282
9	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030	17956.2	0.7690
10	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005	18592.6	0.7962
11	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175	19176.4	0.8212
12	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085	19651.9	0.8416
13	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475	20038.4	0.8581
14	3455,3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 3210	20408.8	0.8740
15	3455,3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 3210, 5845	20772.5	0.8896

Table 17: Summary of Results Using the DCI Method and Demand Pattern 2.0 (Total DCI = 24867.8)

Number of MS	Optimal Locations of MS for **Demand Pattern 2.0**	Total DCI	Coverage Ratio
1	3455	3969.8	0.1596
2	3455, 3840	6923.0	0.2784
3	3455, 3840, 5860	9823.4	0.3950
4	3455, 3840, 5860, 8055	12504.6	0.5028
5	3455, 3840, 5860, 8055, 5875	14741.0	0.5928
6	3455, 3840, 5860, 8055, 5875, 5325	15994.9	0.6432
7	3455, 3840, 5860, 8055, 5875, 5325, 3000	17193.5	0.6914
8	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520	18300.2	0.7359
9	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030	19026.5	0.7651
10	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005	19672.6	0.7911
11	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175	20293.2	0.8160
12	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085	20789.2	0.8360
13	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475	21182.2	0.8518
14	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 5845	21570.8	0.8674
15	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 5845, 3210	21951.2	0.8827

Table 18: Summary of Results Using the DCI Method and Demand Pattern 3.0 (Total DCI = 24109.6)

Number of MS	Optimal Locations of MS for **Demand Pattern 3.0**	Total DCI	Coverage Ratio
1	3455	3816.4	0.1582
2	3455, 3840	6720.2	0.2787
3	3455, 3840, 5860	9475.7	0.3930
4	3455, 3840, 5860, 8055	12049.5	0.4998
5	3455, 3840, 5860, 8055, 5875	14213.3	0.5895
6	3455, 3840, 5860, 8055, 5875, 5325	15440.8	0.6404
7	3455, 3840, 5860, 8055, 5875, 5325, 3000	16596.1	0.6884
8	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520	17668.2	0.7328
9	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030	18672.3	0.7745
10	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005	19310.6	0.8010
11	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175	19901.9	0.8255
12	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085	20390.3	0.8457
13	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475	20773.0	0.8616
14	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 3210	21145.3	0.8771
15	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 3210, 5845	21516.3	0.8924

Table 19: Summary of Results Using the DCI Method and Demand Pattern 4.0 (Total DCI = 11582.7)

Number of MS	Optimal Locations of MS for **Demand Pattern 4.0**	Total DCI	Coverage Ratio
1	3455	2222.2	0.1919
2	3455, 5860	3715.8	0.3208
3	3455, 5860, 8055	5149.4	0.4446
4	3455, 5860, 8055, 5875	6381.4	0.5509
5	3455, 5860, 8055, 5875, 3840	7601.6	0.6563
6	3455, 5860, 8055, 5875, 3840, 3000	8096.9	0.6991
7	3455, 5860, 8055, 5875, 3840, 3000, 4520	8567.4	0.7397
8	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325	9020.9	0.7788
9	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030	9467.7	0.8174
10	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030, 5175	9736.7	0.8406
11	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030, 5175, 6005	9961.9	0.8601
12	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030, 5175, 6005, 5085	10151.1	0.8764
13	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030, 5175, 6005, 5085, 5845	10314.6	0.8905
14	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030, 5175, 6005, 5085, 5845, 3210	10453.3	0.9025
15	3455, 5860, 8055, 5875, 3840, 3000, 4520, 5325, 4030, 5175, 6005, 5085, 5845, 3210, 5475	10587.2	0.9141

Table 20: Summary of Results Using the DCI Method and Demand Pattern 5.0 (Total DCI = 10591.4)

Number of MS	Optimal Locations of MS for **Demand Pattern 5.0**	Total DCI	Coverage Ratio
1	3455	1652.7	0.1560
2	3455, 3840	2897.5	0.2736
3	3455, 3840, 5860	4128.4	0.3898
4	3455, 3840, 5860, 8055	5303.2	0.5007
5	3455, 3840, 5860, 8055, 5875	6398.4	0.6041
6	3455, 3840, 5860, 8055, 5875, 5325	6907.2	0.6522
7	3455, 3840, 5860, 8055, 5875, 5325, 3000	7409.6	0.6996
8	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520	7866.2	0.7427
9	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030	8311.1	0.7847
10	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005	8575.5	0.8097
11	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175	8827.4	0.8335
12	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085	9035.6	0.8531
13	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5845	9206.4	0.8692
14	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5845, 3210	9363.0	0.8840
15	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5845, 3210, 5475	9516.2	0.8985

Table 21: Summary of Results Using the DCI Method and Demand Pattern 6.0 (Total DCI = 9114.5)

Number of MS	Optimal Locations of MS for **Demand Pattern 6.0**	Total DCI	Coverage Ratio
1	3455	1336.8	0.1467
2	3455, 5860	2421.0	0.2656
3	3455, 5860, 3840	3489.0	0.3828
4	3455, 5860, 3840, 8055	4430.5	0.4861
5	3455, 5860, 3840, 8055, 5875	5247.1	0.5757
6	3455, 5860, 3840, 8055, 5875, 5325	5723.3	0.6279
7	3455, 5860, 3840, 8055, 5875, 5325, 3000	6175.2	0.6775
8	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520	6597.2	0.7238
9	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030	6971.4	0.7649
10	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030, 6005	7224.4	0.7926
11	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175	7462.1	0.8187
12	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085	7654.8	0.8399
13	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475	7806.8	0.8565
14	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 5845	7954.5	0.8727
15	3455, 5860, 3840, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 5845, 3210	8102.1	0.8889

Table 22: Summary of Results Using the DCI Method and Demand Pattern 7.0 (Total DCI = 9654.5)

Number of MS	Optimal Locations of MS for **Demand Pattern 7.0**	Total DCI	Coverage Ratio
1	3455	1509.3	0.1563
2	3455, 3840	2660.9	0.2756
3	3455, 3840, 5860	3780.9	0.3916
4	3455, 3840, 5860, 8055	4820.9	0.4993
5	3455, 3840, 5860, 8055, 5875	5689.4	0.5893
6	3455, 3840, 5860, 8055, 5875, 5325	6171.8	0.6393
7	3455, 3840, 5860, 8055, 5875, 5325, 3000	6631.2	0.6869
8	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520	7065.3	0.7318
9	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030	7462.8	0.7730
10	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005	7717.5	0.7994
11	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175	7957.2	0.8242
12	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085	8150.8	0.8443
13	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475	8304.4	0.8602
14	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 5845	8455.9	0.8759
15	3455, 3840, 5860, 8055, 5875, 5325, 3000, 4520, 4030, 6005, 5175, 5085, 5475, 5845, 3210	8605.4	0.8913

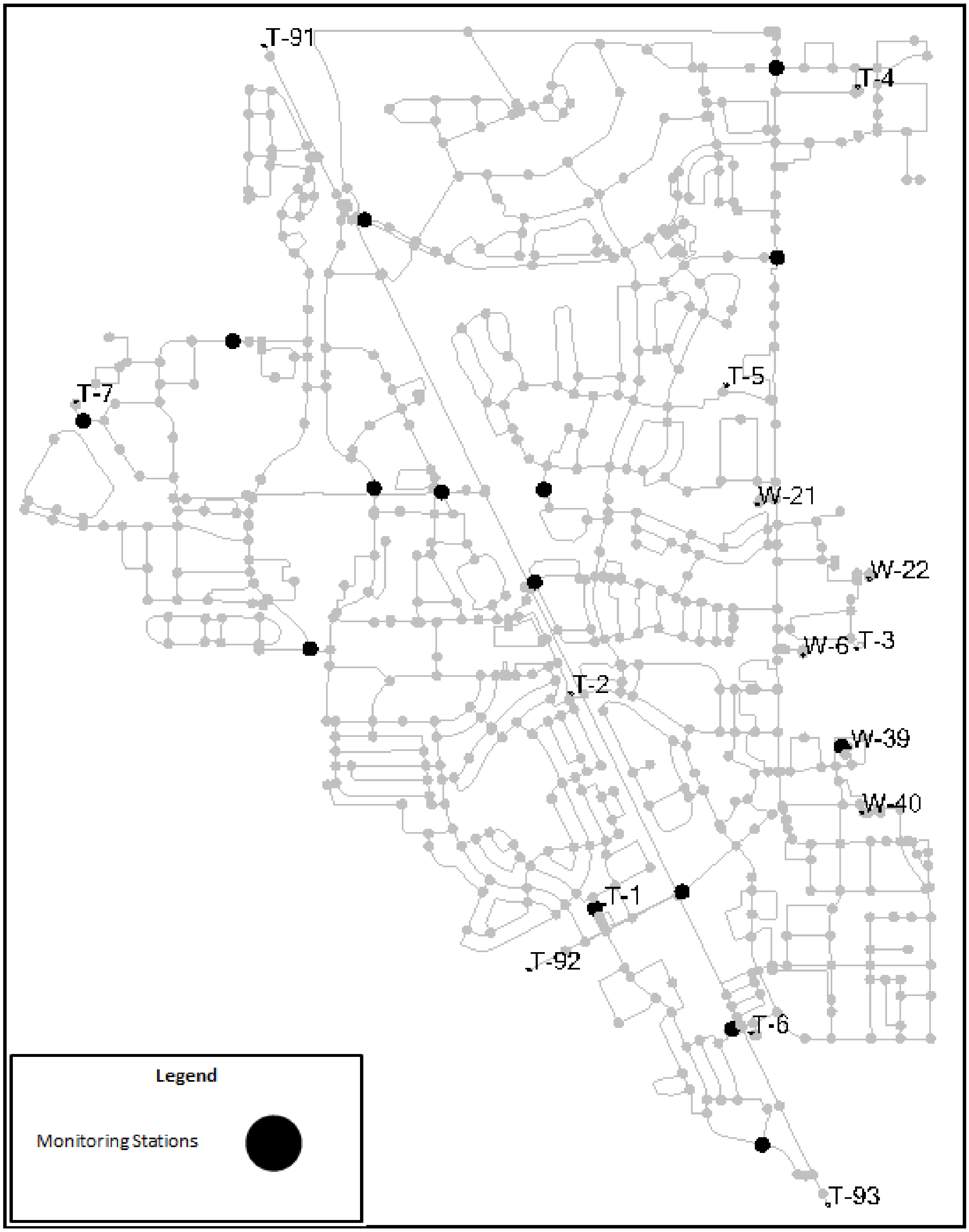

Figure 18: Top 15 Monitoring Stations

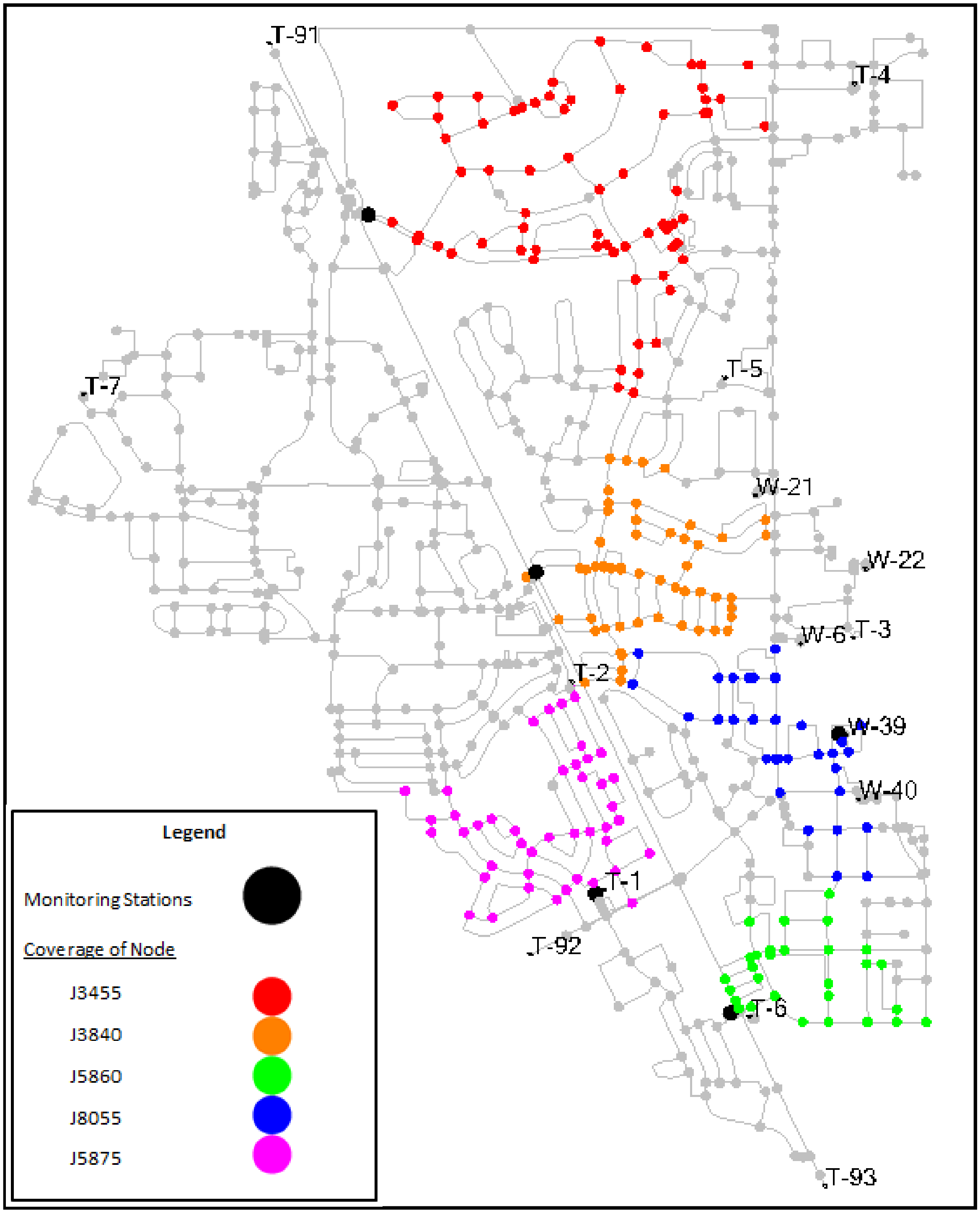

Figure 19: Monitoring Station 1-5 with Corresponding Coverages

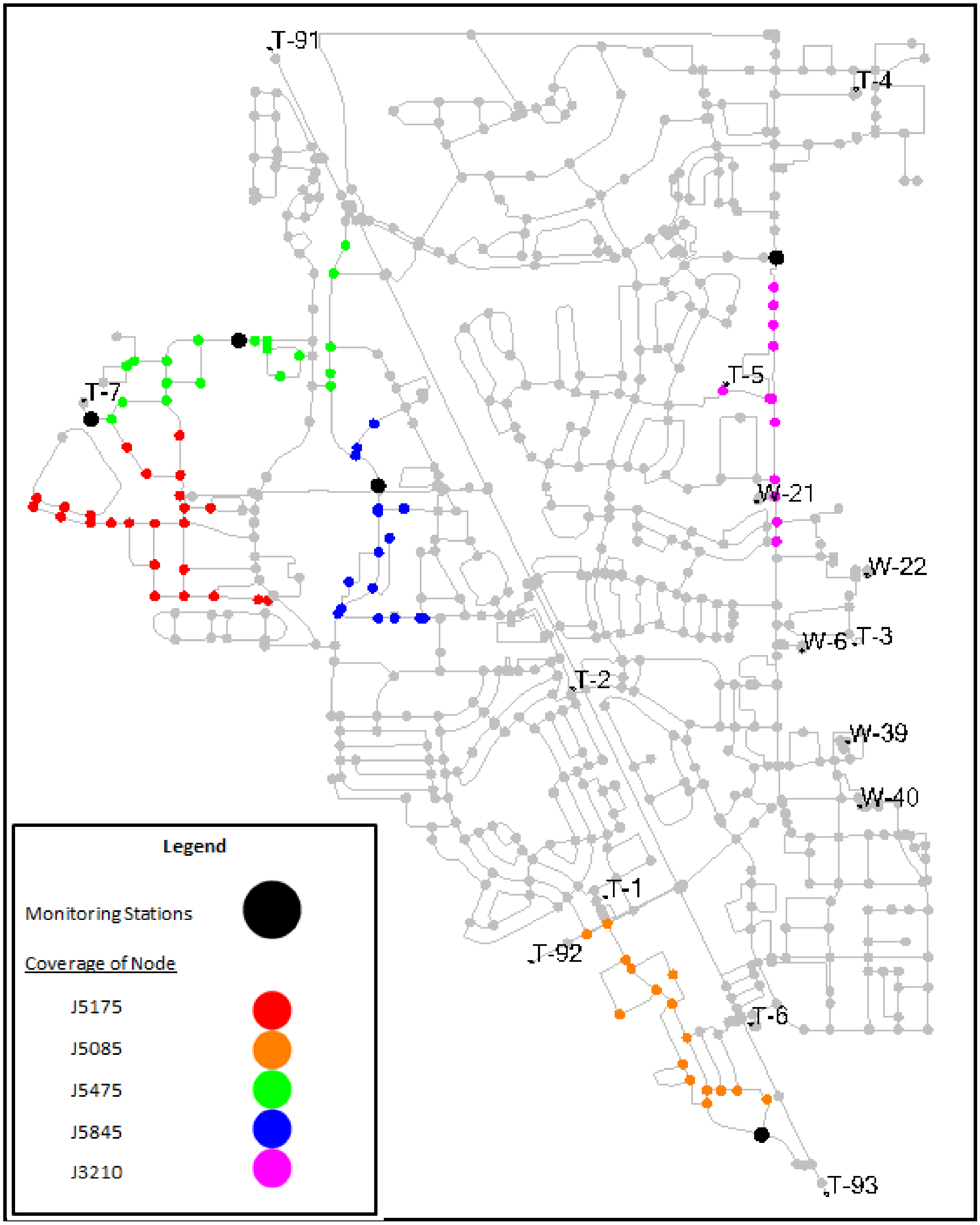

Figure 20: Monitoring Stations 6-10 with Corresponding Coverages

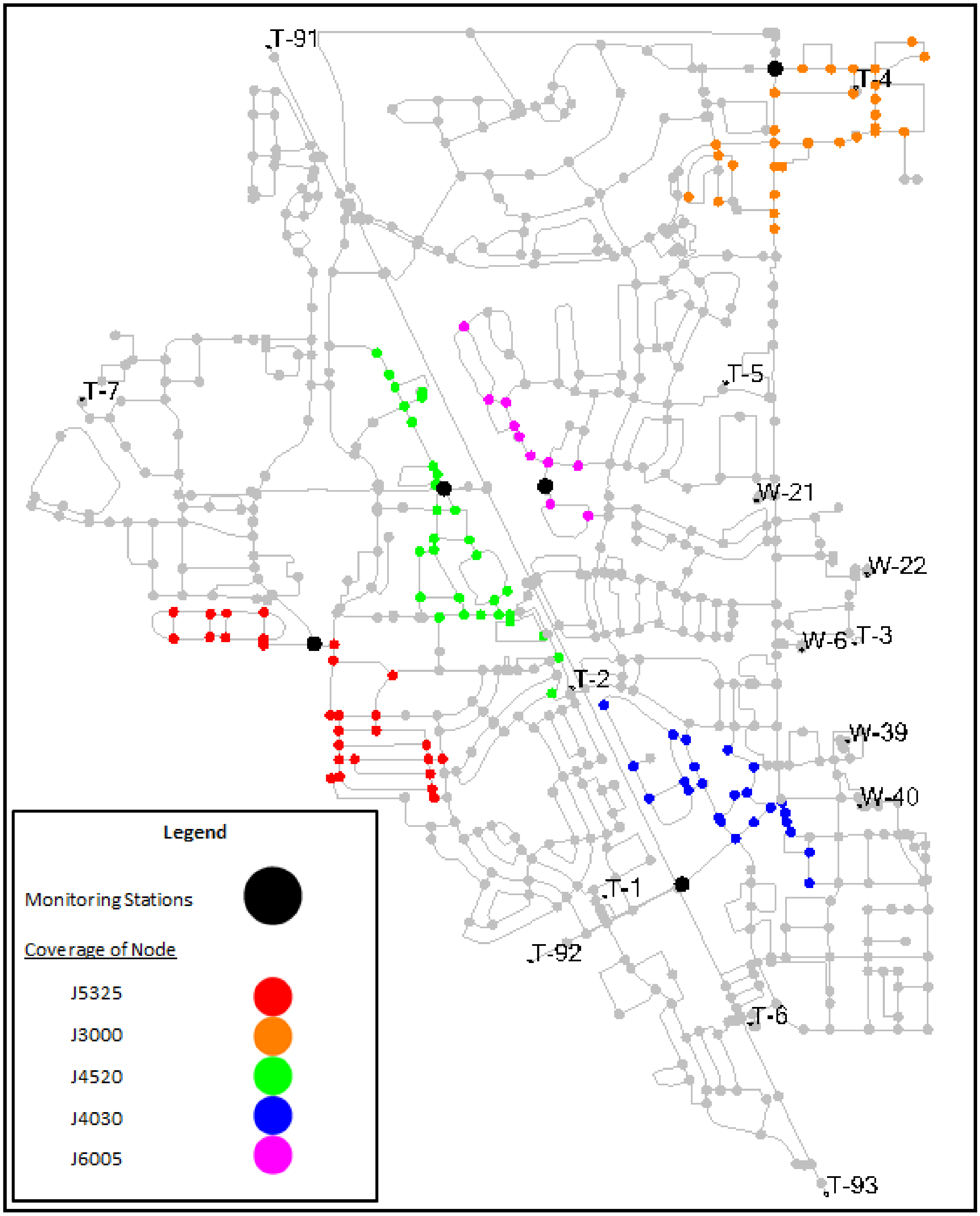

Figure 21: Monitoring Stations 11-15 with Corresponding Coverages

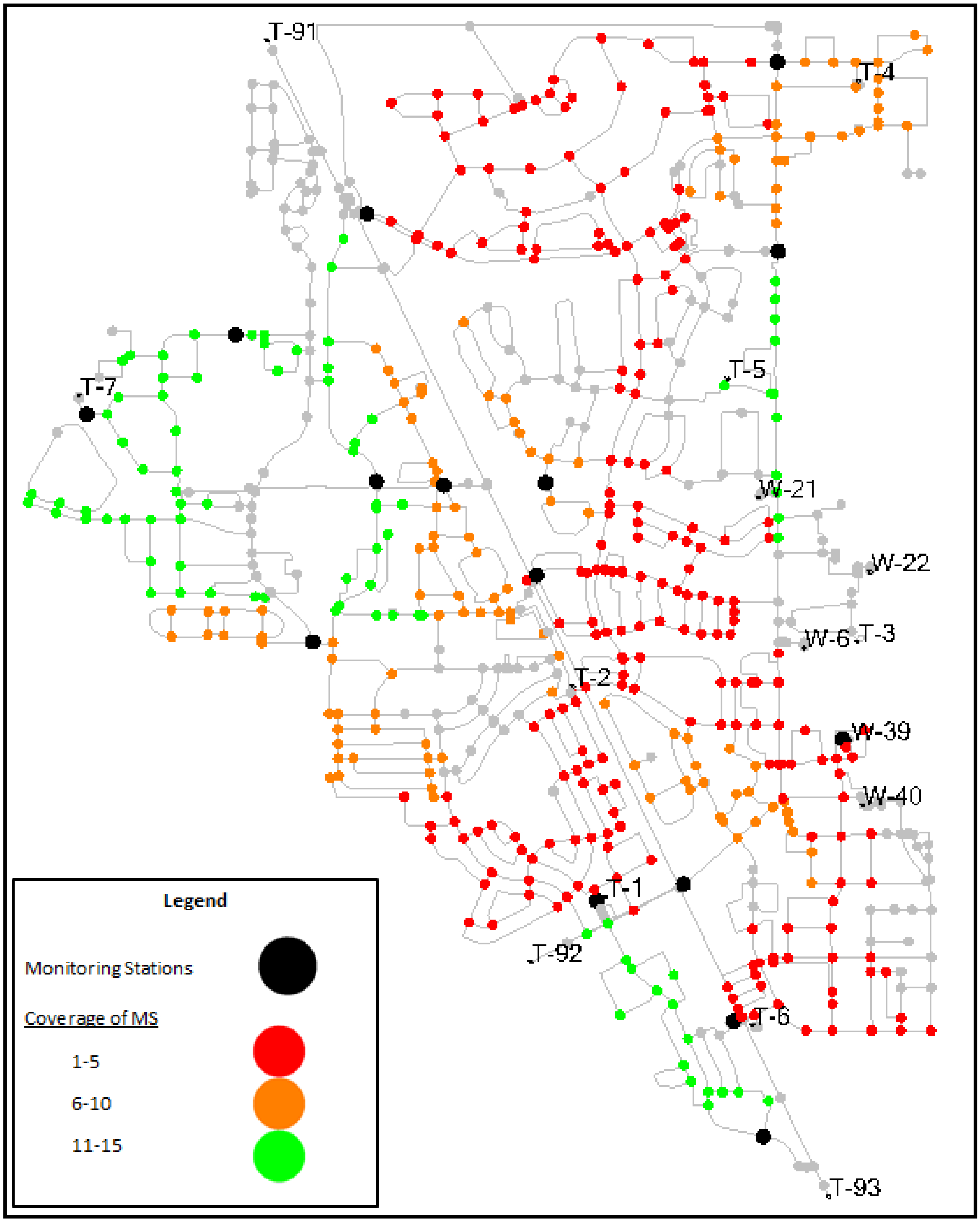

Figure 22: Top 15 Monitoring Stations with Corresponding Coverages

4.10.3 Scenario 8: Pattern 2.0 with Cc=25%, 50%, and 75%

The monitoring stations will cover more nodes with a lower coverage criterion. Table 23 demonstrates how the coverage decreases as the coverage criterion increase. A coverage criterion of 50% should be used because it makes sense that if half of the water in a node downstream came from an upstream node, than the downstream node is representative of the upstream node. Another aspect that the coverage criterion affects is the coverage ratio. The coverage ratio will increase with the decreasing coverage criterion. This is because more nodes are being covered under a single monitoring station. Figure 23-25 show the varying coverages of the 5 monitoring stations.

Table 23: Results of Changing Coverage Criterion

Node	No. of Nodes Covered		
	CC=25%	CC=50%	CC=75%
3455	75	68	17
3840	57	54	47
5860	31	30	20
8055	47	33	22
5875	48	46	32

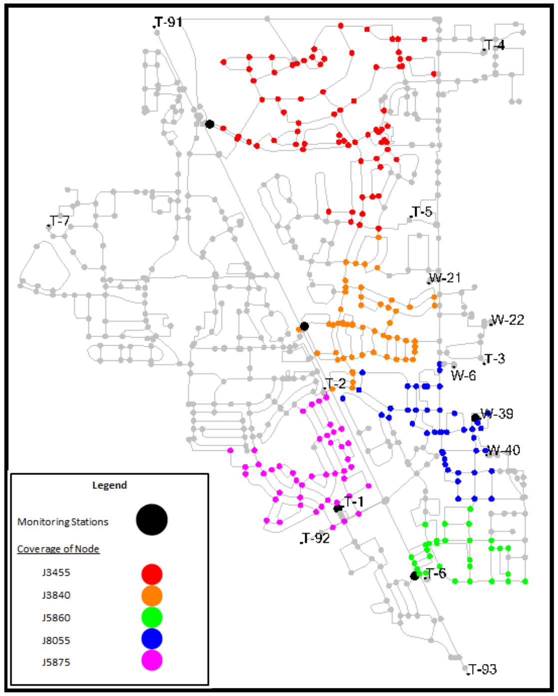

Figure 23: MSs 1-5 with Cc=25%

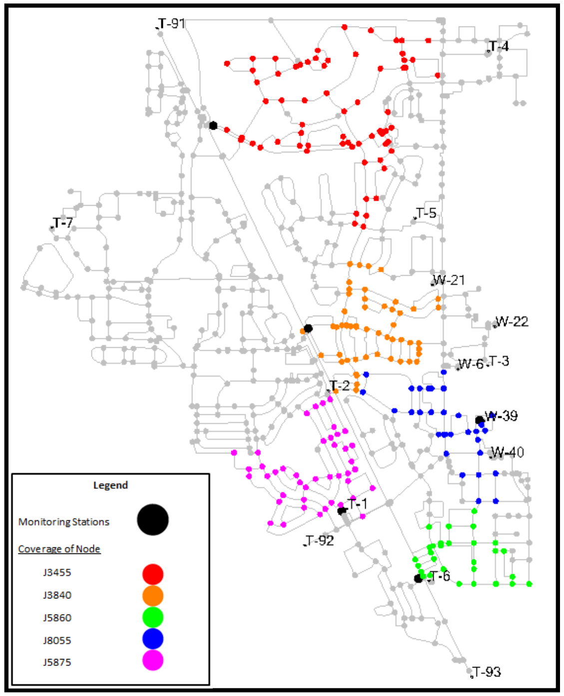

Figure 24: MSs 1-5 with Cc=50%

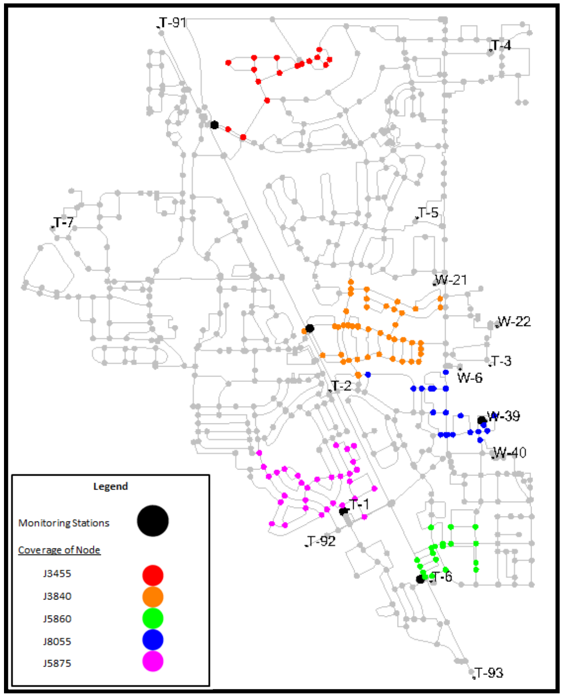

Figure 25: MSs 1-5 with Cc=75%

4.10.4 Scenario 9: 95% Coverage Ratio

In reply to a city's request for added protection due to increased funds, 22 monitoring stations would be needed to achieve a coverage ratio of 95.3% as seen in table 24. Demand pattern 2.0 was used in this analysis but the different temporal distributions will not vary significantly as demonstrated by the results of scenario 1-7. These additional monitoring stations represent enhanced protection a city can employ in the WDS if funds are available. 549 of the 619 nodes are covered, or 88.7%, with all but 17 having a DCI of less than 5. Figure 26 and 27 show the additional coverage of monitoring stations 16-22. Figure 28 shows all 22 monitoring stations for this city with corresponding coverages.

Table 24: Results for Additional MS's in Order to Achieve a 95% Coverage Ratio (Total DCI =24867.8)

Number of MS	Additional Optimal Locations of MS for **Demand Pattern 2.0**	Total DCI	Coverage Ratio
16	8005	22276.7	0.8958
17	8005, 8070	22567.4	0.9075
18	8005, 8070, 3662	22834.7	0.9182
19	8005, 8070, 3662, 4580	23097.6	0.9288
20	8005, 8070, 3662, 4580, 5850	23326.2	0.9380
21	8005, 8070, 3662, 4580, 5850, 5840	23532.6	0.9463
22	8005, 8070, 3662, 4580, 5850, 5840, 6015	23697.1	0.9529

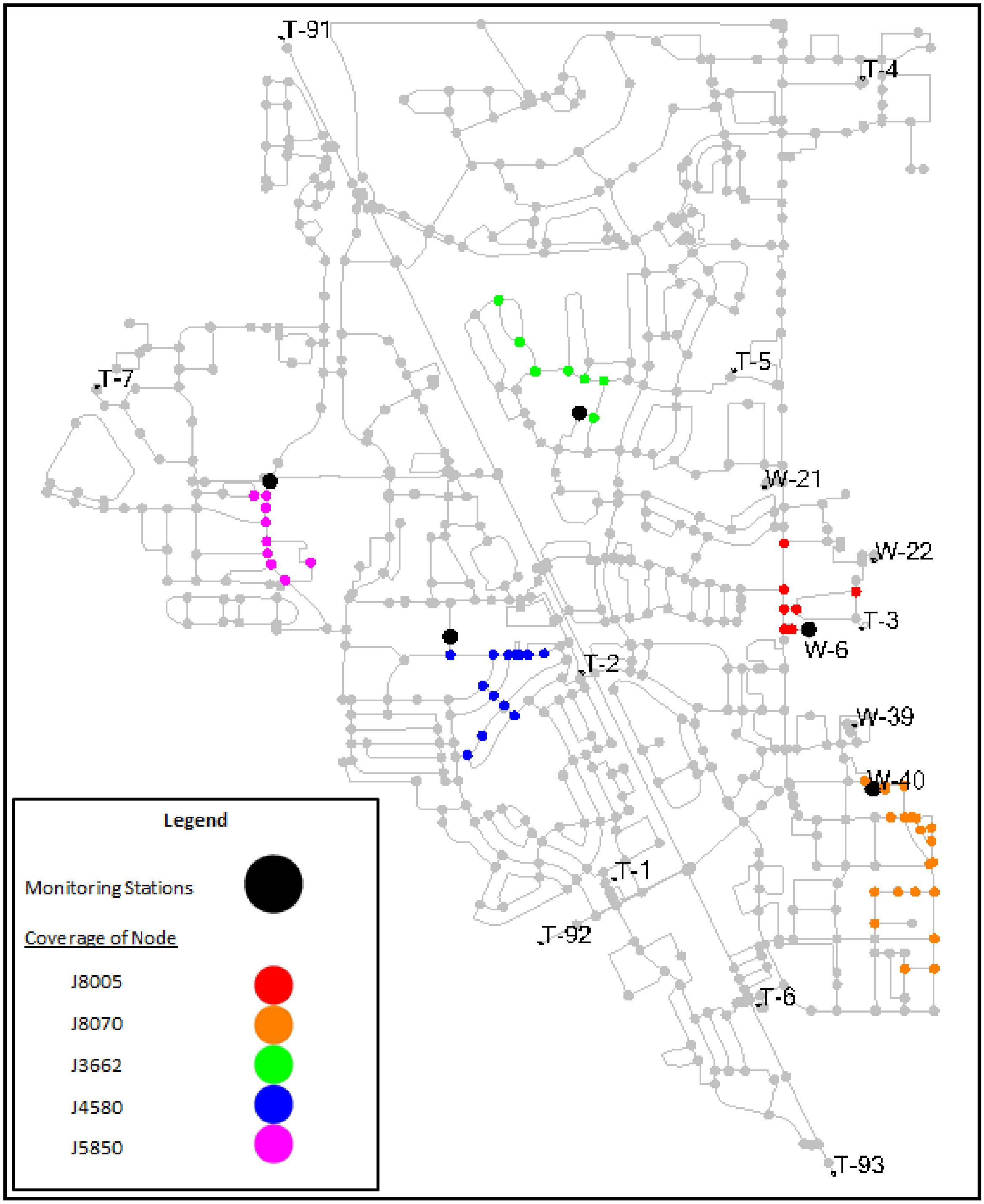

Figure 26: MS 16-20 with Corresponding Coverages

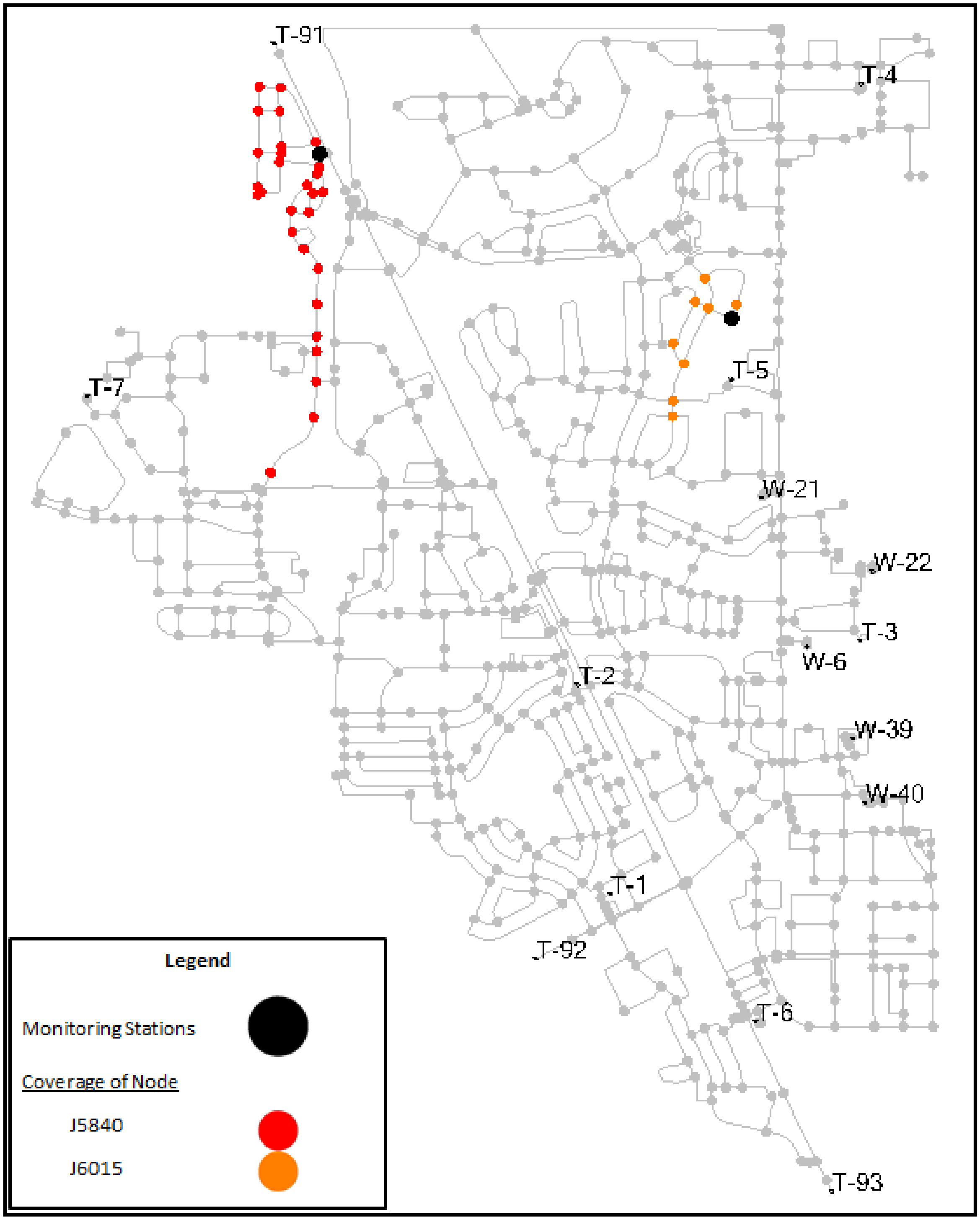

Figure 27: MS 21-22 with Corresponding Coverages

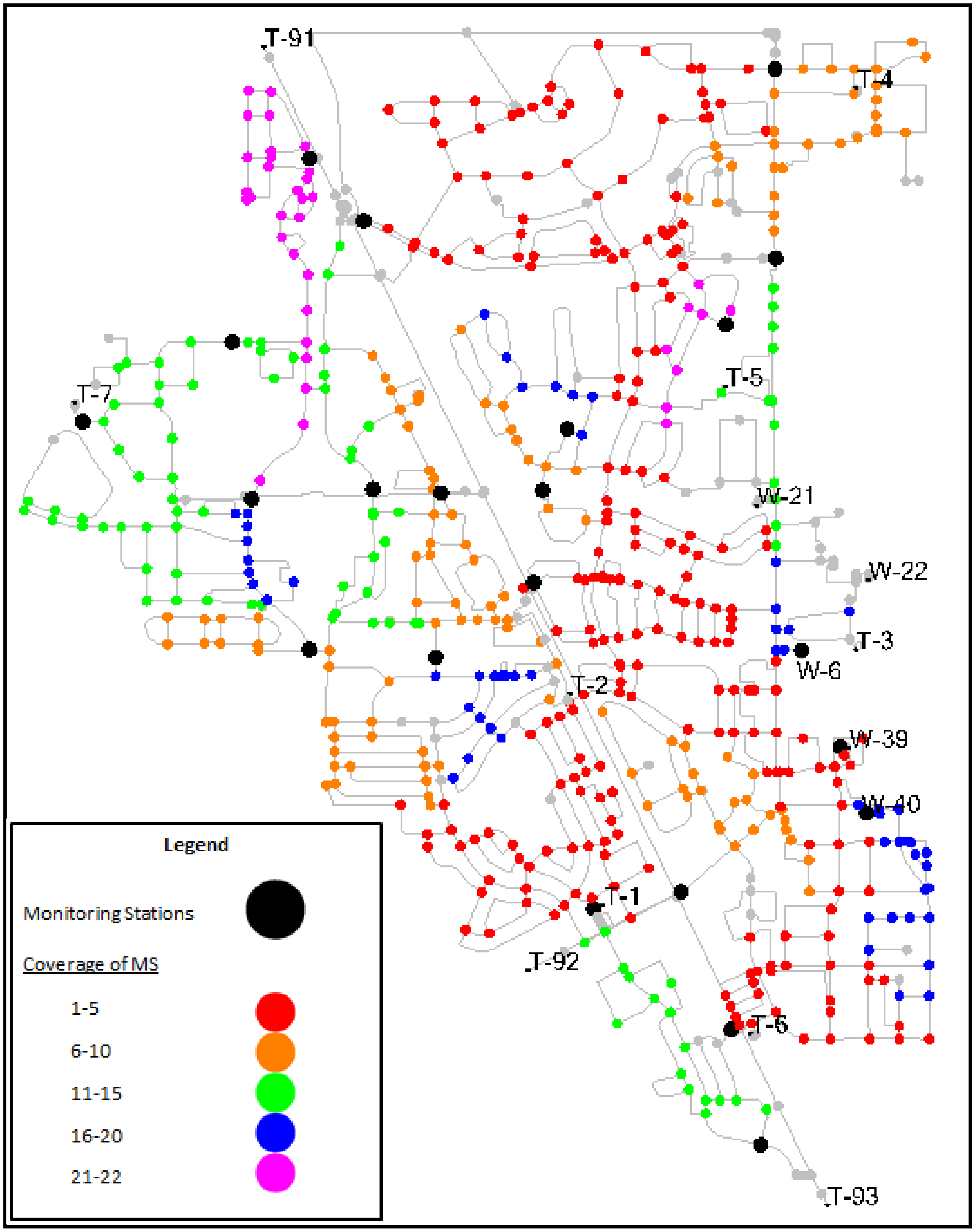

Figure 28: Top 22 Monitoring Stations with Corresponding Coverages

4.10.5 Scenario 10: Demand Coverage vs Demand Coverage Index

The DC results are similar to the DCI results but there are several of the lower ranked monitoring stations that differ. Another big difference is the lower coverage ratio. Table 25 and 26 shows the results of the DC method while table 16 and 17 shows the DCI method. The average for the DC method is about 84% while for the DCI method it is about 90%. The DCI has a better coverage ratio and can be applied to a changing temporal distribution, thus the DCI method can be used for more scenarios with a higher level of accuracy.

Table 25: Results Using the Demand Coverage Method for Max Daily Demand Pattern

Max Daily Demand Pattern			
Number of MS	Optimal Locations of MS for **Max Daily Demand Pattern**	Total TDC	Coverage Ratio
1	3455	224160	0.1334
2	3455, 3840	405739	0.2415
3	3455, 3840, 8055	555266	0.3304
4	3455, 3840, 8055, 5860	694513	0.4133
5	3455, 3840, 8055, 5860, 5875	812113	0.4833
6	3455, 3840, 8055, 5860, 5875, 3000	909536	0.5413
7	3455, 3840, 8055, 5860, 5875, 3000, 4520	1004870	0.5980
8	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030	1078139	0.6416
9	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175	1151368	0.6852
10	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175, 5325	1220845	0.7265
11	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175, 5325, 5840	1266839	0.7539
12	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175, 5325, 5840, 5845	1306295	0.7774
13	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175, 5325, 5840, 5845, 8070	1343785	0.7997
14	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175, 5325, 5840, 5845, 8070, 5085	1380138	0.8213
15	3455, 3840, 8055, 5860, 5875, 3000, 4520, 4030, 5175, 5325, 5840, 5845, 8070, 5085, 6005	1415314	0.8423

Table 26: Results Using the Demand Coverage Method for Demand Pattern 2.0

Pattern 2.0 Demand Pattern			
Number of MS	Optimal Locations of MS for **Pattern 2.0 Demand Pattern**	Total TDC	Coverage Ratio
1	3455	234282	0.1350
2	3455, 3840	420047	0.2420
3	3455, 3840, 8055	575226	0.3315
4	3455, 3840, 8055, 5860	718892	0.4142
5	3455, 3840, 8055, 5860, 5875	840810	0.4845
6	3455, 3840, 8055, 5860, 5875, 3000	944970	0.5445
7	3455, 3840, 8055, 5860, 5875, 3000, 4520	1042487	0.6007
8	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175	1116860	0.6436
9	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325	1188147	0.6846
10	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325, 4030	1253629	0.7224
11	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325, 4030, 5840	1303579	0.7511
12	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325, 4030, 5840, 5845	1344083	0.7745
13	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325, 4030, 5840, 5845, 8070	1383591	0.7972
14	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325, 4030, 5840, 5845, 8070, 3210	1420673	0.8186
15	3455, 3840, 8055, 5860, 5875, 3000, 4520, 5175, 5325, 4030, 5840, 5845, 8070, 3210, 5085	1457661	0.8399

4.11 Comparison of Results

Laurence (Johnson, 2012) performed an analysis on this same model to determine optimal locations for monitoring stations using a heuristic method. His method involved counting how many times a node detected contamination when the tanks were contaminated during their particular booster schedule (Table 5). This was a simple method and his results are seen in figure 29. The results show 3 areas of significance where monitoring stations should be placed. He simulated tanks being contaminated because that is the most likely delivery point if intentional contamination were to occur. It was also assumed that there would be fewer monitoring stations than the number of tanks which is 7. This is a major difference between our results because this study suggested at least 15 monitoring stations.

Results of this study vary significantly from Laurence because his method accounted for contamination events of the tanks only which is the most likely event but all nodes should be assumed likely candidates for contamination. This should be done because people looking to contaminate a WDS will not always pick the most likely location but instead will be intelligent and look for weak spots in the system. This study’s method assumes that any node can be contaminated so monitoring stations are strategically scattered around the WDS while his are clustered in three areas of significance. These three areas are covered by three monitoring stations in this study but this still leaves a huge number of nodes not being monitoring.

Laurence also did not analyze multiple demand patterns which can affect the locations of monitoring stations. Using multiple demand patterns is important because

cities may have different demand patterns depending on location, usage, and seasons which will affect where monitoring stations should be located.

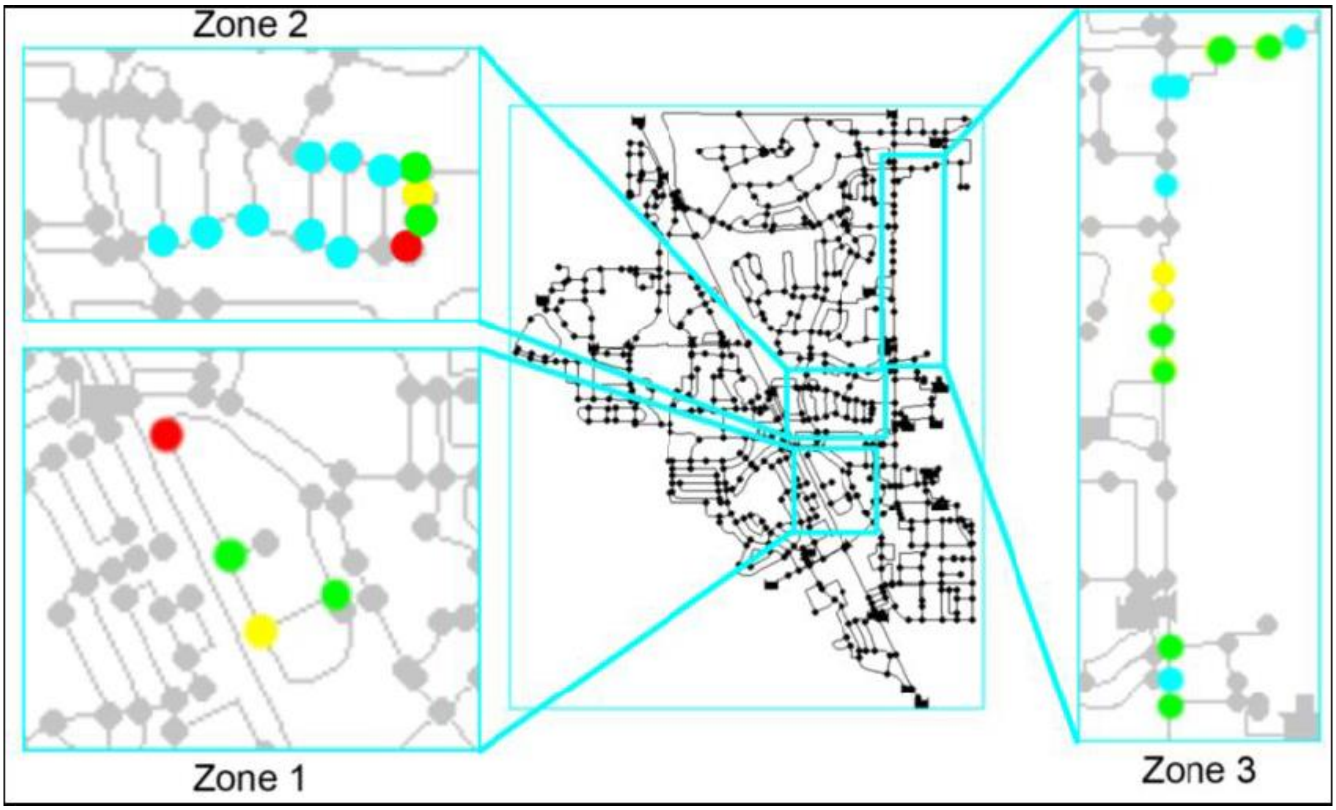

Figure 29: Areas of Significance Determined by Laurence (Johnson, 2012)

4.12 Weaknesses of the DCI Method

The DCI method is a great way to determine the optimal location of monitoring stations but it does have some significant weaknesses. A flaw in the method is that at PRV-118, PRV-119, and PRV-162 there should be monitoring stations to monitor water entering the WDS from the main transmission line. The entire WDS can be seen in figure 30 with the location of the PRV's and top 15 monitoring stations being indicated. The flaw will be examined more closely by looking at PRV-162 in figure 31. This figure shows that water from the main line enters the WDS at PRV-160, PRV-161, and PRV-162 but since there is a monitoring station near PRV-160 that covers the nodes downstream of PRV-162, the DCI method does not indicate that there should be a monitoring station there. This flaw is relatively easy to fix by including monitoring stations near PRV-162. Other locations where this flaw is repeated is at PRV-118 and PRV-119 which are also connected to the main transmission line.

Another flaw is that the DCI method does not take into consideration the water from the tanks being used by the distribution systems. The method only accounts for water being used from the main line. These tanks store water that will ultimately be used by consumers but this water can be contaminated and spread throughout the system. Therefore, there should be a monitoring station near every tank. Tank 2, 3, and 5 are the only tanks without monitoring stations nearby where this flaw would occur.

These flaws are easy to overcome but it is hard to determine how important these extra monitoring stations are compared to the top 15 monitoring station of the WDS. An additional study should be performed to determine if these stations would be in the top 15 monitoring locations.

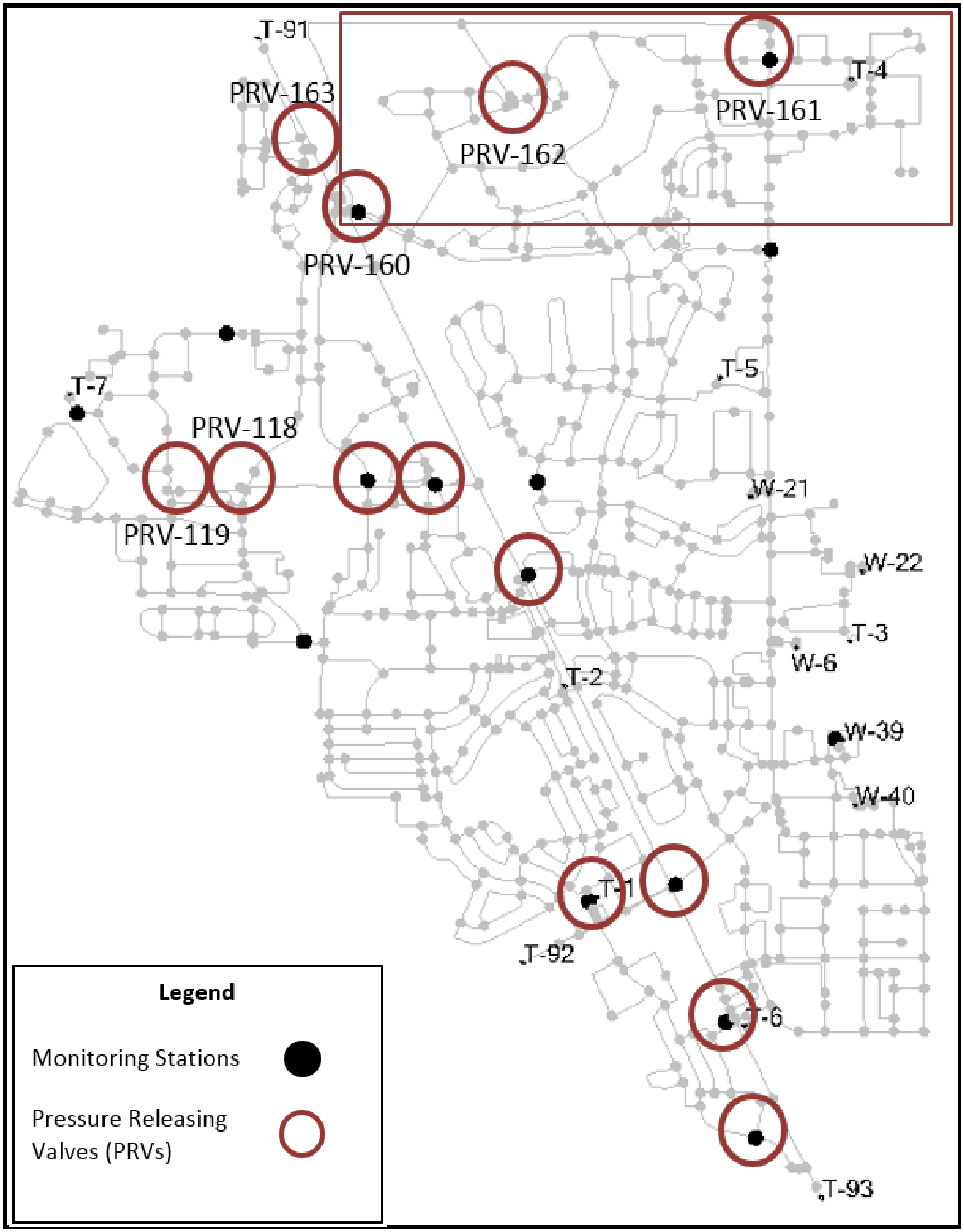

Figure 30: Locations of the Pressure Release Valves (PRVs) Connecting to the Main Transmission Line

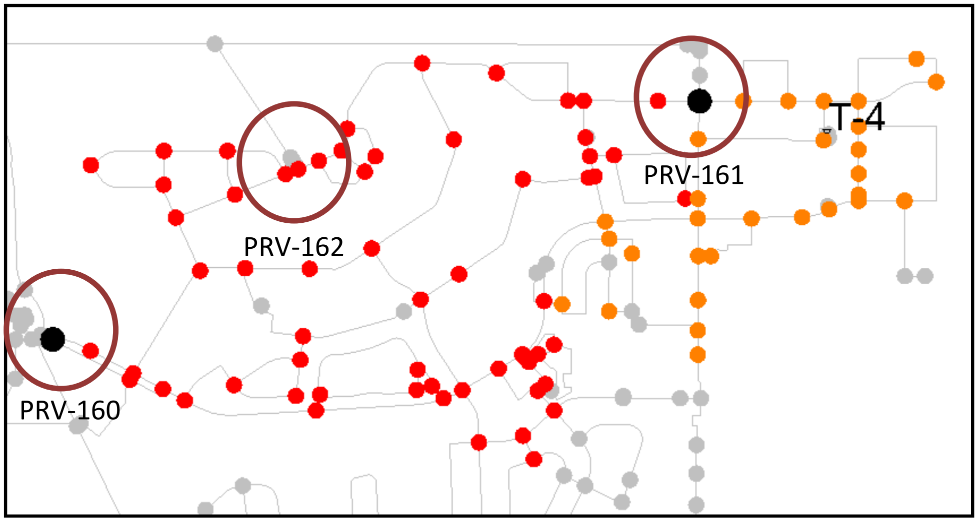

Figure 31: Close Up of PRV-162

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APPENDICES

APPENDIX A

The contents of Appendix A include visual representations of the locations of monitoring stations with their corresponding coverages. The coverage criterion is assumed to be 50% unless otherwise stated.

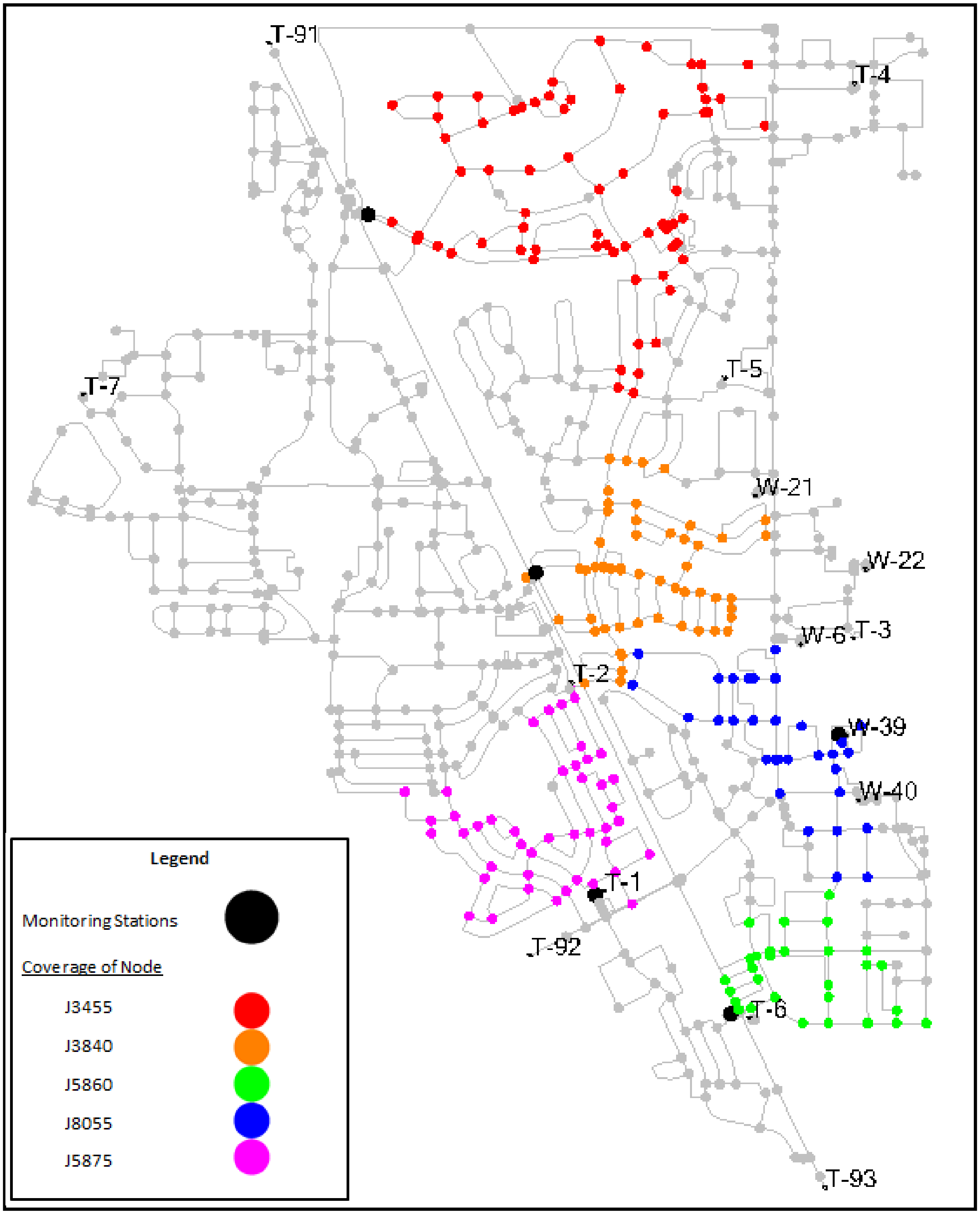

Figure 32: Monitoring Station 1-5 with Corresponding Coverages for Max Daily Demand (Steady State)

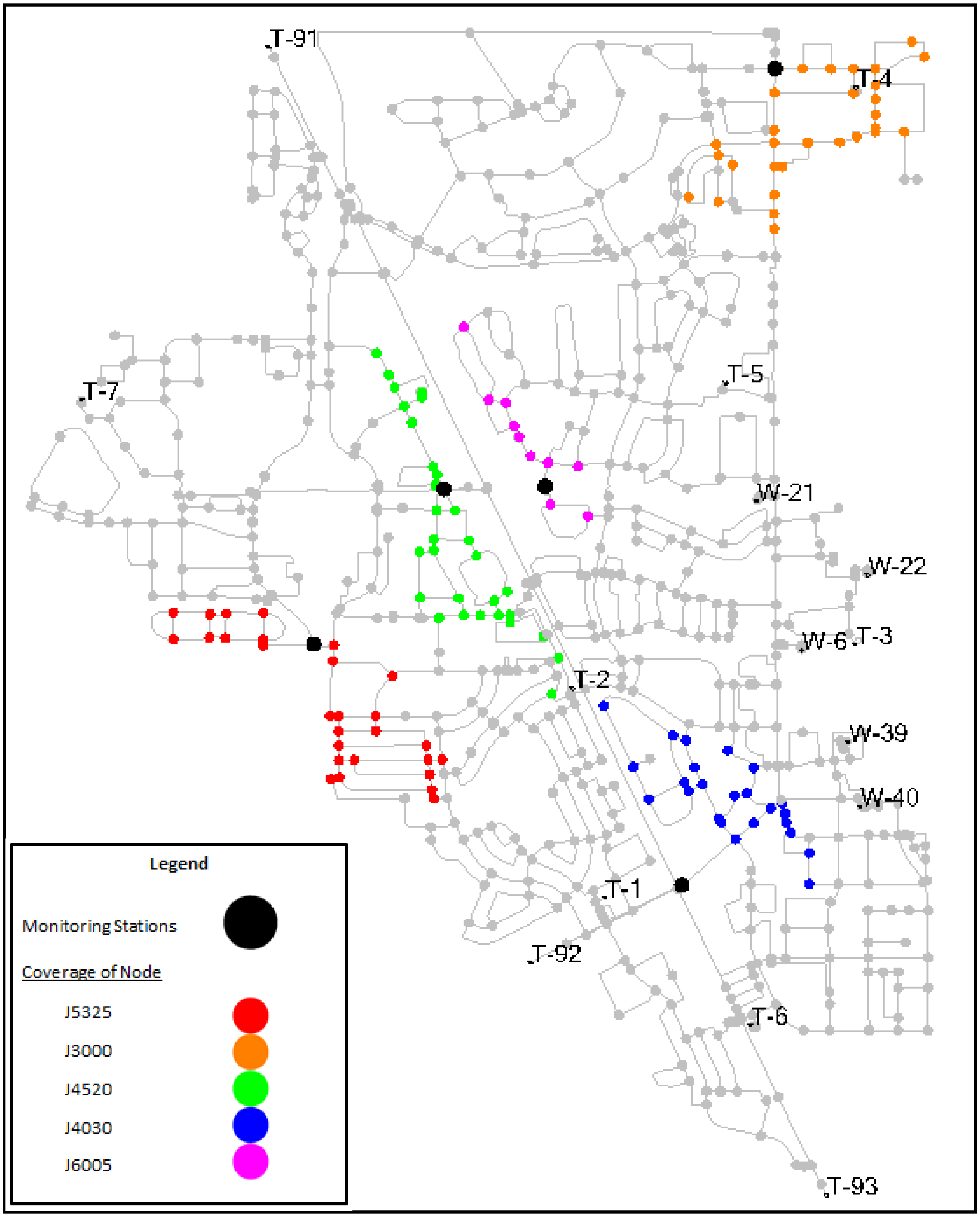

Figure 33: Monitoring Station 6-10 with Corresponding Coverages for Max Daily Demand (Steady State)

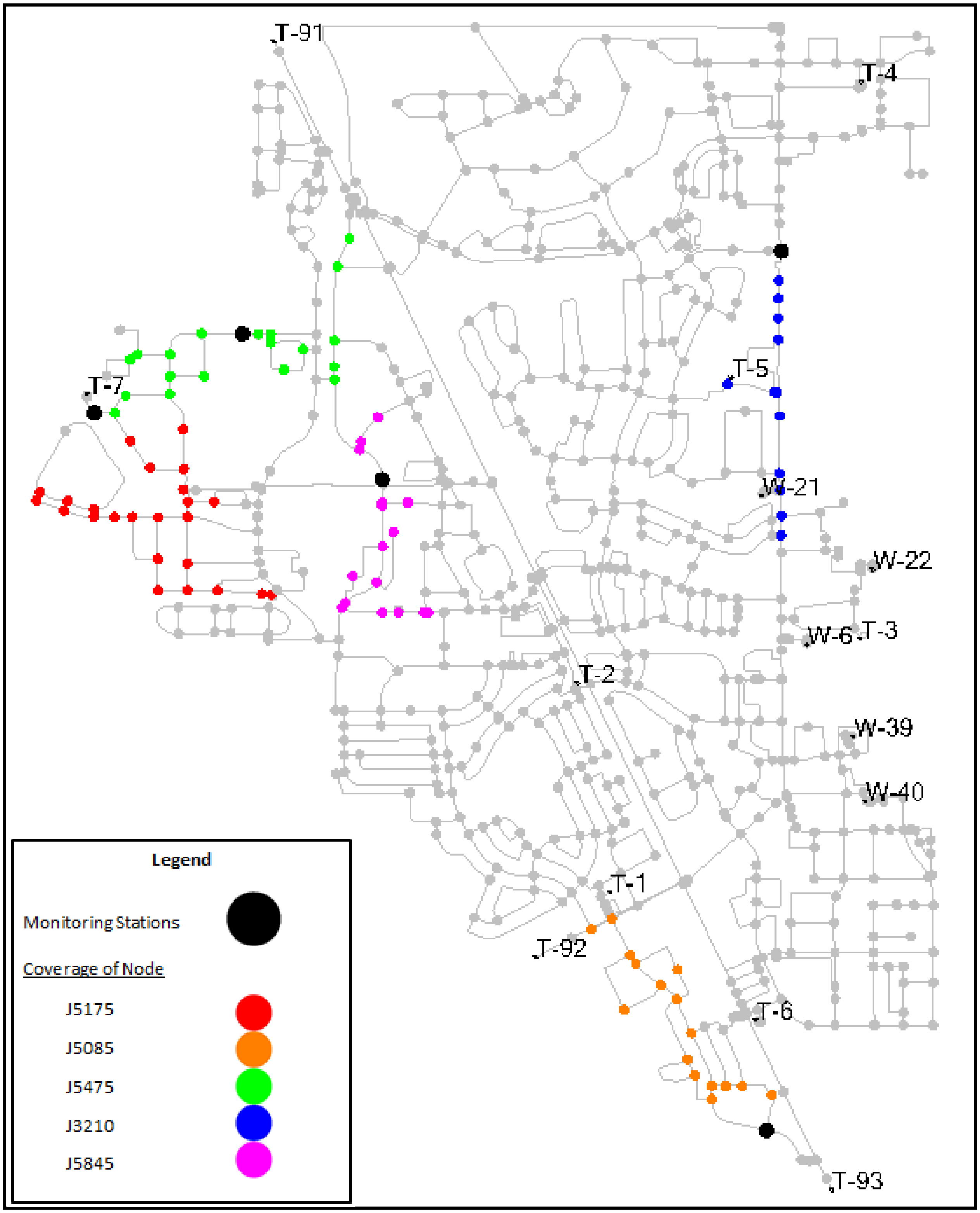

Figure 34: Monitoring Station 11-15 with Corresponding Coverages for Max Daily Demand (Steady State)

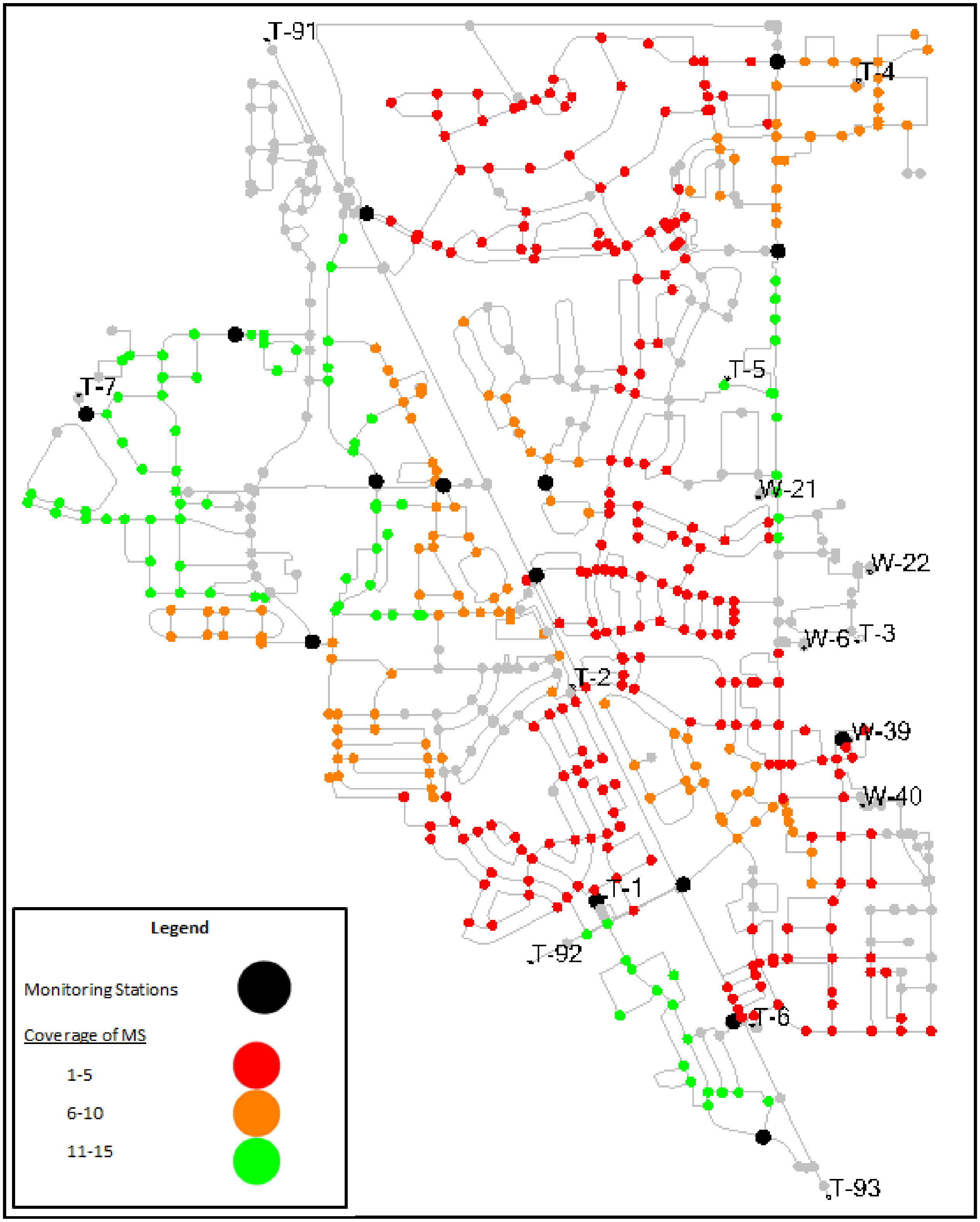

Figure 35: Top 15 Monitoring Stations with Corresponding Coverages for Max Daily Demand (Steady State)

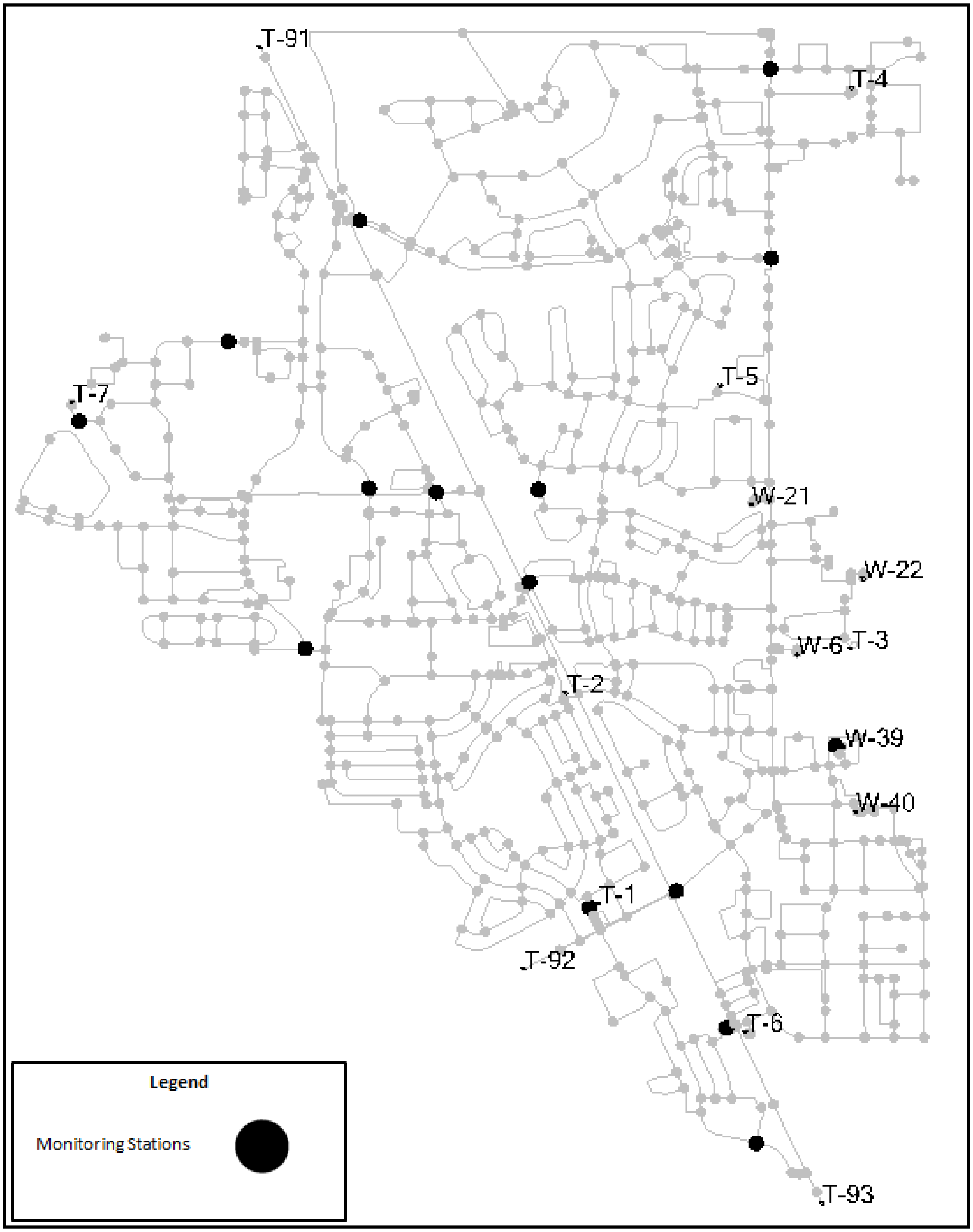

Figure 36: Top 15 Monitoring Stations for Max Daily Demand (Steady State)

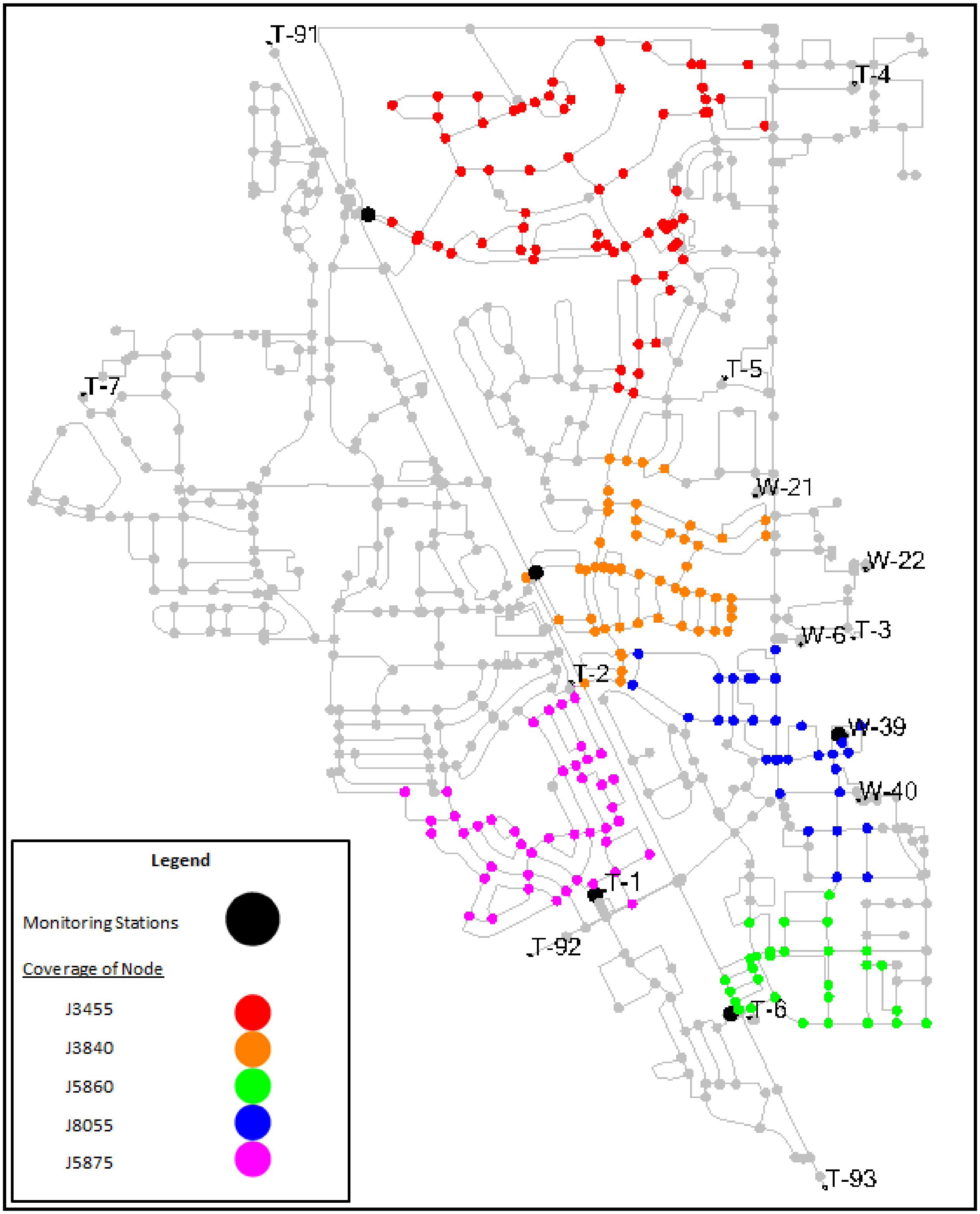

Figure 37: Monitoring Station 1-5 with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

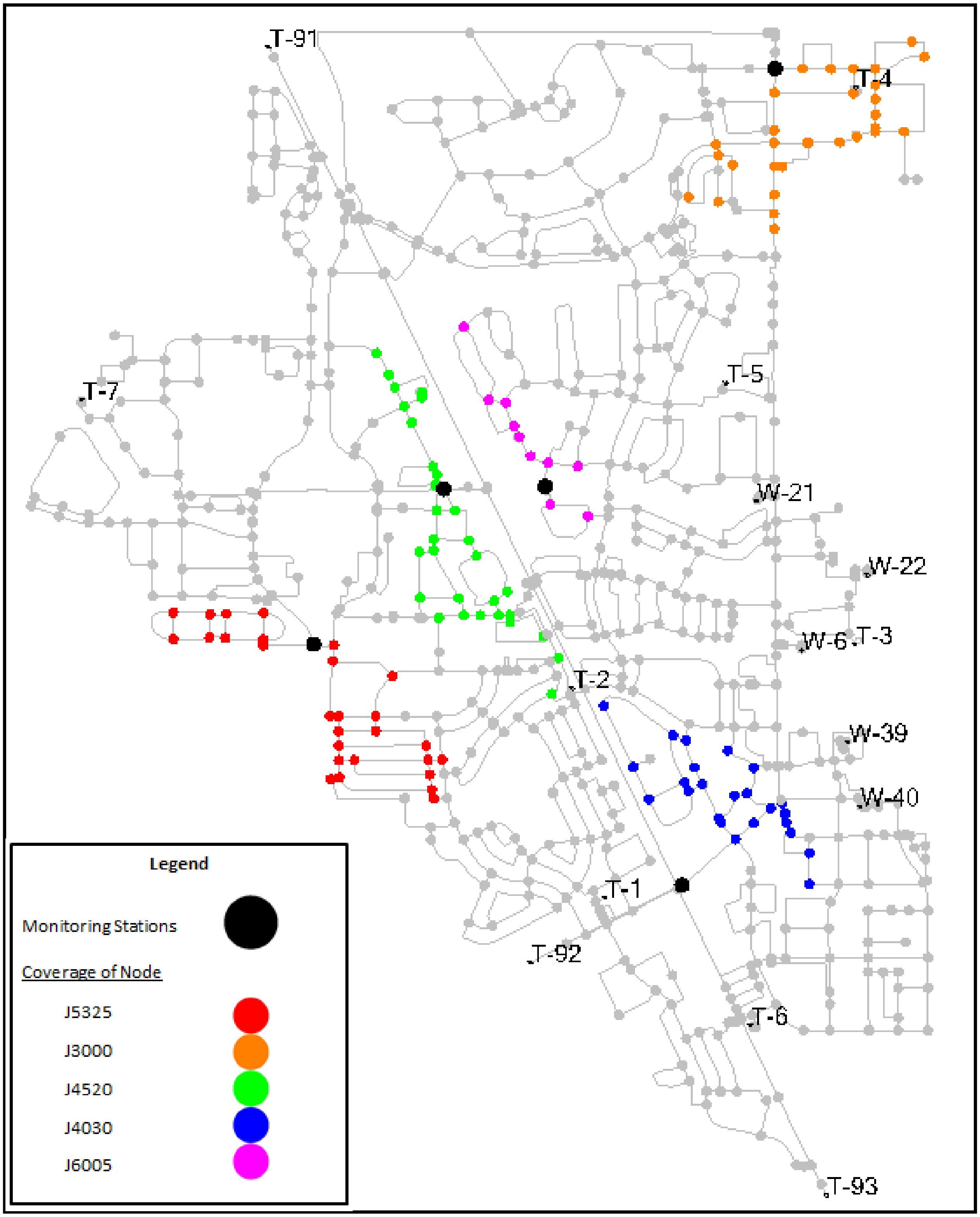

Figure 38: Monitoring Station 6-10 with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

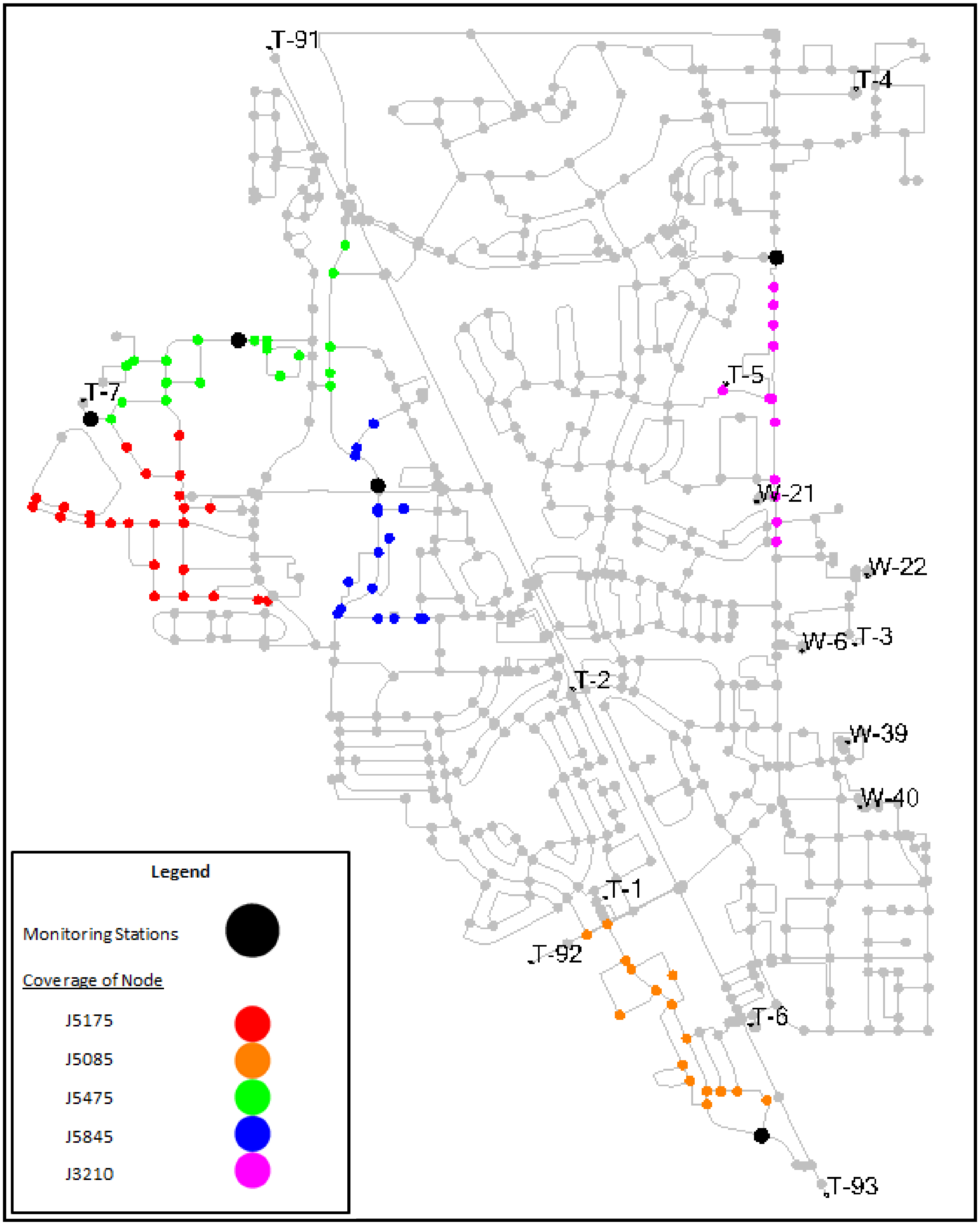

Figure 39: Monitoring Station 11-15 with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

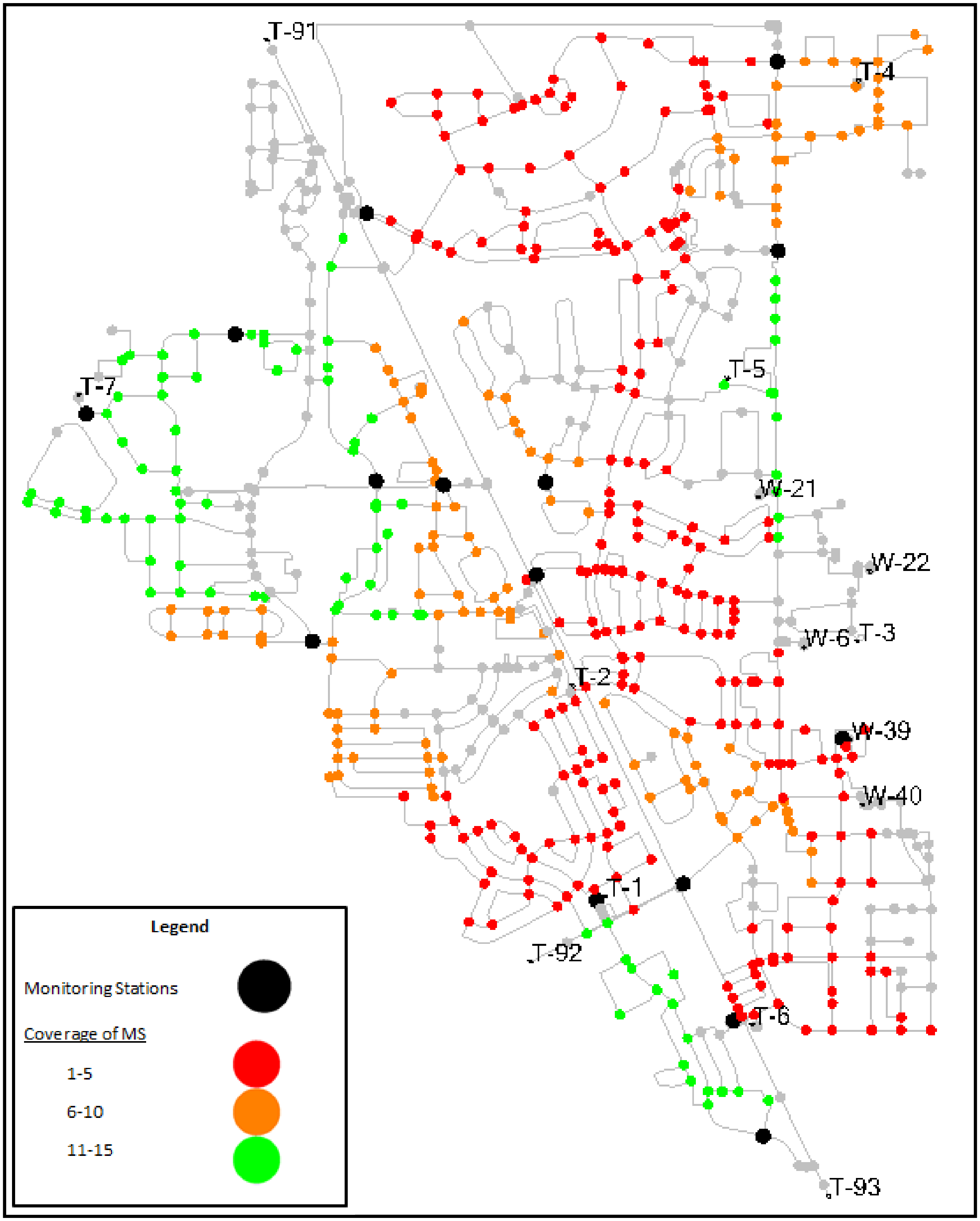

Figure 40: Top 15 Monitoring Stations with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

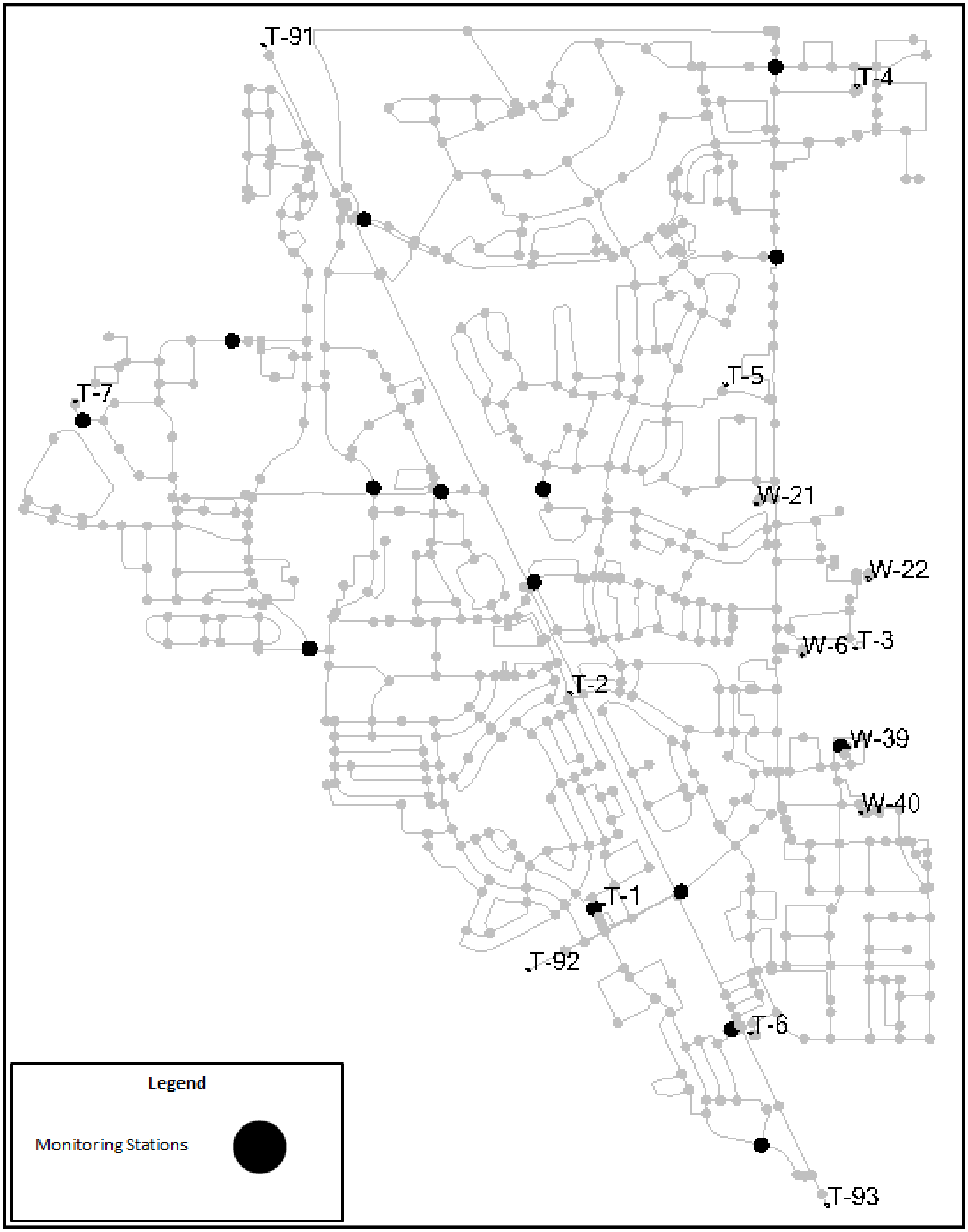

Figure 41: Top 15 Monitoring Stations for Demand Pattern 2.0 (Unsteady State)

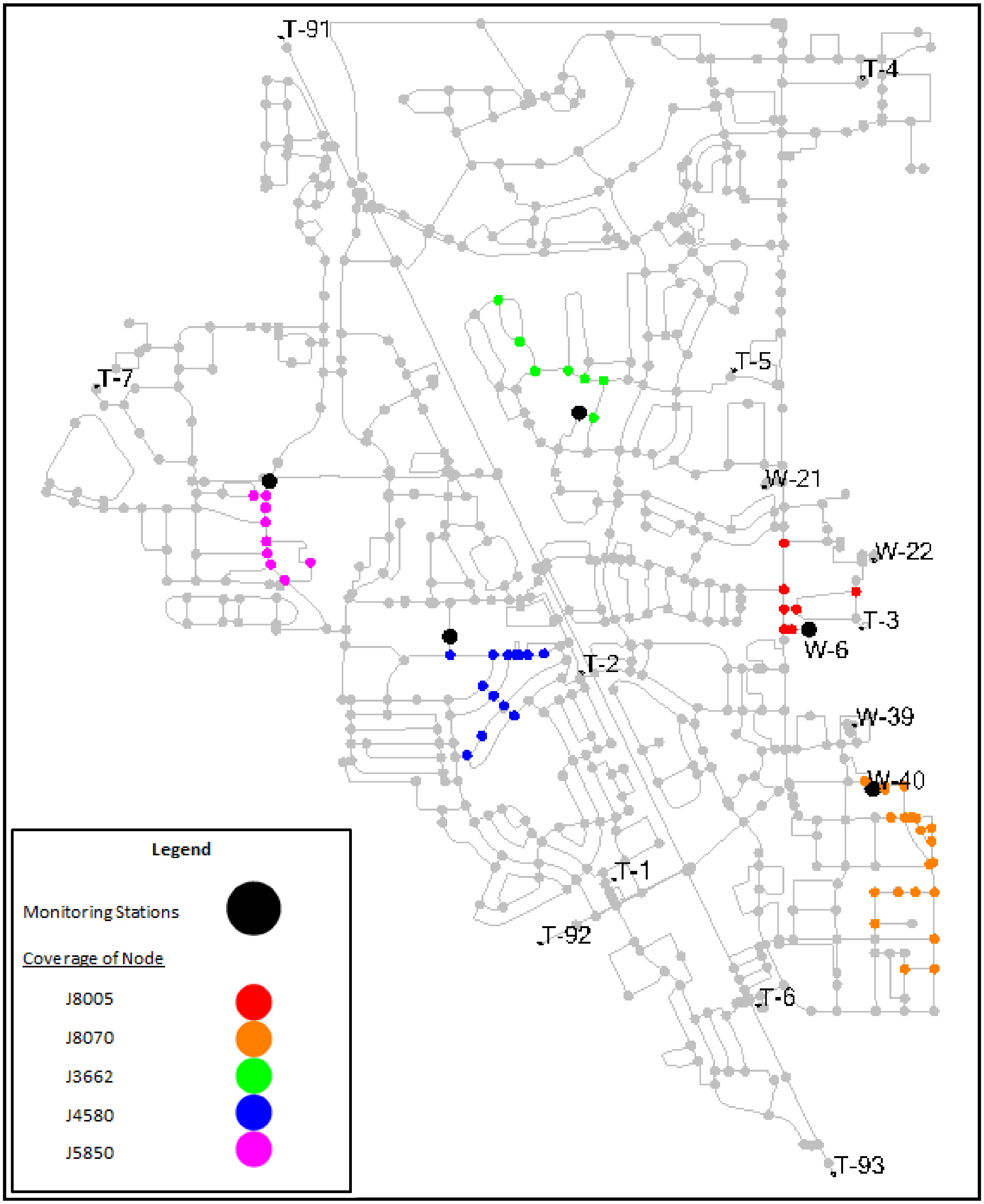

Figure 42: Monitoring Station 16-20 with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

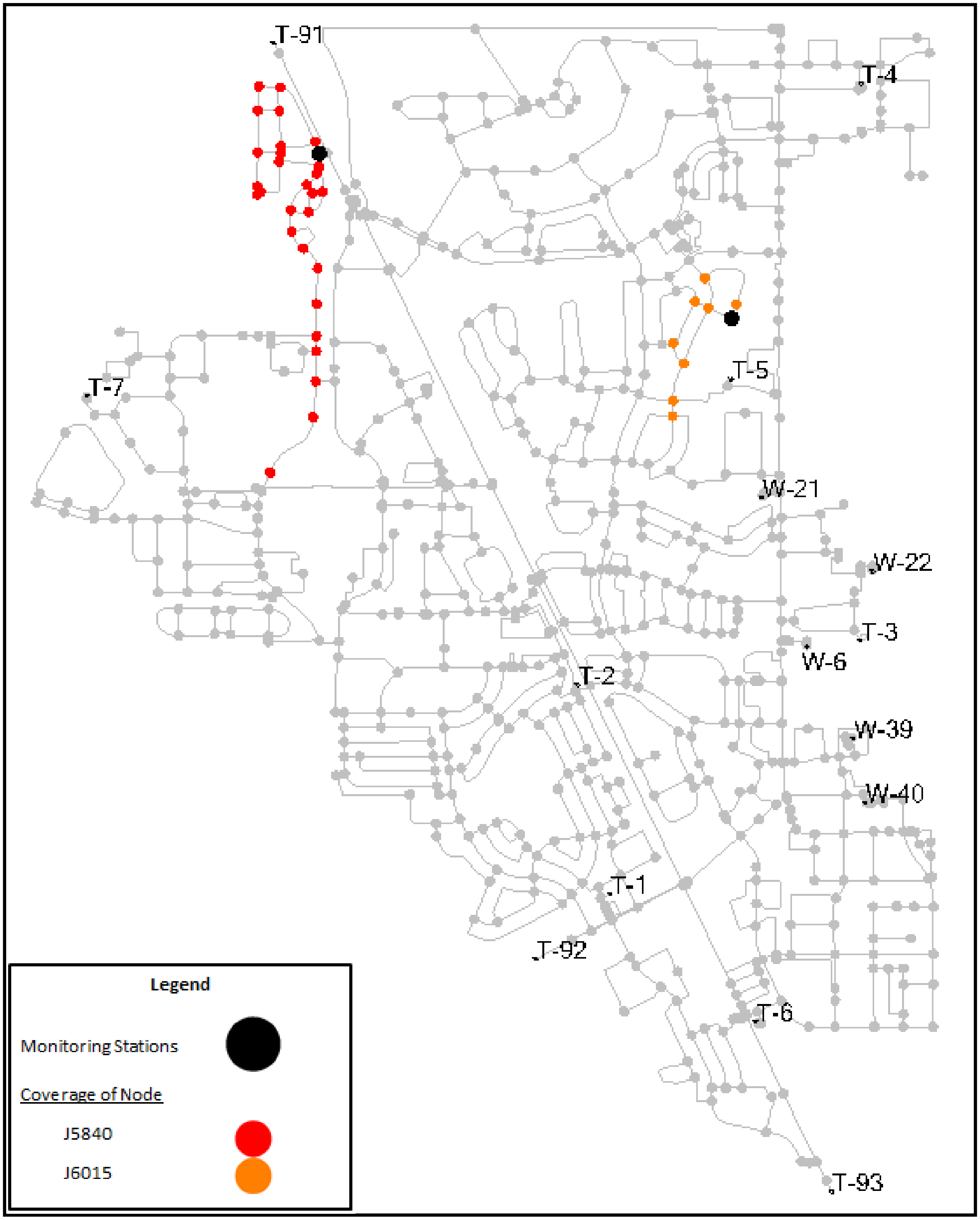

Figure 43: Monitoring Station 21-22 with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

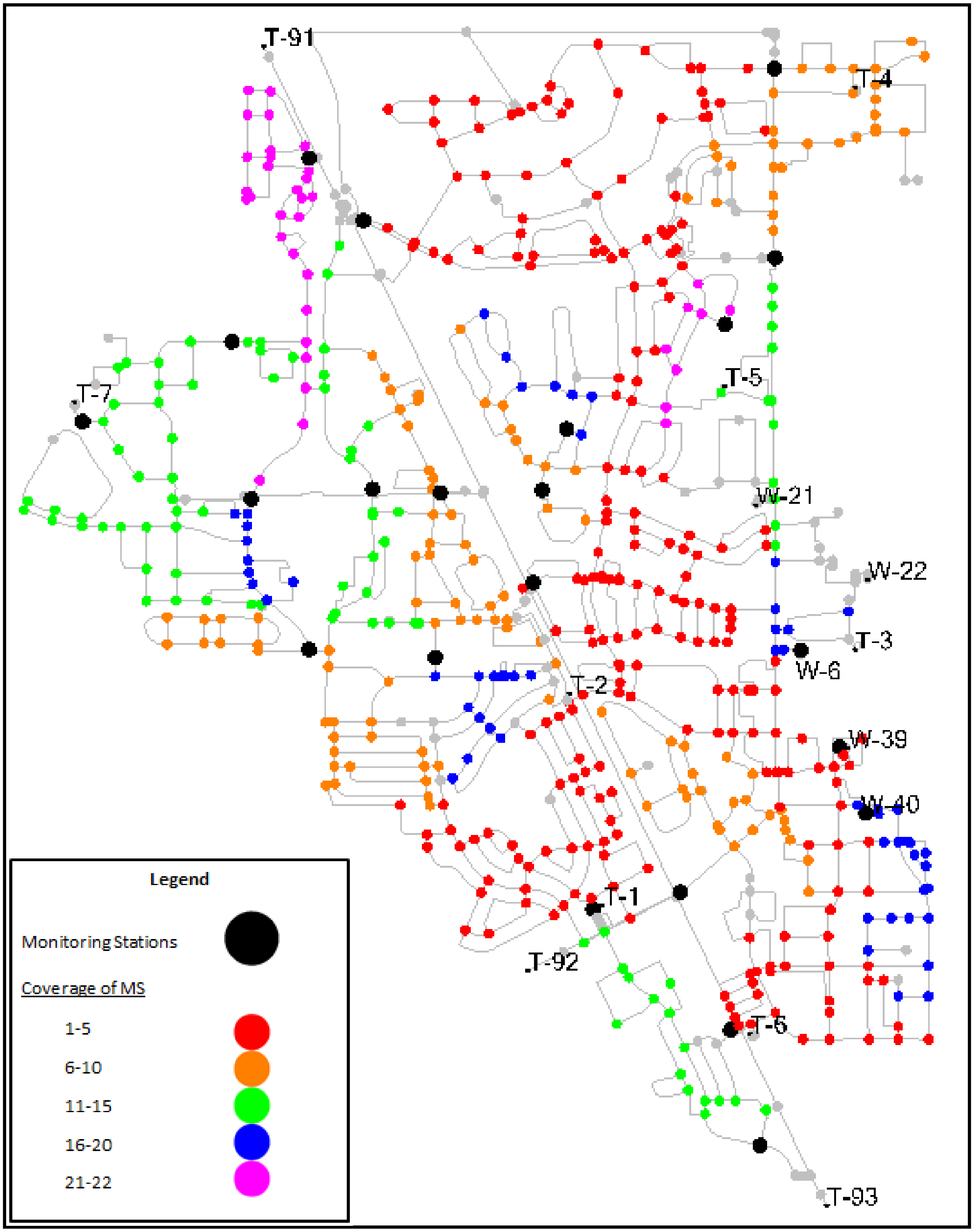

Figure 44: Top 22 Monitoring Stations with Corresponding Coverages for Demand Pattern 2.0 (Unsteady State)

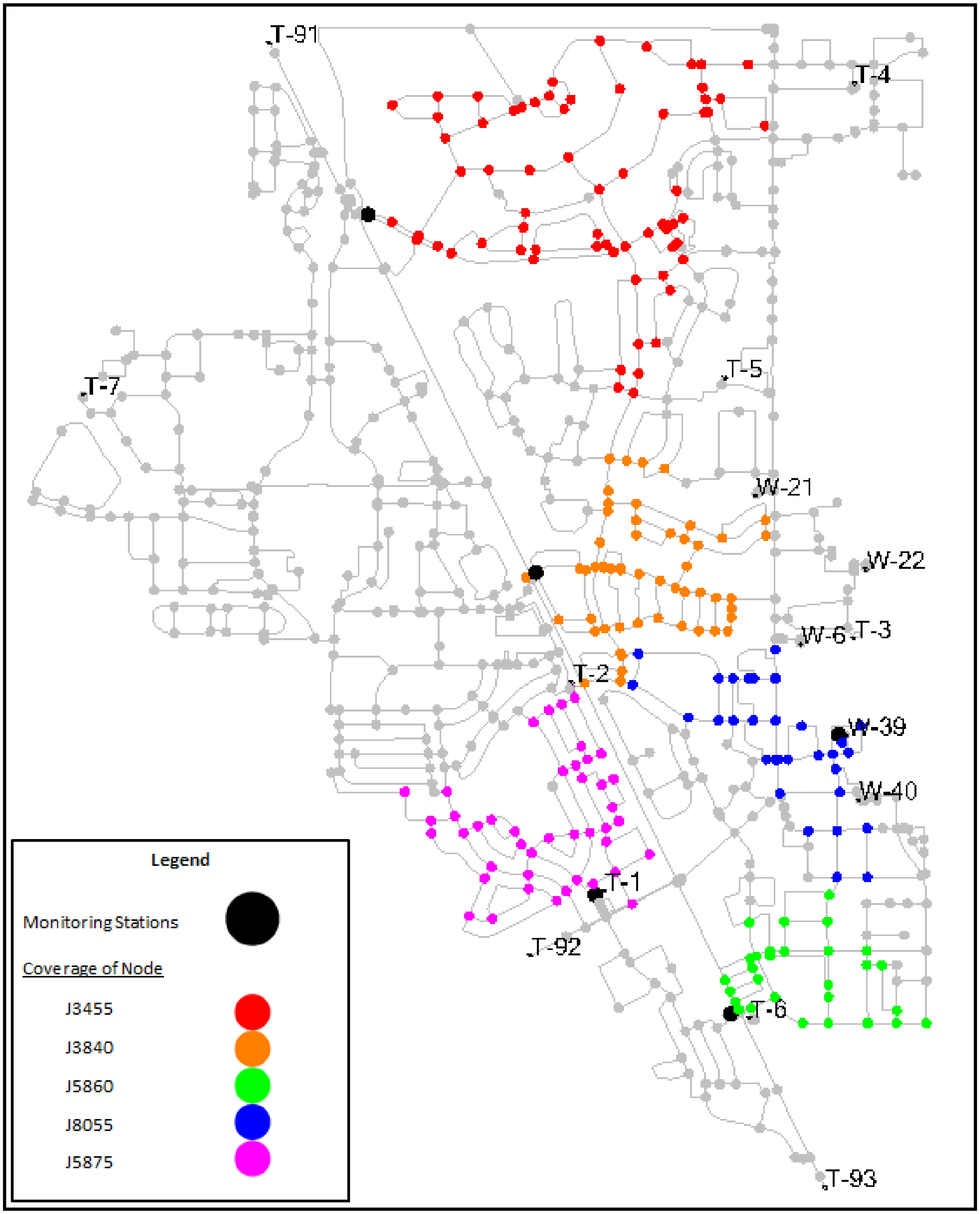

Figure 45: Monitoring Station 1-5 with Corresponding Coverages for Demand Pattern 3.0 (Unsteady State)

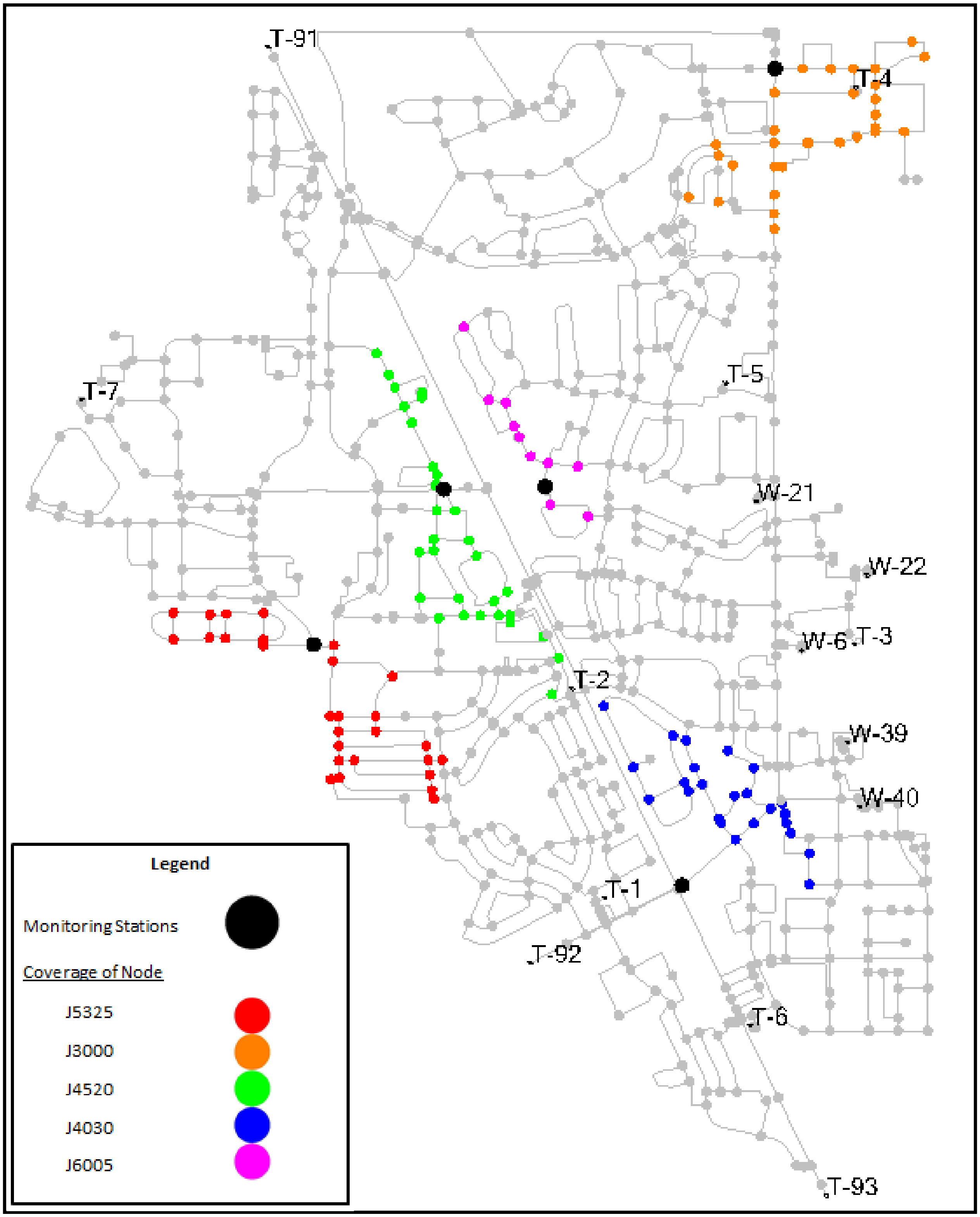

Figure 46: Monitoring Station 6-10 with Corresponding Coverages for Demand Pattern 3.0 (Unsteady State)

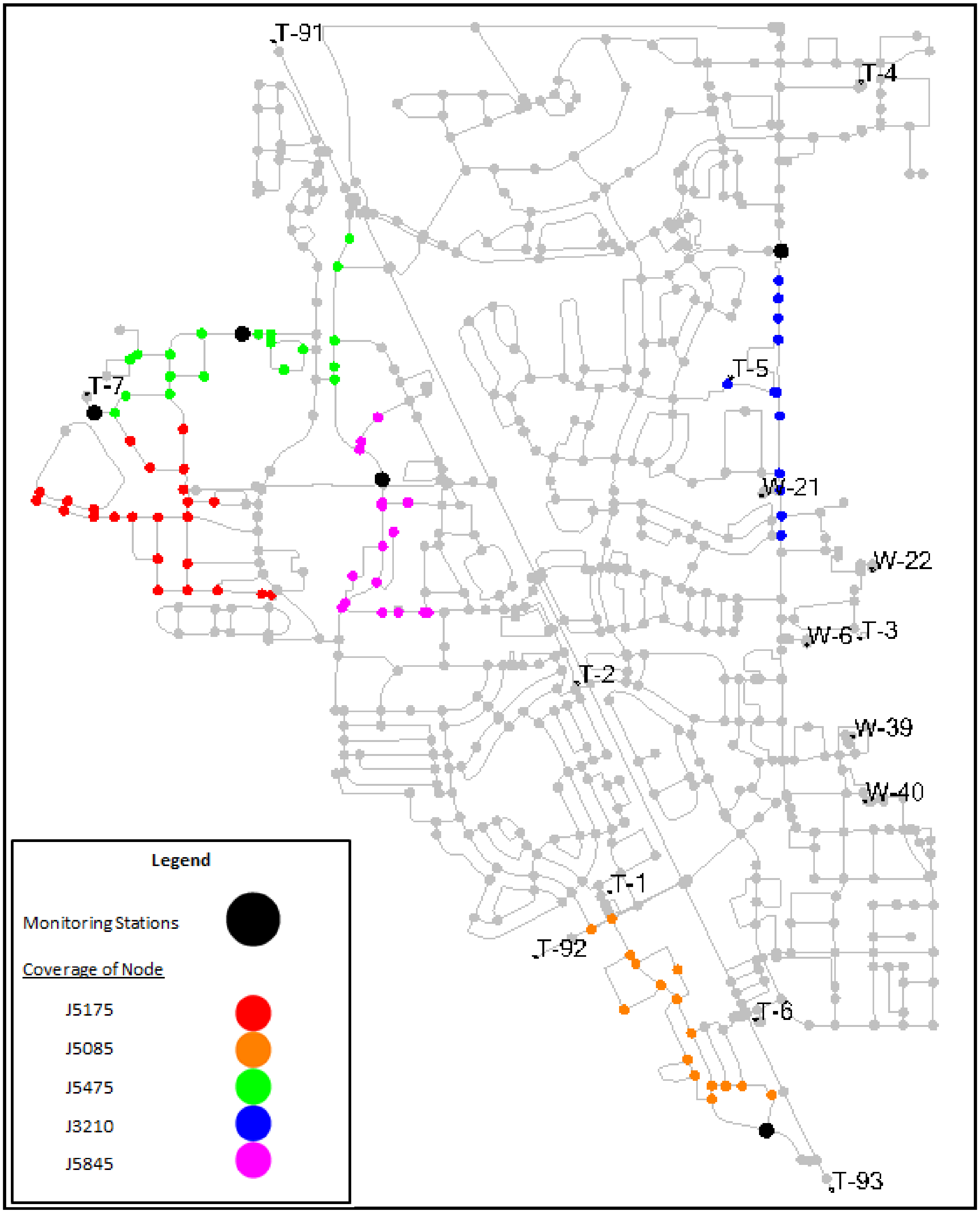

Figure 47: Monitoring Station 11-15 with Corresponding Coverages for Demand Pattern 3.0 (Unsteady State)

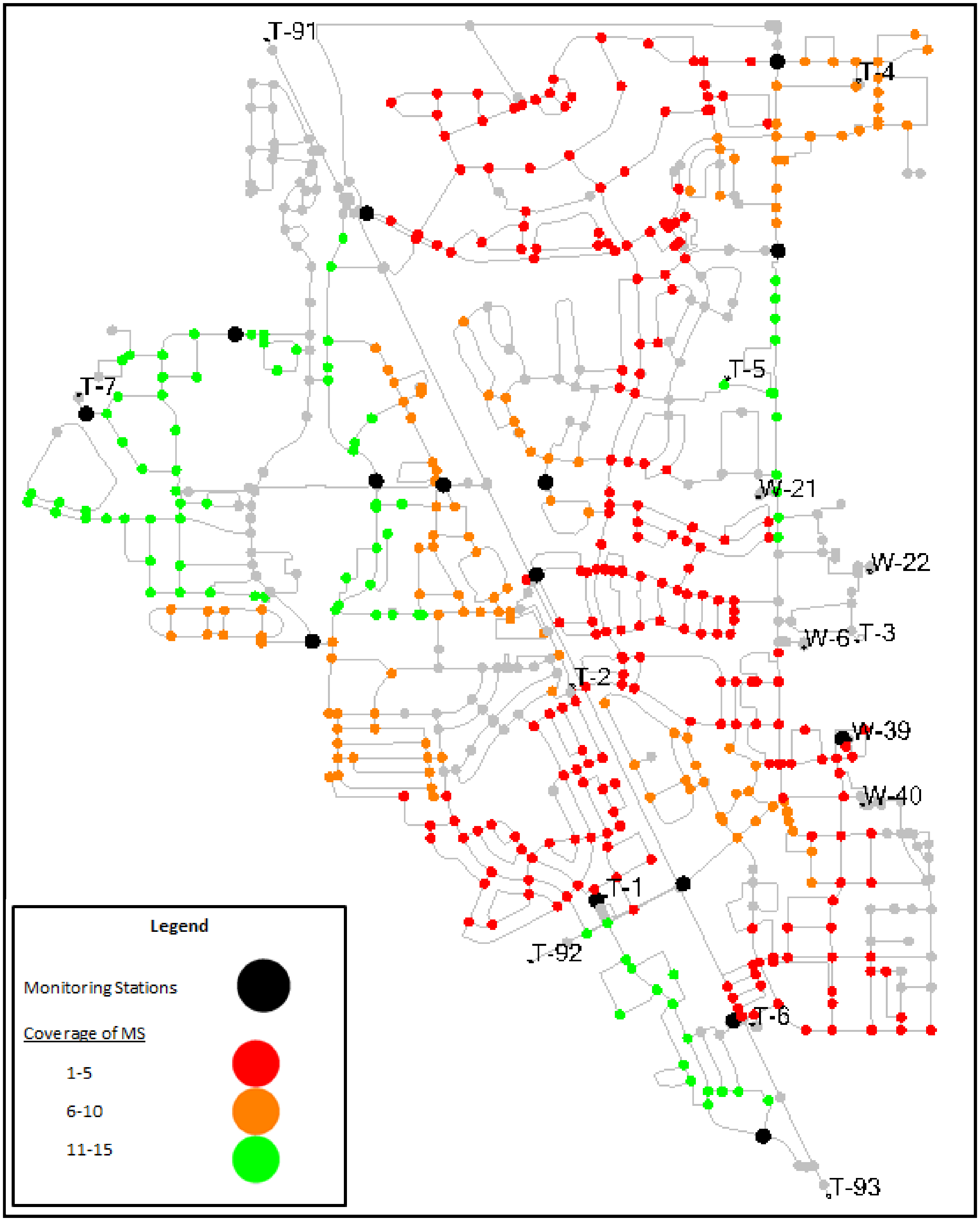

Figure 48: Top 15 Monitoring Stations with Corresponding Coverages for Demand Pattern 3.0 (Unsteady State)

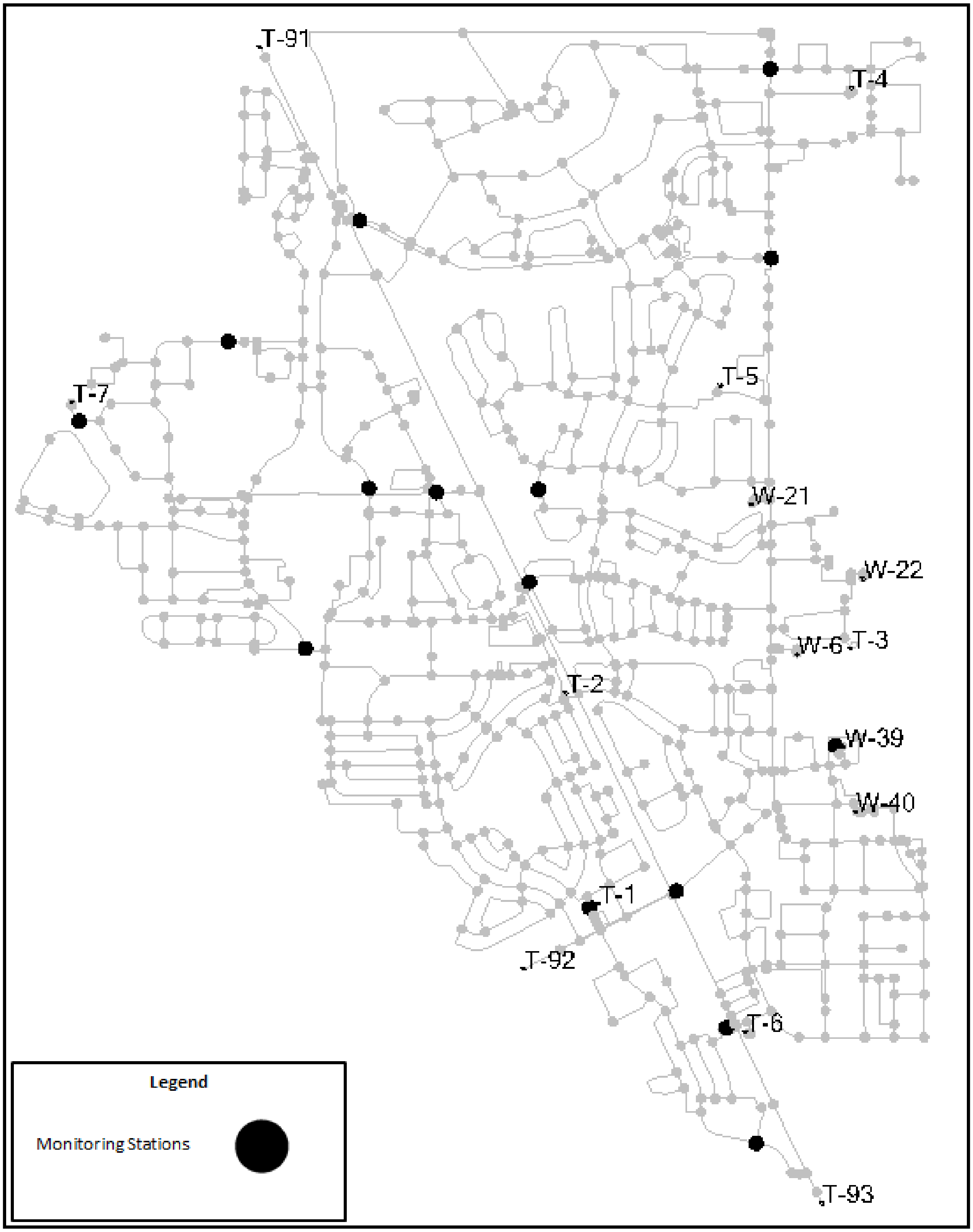

Figure 49: Top 15 Monitoring Stations for Demand Pattern 3.0 (Unsteady State)

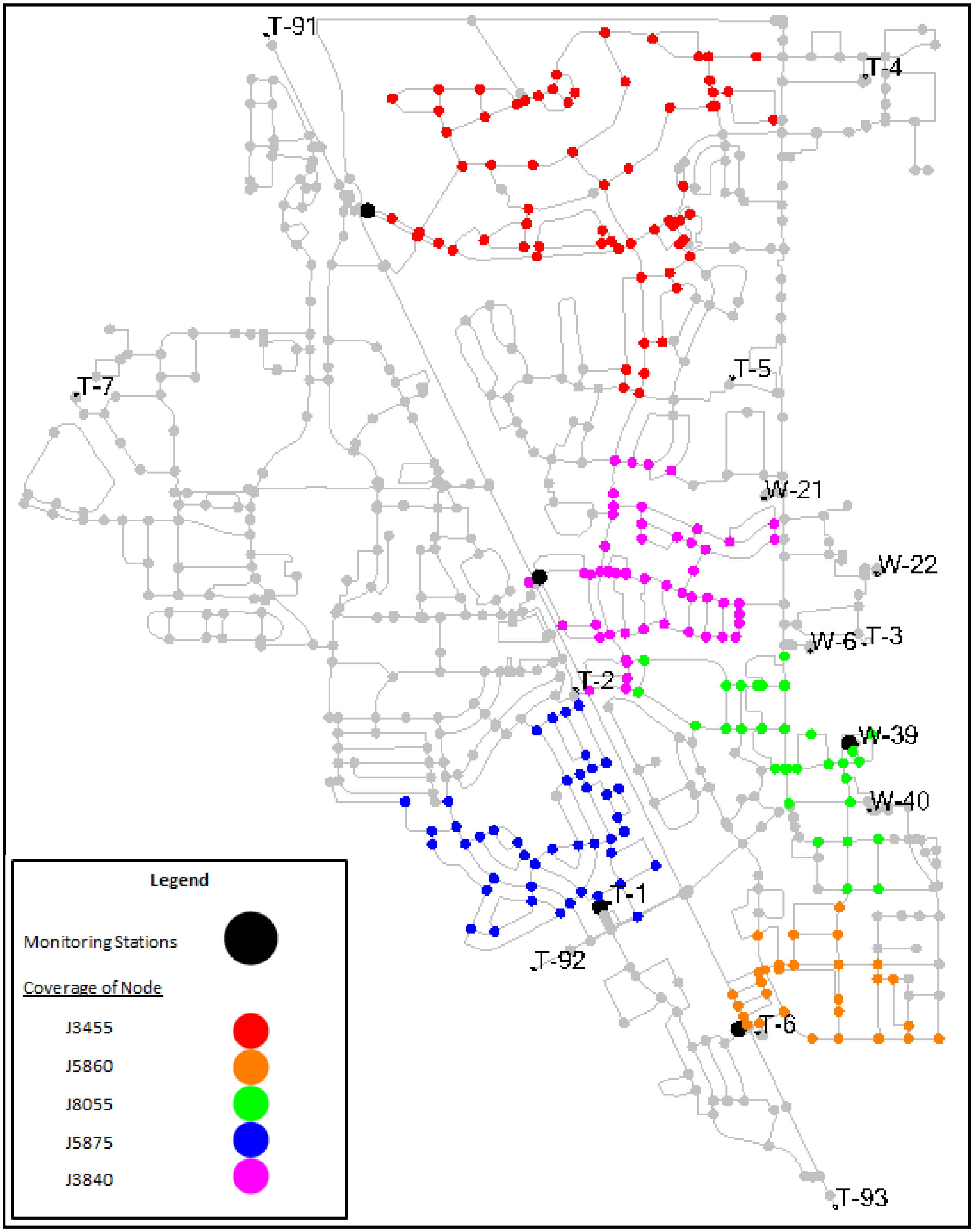

Figure 50: Monitoring Station 1-5 with Corresponding Coverages for Demand Pattern 4.0 (Unsteady State)

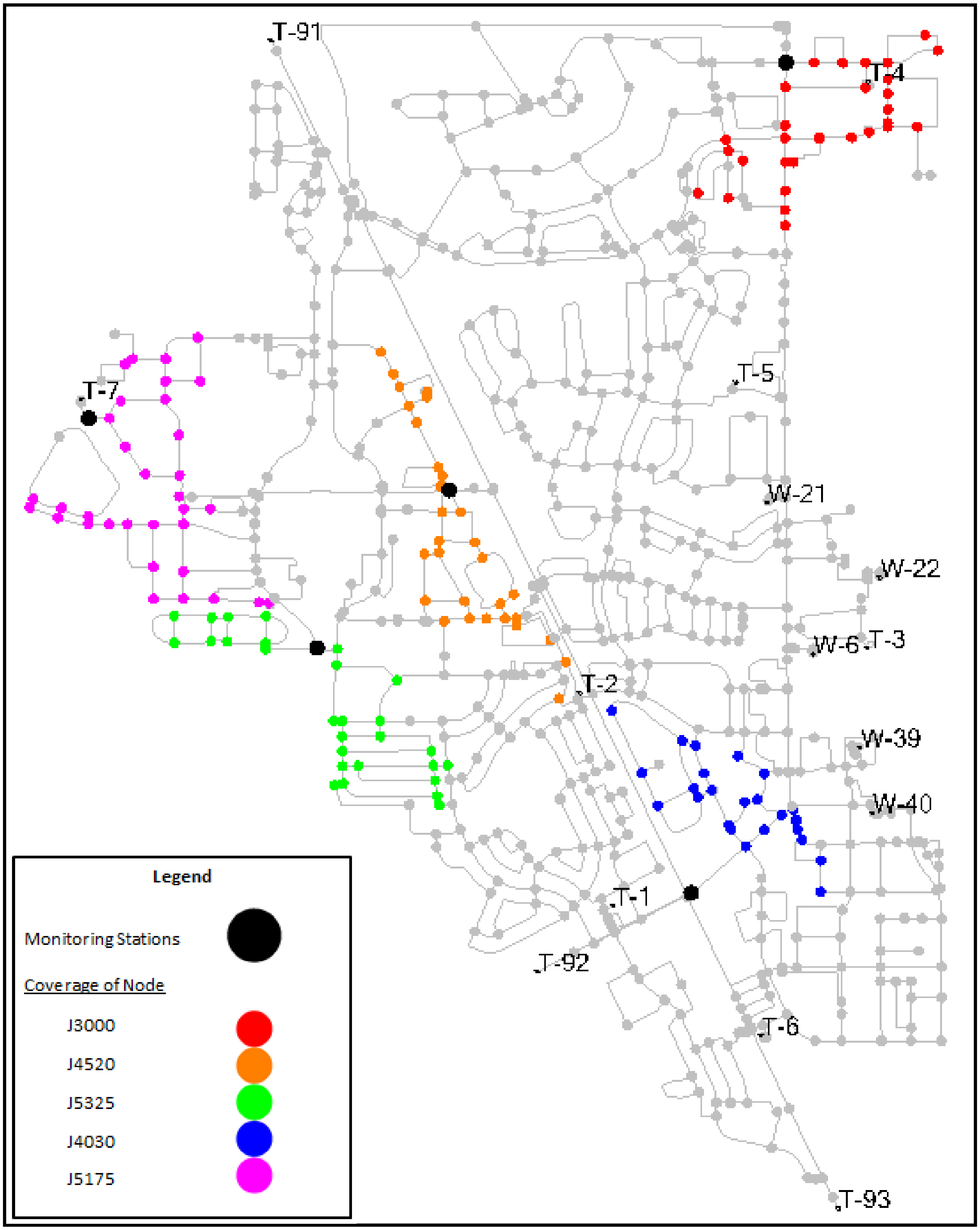

Figure 51: Monitoring Station 6-10 with Corresponding Coverages for Demand Pattern 4.0 (Unsteady State)

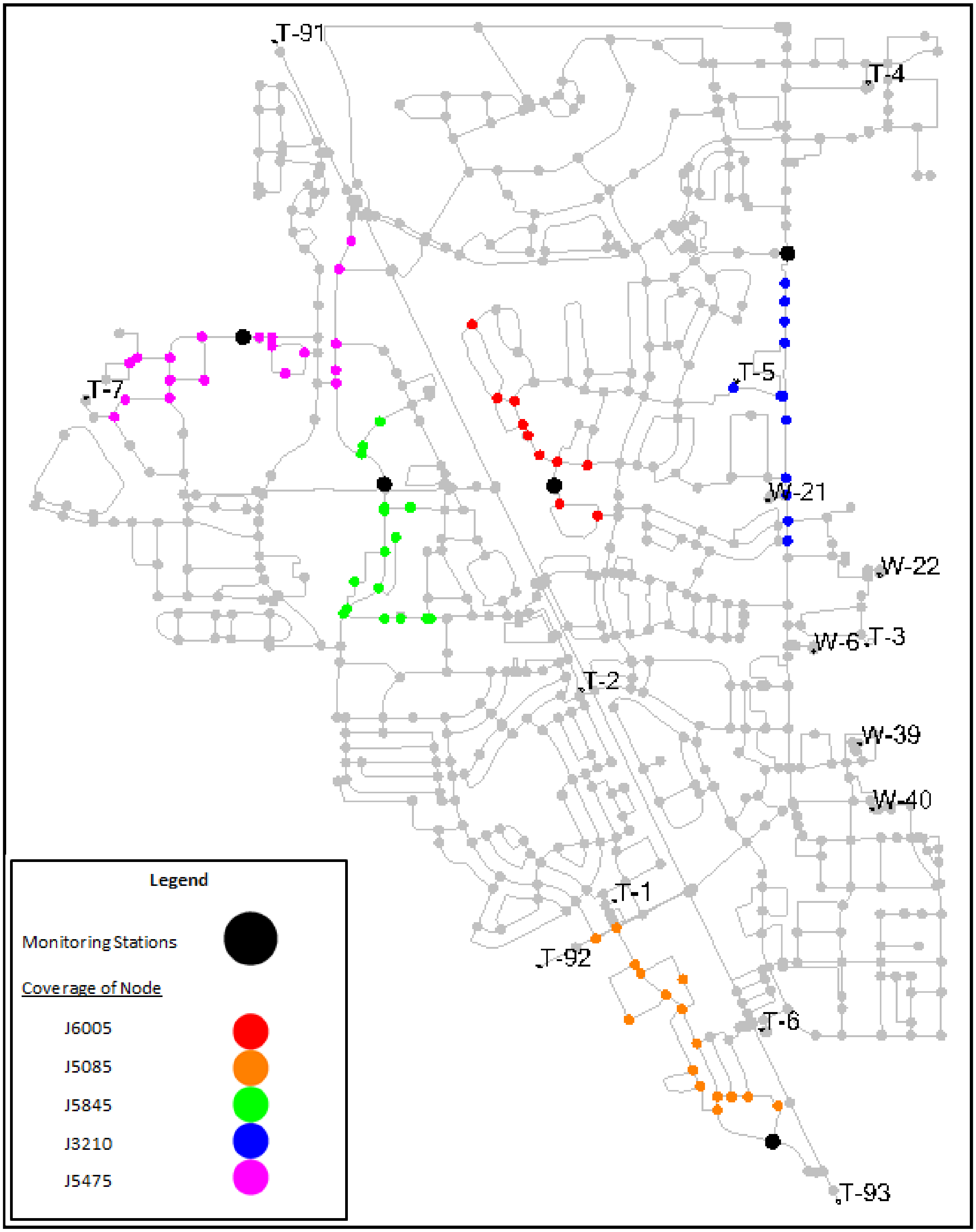

Figure 52: Monitoring Station 11-15 with Corresponding Coverages for Demand Pattern 4.0 (Unsteady State)

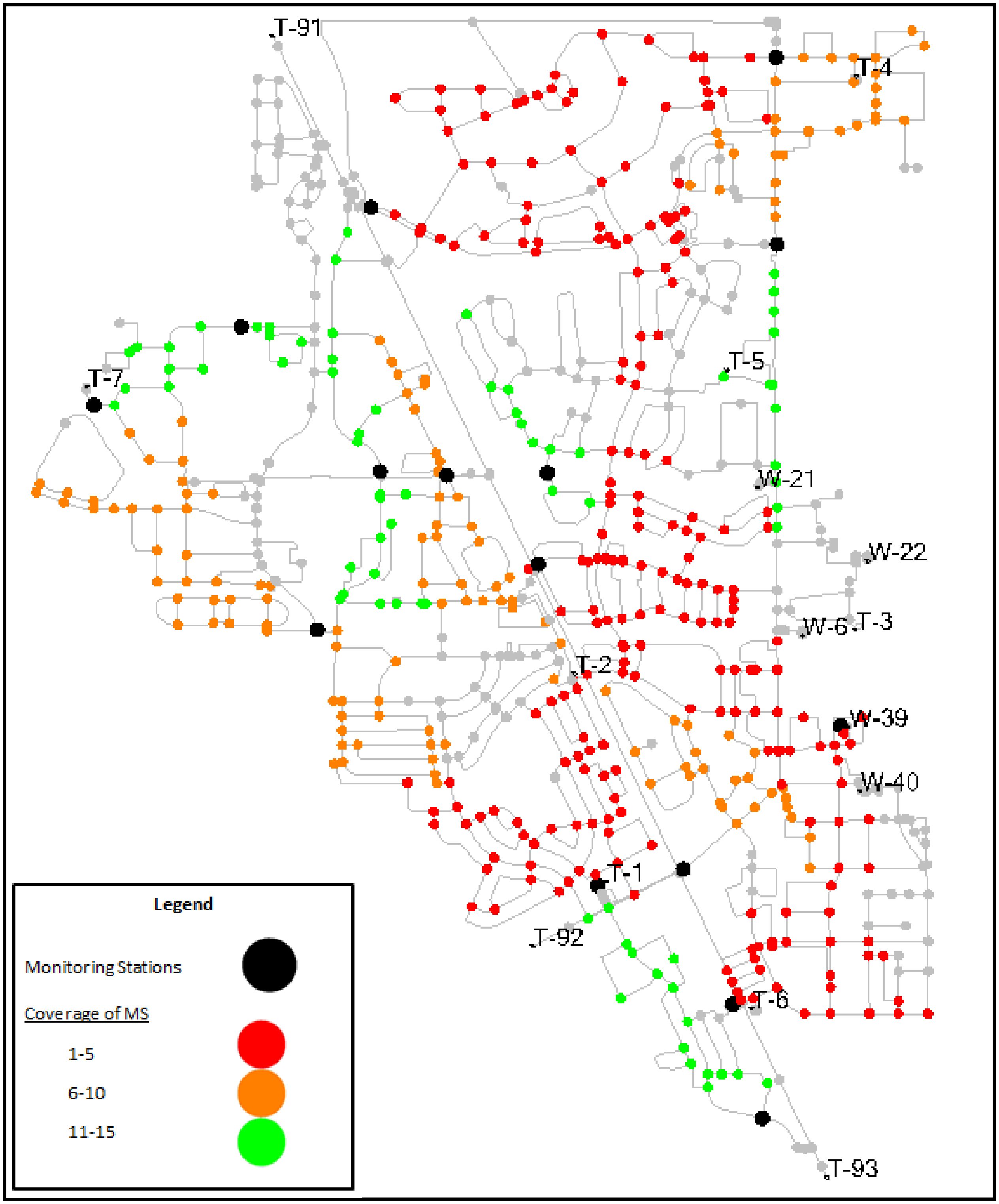

Figure 53: Top 15 Monitoring Stations with Corresponding Coverages for Demand Pattern 4.0 (Unsteady State)

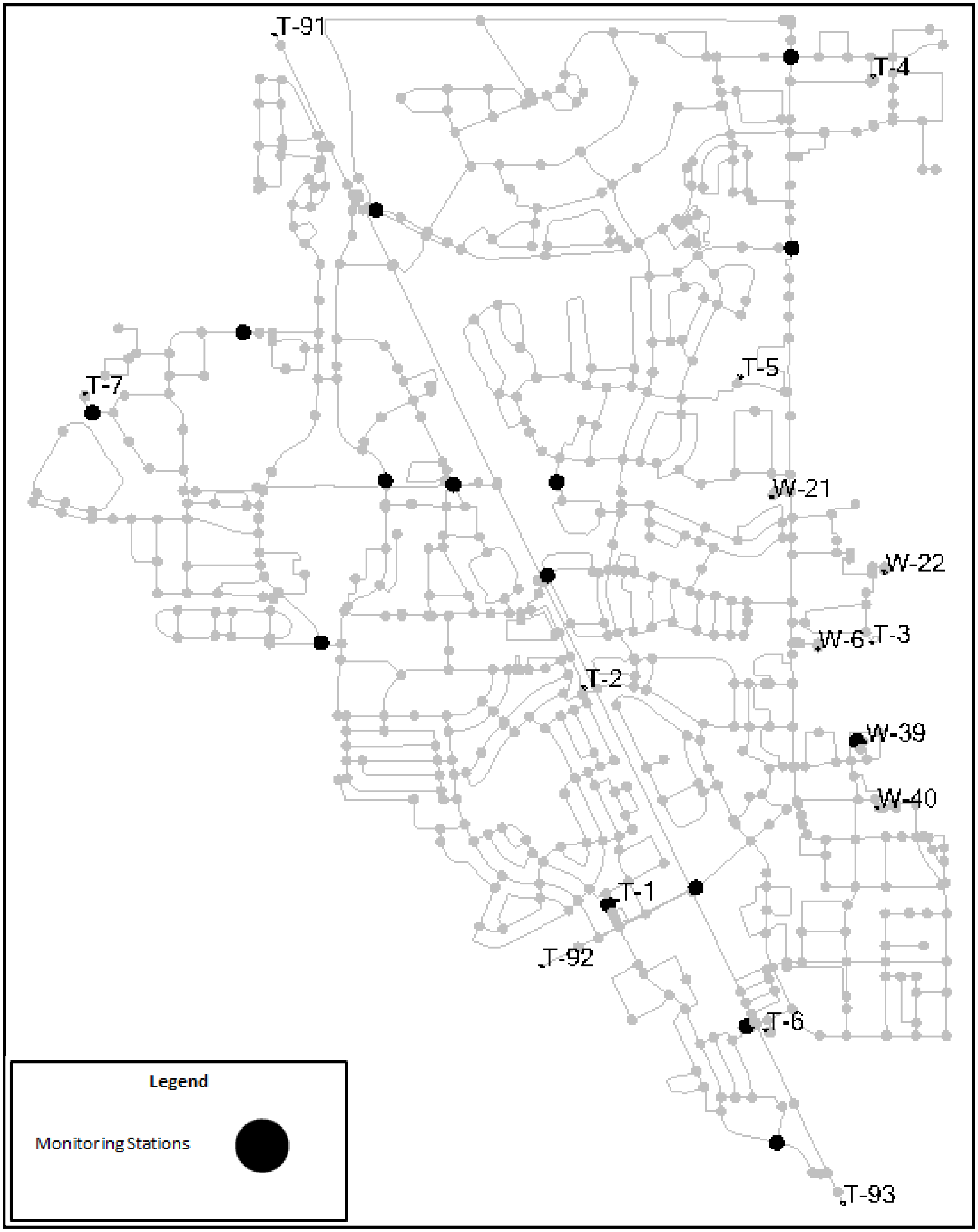

Figure 54: Top 15 Monitoring Stations for Demand Pattern 4.0 (Unsteady State)

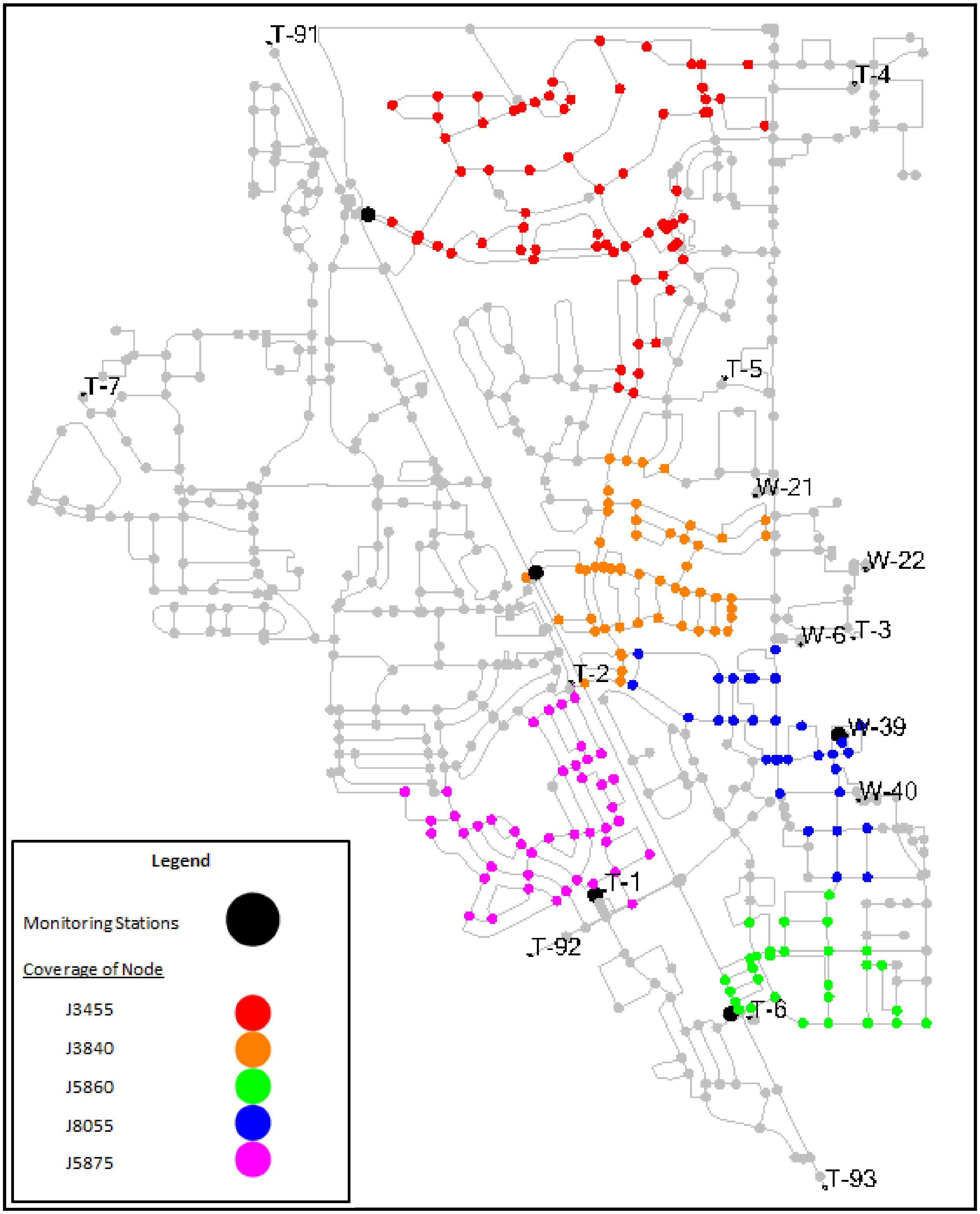

Figure 55: Monitoring Station 1-5 with Corresponding Coverages for Demand Pattern 5.0 (Unsteady State)

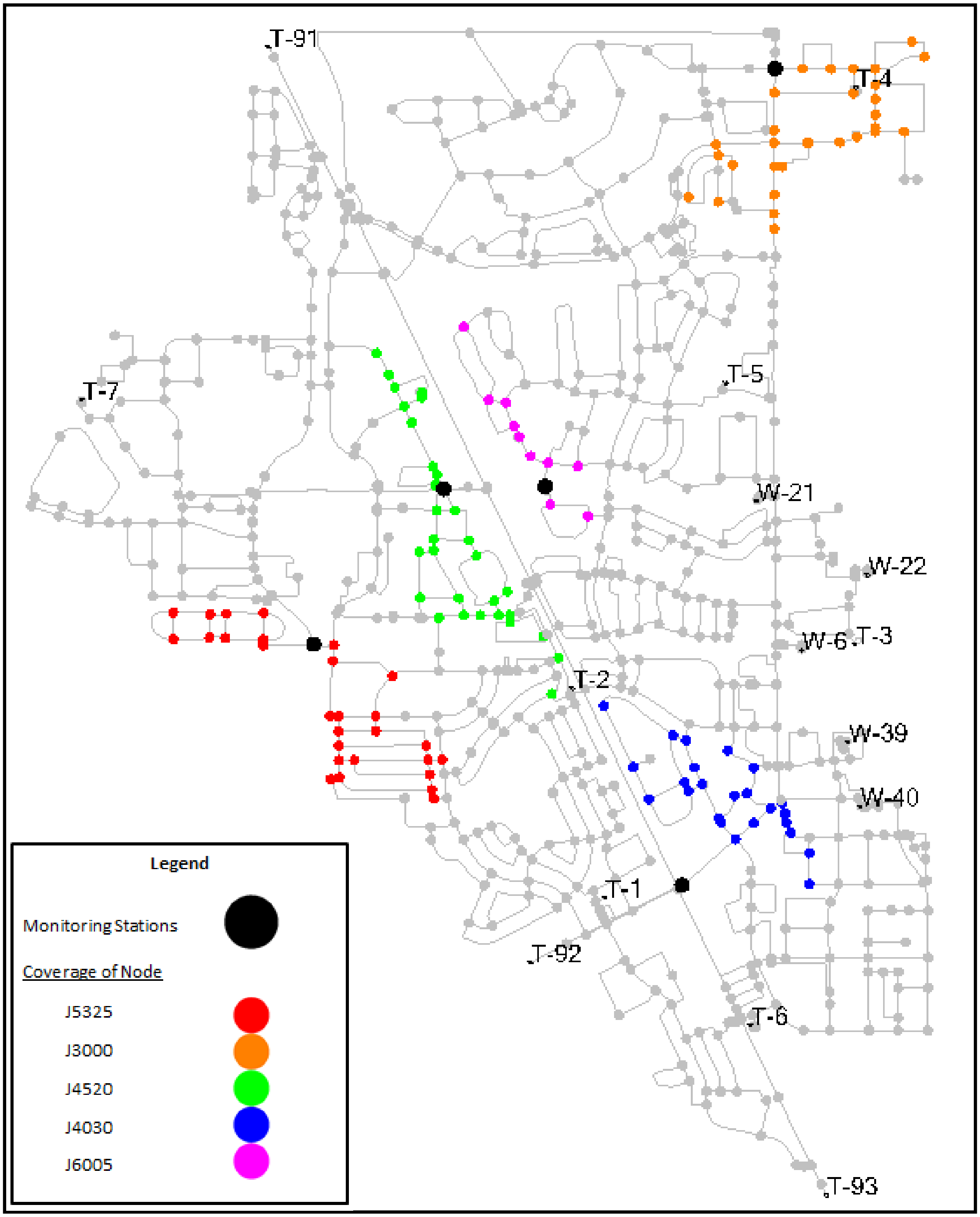

Figure 56: Monitoring Station 6-10 with Corresponding Coverages for Demand Pattern 5.0 (Unsteady State)

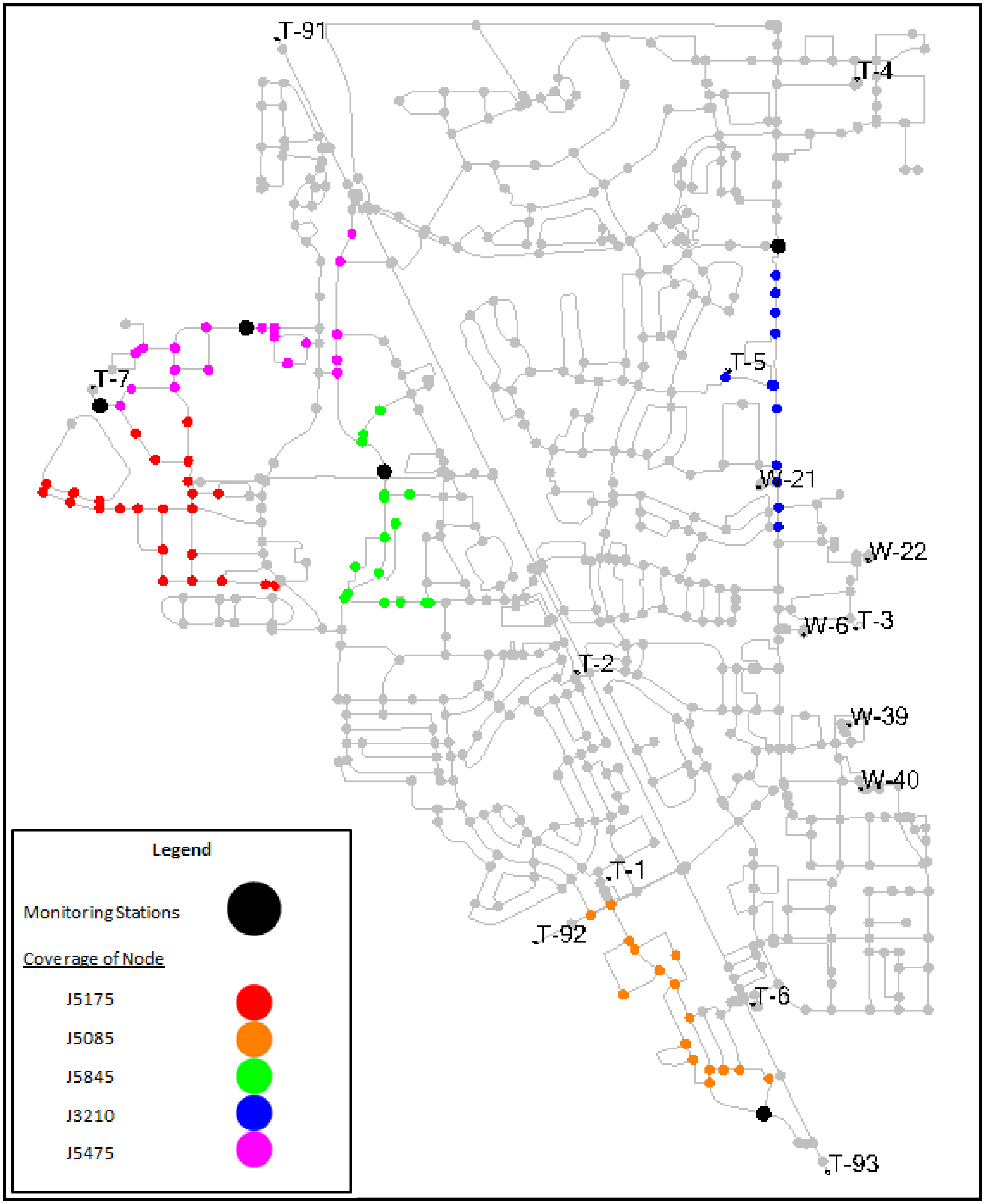

Figure 57: Monitoring Station 11-15 with Corresponding Coverages for Demand Pattern 5.0 (Unsteady State)

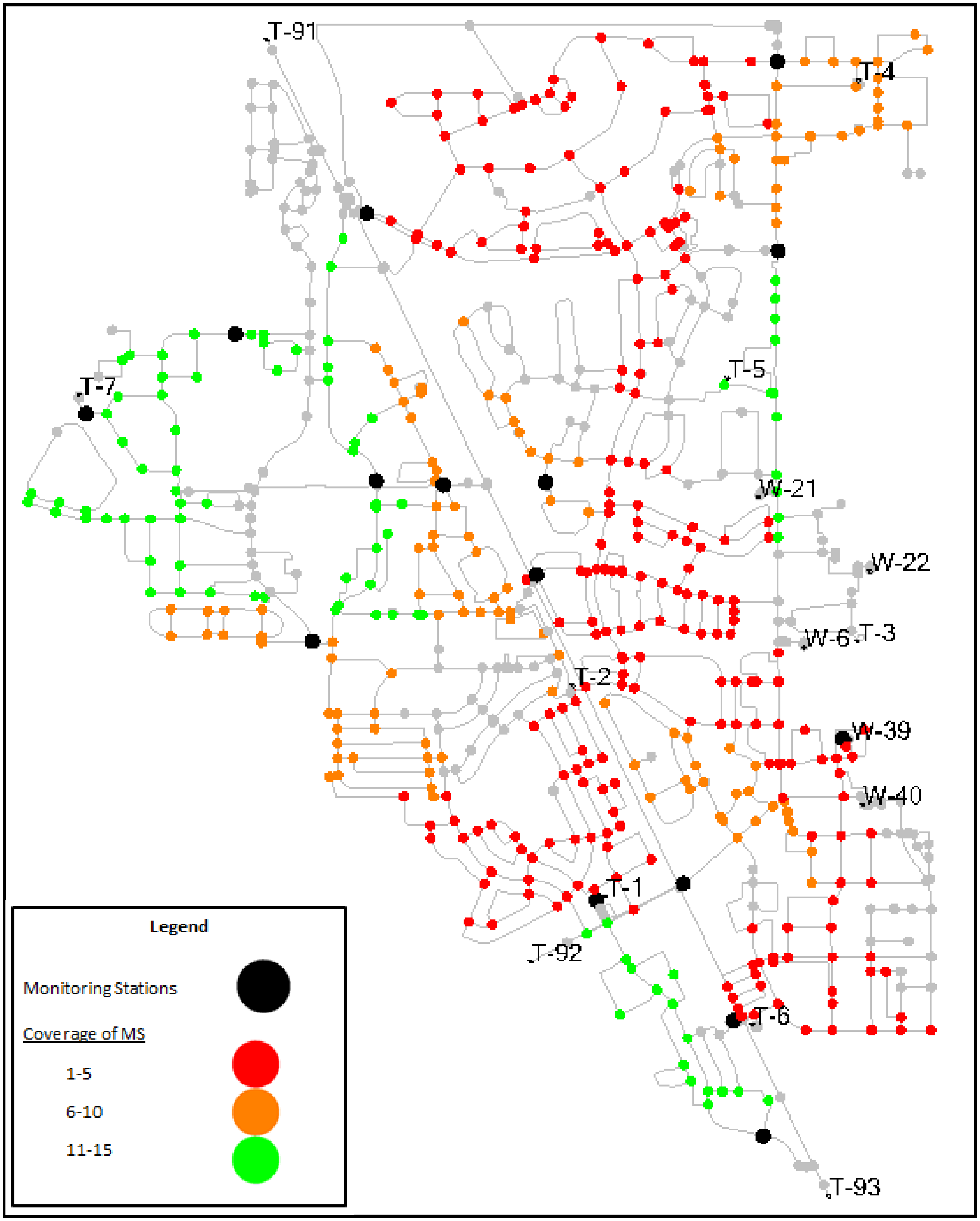

Figure 58: Top 15 Monitoring Stations with Corresponding Coverages for Demand Pattern 5.0 (Unsteady State)

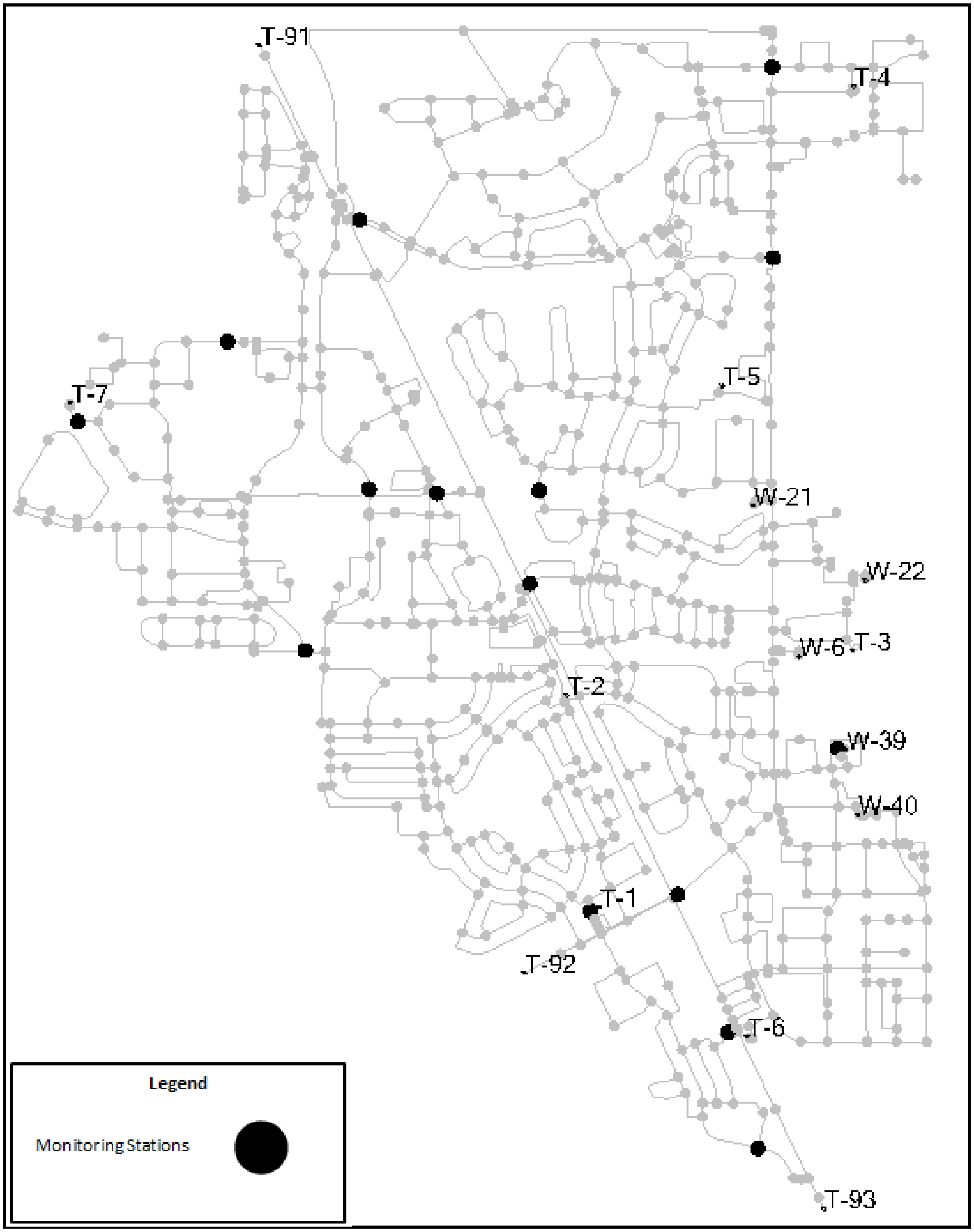

Figure 59: Top 15 Monitoring Stations for Demand Pattern 5.0 (Unsteady State)

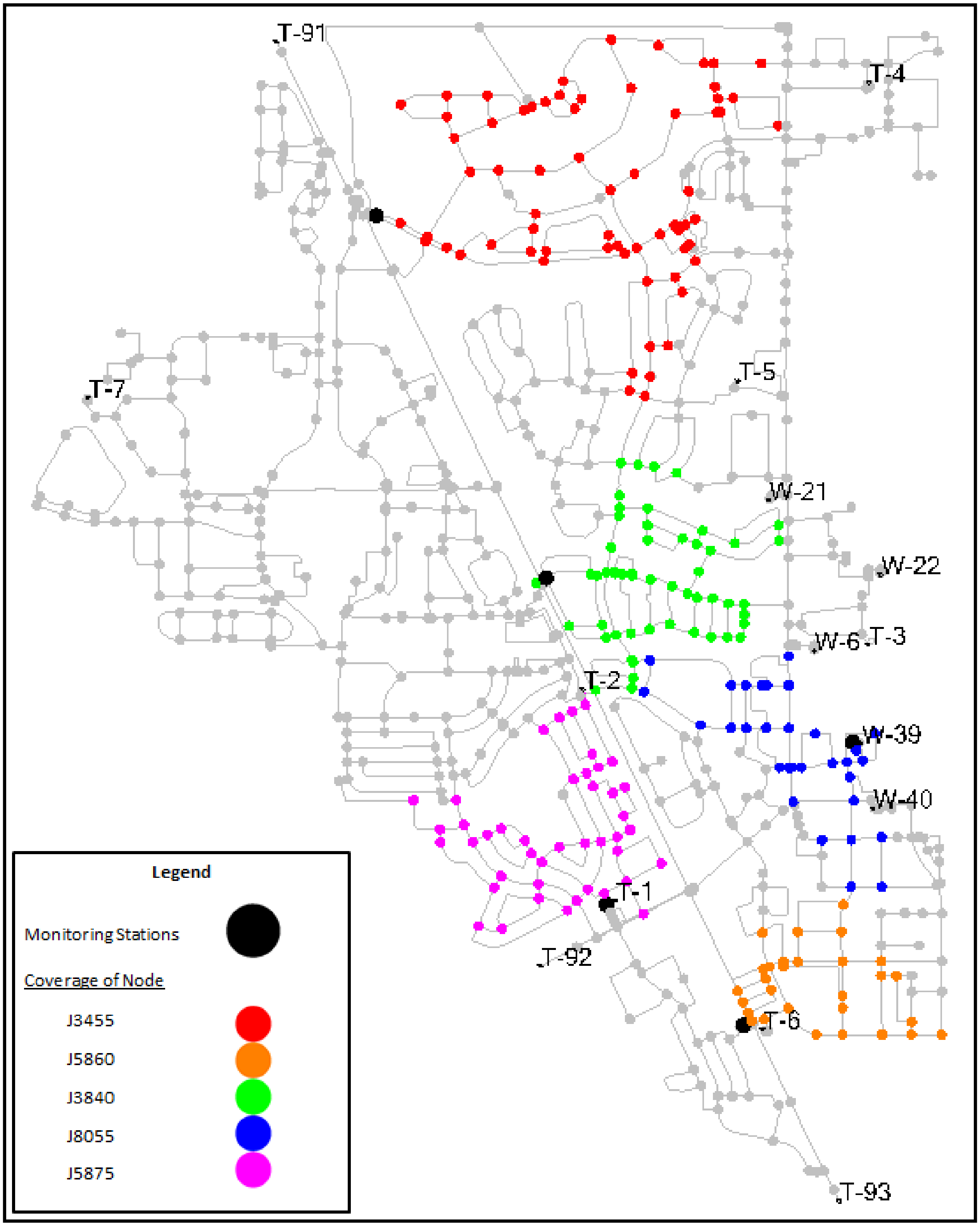

Figure 60: Monitoring Station 1-5 with Corresponding Coverages for Demand Pattern 6.0 (Unsteady State)

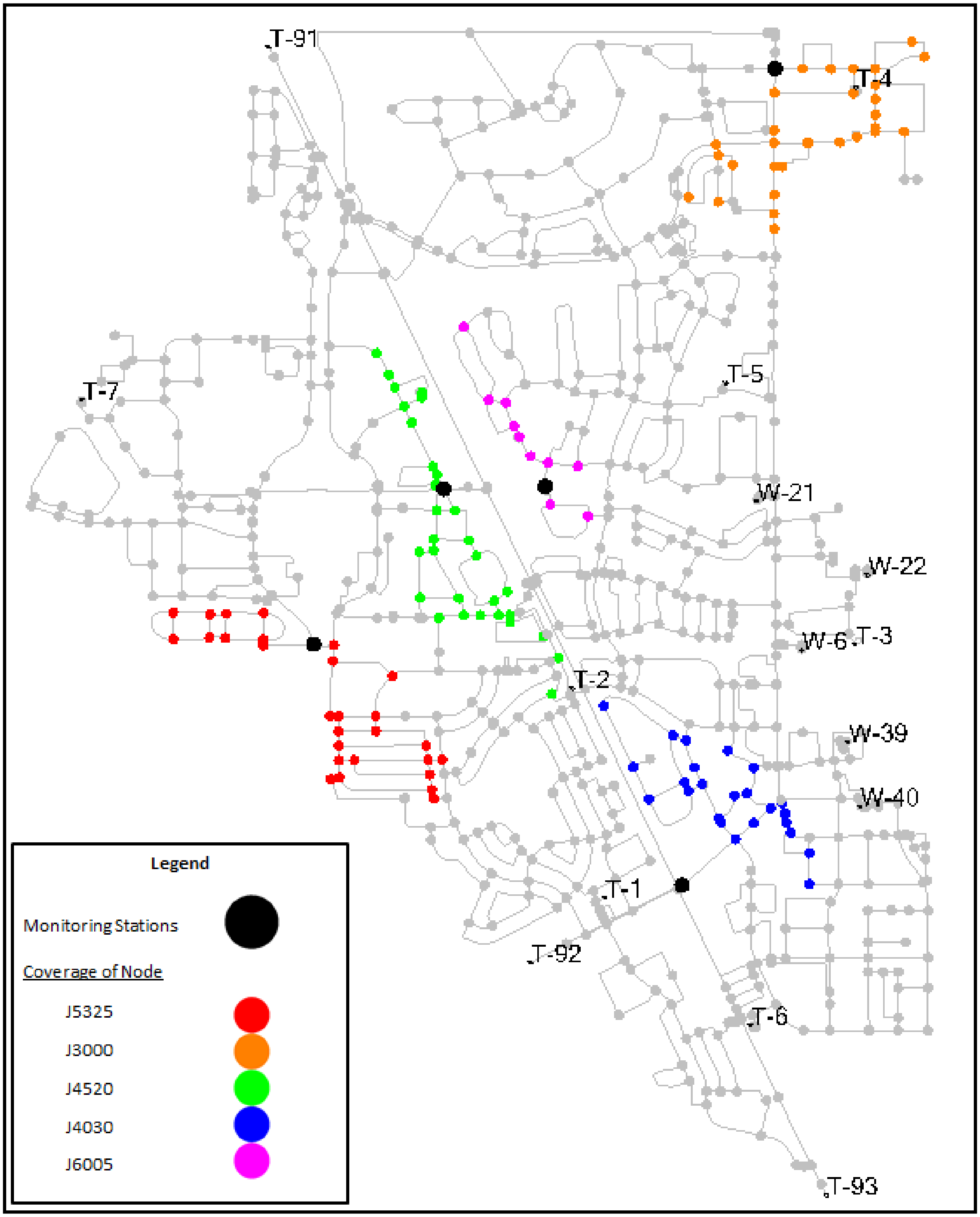

Figure 61: Monitoring Station 6-10 with Corresponding Coverages for Demand Pattern 6.0 (Unsteady State)

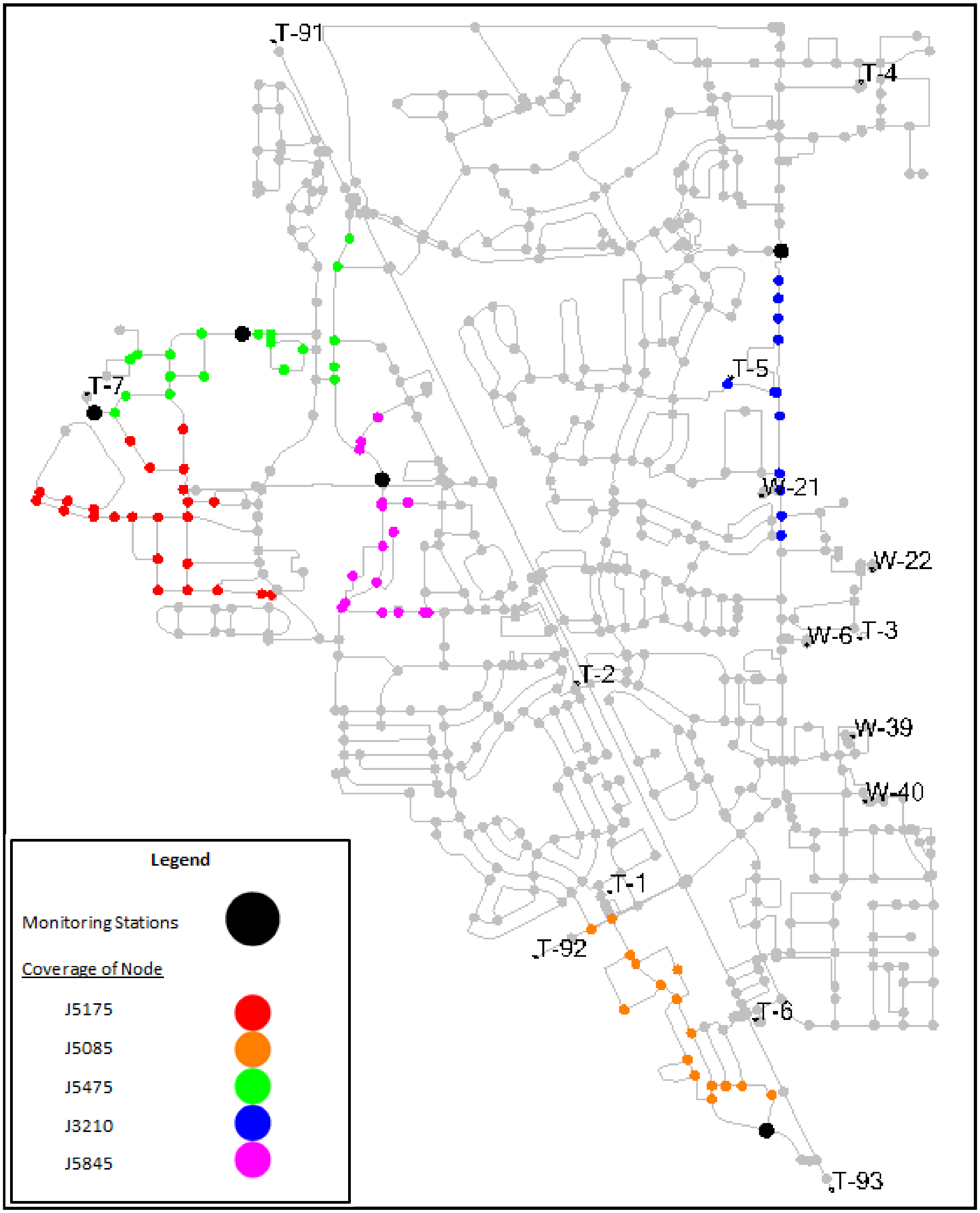

Figure 62: Monitoring Station 11-15 with Corresponding Coverages for Demand Pattern 6.0 (Unsteady State)

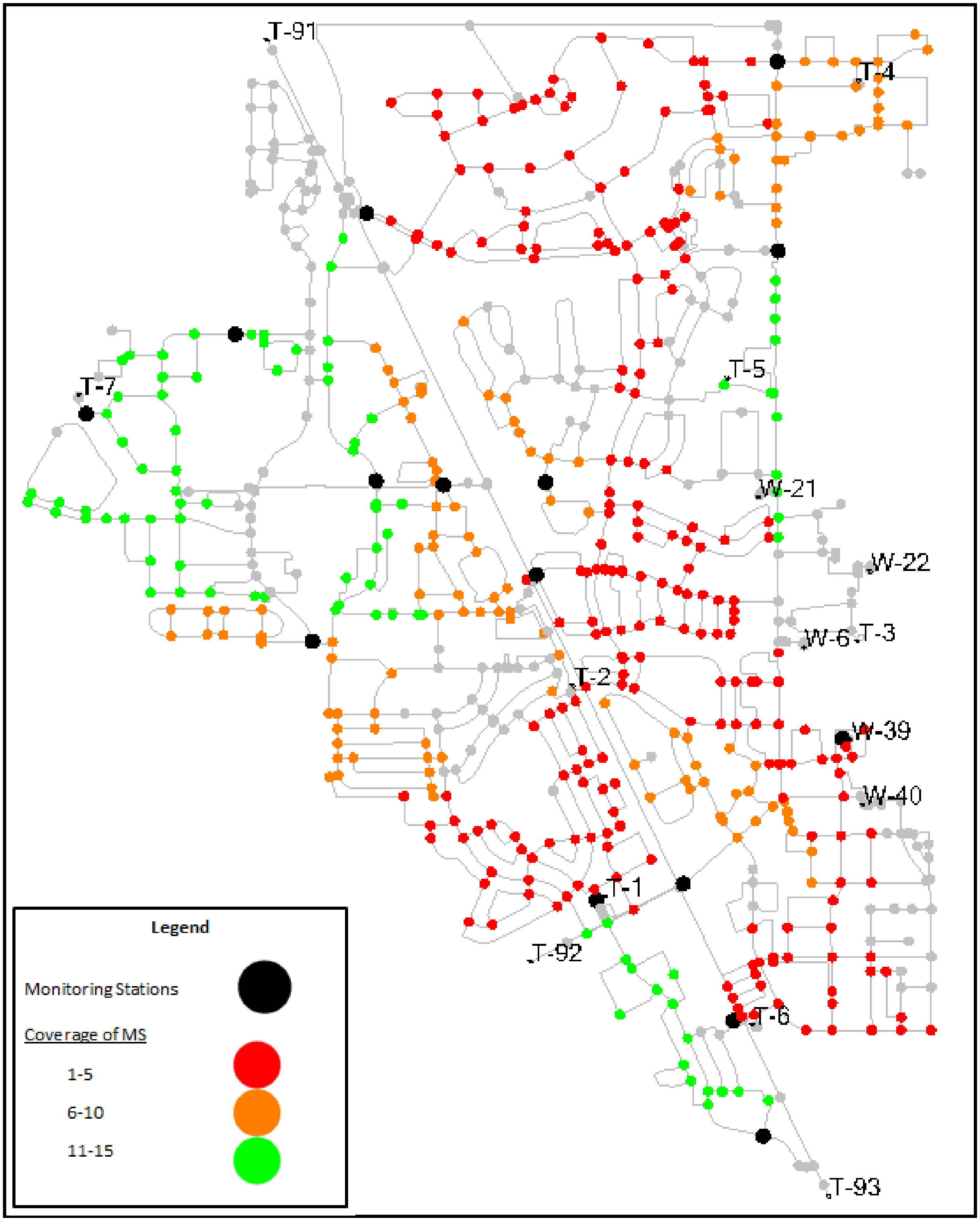

Figure 63: Top 15 Monitoring Stations with Corresponding Coverages for Demand Pattern 6.0 (Unsteady State)

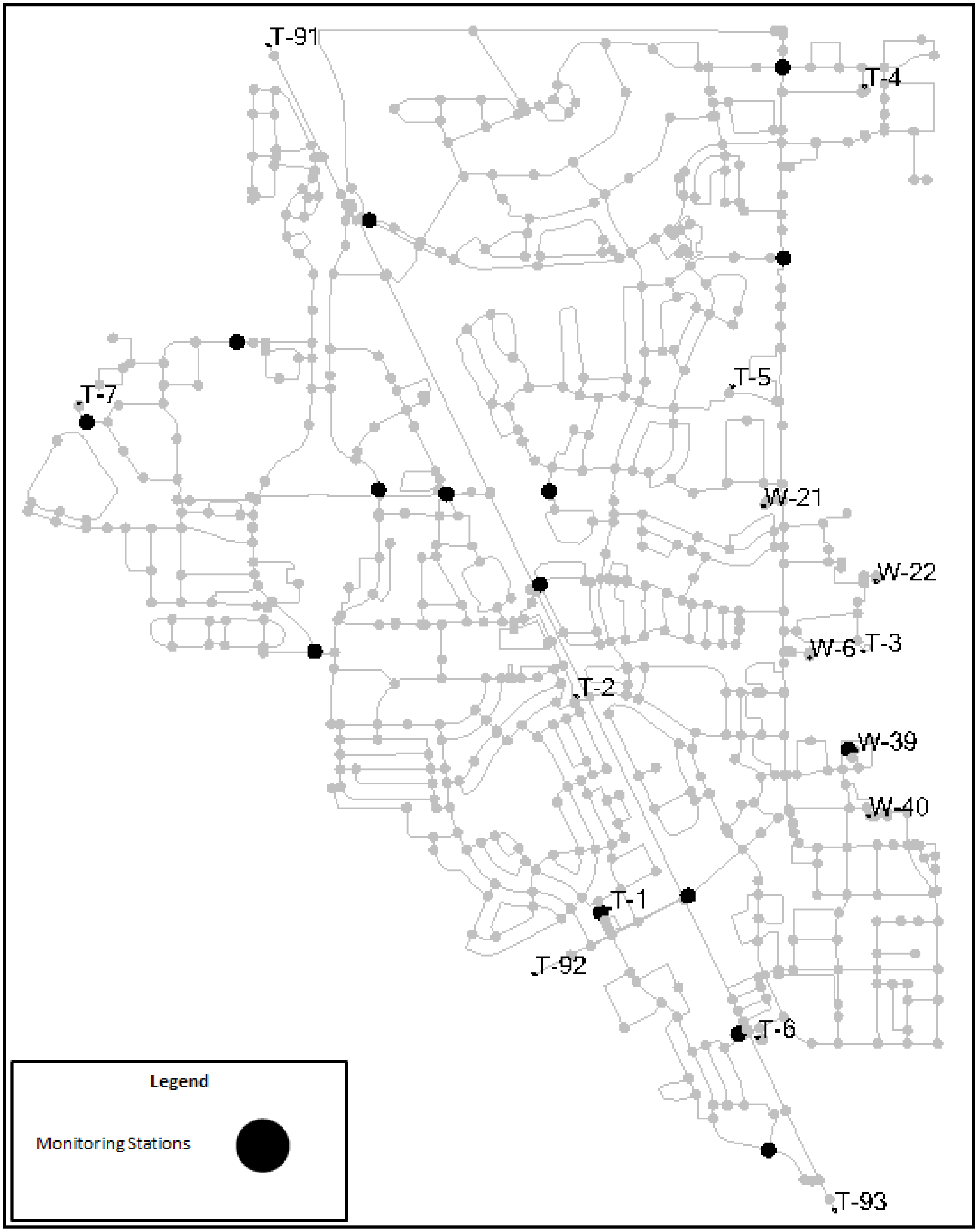

Figure 64: Top 15 Monitoring Stations for Demand Pattern 6.0 (Unsteady State)

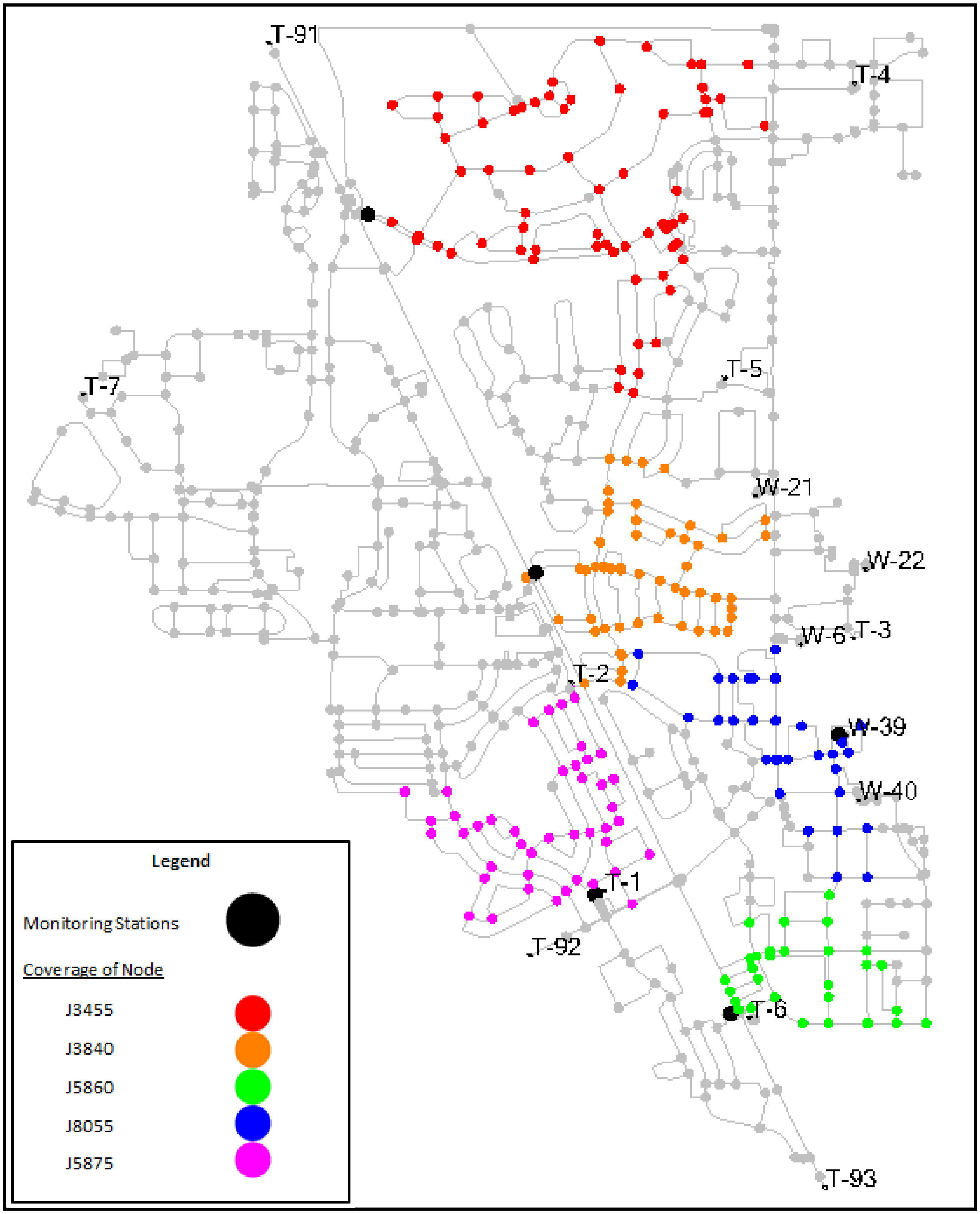

Figure 65: Monitoring Station 1-5 with Corresponding Coverages for Demand Pattern 7.0 (Unsteady State)

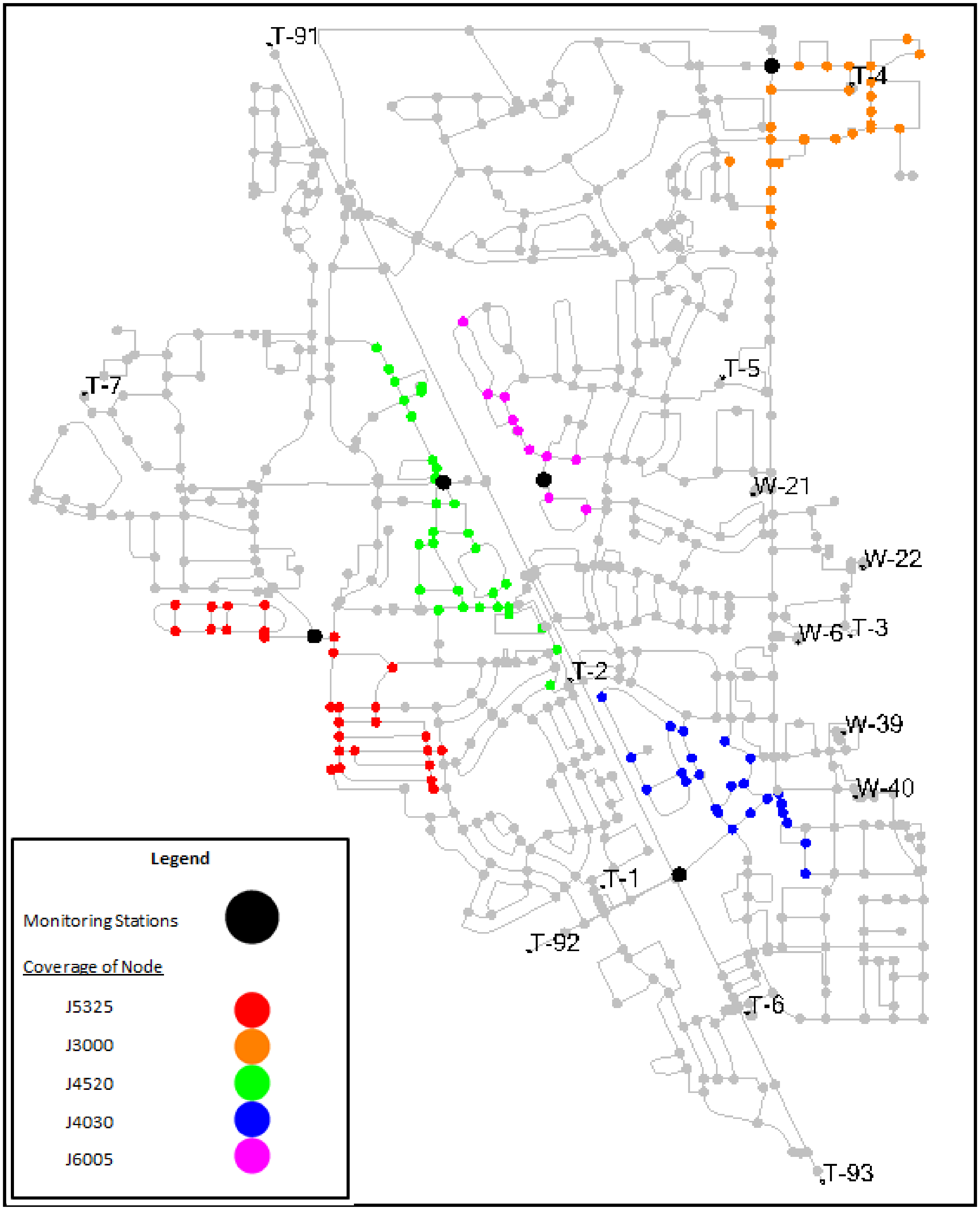

Figure 66: Monitoring Station 6-10 with Corresponding Coverages for Demand Pattern 7.0 (Unsteady State)

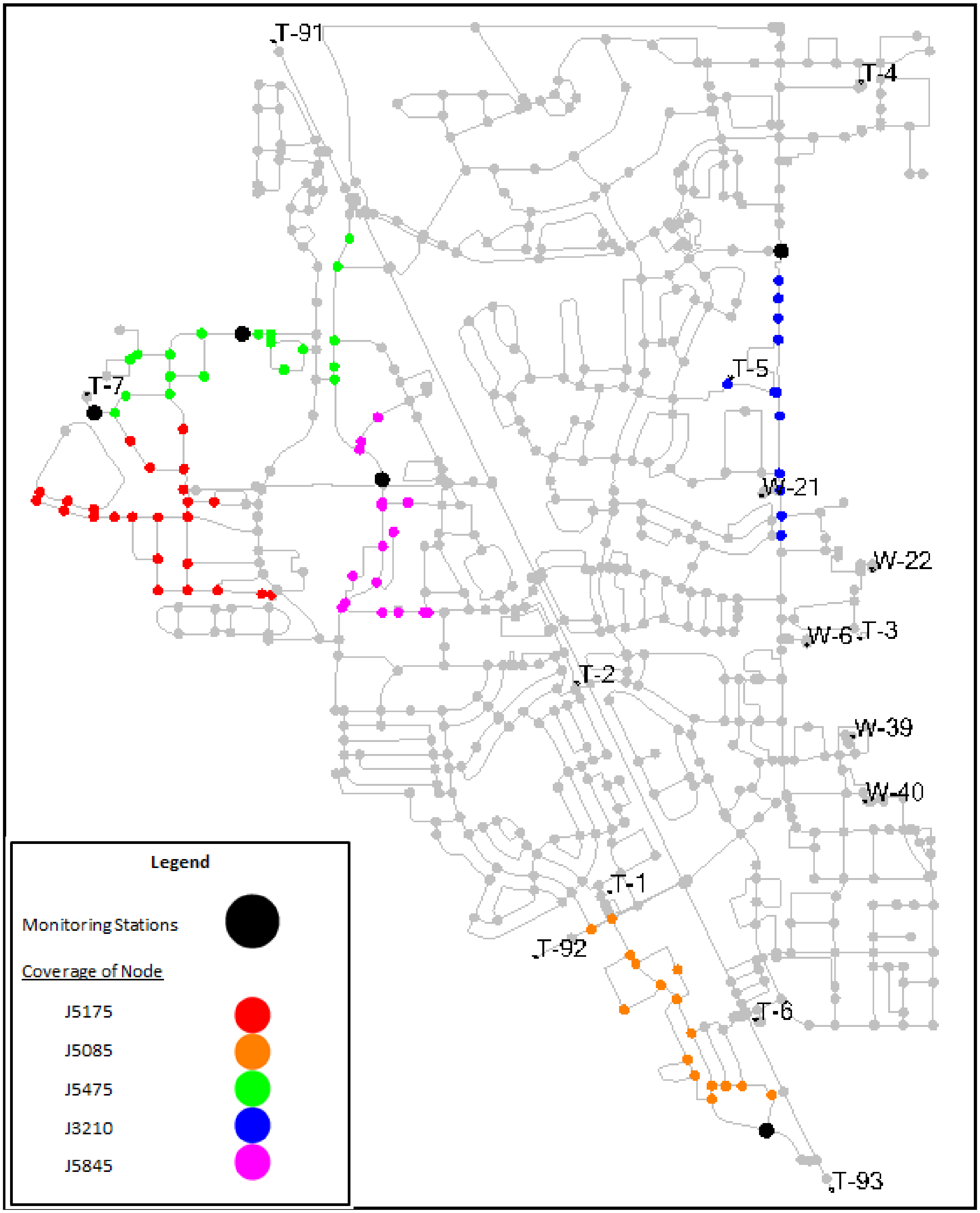

Figure 67: Monitoring Station 11-15 with Corresponding Coverages for Demand Pattern 7.0 (Unsteady State)

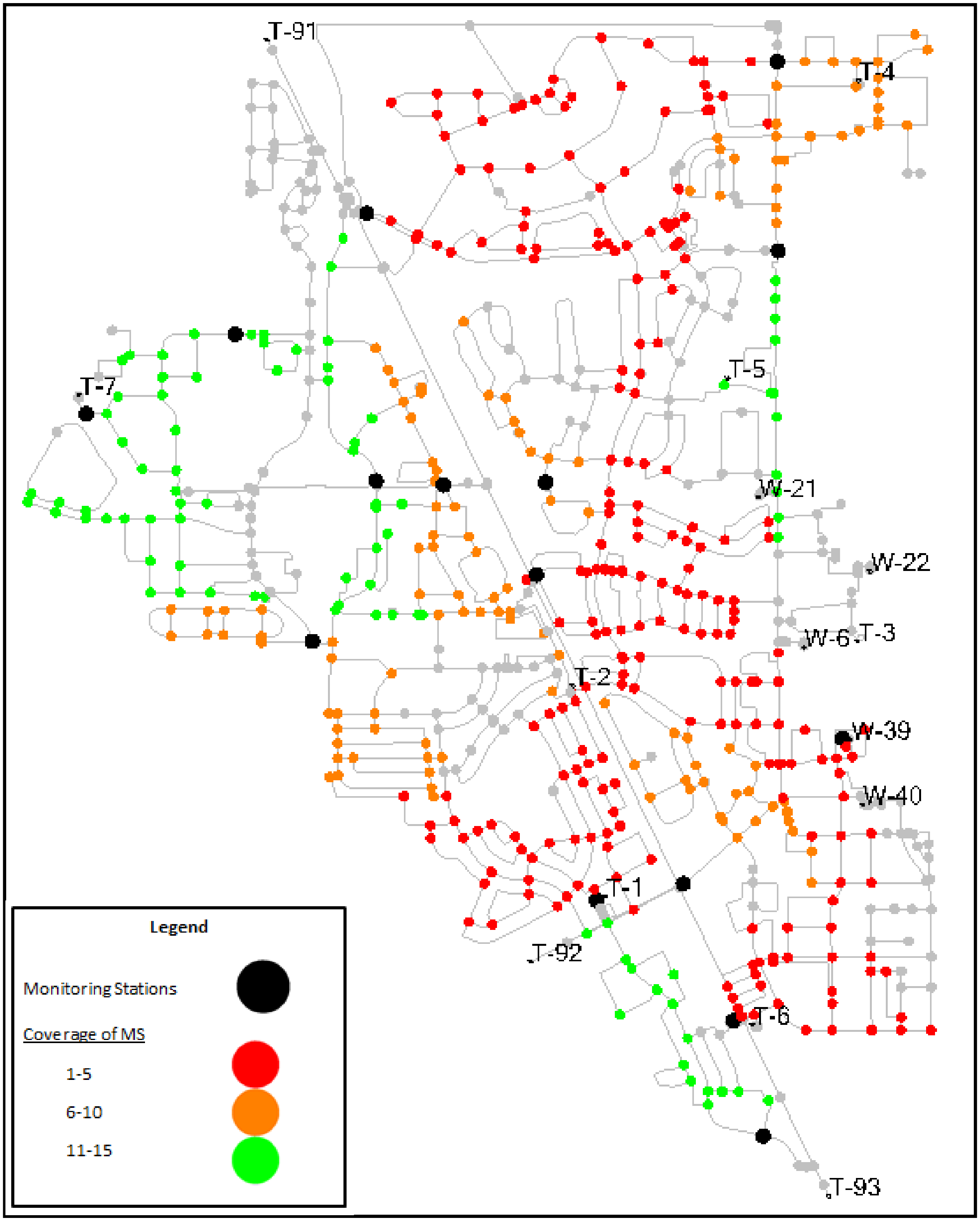

Figure 68: Top 15 Monitoring Stations with Corresponding Coverages for Demand Pattern 7.0 (Unsteady State)

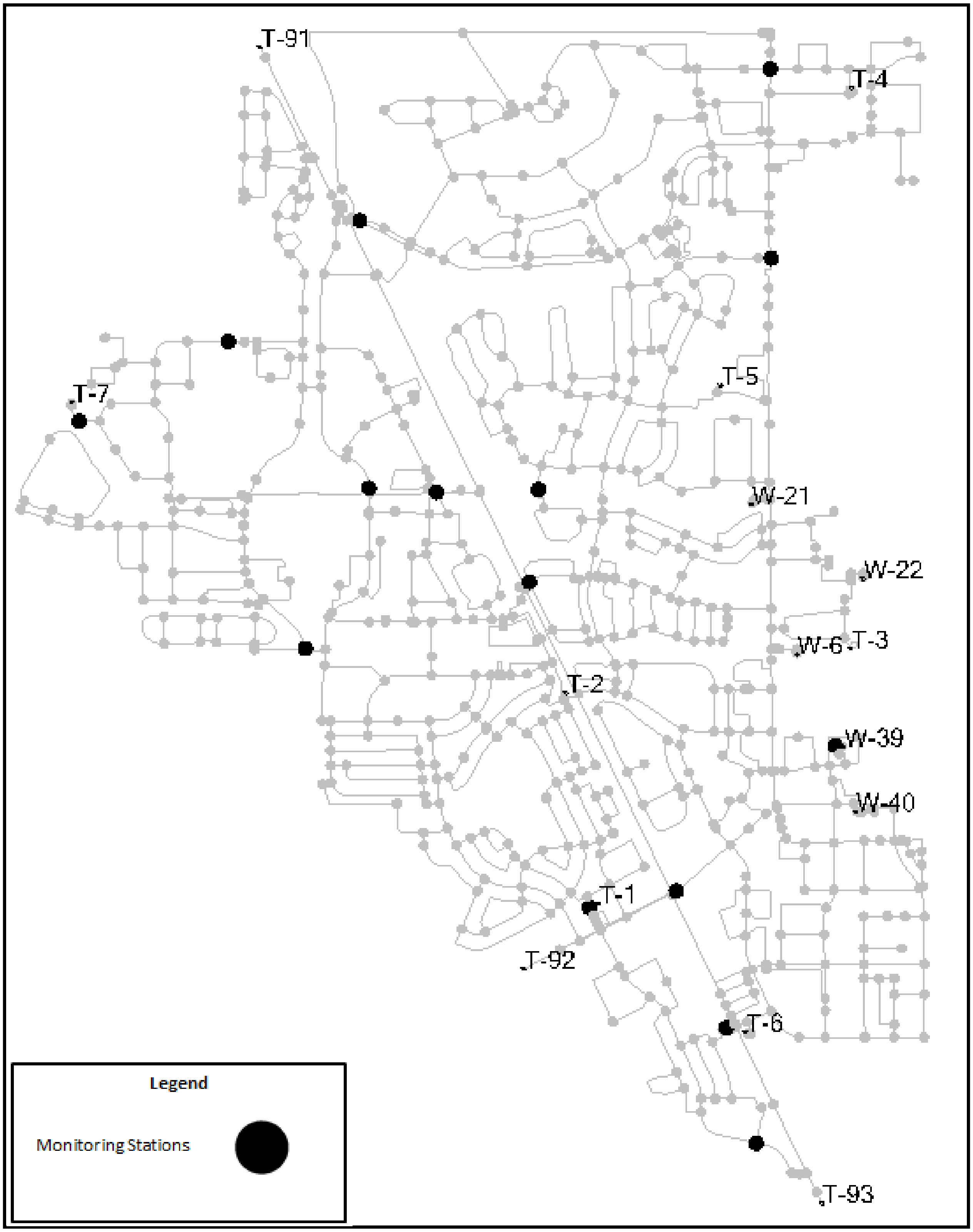

Figure 69: Top 15 Monitoring Stations for Demand Pattern 7.0 (Unsteady State)

APPENDIX B

The contents of Appendix B contain a list compiled by the Environmental Protection Agency of contaminants, including microorganisms, disinfection byproducts, disinfectants, inorganic chemicals, organic chemicals, and radionuclides.

Microorganisms				
Contaminant	**MCLG[1] (MG/L)[2]**	**MCL or TT[1] (MG/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Cryptosporidium	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Giardia lamblia	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste
Heterotrophic plate count (HPC)	n/a	TT[3]	HPC has no health effects; it is an analytic method used to measure the variety of bacteria that are common in water. The lower the concentration of bacteria in drinking water, the better maintained the water system is.	HPC measures a range of bacteria that are naturally present in the environment
Legionella	zero	TT[3]	Legionnaire's Disease, a type of pneumonia	Found naturally in water; multiplies in heating systems
Total Coliforms (including fecal coliform and *E. Coli*)	zero	5.0%[4]	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present[5]	Coliforms are naturally present in the environment; as well as feces; fecal coliforms and *E. coli* only come from human and animal fecal waste.
Turbidity	n/a	TT[3]	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (such as whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff
Viruses (enteric)	zero	TT[3]	Gastrointestinal illness (such as diarrhea, vomiting, and cramps)	Human and animal fecal waste

Disinfection Byproducts				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Bromate	zero	0.010	Increased risk of cancer	Byproduct of drinking water disinfection
Chlorite	0.8	1.0	Anemia; infants and young children: nervous system effects	Byproduct of drinking water disinfection
Haloacetic acids (HAA5)	n/a[6]	0.060[7]	Increased risk of cancer	Byproduct of drinking water disinfection
Total Trihalomethanes (TTHMs)	--> n/a[6]	--> 0.080[7]	Liver, kidney or central nervous system problems; increased risk of cancer	Byproduct of drinking water disinfection

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Disinfectants				
Contaminant	**MCLG[1] (mg/L)[2]**	**MCL or TT[1] (mg/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Chloramines (as Cl_2)	MRDLG=4[1]	MRDL=4.0[1]	Eye/nose irritation; stomach discomfort, anemia	Water additive used to control microbes
Chlorine (as Cl_2)	MRDLG=4[1]	MRDL=4.0[1]	Eye/nose irritation; stomach discomfort	Water additive used to control microbes
Chlorine dioxide (as ClO_2)	MRDLG=0.8[1]	MRDL=0.8[1]	Anemia; infants and young children: nervous system effects	Water additive used to control microbes

Inorganic Chemicals				
Contaminant	**MCLG[1] (MG/L)[2]**	**MCL or TT[1] (MG/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Antimony	0.006	0.006	Increase in blood cholesterol; decrease in blood sugar	Discharge from petroleum refineries; fire retardants; ceramics; electronics; solder
Arsenic	0	0.010 as of 01/23/06	Skin damage or problems with circulatory systems, and may have increased risk of getting cancer	Erosion of natural deposits; runoff from orchards, runoff from glass and electronicsproduction wastes
Asbestos (fiber > 10 micrometers)	7 million fibers per liter (MFL)	7 MFL	Increased risk of developing benign intestinal polyps	Decay of asbestos cement in water mains; erosion of natural deposits
Barium	2	2	Increase in blood pressure	Discharge of drilling wastes; discharge from metal refineries; erosion of natural deposits
Beryllium	0.004	0.004	Intestinal lesions	Discharge from metal refineries and coal-burning factories; discharge from electrical, aerospace, and defense industries
Cadmium	0.005	0.005	Kidney damage	Corrosion of galvanized pipes; erosion of natural deposits; discharge from metal refineries; runoff from waste batteries and paints

Chromium (total)	0.1	0.1	Allergic dermatitis	Discharge from steel and pulp mills; erosion of natural deposits
Copper	1.3	TT[7]; Action Level=1.3	Short term exposure: Gastrointestinal distress Long term exposure: Liver or kidney damage People with Wilson's Disease should consult their personal doctor if the amount of copper in their water exceeds the action level	Corrosion of household plumbing systems; erosion of natural deposits
Cyanide (as free cyanide)	0.2	0.2	Nerve damage or thyroid problems	Discharge from steel/metal factories; discharge from plastic and fertilizer factories
Fluoride	4.0	4.0	Bone disease (pain and tenderness of the bones); Children may get mottled teeth	Water additive which promotes strong teeth; erosion of natural deposits; discharge from fertilizer and aluminum factories
Lead	zero	TT[7]; Action Level=0.015	Infants and children: Delays in physical or mental development; children could show slight deficits in attention span and learning abilities Adults: Kidney problems; high blood pressure	Corrosion of household plumbing systems; erosion of natural deposits
Mercury (inorganic)	0.002	0.002	Kidney damage	Erosion of natural deposits; discharge from refineries and factories; runoff from landfills and croplands
Nitrate (measured as Nitrogen)	10	10	Infants below the age of six months who drink water containing nitrate in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaking from septic tanks, sewage; erosion of natural deposits

Nitrite (measured as Nitrogen)	1	1	Infants below the age of six months who drink water containing nitrite in excess of the MCL could become seriously ill and, if untreated, may die. Symptoms include shortness of breath and blue-baby syndrome.	Runoff from fertilizer use; leaking from septic tanks, sewage; erosion of natural deposits
Selenium	0.05	0.05	Hair or fingernail loss; numbness in fingers or toes; circulatory problems	Discharge from petroleum refineries; erosion of natural deposits; discharge from mines
Thallium	0.0005	0.002	Hair loss; changes in blood; kidney, intestine, or liver problems	Leaching from ore-processing sites; discharge from electronics, glass, and drug factories

Organic Chemicals				
Contaminant	**MCLG[1] (MG/L)[2]**	**MCL or TT[1] (MG/L)[2]**	**Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)**	**Sources of Contaminant in Drinking Water**
Acrylamide	zero	TT[8]	Nervous system or blood problems; increased risk of cancer	Added to water during sewage/wastewater treatment
Alachlor	zero	0.002	Eye, liver, kidney or spleen problems; anemia; increased risk of cancer	Runoff from herbicide used on row crops
Atrazine	0.003	0.003	Cardiovascular system or reproductive problems	Runoff from herbicide used on row crops
Benzene	zero	0.005	Anemia; decrease in blood platelets; increased risk of cancer	Discharge from factories; leaching from gas storage tanks and landfills
Benzo(a)pyrene (PAHs)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Leaching from linings of water storage tanks and distribution lines
Carbofuran	0.04	0.04	Problems with blood, nervous system, or reproductive system	Leaching of soil fumigant used on rice and alfalfa
Carbon tetrachloride	zero	0.005	Liver problems; increased risk of cancer	Discharge from chemical plants and other industrial activities
Chlordane	zero	0.002	Liver or nervous system problems; increased risk of cancer	Residue of banned termiticide
Chlorobenzene	0.1	0.1	Liver or kidney problems	Discharge from chemical and agricultural chemical factories
2,4-D	0.07	0.07	Kidney, liver, or adrenal gland problems	Runoff from herbicide used on row crops
Dalapon	0.2	0.2	Minor kidney changes	Runoff from herbicide used on rights of way

1,2-Dibromo-3-chloropropane (DBCP)	zero	0.0002	Reproductive difficulties; increased risk of cancer	Runoff/leaching from soil fumigant used on soybeans, cotton, pineapples, and orchards
o-Dichlorobenzene	0.6	0.6	Liver, kidney, or circulatory system problems	Discharge from industrial chemical factories
p-Dichlorobenzene	0.075	0.075	Anemia; liver, kidney or spleen damage; changes in blood	Discharge from industrial chemical factories
1,2-Dichloroethane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
1,1-Dichloroethylene	0.007	0.007	Liver problems	Discharge from industrial chemical factories
cis-1,2-Dichloroethylene	0.07	0.07	Liver problems	Discharge from industrial chemical factories
trans-1,2-Dichloroethylene	0.1	0.1	Liver problems	Discharge from industrial chemical factories
Dichloromethane	zero	0.005	Liver problems; increased risk of cancer	Discharge from drug and chemical factories
1,2-Dichloropropane	zero	0.005	Increased risk of cancer	Discharge from industrial chemical factories
Di(2-ethylhexyl) adipate	0.4	0.4	Weight loss, liver problems, or possible reproductive difficulties.	Discharge from chemical factories
Di(2-ethylhexyl) phthalate	zero	0.006	Reproductive difficulties; liver problems; increased risk of cancer	Discharge from rubber and chemical factories
Dinoseb	0.007	0.007	Reproductive difficulties	Runoff from herbicide used on soybeans and vegetables

Dioxin (2,3,7,8-TCDD)	zero	0.00000003	Reproductive difficulties; increased risk of cancer	Emissions from waste incineration and other combustion; discharge from chemical factories
Diquat	0.02	0.02	Cataracts	Runoff from herbicide use
Endothall	0.1	0.1	Stomach and intestinal problems	Runoff from herbicide use
Endrin	0.002	0.002	Liver problems	Residue of banned insecticide
Epichlorohydrin	zero	TT[8]	Increased cancer risk, and over a long period of time, stomach problems	Discharge from industrial chemical factories; an impurity of some water treatment chemicals
Ethylbenzene	0.7	0.7	Liver or kidneys problems	Discharge from petroleum refineries
Ethylene dibromide	zero	0.00005	Problems with liver, stomach, reproductive system, or kidneys; increased risk of cancer	Discharge from petroleum refineries
Glyphosate	0.7	0.7	Kidney problems; reproductive difficulties	Runoff from herbicide use
Heptachlor	zero	0.0004	Liver damage; increased risk of cancer	Residue of banned termiticide
Heptachlor epoxide	zero	0.0002	Liver damage; increased risk of cancer	Breakdown of heptachlor
Hexachlorobenzene	zero	0.001	Liver or kidney problems; reproductive difficulties; increased risk of cancer	Discharge from metal refineries and agricultural chemical factories
Hexachlorocyclopentadiene	0.05	0.05	Kidney or stomach problems	Discharge from chemical factories
Lindane	0.0002	0.0002	Liver or kidney problems	Runoff/leaching from insecticide used on cattle, lumber, gardens

Methoxychlor	0.04	0.04	Reproductive difficulties	Runoff/leaching from insecticide used on fruits, vegetables, alfalfa, livestock
Oxamyl (Vydate)	0.2	0.2	Slight nervous system effects	Runoff/leaching from insecticide used on apples, potatoes, and tomatoes
Polychlorinated biphenyls (PCBs)	zero	0.0005	Skin changes; thymus gland problems; immune deficiencies; reproductive or nervous system difficulties; increased risk of cancer	Runoff from landfills; discharge of waste chemicals
Pentachlorophenol	zero	0.001	Liver or kidney problems; increased cancer risk	Discharge from wood preserving factories
Picloram	0.5	0.5	Liver problems	Herbicide runoff
Simazine	0.004	0.004	Problems with blood	Herbicide runoff
Styrene	0.1	0.1	Liver, kidney, or circulatory system problems	Discharge from rubber and plastic factories; leaching from landfills
Tetrachloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from factories and dry cleaners
Toluene	1	1	Nervous system, kidney, or liver problems	Discharge from petroleum factories
Toxaphene	zero	0.003	Kidney, liver, or thyroid problems; increased risk of cancer	Runoff/leaching from insecticide used on cotton and cattle
2,4,5-TP (**Silvex**)	0.05	0.05	Liver problems	Residue of banned herbicide
1,2,4-Trichlorobenzene	0.07	0.07	Changes in adrenal glands	Discharge from textile finishing factories

1,1,1-Trichloroethane	0.20	0.2	Liver, nervous system, or circulatory problems	Discharge from metal degreasing sites and other factories
1,1,2-Trichloroethane	0.003	0.005	Liver, kidney, or immune system problems	Discharge from industrial chemical factories
Trichloroethylene	zero	0.005	Liver problems; increased risk of cancer	Discharge from metal degreasing sites and other factories
Vinyl chloride	zero	0.002	Increased risk of cancer	Leaching from PVC pipes; discharge from plastic factories
Xylenes (total)	10	10	Nervous system damage	Discharge from petroleum factories; discharge from chemical factories

Radionuclides

Contaminant	MCLG[1] (MG/L)[2]	MCL or TT[1] (MG/L)[2]	Potential Health Effects from Long-Term Exposure Above the MCL (unless specified as short-term)	Sources of Contaminant in Drinking Water
Alpha particles	none[7] ---------- zero	15 picocuries per Liter (PCI/L)	Increased risk of cancer	Erosion of natural deposits of certain minerals that are radioactive and may emit a form of radiation known as alpha radiation
Beta particles and photon emitters	none[7] ---------- zero	4 millirems per year	Increased risk of cancer	Decay of natural and man-made deposits of certain minerals that are radioactive and may emit forms of radiation known as photons and beta radiation
Radium 226 and Radium 228 (combined)	none[7] ---------- zero	5 PCI/L	Increased risk of cancer	Erosion of natural deposits
Uranium	zero	30 UG/L as of 12/08/03	Increased risk of cancer, kidney toxicity	Erosion of natural deposits

Notes

[1] **Definitions**:

- Maximum Contaminant Level Goal (MCLG) – The level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health goals.
- Maximum Contaminant Level (MCL) – The highest level of a contaminant that is allowed in drinking water. MCLs are set as close to MCLGs as feasible using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards.
- Maximum Residual Disinfectant Level Goal (MRDLG) – The level of a drinking water disinfectant below which there is no known or expected risk to health. MRDLGs do not reflect the benefits of the use of disinfectants to control microbial contaminants.)
- Treatment Technique (TT) – A required process intended to reduce the level of a contaminant in drinking water.
- Maximum Residual Disinfectant Level (MRDL) – The highest level of a disinfectant allowed in drinking water. There is convincing evidence that addition of a disinfectant is necessary for control of microbial contaminants.
- [2] Units are in milligrams per liter (MG/L) unless otherwise noted. Milligrams per liter are equivalent to parts per million (PPM).
  [3] EPA's surface water treatment rules require systems using surface water or ground water under the direct influence of surface water to

  (1) disinfect their water, and
  (2) filter their water or
  meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:
  - *Cryptosporidium*: Unfiltered systems are required to include *Cryptosporidium* in their existing watershed control provisions
  - *Giardia lamblia*: 99.9% removal/inactivation.
  - Viruses: 99.99% removal/inactivation.
  - *Legionella*: No limit, but EPA believes that if *Giardia* and viruses are removed/inactivated, according to the treatment techniques in the Surface Water Treatment Rule, *Legionella* will also be controlled.
  - Turbidity: For systems that use conventional or direct filtration, at no time can turbidity (cloudiness of water) go higher than 1 Nephelometric Turbidity Unit (NTU), and samples for turbidity must be less than or equal to 0.3 NTUs in at least 95 percent of the samples in any month. Systems that use filtration other than the conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs.
  - Heterotrophic Plate Count (HPC): No more than 500 bacterial colonies per milliliter.
  - Long Term 1 Enhanced Surface Water Treatment: Surface water systems or groundwater under the direct influence (GWUDI) systems serving fewer than 10,000 people must comply with the applicable Long Term 1 Enhanced Surface Water Treatment Rule provisions (such as turbidity standards, individual filter monitoring, *Cryptosporidium* removal requirements, updated watershed control requirements for unfiltered systems).
  - Long Term 2 Enhanced Surface Water Treatment Rule: This rule applies to all surface water systems or ground water systems under the direct influence of surface water. The rule targets additional *Cryptosporidium* treatment requirements for higher risk systems and includes provisions to reduce risks from uncovered finished water storage facilities and to ensure that the systems maintain microbial protection as they take steps to reduce the formation of disinfection byproducts.
  - Filter Backwash Recycling: The Filter Backwash Recycling Rule requires systems that recycle to return specific recycle flows through all processes of the system's existing conventional or direct filtration system or at an alternate location approved by the state.

[4] No more than 5.0% samples total coliform-positive (TC-POSITIVE) in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-POSITIVE samples, and one is also positive for *E.coli* fecal coliforms, system has an acute MCL violation.

[5] Fecal coliform and *E. coli* are bacteria whose presence indicates that the water may be contaminated with human or animal wastes. Disease-causing microbes (pathogens) in these wastes can cause diarrhea, cramps, nausea, headaches, or other symptoms. These pathogens may pose a special health risk for infants, young children, and people with severely compromised immune systems.

[6] Although there is no collective MCLG for this contaminant group, there are individual MCLGs for some of the individual contaminants:

- Trihalomethanes: bromodichloromethane (zero); bromoform (zero); dibromochloromethane (0.06 MG/L): chloroform (0.07 MG/L.
- Haloacetic acids: dichloroacetic acid (zero); trichloroacetic acid (0.02 MG/L); monochloroacetic acid (0.07 MG/L). Bromoacetic acid and dibromoacetic acid are regulated with this group but have no MCLGs.

[7] Lead and copper are regulated by a treatment technique that requires systems to control the corrosiveness of their water. If more than 10% of tap water samples exceed the action level, water systems must take additional steps. For copper, the action level is 1.3 MG/L, and for lead is 0.015 MG/L.

[8] Each water system must certify, in writing, to the state (using third-party or manufacturer's certification) that when acrylamide and epichlorohydrin are used to treat water, the combination (or product) of dose and monomer level does not exceed the levels specified, as follows:

- Acrylamide = 0.05% dosed at 1 MG/L (or equivalent)
- Epichlorohydrin = 0.01% dosed at 20 MG/L (or equivalent)