Planning for Water Shuttle Operations

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Certification Statement

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Abstract

The problem was that reliable estimates of the rate and timing of water shuttle throughput to premises in Harrison Township were not available, given the multiple potential combinations of water sources, shuttle routes, and mutual aid resources. The purpose of this study was to develop a model capable of producing reliable estimates of throughput rates and benchmark achievement times for water shuttle operations in Harrison Township. The evaluative research method was used to answer the following questions: 1) What water handling apparatus are available and what are their locations and performance characteristics? 2) What potential fill sites are available? 3) What potential shuttle routes link fill sites with premises within the study area? 4) What is the potential water delivery rate to each premise within the study area? 5) How long will it take to reach water delivery benchmark rates? The procedures used to answer these questions included a literature review, data gathering, and the development of a mathematical model. Surveys of apparatus assessed their water handling characteristics. Surveys of fill sites assessed flow rates and working space. The road network was assessed for water shuttle traffic capacity. Estimates of potential throughput rates and benchmark time achievement were developed for all premises in the study area. Benchmarks included commencement of initial attack, readiness for nursing and operation of the fill and dump sites, and reaching key throughput rates. Model results showed that throughput of 250 gpm was achievable at 23.1 minutes and 500 gpm at 24.1 minutes, on average, falling short of national standards. Recommendations included the need to develop standard water supply procedures and better estimates for subsidiary task accomplishment, and that the study's methodology be applied to the rest of the county to create a common basis for water supply planning.

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Planning for Water Shuttle Operations

The Bellefontaine Fire Department (BFD) serves the residents of the City of Bellefontaine, Ohio through provision of fire protection and emergency medical services (EMS) as an organic unit of the municipal government. Under long-standing contract arrangements, the BFD also provides fire and EMS protection to the residents of Harrison and Lake Townships, two unincorporated rural jurisdictions bordering the city.

The city of Bellefontaine itself has an established system of municipal water mains and hydrants for fire protection, and this system extends into a limited part of the townships along the city's fringe. Most of the unincorporated township areas are dependent on alternative water supplies for fire protection, generally in the form of water tender shuttle operations. Harrison Township has been the focus of significant development of sources of natural water supply through the installation of dry hydrants in streams and lakes.

The problem is that reliable estimates of the rate and timing of water shuttle throughput to premises in Harrison Township are not available, given the multiple potential combinations of water sources, shuttle routes, and mutual aid resources. Tactically, this leaves a prospective incident commander reliant on guesswork as to when key water supply benchmarks might be met, or if they are likely to be met at all. Strategically, this means that development of new water sources or purchase of new water handling apparatus to improve the water supply situation is done without a firm understanding of where and how best to allocate funds.

The purpose of this research was to take stock of existing water supply resources and infrastructure and use this inventory to develop a model capable of providing realistic estimates of what water supply throughput is possible for premises in unincorporated Harrison Township. The evaluative research method was used to answer the following five questions: (1) What water handling apparatus (engines and water tenders) are available for use in the study area, and what are their locations and performance characteristics? (2) What potential water supply sources (fill sites) are available for the study area and what are their flow potentials? (3) What are the potential water shuttle routes linking sources of water supply with premises within the study area? (4) What is the potential water delivery rate to each premise within the study area? (5) How long will it take to reach water delivery benchmark rates (e.g., 250 or 500 gallons per minute) for each premise within the study area?

Background and Significance

To the uninitiated, water shuttle operations are simple, with no more than a paragraph or two devoted to them in fire service training manuals. In reality, these operations are freighted with complexity and require significant planning, training, and coordination to be safe and successful.

Logan County, Ohio lies in the west-central part of the state on the eastern edge of the Corn Belt agricultural region (Green, Kipka, David, & McMaster, 2018). The county features mostly rolling terrain resulting from an underlying post-glacial geomorphology. Because of this, Logan County has numerous kettle lakes and high-volume, coldwater streams fed by productive buried-valley aquifer systems. Harrison Township is an unincorporated rural jurisdiction lying to the west of the City of Bellefontaine and centrally located within the county. The unincorporated township area has a population of 1,617 residents living on 22.84 square miles, with an average population density of 70.8 residents per square mile (U.S. Census Bureau, 2021). There are no concentrated areas of development in the township, and 694 addressed premises comprising residential, commercial, and agricultural occupancies are scattered along the township's road network.

The Bellefontaine Fire Department (BFD) provides fire protection to the township under a long-standing contract arrangement. The BFD operates from a single station located in the central city, so incidents in the township generally involve extended response times (Figure 1). Within the developed areas of the city, a municipal water main and hydrant system provides water for fire suppression. This water system extends to a few important facilities in unincorporated Harrison Township so that a small portion of the area is provided with municipal hydrants. Water supply for the rest of the township is drawn from natural sources: a lake and two major streams. A total of eight dry hydrants have been installed in the township, including a traditional excavated installation in the lake and seven deployable bridge-mounted installations in the streams. The design of the bridge-mounted hydrants was the subject of earlier research by the author for the Executive Fire Officer program (Keller, 2020).

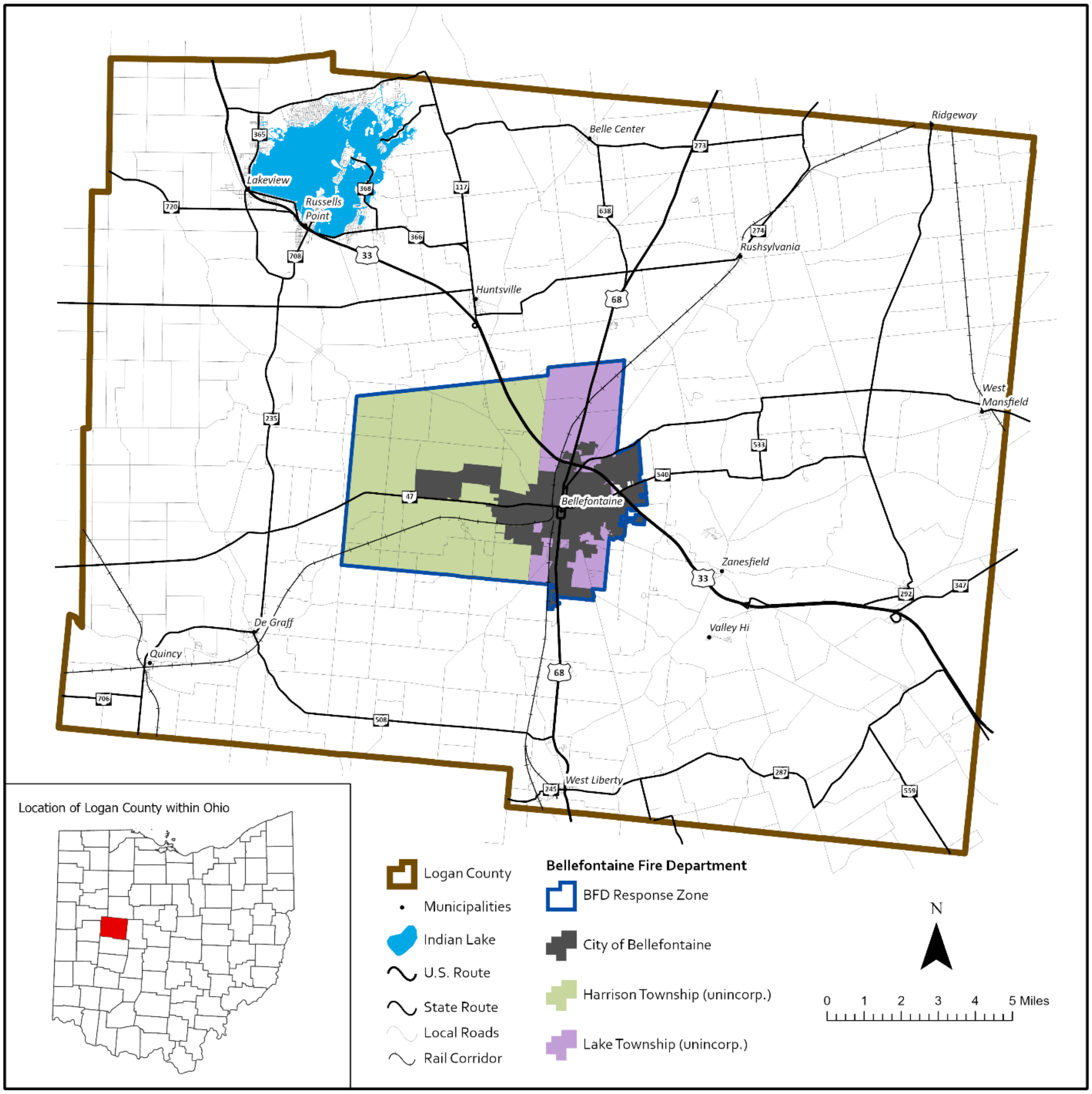


Figure 1. Bellefontaine Fire Department response area.

Supplying water in adequate quantities for fires and other emergency incidents in Harrison Township often involves the use of water tender shuttle operations. The BFD is a small organization with limited staffing and only one water tender apparatus. Any major incident requires the mobilization of resources from mutual aid partners in and around Logan County, and water shuttle operations are no exception.

In Ohio, responsibility for fire protection falls to municipal and township governments. There is no provision in Ohio law for a county-level fire authority, so coordination is generally done informally via fire chiefs' associations. Besides the BFD, there are 15 other departments providing fire protection to parts of Logan County, all but one of which is a fully volunteer organization. Among these departments, there are no standard operating procedures for water supply or any other function. There is also no standardization of equipment. Because of this, every water shuttle operation is an ad hoc affair, put together on the spot from the resources available. These operations are inefficient and oftentimes unsafe.

High-capacity water supply is not only needed for barn fires and other rural fire incidents. Hazardous materials incidents may also have similar water supply demands. A 2019 conflagration at a metal recycling facility in the northwestern Ohio city of Delta required the mobilization of water tenders from Ohio and Michigan for a multi-day water shuttle ("Metal X Fire," 2019). The study area has two major hazardous materials exposures: a major freight railway line and the four-lane divided highway. Both of these transportation corridors have significant hazardous materials traffic. Water shuttle operations have also been used to supplement or replace municipal water supply systems in several high-profile Ohio incidents in recent years. In 2014, the city of Toledo's water supply was compromised by a toxic algal bloom on Lake Erie. A large-scale water shuttle operation was used to supply the city's water treatment plant from uncontaminated sources (Chappell, 2014). In 2018, a water shuttle was used to temporarily supply the evaporative cooling units for a hospital in the southern Ohio city of Portsmouth (Corrigan, 2018). Although the study area has neither a water treatment plant nor a hospital, the City of Bellefontaine has both. In the event of a disruption to water supplies in the city, the best and nearest alternative water supplies are the study area's lakes and streams.

The goal of the Executive Analysis of Fire Service Operations in Emergency Management (EAFSOEM) course within the Executive Fire Officer Program is: "…to provide the students with the knowledge and skills they need to effectively analyze fire service operations in emergency management to better prepare their communities for large-scale, multiagency, all-hazard incidents" (U.S. Fire Administration [USFA], 2016, p. vii). This research supports that goal by analyzing the ability of the BFD and its mutual aid partners to effectively mount a water shuttle operation in support of efforts to mitigate a conflagration, hazardous materials spill, or other disaster.

This research further supports the United States Fire Administration organizational goal to "Build a culture of preparedness in the fire and emergency medical services" by "[enhancing] the fire and EMS' ability to identify, prevent, prepare for and mitigate community risks" (USFA, 2019, p. 13). The goal to "Ready the nation's fire and emergency medical services for all hazards" by "[encouraging] data-driven decision-making and information sharing" is also addressed (USFA, 2019, p. 14). Specifically, the research enhances our ability to effectively and safety respond to fires, hazardous materials incidents, and natural disasters requiring high-capacity water supply in an area that is currently poorly served by water supply infrastructure. It does this using a geospatial modeling approach based on data, rather than guesswork.

The author's membership on two fire service committees also informed this research project. At the state level, the author is a member of the Ohio Fire Chiefs' Association Water Supply Technical Advisory Committee (WSTAC), a volunteer group devoted to research, training, and standardization of all things relating to fire department water supply, with a special interest in the needs of rural communities. The author is also a member of the National Fire Protection Association (NFPA) Technical Committee on Wildland and Rural Fire Protection, the group charged with maintaining the rural water supply standard, NFPA 1142 *Standard on water supplies for suburban and rural fire protection* (National Fire Protection Association [NFPA], 2022).

Literature Review

As a full-time employee of the U.S. Department of Agriculture, the author is afforded unrestricted access to many scientific and technical journals via the National Agricultural Library, a privilege that was greatly helpful for carrying out this literature review. The author also wishes to thank the staff of the National Emergency Training Center (NETC) Library, who were of great assistance in tracking down articles from a very obscure technical journal.

Water Shuttle Operations

While the water shuttle is an important means of supporting firefighting efforts in rural and suburban areas, the concept receives only minimal coverage in textbooks used for hydraulics and pump operations training courses (Crapo, 2017) if there is any mention at all (Spurgeon, 2012). The classic texts covering the topic are the *Rural Firefighting Operations* series by Davis (1987) and *The Fire Department Water Supply Handbook* by Eckman (1994). While both are decades old, they remain conceptionally relevant, even as technological improvements have occurred. A more recent addition, *The Rural Firefighting Handbook* (Colletti, 2012) is an updated and condensed version of the older works by Davis. Annex material in the NFPA 1142 *Standard on water supplies for suburban and rural fire protection* provides some overview of water shuttle operations, although this material is neither prescriptive nor intended as a training guide (NFPA, 2022).

Because water shuttle operations tend to be a niche, rural specialty, training on the subject generally falls outside the mainstream fire academy and related publishing venues. Much of the training and best practice promulgation that does occur is driven by a cottage industry of interested parties. A notable example of this industry includes the Maryland-based consulting group GBW Associates, LLC (www.gotbigwater.com), whose members travel nationally to provide training on water shuttles and related topics. Another example is the Ohio Fire Chiefs' Association Water Supply Technical Advisory Committee (WSTAC), a volunteer group (of which the author is a member) that conducts research and provides training on alternative water supply topics for Ohio's fire departments (www.wstac.org). Although there is no centralized, definitive textbook or training program on the topic of water shuttle operations, this decentralized network of informal researchers and training providers continues to advance the field.

A water shuttle is a method of supplying water to an incident scene in areas that are outside of the municipal water main and hydrant system, or in areas where these systems are inadequate for incident needs. Water tenders are the backbone of the water shuttle. These are commonly mobile water supply apparatus that are purpose-built for fire service use, although civilian tank trucks are sometimes pressed into service. Water tenders are loaded at a designated location (fill site), then proceed along a designated roadway route to an offload point (dump site) proximal to the supported incident. Empty water tenders then return to the fill site for another load, repeating the process as needed. Conceptually, the water tenders are taking the place of hose- or pipeline conduits for conveying water from the source to the demand point. The diagram below (Figure 2), from the WSTAC training curriculum, provides an overview of the process (Keller & Collet, 2017).

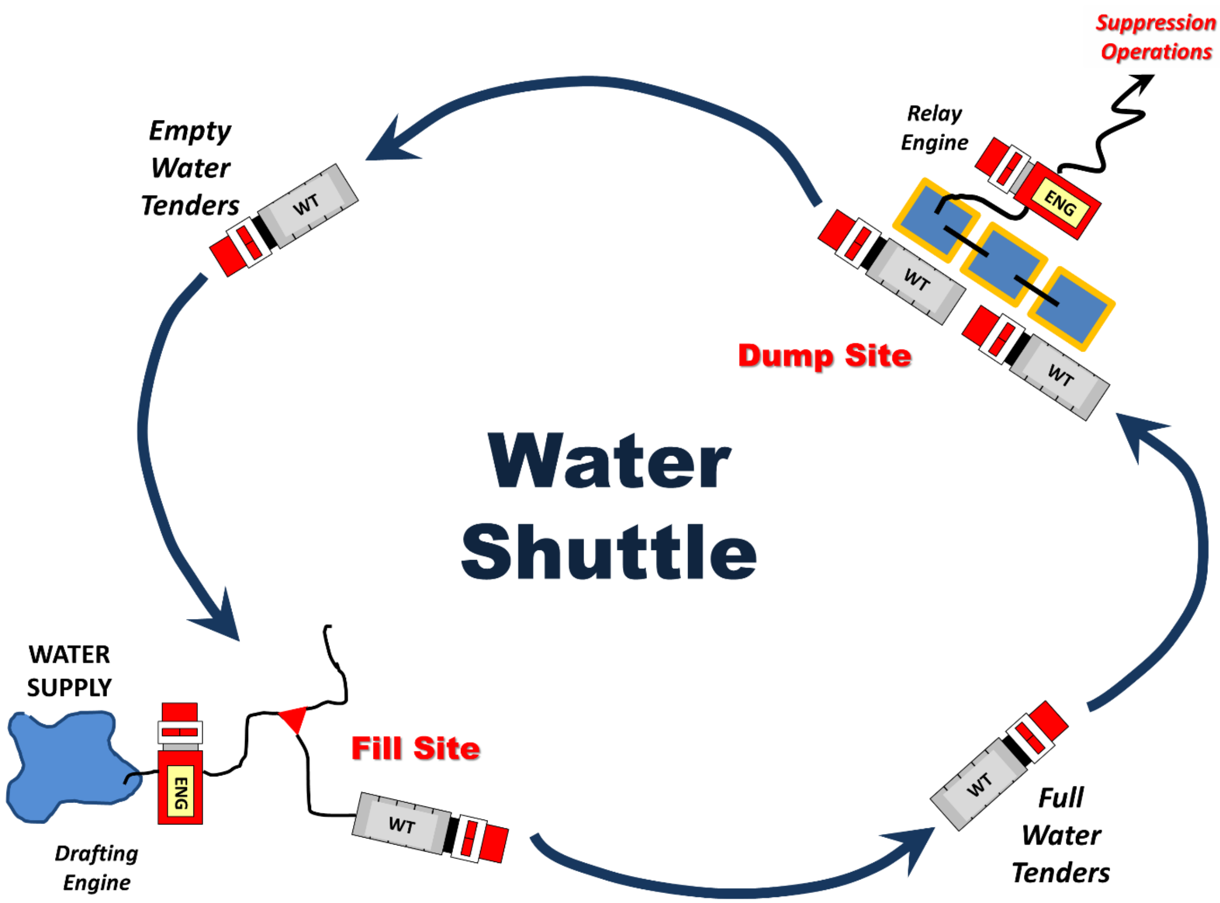


Figure 2. Water shuttle concept of operations.

Water Shuttle Performance

Water shuttle performance is measured in terms of throughput: the rate at which water is delivered to the incident scene, expressed in terms of gallons per minute (gpm). The overall performance of the shuttle is the sum of the individual contributions of all the participating water tenders as each completes a cycle of the shuttle route. In a study of conceptually similar manufacturing processes, it was noted that maximum throughput is the same thing as minimum cycle time (McCormick, Pinedo, Shenker, & Wolf, 1989). This maxim holds true for water shuttles as well.

Several methods exist for estimating water tender performance in a shuttle operation. These methods all derive from the basic relationship:

$$throughput\ (gpm) = \frac{usable\ tank\ volume\ (gallons)}{time\ to\ complete\ shuttle\ (minutes)} \qquad (1)$$

In annex material, the NFPA 1142 standard refers to this performance as continuous flow capability (CFC), and provides the following formula for estimating CFC for a water tender (equation C.10a):

$$Q = \left(\frac{V}{A + T1 + T2 + B}\right)k \qquad (2)$$

where:

Q = continuous flow capability (gpm)

V = tank volume of water tender (gallons)

A = time for water tender to drive 200 feet, offload water into a portable tank, and return 200 feet to the starting point (minutes)

T1 = time for water tender to travel from the dump site to the fill site (minutes)

T2 = time for water tender to travel from the fill site to the dump site (minutes)

B = time for water tender to drive 200 feet, be loaded with water at the fill site, and return 200 feet to the starting point (minutes)

k = a coefficient accounting for unusable tank capacity due to limitations of the water tender's design; a value of 1.0 is used for vacuum apparatus (pressurized tank) and 0.9 for all other water tenders

The travel time factors *T1* and *T2* are calculated using the following formula (equation C.10b):

$$T = 0.65 + XD \quad (3)$$

where:

T = average time required to complete the trip one-way (minutes)

X = average speed factor, calculated as (60 / average speed) in miles per hour (mph)

D = one-way distance (miles)

An average speed of 35 mph is recommended by NFPA 1142 as generally safe for water shuttle operations, although lower speeds are recommended for challenging roadway conditions. The constant value of 0.65 is used to account for acceleration and deceleration. This constant was "developed by the Rand Corporation" although no further information is provided (NFPA, 2022).

An alternative method for estimating performance is provided by Davis (1987). This method is similar to that of NFPA 1142, but provides a more granular approach to the time factors:

$$TDR = \frac{TC}{SCT} \quad (4)$$

where:

TDR = tanker (water tender) delivery rate (gpm)

TC = tank capacity (gallons)

SCT = shuttle cycle time (minutes)

Shuttle cycle time (SCT) is comprised of multiple constituent factors, each of which is described in detail. The overall time is calculated as follows:

$$SCT = (OPT + OT + OBT + TTE + FPT + FT + FBT + TTF) \quad (5)$$

where:

OPT = offload preparation time (minutes)

OT = offload time (minutes)

OBT = offload breakdown time (minutes)

TTE = empty travel time (minutes)

FPT = fill preparation time (minutes)

FT = fill time (minutes)

FBT = fill breakdown time (minutes)

TTF = loaded travel time (minutes)

Finally, Eckman (1994) provides the following method for estimating performance:

$$CFC = \frac{V}{(HT + TT + WT)} \quad (6)$$

where:

CFC = continuous flow capability (gpm)

V = usable water tender tank capacity (gallons)

HT = handling time (minutes)

TT = travel time (minutes)

WT = waiting time (minutes)

In this case, the time costs involved in filling and unloading the water tender are combined as handling time (*HT*) and are not further decomposed. Travel time (*TT*) combines both the filled and empty legs, but otherwise is calculated as per NFPA 1142. Unique to Eckman, however, is the inclusion of waiting time (*WT*) as a cost factor. This accounts for time spent by water tenders queueing at the dump and fill sites due to resource saturation or operational inefficiencies.

The three methods described here are closely related, but each has a different focus and related strengths. The NFPA 1142 method has the advantage of simplicity and some degree of standardization through prescribed methods for measuring time required to load and unload water tenders. As part of the national consensus standard, this is also the method referenced by insurance rating bureaus. Davis, writing from the standpoint of a fire service instructor, has a focus on decomposing the fireground tasks that contribute to the overall time cost. This allows training and procedures to be tailored with an eye toward reducing the time cost, thus increasing efficiency and throughput. Eckman addresses the real-world complexity of water shuttles by introducing queueing time as a cost factor. This phenomenon is commonly observed during water shuttles, and its impact cannot be ignored if reliable estimates are to be obtained. An ideal estimation formula would combine the strengths of the three methods described above: the standardization of NFPA 1142, the task decomposition of Davis, and the allowance for queueing of Eckman.

Water Shuttle Phases and Components

The water shuttle occurs in two sequential phases: resource concentration (response phase) and steady-state operations (shuttle phase). The response phase involves all actions required to move participating resources from their home stations to their assigned area of the water shuttle. This is understood to occur via roadways. Because a water shuttle normally involves multiple mutual aid organizations, resources are likely to be arriving from several directions and at different times. The shuttle phase consists of all tactical actions necessary for the on-scene resources to deliver water to the incident demand point, in other words, what is normally thought of as a water shuttle operation.

No single event separates the response and shuttle phases, instead these two phases overlap. The shuttle phase begins when the minimum required resources are in place to commence water delivery, but the response phase continues as additional resources report to the incident. The capacity of the water shuttle continues to grow until all dispatched resources are on scene, which also signals the completion of the response phase.

Response Phase: Buildup of Resources

The response phase of a water shuttle operation encompasses those actions necessary for the responding resources to move from their home location to the location of their incident assignment, which could be the dump site, fill site, or a staging area. This process has parallels in many commercial applications where efficient point-to-point routing of vehicles is needed.

Parallels in other industries.

The need to optimize vehicle routes for the delivery or collection of goods has a long history as a topic of interest in the field of commercial logistics. One of the earliest and most famous attempts to solve an optimal route problem in this field is the "Traveling Salesman Problem" (TSP). The TSP seeks to calculate the most efficient route for a hypothetical person visiting a sequence of cities (Flood, 1956). Commodity flow analysis is another related logistics problem. This field seeks to characterize and optimize the shipment of goods within a defined region or city. An overview of then-current commodity flow study research by Smith (1970) identified that regional commodity flows cannot be assumed to always follow the shortest or most efficient routes, but rather each case responds to local priorities and requirements that may not be readily quantifiable. What constitutes "efficiency" cannot be universally defined and is unique to each situation. In the same paper, impedance factors such as distance and time were characterized as a sort of friction that must be overcome, exerting limitations on the achievable efficiency of the system. These concepts are applicable to water shuttle planning in that the shortest route is not always the most desirable, and that the shuttle's throughput is constrained by loading, unloading, and travel time in addition to water tender capacity and supply source flow rates. Specific insights from the field of commodity flow study are generally of limited applicability for water shuttle planning, however. In a study of goods movement in and around the Melbourne, Australia region, Ogden (1978) found that movement of bulk commodities from fixed sites – such as gravel from a quarry, or petroleum from a depot – was not well modeled by conventional commodity flow study methods, which are better suited to optimizing situations with multiple possible origins and destinations. Water shuttle operations have a fixed origin at the fill site, and a fixed destination at the dump site, making them comparable to the poorly modeled situations noted in the paper.

Network Analysis using Geospatial Information Systems (GIS)

The fire service is not the first nor the only industry with a need to understand complex routing and delivery problems. Transportation planners have made extensive use of GIS for analysis of these issues, and for modeling of potential solutions. Data for GIS analysis of transportation issues falls into three basic categories, as defined by Thill (2000). The first is raster data, which includes factors that are continuously variable across the landscape, rather than existing as discrete features. Examples of this include elevation, temperature, or precipitation. These data are represented in a GIS by means of a matrix of cells (raster), with different cell sizes used to create variable degrees of resolution. Vector data is the second data type, and this includes features that can be represented by discrete points, lines, or polygons. Examples of vector data include fire stations, roads, and response zones.

Deriving from raster and vector data is the third type: network data. Networks in a GIS include point features (nodes) and linear features (links) connected by defined relationships and including attributes (tabular information) that allow for modeling, rather than just map creation. The concept of networks in GIS is itself based on the much older field of graph theory, a branch of mathematics that produced the first link/node methods of solving network problems, such as finding the shortest or most efficient path between two points. The network analysis tools available in modern GIS software are all ultimately derived from the graph theory conceptual frameworks (Curtin, 2007).

Derivation of usable intelligence from geospatial data is further defined by Thill (2000) as a three-step process of data management, manipulation, and analysis. First, raw data from various sources are collected, vetted, organized, and stored as part of a data management process. Derived products are created using raw data as part of the data manipulation process. Finally, these derived products are used to create geospatial models as part of the data analysis process. Models can then be used to realistically simulate existing and potential situations to inform planning and operations.

Existing GIS tools are applicable to efficiently planning routes for the response phase and estimating the likely travel times involved. Some of the available GIS tools include widely used consumer grade mobile trip planning applications such as Google Maps. More robust and capable GIS tools operating on the same principles are available for professional use, such as the Network Analyst extension for the ArcGIS software suite (ArcGIS Network Analyst Extension product website, n.d.). Professional grade tools such as Network Analyst allow for the rapid calculation of optimal travel routes and travel time estimates but require technical proficiency to use.

Safety during the response phase.

Within the fire service, water tenders have a reputation as an inherently unsafe class of apparatus, especially prone to rollover accidents. This is not a new development: both Davis (1987) and Eckman (1994) discuss this issue in their texts. The U.S. Fire Administration published a dedicated report on the topic nearly two decades ago: *FA-248 Safe operation of fire tankers* (U.S. Fire Administration [USFA], 2003). This report included case summaries of 38 water tender accidents resulting in firefighter fatalities between 1990 and 2001, along with analysis of contributing factors to those incidents. The report further identified general safety considerations relating to water tender design and operations, driver training, and rural roadways.

In discussions with firefighters and fire officers, the author has heard the opinion repeatedly expressed that factors inherent in the design of water tenders make them unsafe. It is probably fairer to say that design characteristics intrinsic to water tenders make them a class of apparatus that demands respect and attentiveness from their operators, more so than even other fire apparatus. In the USFA report, mechanical issues were seldom identified as a contributing factor in the case study mishaps. Rather, driver error was almost universally identified as the primary issue. Water tenders are not inherently unsafe, instead water tenders driven too aggressively for the conditions prevailing on rural roads – narrow lanes, weak shoulders, numerous curves – are the real issue (USFA, 2003).

Rural roadways can present a challenging driving environment, yet numerous vehicles traverse these routes each day without incident. Driver training, a respect for the characteristics of the water tender, and an overall culture of safety are the keys to preventing potentially deadly rollover accidents.

Shuttle Phase: Steady-State Operations

In instructional materials developed by the author for WSTAC training events, operations of the shuttle phase are broken down into four principal components for analysis: fill site, dump site, route, and water tenders (Keller & Collet, 2017). This allows each component to be considered both separately and as a part of the overall system. These components were identified through analysis of available texts (Davis, 1987; Eckman, 1994) and through the observations of the author and other WSTAC members.

For purposes of this study, the primary consideration for each of these shuttle phase components is their contribution to overall shuttle time and thus throughput of water from the point of supply to the point of delivery proximal to the incident scene. The fill site component encompasses all activities required to load empty water tenders at the point of water supply, while the dump site component comprises all actions related to offloading of water at the point of delivery. The shuttle route component considers the travel time required for water tenders to complete the circuit between fill and dump site. Finally, the water tenders themselves and how their performance characteristics impact time requirements relative to the other components must be considered.

The Vehicle Routing Problem (VRP).

The Vehicle Routing Problem (VRP) is the most applicable commercial logistics concept for water shuttle route optimization. The VRP may be defined as "… a set of routes that starts and ends at its own depot, each performed by a single vehicle in a way that minimizes the … transportation cost and fulfills the demands of the customers and operational constraints"

(Daneshzand, 2011, p. 127). Logistics situations requiring a VRP solution include those requiring the delivery or collection of goods or commodities, or some combination of collection and delivery by the same vehicle. A log truck picking up timber from logging sites for delivery to a mill is an example of a collection VRP, while a dump truck hauling gravel from a quarry to a construction site is an example of a delivery VRP. A parcel service truck that both delivers and collects packages along its route is an example of a mixed VRP.

Daneshzand (2011) describes five basic variations of the VRP, as well as seven additional complex VRP concepts. A water shuttle operation would be classified as a type of capacitated vehicle routing problem (CVRP). The throughput of the system is limited (capacitated) by the tank volume of the delivery vehicles (water tenders). The CVRP has traditionally been considered a complex problem to solve, in that it involves the route planning aspects of the Traveling Salesman Problem (TSP) with the need to manage a limited cargo capacity – called the "Bin Packing Problem" (Ralphs, Kopman, Pulleyblank, & Trotter, 2003). The water shuttle is a low-complexity distributive CVRP in that it has only a single depot (the fill site) and a single customer (the dump site).

The component elements of a VRP may be further analyzed to better understand the overall system. Daneshzand (2011) identifies five basic components of every VRP: the network, the customers, the depots, the vehicles, and the drivers. These components interact to define the parameters and impedances of the VRP system, and are represented in the water shuttle as follows:

- Network: the roadway route that the water tenders must traverse between the fill site and dump site; the length of this route defines travel time (impedance factor)

- Customer: the dump site, the location of which helps define the route; handling time at the dump site is another impedance factor
- Depot: the fill site, the location of which helps define the route; handling time at the fill site is another impedance factor
- Vehicles: the water tenders, the tank capacity of which, along with design features governing loading (fill) and unloading (dump) rates influence time spent at the dump and fill sites
- Drivers: the water tender apparatus operators, the skill level of which can increase or decrease the other time impedance factors described above

Daneshzand (2011) identifies three industry VRP situations that have received extensive study in the literature: the collection of milk from dairies, delivery of ready-mix concrete, and municipal waste pickup. Research supporting each of these commercial VRPs is worth examining for lessons applicable to fire service water shuttle planning. The author additionally found considerable parallels to water shuttle planning in the problems facing the railroad and maritime shipping industries.

Parallels with the maritime shipping industry.

In the maritime shipping industry, a distinction is made between navigation and dwell time. Navigation time refers to the period when a ship is actively steaming between ports and is comparable to the time water tenders are traveling between the fill and dump sites. Dwell time refers to the handling time required for activities at the port, including maneuvering in and out of the port, and the loading and unloading of cargo (Flood, 1954; Wang, Zhang, & Wang, 2016). Dwell time is comparable to the handling time required at the dump and fill sites in a water shuttle. Decomposition of the various time costs that make up dwell time to the extent possible allows for the isolation of those factors requiring the greatest time, thereby allowing them to be analyzed for potential efficiencies (Dulebenets, 2018). A similar process can be applied to the procedures for loading and unloading water tenders at the dump and fill sites. Rather than view the dwell time at either site as an undifferentiated bloc, specific processes, techniques, and equipment can be identified for improved efficiency.

Minimizing navigation time is not always the most efficient approach in maritime shipping because vessels arriving at a port too early will be idled while awaiting entry. This incurs real costs in terms of increased fuel expenditures to achieve the higher speeds needed to reduce navigation time, as well as greatly increased air pollutant emissions. The goal in the maritime industry is to optimize – not minimize – ship speeds during navigation in order to arrive at the port in time to be serviced immediately, thus saving on overall fuel costs (Fagerholt, Laporte, & Norstad, 2010; Norstad, Fagerholt, & Laporte, 2011). This is achieved by balancing the numerous competing time demands on ships and ports as optimally as possible to reduce congestion and unnecessary fuel use (Dulebenets, 2018). A similar dynamic can be seen in water shuttle operations, where water tender drivers at times needlessly rush between the dump and fill sites, only to find themselves arriving to a queue to load or unload. The unnecessary cost in this case is safety, as pointlessly driving at a higher speed increases the risk of a mishap.

Parallels with the freight railroad industry.

Estimating the throughput potential of railway lines has parallels to the estimation of water shuttle throughput in that vehicles of known capacity are picking up and delivering a commodity along defined routes. In a study of methods for estimating railway capacity, Liao, Li, Miao, & Corman (2021) used a two-by-two matrix approach to frame the components, with infrastructure and vehicle factors on one axis and technical and operational constraints on the other. A similar approach may be applied to water shuttle operations to help frame the interacting components, with the four components described above becoming parts of the matrix. Water tenders, as the only mobile element, are counted as vehicles whereas the engines assigned to the fill and dump sites are considered to be part of the infrastructure. The other three components – the route and the fill and dump sites – are individually considered in each cell of the matrix (Figure 3).

	Technical Constraints	**Operational Constraints**
Infrastructure	**Shuttle Route** • Road design • Road condition • Weather conditions **Fill Site** • Available flow rate • Traffic flow design • Fill procedures and equipment **Dump Site** • Traffic flow design • Dump procedures and equipment	**Shuttle Route** • Speed limits (posted) • Speed limits (administrative) • Traffic flow (one- or two-way) **Fill Site** • Crew staffing • Crew proficiency **Dump Site** • Crew staffing • Crew proficiency
Vehicles (Water Tenders)	**Route Operations** • Motor power • Mechanical condition • Tank baffling • Braking systems **Fill Operations** • Tank capacity • Maximum fill rate • Fill connection design **Dump Operations** • Tank capacity • Maximum dump rate • Dump outlet design	**Route Operations** • Driver proficiency **Fill Operations** • Driver proficiency **Dump Operations** • Driver proficiency

Figure 3. Water shuttle factors and constraints.

Parallels with concrete delivery routing.

The time-sensitive process of delivering ready-mix concrete (RMC) to construction jobsites is another truck-based shuttle process with similarities to fire service water shuttles. This complex process has been a longstanding issue for the concrete industry and is known as the "Concrete Delivery Problem" (CDP). As with the fire service water shuttle, the CDP seeks to find the most efficient route solution to repetitively deliver a product (concrete) from a source (the RMC production plant) to a destination (the construction site), using a fleet of vehicles of mixed capability, over an existing road network, and under tight time constraints. Routing must be carefully orchestrated because poorly timed deliveries can result in layers of concrete that fail to properly bond once laid, or in wasted product in idling trucks (Kinable, Wauters, & Berghe, 2014).

As with water tenders, the RMC transport trucks available often vary in capacity. They also often present a heterogenous mix of loading and unloading efficiency, which is further influenced by associated handling characteristics at the RMC production plant and jobsite. This tends to make the CDP dispatching process very complex (Schmid, Doerner, Hartl, Savelsbergh, & Stoecher, 2009). Considerable effort has been made in the construction industry to develop methods to automate the CDP dispatching process to improve efficiency and generate cost savings. However, the complexity of the process, along with the large number of interacting variables, has limited progress. Instead, the process has largely remained in the hands of experienced dispatchers who respond to dynamic situations using professional judgment learned through trial-and-error (Maghrebi, Sammut, & Waller, 2015).

A further complicating factor for CDP dispatching is the issue of mechanical casualties among the RMC delivery trucks. Loss of a truck in the midst of a delivery operation due to mechanical issues can create havoc in a carefully organized process with little flexibility in available capacity. In a fire service water shuttle, excess capacity can be built into the operation by adding additional tenders as a reserve. This is possible because the product being delivered (water) does not spoil when tenders are idle. This is not true for RMC, the delivery of which must be carefully timed to maintain product consistency within acceptable limits (Yan, Lin, & Liu, 2011).

Parallels with dairy truck routing.

Collecting milk from geographically distributed dairies for delivery to a central processing facility is another version of the VRP. In this case, the process is collective rather than distributive in nature, but still has parallels to fire service water shuttle operations. Dairy tank trucks leave a central facility, visit a series of dairies along a planned route, and then return to the central facility to unload the collected milk. There is great interest in optimizing the routes because the process must follow tight time restrictions to prevent spoilage of the product. As with water shuttles, dairy routing often involves a heterogenous fleet of vehicles with varying capacities. Likewise, the process also must account for dwell times that vary according to characteristics of the trucks, the dairies, and the processing facility. Inefficient routing results in the same kind of queueing delays seen in water shuttles (Sankaran & Ubgade, 1994). Caramia & Guerriero (2010) noted additional difficulties in dairy routing in mountainous regions of Italy, where vehicle weight and size restrictions made planning for a heterogenous truck fleet especially complex. These same researchers were able to successfully develop automated methods to identify optimal routing solutions for their study area. Facing similar complexities due to restrictive terrain, Norwegian researchers Pasha, Hoff, & Lokketangen (2014) were also able to develop automated decision support systems. These researchers noted that existing manual routing solutions that were developed organically over years of trial and error were often very similar to the optimal routes derived using computer modeling methods. As with fire service water shuttles, the problem of dairy truck routing has its roots in rural areas and has many similarities. In both cases, a heterogeneous fleet must navigate restrictive road networks, while variability in the capabilities of both vehicles and handling facilities create additional complexity and introduce potential bottlenecks. The development of computer-based decision support systems for dairy routing, suggests that similar systems may be possible for water shuttles, even though they have proven difficult for other applications such as concrete delivery.

Parallels with municipal solid waste collection.

The collection of municipal solid waste (MSW) by trucks for delivery to a central disposal facility is another instance of the VRP with some similarities to fire service water shuttle operations. As with a water shuttle, MSW trucks circulate along a road network between two locations, in this case a central depot or garage and a waste disposal site (landfill). Unlike a water shuttle, the MSW trucks make multiple stops along the route to collect waste, and their routes are designed around these stops as much as around the two primary locations. A study of Taiwanese MSW collection systems found that the use of GIS tools for route planning and optimization was highly effective in reducing overall distance travelled, time required, and expenditures in general, even using 1990s-era software platforms (Chang, Lu, & Wei, 1997). A study for the city of Danang, Vietnam found that as cities grow in size, the MSW collection systems become so complex that manual planning systems become ineffective, resulting in illegal dumping and burning of waste. The authors suggest that for any complex routing problem, the use of GIS has become essential (Son & Louati, 2016). This is likely true of water shuttle operations as well, in that use of GIS for planning would greatly improve efficiency.

In a broad survey of MSW collection systems in developing countries, Sulemana, Donkor, Forkuo, & Oduro-Kwarteng (2018) found that although GIS systems are highly effective in optimizing collection routes and reducing costs, they were not widely used. Instead, most cities relied on manual route planning, with drivers allowed to make ad hoc changes to routes, resulting in inefficient use of resources. This situation has parallels in many rural areas of the United States where uptake of GIS technology is often low. In particular, water shuttle operations for rural fire departments are often improvised affairs, rarely receiving extensive pre-incident analysis or planning, or making use of GIS tools.

A study of MSW collection planning in rural Cape Verde found that the inclusion of elevation data to create three-dimensional road networks in GIS models provided more realistic results. This was because the modeled route operations were able to factor in the impact of navigating hilly terrain on heavy trucks, and thus improve the quality of time requirement estimates. Notably, it was found that in many cases the shortest route was not always the most optimal one due to the impacts of terrain (Tavares, Zsigraiova, Semiao, & Carvalho, 2009). Similar results would likely be seen if elevation data were used in water shuttle GIS models and would create the possibility to plan traffic such that laden water tenders mostly travel downhill segments, while empty tenders travel uphill.

While GIS tools are recognized as highly useful for MSW route planning, research has shown that they can be made more effective by combining them with non-spatial mathematical modeling methods. Sulemana, Donkor, Forkuo, & Oduro-Kwarteng (2018) found that while GIS models were effective for optimizing routes, they were improved by combination with numerical methods that captured performance characteristics of vehicles, facilities, and personnel. In a study of MSW collection routing in Taiwan, modeling methods based on biological models were found to be highly effective in grouping pickup locations into optimized clusters (Huang & Lin, 2015). A similar study from Denmark that used a different numeric method found similar success in clustering optimization (Buhrkal, Larsen, & Ropke, 2012). A study in Texas was also successful in optimizing route structures through a combination of GIS and numerical modeling methods (Kim, Kim, & Sahoo, 2006). These studies all suggest that a similar approach would likely improve planning for water shuttle operations, perhaps by combining GIS route planning methods with numerical models of water tender, fill site, and dump site performance characteristics.

Technological solutions are often suggested as ways to improve water shuttle performance, and this is also true of MSW operations. A study of Malaysian MSW collection systems sought to optimize routing using internet-connected “smart bins” capable of providing real-time fullness updates, along with GIS routing tools that incorporated live traffic data and networked collection vehicles. This system allowed route assignments to be adjusted on the fly according to actual conditions as reported by the monitoring technologies (Hannan et al., 2018). Similar technological solutions could probably be applied to water shuttle operations but would be expensive and are unlikely to be available for widespread uptake by rural fire departments any time soon.

Navigation Time: Route Operations

The water shuttle route connects the point of loading (fill site) with the point of delivery (dump site). The route is a series of roadway segments that will be traversed by the water tenders participating in the shuttle operation. The time required to complete the empty and loaded legs of the route constitute the navigation time of the water shuttle operation.

Route efficiency.

As noted above in the discussion of parallels with municipal solid waste collection route planning, the identification of optimal clusters of destinations is an important step in developing an optimal route solution (Buhrkal et al., 2012; Huang & Lin, 2015). This is considered generally applicable to many instances of the capacitated VRP. Laporte (2009) noted that a "cluster first, route second" approach is very effective, and is a method that is commonly adopted by experienced manual dispatchers in many industries, even when they are not formally trained. For a water shuttle, identifying similar logical groups of potential dump sites would also be beneficial. While a given water shuttle operation will only service a single dump site, grouping potential dump sites into pre-identified routes would facilitate the planning process.

When planning routes for water shuttle operations, the conventional wisdom is that routes should be in the form of a loop whenever possible. The reason for this is that water tenders moving in opposite directions are not forced to pass one another on narrow, rural roads where there is a danger of one or both leaving the roadway (Eckman, 1994). While loop routes are no doubt safer in general, they are not always possible or practical, and other configurations must sometimes be considered.

The configuration of shuttle routes in the maritime shipping industry are described as either circular, pendular, or combination. A circular configuration involves a ship visiting each port only once as it completes its shuttle circuit. A pendular configuration sees a ship moving back and forth between end ports on a linear route, visiting intermediate ports along the way once or twice per circuit. Combination routes are those with both circular and pendular segments (Christiansen, Fagerholt, Nygreen, & Ronen, 2013). This taxonomy of route configurations is a useful way to categorize fire service water shuttle routes.

While the shortest possible route is generally desirable, this is not always the most efficient route. Routes providing for the uninterrupted, two-way flow of traffic are not only safer, but are also more efficient than potentially shorter routes that require complex passing maneuvers when vehicles meet (Drezner & Wesolowsky, 1997). The "Red Ball Express" system of truck convoys supplying the rapidly advancing American forces after D-Day was organized as a massive one-way loop, preventing loaded and unloaded trucks from meeting, and thereby maximizing throughput of supplies (Huston, 1965; van Creveld, 2004). A study of freight truck routing in Japan found that accounting for fuel consumption in addition to travel distance yielded reduced costs and pollution emissions, even with somewhat longer routes. The shortest routes often included difficult terrain and greater congestion, resulting in higher overall fuel use and more idle time spent refueling and waiting on traffic (Xiao, Zhao, Kaku, & Xu, 2012). A myopic focus on minimizing total travel distance will not yield optimized routes. While travel time is important, other factors – such as safety in the case of water shuttles – must be given appropriate weight.

Double-tracked railway lines are an example of routing that separates opposing traffic to increase throughput, even when this means potentially longer trips for a given train. A single-tracked railway has limited capacity due to the need for one train to be idled at a siding while making way for a higher-priority train traveling in the opposite direction. Double-tracked lines eliminate these delays and increase the throughput of the system (Sogin, Lai, Dick, & Barkan, 2013). At the outbreak of the First World War, double-tracked lines of the German system were capable of handling 60 trains per day, versus 40 for a single-tracked line (van Creveld, 2004). Modern railroad industry planning assumptions set the absolute maximum number of trains per day for a single-track line at 60, and this assumes optimal conditions (Lai & Barkan, 2009). In a simulation study of Croatian railways, a double-tracked line was found capable of handling up to 128 trains per day, assuming optimal scheduling (Ljubaj & Mlinaric, 2019). Similar benefits of two-way traffic flow apply to water shuttle operations, based on observations of numerous training evolutions by the author and other WSTAC members. Understanding what roadways can safely support two-way traffic is thus important to optimizing shuttle operations.

Roadway requirements.

Ohio public roadways outside of municipal corporations are classified according to the jurisdiction responsible for their maintenance. Roads may be part of the state highway system or a part of a county or township road system. For newly created county and township roads, a minimum total width of 30 feet is mandated by the Ohio Revised Code, although minimum lane widths are not specified. The minimum width requirements for county and township roads have varied considerably throughout Ohio's more than two centuries of statehood, and a wide range of roadway and lane widths may be encountered in rural areas (Ohio Auditor of State, 2018; Width of County Roads, 1986). Lane and shoulder width requirements for state highways are variable depending on road use and setting, but a minimum width of 12 feet for each lane of travel is generally applicable (Ohio Department of Transportation [ODOT], 2021).

Lane width guidelines specific to fire department needs in a rural setting are provided by the National Fire Protection Association (NFPA) in the *NFPA 1140 Standard for wildland fire protection* (NFPA, 2022). This standard calls for a minimum clear width of 12 feet for each lane of travel, excluding shoulder width (section 11.2.3). Although the NFPA 1140 standard is meant to apply to roadways in new developments rather than to existing public roadways and does not have the force of law in Ohio, it does provide consensus-based guidance as to what constitutes a safe minimum lane width for fire apparatus operations. Using the NFPA 1140 standard as a guide, the minimum width of available traveled way for safe, two-way water tender traffic must then be 24 feet, excluding any shoulder width. Any roadway of lesser width is suited to one-way traffic only.

Water Tender Performance and Design

Several design features of a water tender interact to determine its water handling efficiency. The most obvious of these is tank volume, but capacity alone does not determine apparatus throughput potential. The rates at which the tank can be filled and emptied are equally important in determining the efficiency of a water tender (Keller & Browne, 2016).

Water tender capacity.

Water tenders of increasingly large capacity are often purchased with the intent of improving water shuttle throughput. Similar efforts have been made in the municipal solid waste (MSW) industry, where the use of larger collection trucks is sometimes contemplated as a means to improve efficiency. A proposed increase in the carrying capacity of MSW collection trucks in New York City was found to be unlikely to yield the desired results. While the trucks could collect waste from more sites along a route before needing to be emptied, the increased capacity was offset by much longer handling times at the landfill and greater difficulty maneuvering on congested streets (Bhat, 1996).

A similar case in Brazil found that while larger trucks sometimes improved efficiency, some conditions favored multiple smaller trucks instead. The authors suggest that increasing vehicle capacity does not universally yield a linear increase in efficiency, rather that the characteristics of the fleet must be tailored to local conditions to obtain what optimization is realistically achievable (Vecchi et al., 2016). The same dynamics of capacity are likely applicable to water tenders. Larger capacity may yield greater efficiency in some cases, but in other cases – such as in areas of restrictive terrain – a larger number of smaller tenders may be the optimal solution.

The process of hauling manure slurry from livestock operations for application to crop fields is a shuttle operation with many similarities to fire service water shuttles. Slurry is shuttled by tank trailers from a storage lagoon or tank (fill site) to a field for application by a spreader or injector system (dump site). Time and cost efficiency are of great interest in this process. There are generally limited suitable weather windows for application, and fuel and labor costs must be minimized due to low profit margins in production agriculture. In a study of manure hauling operations for Michigan dairies, Harrigan (1997) developed a model of the process to better identify efficiencies. It was found that while using larger capacity haul tanks improved throughput, the performance increases were not linear since the larger tanks also required longer handling times to load and unload. Larger tank capacities were found to be most effective when haul distances were relatively long, versus fields closer to the dairy. Further work on the subject by Harrigan (2010) more precisely quantified the impacts of larger tanks. For a 20 percent increase in tank volume, throughput was increased by eight percent with a short, 0.1-mile haul distance. For a 10-mile haul throughput was increased by 16 percent over the original tank size. Eckman (1994) makes a similar observation regarding water tenders, noting that fire departments with longer shuttle distances should consider larger tank capacities, although he does not offer evidence as to why this is the case. A related dynamic regarding capacity has been noted by WSTAC members. Larger capacity water tenders are generally regarded as more efficient in the flatter terrain of western Ohio, whereas smaller apparatus are better suited to the hilly terrain of eastern Ohio. Although the performance differences have not been quantified, the concept is a generally accepted rule of thumb among committee members.

Water tender loading performance.

The speed of loading water tenders at the fill site is often the subject of considerable interest, however there are physical limits to what can be achieved. The use of polypropylene ("poly") for tank construction on fire apparatus has become dominant since the introduction of the material in the 1980s. While the occasional new-build water tender has a stainless-steel tank, poly is by far the most common material in use. Tanks of other materials are still encountered among older legacy apparatus. These materials include fiberglass, aluminum, and stainless, galvanized, and untreated steel (Fire Apparatus Manufacturer's Association [FAMA], 2018). Poly tanks have numerous advantages over other materials, and these advantages account for its ubiquity. Poly tanks are lighter than those made of other materials, are generally impervious to corrosion, and can be readily built to custom shapes. Although more expensive than other materials initially, poly tanks tend to be more cost-effective over the life of the apparatus due to reduced fuel and maintenance costs (FAMA, 2018).

The principal disadvantage of poly tanks are inherent limitations on the rate and pressure of fill. The two primary manufacturers of these tanks for fire apparatus use are United Plastic Fabricating (UPF) and Pro Poly of America, Inc. Both manufacturers stipulate a maximum rate of fill of 1,000 gallons per minute (gpm) and a maximum pressure at the fill inlet of 100 psi for poly tanks of 1,000-gallon capacity or greater (Pro Poly of America, Inc., n.d.; United Plastic Fabricating [UPF], 2018). Exceeding these limits can result in damage to the tank and voids the manufacturer's warranty. These limitations stand in contrast to minimum performance requirements for water tenders ("mobile water supply apparatus") laid out in chapter 18 (water tanks) of the NFPA 1901 standard. Section 18.5.2 of that document requires the provision of an external fill connection that leads directly to the tank and that is capable of a minimum filling rate of 1,000 gpm (National Fire Protection Association [NFPA], 2016). For water tenders equipped with poly tanks, this means that the minimum acceptable fill rate for the apparatus is also the maximum acceptable fill rate for the water tank (NFPA 1901 is silent on fill pressures).

In some cases, poly tanks carry warning labels to alert the fill site crew of the manufacturer limitations, but in many cases these labels are not present or not readily visible to the fill site crew. Figure 4 below shows an example of this with a newly purchased (2020), poly tank equipped water tender.

Figure 4. New apparatus with poly tank but no warning labels.

In this example, the apparatus fill connections are identified by manufacturer-provided labels, and a county-specific capability placard is affixed, but there is no warning to the fill site crew regarding over-pressurization or filling at potentially damaging rates. Compounding the issue is that many water shuttle operations are likely to use water tenders of a variety of vintages and tank construction materials, many of which can be filled at rates exceeding those acceptable for poly tanks. Without clear warning labels or procedures that keep rates and pressures in a safe range, the fill crew will be hard pressed to prevent damage to poly tanks. There is, unfortunately, no requirement in NFPA 1901 or any other standard for providing these labels.

The classic rural water supply texts address water tender loading, emphasizing the importance of minimizing the time needed to do this. Davis (1987) does not address the issue of poly tank fill rates, while Eckman (1997) discusses the existence of tanks with fill rate limitations but does not mention poly tanks specifically. Davis strongly recommends the practice of filling water tenders from the top of the tank to speed the process even while admitting that from a hydraulic standpoint it should not matter from where the tank is filled. Contra Davis, Eckman condemns filling from the top as both unsafe and inefficient. Current best practices from the WSTAC likewise do not recommend filling from the top for the same reasons. Even so, the author still encounters fire departments using this technique, entirely convinced that it is faster because there is no need to "push up the tank water." There is a lack of awareness of the potential hazards involved in climbing on apparatus, even though there has been at least one entirely avoidable fatality in Ohio due to a fall from the top of an engine (National Institute for Occupational Safety and Health [NIOSH], 2009). The safest and most efficient way to load a water tender is by fill site crewmembers working with both feet on the ground, with no climbing on tailboards or apparatus tops. Water tenders that are not designed to support this can generally be modified with new direct tank fills or pipe extensions to existing fill ports (Eckman, 1994).

Given that for any water shuttle operation there is likely to be a mix of tank materials present, that many of these tanks could be damaged by excessive pressure or flow rates, and that these tanks may not be readily apparent to the fill crew, prudence seems advisable. Without a flow meter or pressure gage at the fill connection, fill site crew would need to rely on hydraulic calculations to stay within safe ranges. Assuming that in most cases supplying a water tender's fill ports is similar to an open hose butt flow situation, Sylvia's (1970) classic hydraulics text offers a means to calculate pump pressures that will maintain safe conditions. Sylvia's formula for open hose butt flow (p. 246) is:

$$GPM = 29.7d^2\sqrt{P}\,(0.90) \qquad (7)$$

Where:

GPM = gallons per minute flow

d = hose diameter (inches)

P = discharge pressure (psi)

Knowing the desired maximum fill pressure and rate (100 psi and 1,000 gpm for poly tanks), and the friction loss for the fill hose layout, the necessary pressure for the filling engine can be calculated using the following formula from the NFPA *Fire Protection Handbook* (Wieder, 2008):

$$FL = cq^2l \qquad (8)$$

Where:

FL = friction loss (psi)

c = friction loss coefficient (psi), specific to hose diameter and construction

q = flow rate (gpm/100)

l = length of hose divided by 100 (ft)

As an example of how this could be used in practice, consider the following scenario. A typical fill site organized according to WSTAC recommendations has a water supply engine pumping into the following hoselay:

- Engine to manifold: 5.0-inch x 100 ft
- Manifold to water tender: two parallel 2.5-inch x 50 ft

This scenario is designed to fill water tenders with double 2.5-inch fill ports and provides two fill stations via the manifold, though only one water tender is filled at a time (Figure 5).

Figure 5. Example of a WSTAC recommended fill site setup.

If the goal is to not exceed the maximum acceptable parameters for a poly tank of 1,000 gpm and 100 psi using two 2.5-inch fill ports while filling at the maximum rate allowable, then solving for equation 7 yields an outlet pressure of approximately 9.0 psi based on 1,000 gpm flow divided between two 2.5-inch fill lines (500 gpm per line). Friction loss for this hoselay using equation 8 and coefficients from table 13.3.8 of the NFPA *Fire Protection Handbook* (Wieder, 2008) is as follows:

- 5.0-inch x 100 ft at 1,000 gpm: 8 psi
- 2.5-inch x 50 ft at 500 gpm: 25 psi
- Manifold appliance: 10 psi
- Total friction loss: 43 psi

This would mean that a pump pressure of 52 psi should be used at the supply engine to maintain the desired pressure and flow at the water tender fill ports, theoretically maximizing flow while protecting any poly tanks. In practice, lower target flows and pressures would likely be used to create a margin of safety and limit potential damage to poly tanks.

Water tender offload performance.

The efficiency with which a water tender can unload its tank contents at the point of delivery is the most important factor in determining the time it will spend at the dump site. In the past, a variety of methods was used for unloading water tenders, including high-flow gravity dump chutes, jet-assisted dump chutes, and directly pumping the water from the tank. Modern water tenders unload by one of two means: gravity dumping via large-diameter chutes, and pressurized unloading for vacuum-type apparatus. Well-designed water tenders can quickly unload and continue to the fill site, whereas less efficient apparatus will linger at the dump site. It is important to understand the offload rate of all water tenders participating in a planned shuttle operation because this will be a large determinant of dwell time for the apparatus at the dump site (Davis, 1987; Eckman, 1994).

Water tenders that are compliant with the requirements of *NFPA 1901 Standard for automotive fire apparatus* must be able to offload through any transfer outlet at least 90 percent of tank contents at a rate of not less than 1,000 gallons per minute (gpm) (section 18.5.2.2) (NFPA, 2016). The NFPA 1901 standard, however, does not provide a method for testing and certification of offload rates. A recommended method for determining offload rates is provided in NFPA 1142 in annex section C.12 (NFPA, 2022) which appears to be based on much earlier work by Davis (1987), who details a similar procedure. The volumetric method described requires weighing the apparatus when full, then offloading for one-minute periods and re-weighing the apparatus each time. The change in weight is converted to the equivalent volume of water, with offload rates in gallons per minute then calculated.

The NFPA 1142 procedures provide a reasonable estimate of water tender offload rates but are not mandatory in nature, and therefore not in standard use by manufacturers or fire departments. For vacuum-type water tenders operating in pressurized mode, offload rates are consistent and may be directly measured by timing the complete emptying of the tank. The offload performance of gravity-type water tenders is more complex, with the rate decreasing as the tank empties and pressure head declines. This is an important consideration for gravity offloading as some part of the load cannot be efficiently unloaded as the rate declines. This phenomenon is accounted for in annex section C.10 of NFPA 1142, which considers ten percent of the load of gravity-type apparatus unusable due to this inefficiency, along with spillage and other losses (NFPA, 2022).

While the method recommended by NFPA 1142 provides reasonably accurate performance estimates, it has the disadvantage of inconvenience. In the author's experience, some fire departments are reluctant to commit the time and effort required of this procedure because the utility of the resulting information is not always well understood. Researchers working on the calibration of industrial storage tanks in Russia encountered similar issues with plant managers resistant to cumbersome volumetric methods (Nosach & Belyaev, 2001). Geometric methods were preferred by the plant managers as these required only external measurements of tanks to provide the desired estimates. Tanks in the real world, however, are not perfect geometric shapes, and instead have bulges, dents, and other imperfections that result in imperfect estimates using geometric methods. The recommendation of these researchers was that geometric methods could be used to generate reasonable estimates, but only if carefully calibrated based on detailed studies of real tanks, and with a minimum of shortcuts and assumptions. Similarly, the tanks on fire apparatus often have unique configurations due to notches, cut-outs, sleeves, and internal baffles and piping. Geometric methods may be useful in developing performance estimates for apparatus from reticent fire departments, but these estimates should be calibrated using empirical data from other apparatus when possible.

Beyond simple estimates of tank volume, understanding the performance of water tenders during offloading requires methods for estimating the rate of tank emptying (efflux) for apparatus for which empirical measurements are not available. Because unloading a water tender's tank using gravity is physically no different than efflux from any other tank, the methods of Bernoulli and Torricelli can be used to estimate the time required to empty the tank (Hickey, 2008; Linder, 2008; Sylvia, 1970).

The Torricelli equation is commonly used for solving the problem of efflux from a vertical cylinder with an orifice at the bottom. For tanks in which the liquid surface area does not change as the tank drains (i.e., those with straight, uncurved sides), and for which the liquid will be drained over the entire height of the tank, the following equation provides an estimate of efflux time (Crowl, 1992):

$$t = \left(\frac{S}{C \cdot A}\right)\left(\frac{2h}{g}\right)^{\frac{1}{2}} \quad (9)$$

Where:

t = total efflux time (s)

S = liquid surface area (ft^2)

A = cross-sectional area of drain orifice (ft^2)

C = discharge coefficient (unitless)

h = tank height (ft)

g = acceleration due to gravity (32.2 ft/s^2)

While the above equation is appropriate for some water tender tank configurations, many water tenders have tank configurations with curving walls. The Fire Apparatus Manufacturers' Association (FAMA) identifies the following tank shapes in common use on modern fire apparatus: rectangular, rectangular tee, elliptical, and elliptical tee (FAMA, 2018). These are all variations of horizontal cylinders, with the shape referring to the profile of the rear of the tank. In addition to these basic tank shapes, the author has also personally observed circular cylinder tanks on older apparatus. In all, five basic configurations can be used to describe most water tenders in operation (Figure 6, below).

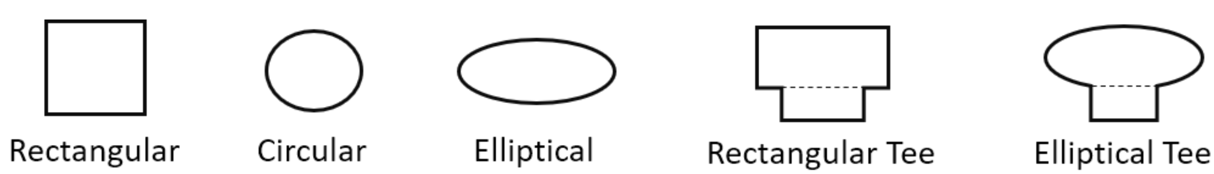


Figure 6. Water tender tank configurations as viewed from apparatus rear

Modified versions of the basic Torricelli equation have been developed to estimate efflux times for tanks with a liquid surface area that varies during emptying. This problem is of great interest in the chemical process industries where there is a need to understand efflux rates for variously shaped tanks, both for routine industrial purposes as well as for accidental releases (Sommerfeld, 1992). Modified Torricelli equations have been developed for a variety of potential tank shapes, to include annular and toroidal containers (Hart & Sommerfeld, 1995); spheres (Crowl, 1992; Hart & Sommerfeld, 1993) and conical, paraboloid, and ellipsoidal containers (Lee & Sommerfeld, 1994).

Of particular value to the problem at hand, specific equations have been developed for both circular and elliptical horizontal cylinders, both common tank shapes for water tenders. Circular horizontal cylinders are a common tank shape for many industrial applications, and modified Torricelli methods for these tanks were developed and refined by several researchers (Crowl, 1992; Hart & Sommerfeld, 1996; Sommerfeld & Stallybrass, 1992; Sommerfeld & Stallybrass, 1993). For circular horizontal cylinders, efflux time may be estimated using the following equation:

$$t = \frac{\sqrt{8} \cdot L \cdot D^{\frac{3}{2}}}{3A \cdot C \cdot g^{\frac{1}{2}}} \qquad (10)$$

Where:

t = total efflux time (s)

L = tank length (ft)

D = tank diameter (ft)

A = cross-sectional area of drain orifice (ft^2)

C = discharge coefficient (unitless)

g = acceleration due to gravity (32.2 ft/s^2)

Methods for estimating efflux times for elliptical horizontal cylinders have less widespread industrial application but are of some importance to the textile dyeing industry, which makes common use of such tanks (Sommerfeld, 1990; Sommerfeld & Hart, 1996; Sommerfeld & Stallybrass, 1991). For elliptical horizontal cylinders, efflux time may be estimated using an equation that is closely related to the one presented above for circular cylinders:

$$t = \frac{\sqrt{8} \cdot a \cdot L \cdot (2b)^{\frac{3}{2}}}{3A \cdot C \cdot b \cdot g^{\frac{1}{2}}} \quad (11)$$

Where:

t = total efflux time (s)

a = semi-major axis (one-half of tank width) (ft)

L = tank length (ft)

b = semi-minor axis (one-half of tank height) (ft)

A = cross-sectional area of drain orifice (ft^2)

C = discharge coefficient (unitless)

g = acceleration due to gravity (32.2 ft/s^2)

The set of equations above (9, 10, and 11) can provide reasonable efflux time estimates for three of the common water tender tank configurations described in Figure 6, above: rectangular, circular, and elliptical. Such formula-based methods have been tested experimentally and found to provide very reliable estimates (Joye & Barrett, 2003; Reddy &

Subbarao, 2011), suggesting that their application to the problem of water tender performance is a reasonable approach.

The case of the two tee-tank configurations presents an additional dimension of complexity. While specific literature addressing these tank configurations was not found, the author believes that efflux times for such tanks can be estimated using combinations of the three equations presented above. For tee-tanks, the bottom section is essentially a trough that can be treated as a small rectangular tank. Thus, for rectangular and elliptical tee configurations, overall efflux time may be estimated by summing estimates for the upper and lower sections.

Each of the Torricelli-derived equations described above include the discharge coefficient C. This coefficient is meant to account for friction losses due to disruption of laminar flow at the discharge orifice and is the same as Sylvia's (1970) coefficient of discharge, which that author annotated as C_d (p. 52). This coefficient is familiar to firefighters as it is used in hydrant flow testing (Linder, 2008). An essentially similar coefficient is used to account for friction loss in hoselines (Wieder, 2008), although in this case it is accounting for the lack of smoothness particular to the construction of a given section of hose. The discharge coefficient is in some respects a catch-all for any factors that reduce observed flow rates below a calculated value for a theoretically frictionless system. For flow through orifices, values for C typically range from 0.60 (high friction loss) to 0.99 (very low friction loss) depending on the configuration of the outlet (Linder, 2008; Sylvia 1970). In the case of efflux from water tenders, the discharge coefficient is not only accounting for turbulence at the dump valve. This coefficient may also be thought of as accounting for any other factors particular to a given apparatus that might restrict flow, such as tank baffling or inadequate venting. With careful testing, it is likely possible that these various constituent factors could be teased out to improve apparatus design, but at present this level of granular detail is not yet available.

Safety considerations in water tender design.

Part of the reason for the poor safety reputation of water tenders likely stems from the fact that historically many of these apparatus were indeed poorly designed, locally fabricated, and repurposed from other uses. These efforts to save money resulted in many unsafe vehicles, many of them far over their weight ratings and lacking adequate brakes and suspension (Stewart, 2008; USFA, 2003). As these older home-made water tenders have gradually aged out of the fleet, modern, purpose-built apparatus have taken their place. While a non-negligible number of old and unsafe water tenders remains in service, the poor safety reputation of these is not applicable to a modern apparatus that is compliant with the NFPA 1901 standard (NFPA, 2016).

Water tender design may be thought of as a tradeoff of competing priorities: the need to maximize tank capacity versus the need to produce an apparatus within a safe design envelope. A safe and road-legal vehicle can only be so tall, so wide, and weigh so much and still be within practical design parameters. In Ohio, fire service apparatus must abide by dimensional and weight limits established in state law and regulated by the Ohio Department of Transportation (ODOT). Specifically, vehicle height is limited to a maximum of 13.5 feet, while width is limited to 8.5 feet (excluding side mirrors). The width of straight trucks is generally limited to 50.0 feet, while tractor-trailer combinations generally may not exceed a total length of 65.0 feet (ODOT, 2019).

Available truck chassis for fire apparatus are bound to follow the ODOT standards pertaining to maximum vehicle dimensions. To maximize water carrying capacity, this means increasing the height, width, and length of the tank while keeping the overall vehicle within acceptable limits. Most fire apparatus (and commercial trucks, for that matter) are built to the maximum allowable width, with water tank width generally close to the overall vehicle width. Adding length to an apparatus to accommodate a longer tank is possible but will eventually require an additional rear axle (or moving to a tractor-trailer design). This leaves adding height up to the allowable maximum as a common option for increasing tank volume. Even within a nominally safe design envelope, this produces vehicles that have a high center of gravity. This coupled with the poor condition of many rural roadways creates a situation where drivers must be continually on guard to avoid serious mishaps (USFA, 2003).

The potential for rollover incidents is an issue for tank trucks of all kinds, not just fire department water tenders. Echoing the USFA report, research on commercial tank trucks also identifies driver error as the principal contributing factor in rollover accidents. Pape et al. (2008) identified driver error as the principal cause of 75 percent of rollover accidents studied, and excessive speed contributed to 52 percent of rollovers. Research on tank truck rollover incidents in Kansas and Nebraska similarly found driver error to be a dominant contributing factor (Iranitalab, Khattak, & Bahouth, 2020). These studies further demonstrate that while tank trucks are a challenging class of vehicle to drive, they are not inherently unsafe, even on rural roadways. As Davis (1987) points out, thousands of commercial tank trucks travel rural roads all day, every day with rollover accidents being very uncommon. The issue with water tenders is probably more that the drivers lack the day in, day out familiarity of handling these vehicles that drivers of dairy, fuel, and other commercial tank trucks develop from years of practical experience.

While driver training is an appropriate focus for risk reduction, any technical improvements to the design of water tenders that assist drivers are also worthy of investigation.

Technological advances such as electronic stability aids are helpful but are not a panacea for the prevention of rollovers. Such devices are only effective when drivers understand their limitations. Beyond technological solutions, minor design changes can have outsize effects in terms of vehicle stability. Selecting tank shapes with a lower center of gravity can greatly improve stability. Even something as simple as using lower-profile tires can lower the center of gravity enough to significantly improve stability (Pape et al., 2008).

A major difference between commercial tank trucks and fire department water tenders is that commercial trucks are often driven partially loaded, creating potential for liquid slosh that increases the chance of a rollover (Yu & Chu, 2019; Zheng, Zhang, Ren, Wei, & Song, 2017). During a water shuttle, water tenders are generally only driven when completely full or empty, minimizing potential slosh risk. Modern water tenders built to NFPA 1901 requirements are also extensively baffled, and even many older apparatus have been retrofitted with baffles (NFPA, 2016). Commercial tank trucks used for food products are generally not baffled for sanitary reasons, and so are not directly comparable with fire department water tenders.

The shape of the tank contributes to vehicle stability: tank shapes producing a lower center of gravity for a given volume are more stable. Elliptical tanks are more stable than a circular tank of equivalent volume, for example (Shojaeefard, Talebitooti, Satri, & Amiryoon, 2014). The most stable potential tank shape was found to be the Reuleaux triangle, an upright triangular shape with rounded edges (Kolaei, Rakheja, & Richard, 2014). Uptake of this configuration by fire departments seems unlikely, however, in that while inherently safer, it carries many of the disadvantages of other non-rectangular tanks in terms of limited volume and compartment space (Keller, 2021).

Dwell Time: Operations at the Fill and Dump Sites

Actions at the fill and dump sites constitute the dwell time components of a water shuttle operation, contrasting with the navigation time incurred by water tenders moving between the two sites. While activities at the fill and dump sites are of a different character, the two sites also share several common characteristics in terms of traffic flow and safety concerns. In the author's experience, improving efficiency at these sites tends to be the primary focus of training on water shuttle operations perhaps at the expense of other components that may yield greater efficiencies.

Fill site operations.

For a given water shuttle operation, the fill site is the designated location where water tenders are loaded. In most cases, there is a single fill site, although multiple fill sites are sometimes used. The fill site can be based on any competent source of water supply including both pressurized and static sources. Typical water supply sources include pressurized municipal hydrants, and dry (suction) hydrants emplaced in lakes, ponds, streams, or cisterns. Other more exotic sources are also sometimes used such as irrigation wells or swimming pools, all of which depends on the needs and resources available to a particular jurisdiction. The water source must be both physically and legally accessible by the fire department (NFPA, 2022; Stewart, 2008). Fill sites may be planned in detail or may be ad hoc affairs established in the heat of an incident.

Davis (1987) limits his discussion of fill site design to a few paragraphs. While all of Davis' recommendations on this subject are valid, they are also a product of an earlier era when the fundamentals of water shuttle operations were still forming. Davis does provide a very useful breakdown of the tasks that must be performed to fill a water tender. Of note, he emphasizes the need to consider not just the physical filling of tank, but all the supporting tasks needed to make this happen. Davis breaks the loading of a water tender at the fill site into three distinct phases: fill preparation time (FPT), fill time (FT), and fill breakdown time (FBT). Fill time represents the time required for the physical filling of the water tender's tank. Time required for this will depend on characteristics of the apparatus as well as procedures and equipment used by the fill site crew, for example: hose size and fill pressure and rate. The FPT phase includes all actions preliminary to flowing water into the water tender, notably connection of the fill lines. The FBT includes all actions necessary to get the loaded water tender on its way, such as disconnection of fill lines. Although Davis discusses the opening and closing of tank vents as a time cost in some detail, this activity is not generally necessary with modern apparatus. Perhaps the key takeaway from Davis' discussion on fill site tasks is that the time required for supporting actions in the FPT and FBT phases is non-negligible, has the potential to add significantly to dwell time, and should be studied carefully to identify potential efficiency gains.

Writing a few years later, Eckman (1994) devotes an entire chapter to the topic of fill site layout and operations. While Eckman does not provide the sort of granular task analysis of Davis (1987), he does specify a model staffing structure for the fill site. Many of Eckman's recommendations remain relevant today, and there is an obvious affinity present in current WSTAC training materials even as these concepts have evolved over time with experience and improved technology (Keller & Collet, 2017). Eckman recognized that while fill sites may vary in their specifics, there were some things common to all of them. A dense network of fill sites reduces the average shuttle route distance and fill sites should be planned in advance whenever possible. Fill sites should have two "loading stations" so that a second water tender can be prepared for filling while the first one is being filled. The fill site crew, led by a fill site officer, should control all activities at the fill site including apparatus movement. Most germane of all, Eckman pointed out that the flow rates generated at the fill site will always exceed what is delivered to the dump site due to systemic losses of flow in the shuttle system.

Although there are many site-specific variables that can necessitate changes to basic design, the key elements of a safe and efficient fill site as taught by the WSTAC are:

- One-way traffic flow: the need for backing is eliminated whenever possible
- Ground guides: while in the designated fill site area, water tenders move only under the direction of the fill site crew (spotter or ground guide)
- Pit crew approach: the water tender is serviced by the fill site crew while the apparatus driver remains in the cab

Designing fill sites to allow for unidirectional flow of water tenders promotes both efficiency and safety. Any time fire apparatus are required to perform a backing maneuver, a hazard is created for ground crew operating nearby. This is a topic of such concern that the NFPA 1451 *Standard for a fire and emergency service vehicle operations training program* requires that the operation of apparatus in reverse is to be eliminated "whenever possible" (NFPA, 2018, para. 8.1.2). Backing maneuvers are also slow to perform, adding to the water tender's dwell time at the fill site.

Figure 7 below shows a generic fill site layout as promulgated by the WSTAC. This layout is an evolution of Eckman's (1994) recommendations. Typically, an engine company is assigned to operate the fill site. The engine pumps water to a manifold (or wye) appliance through a section of large diameter hose. From the manifold, sections of 2.5-inch hose are laid out to two fill stations, with either one or two supply lines going to each station. Water tenders are maneuvered into these two stations and connected to the fill lines, although only one is actually filled at a time to provide all flow to that tender.

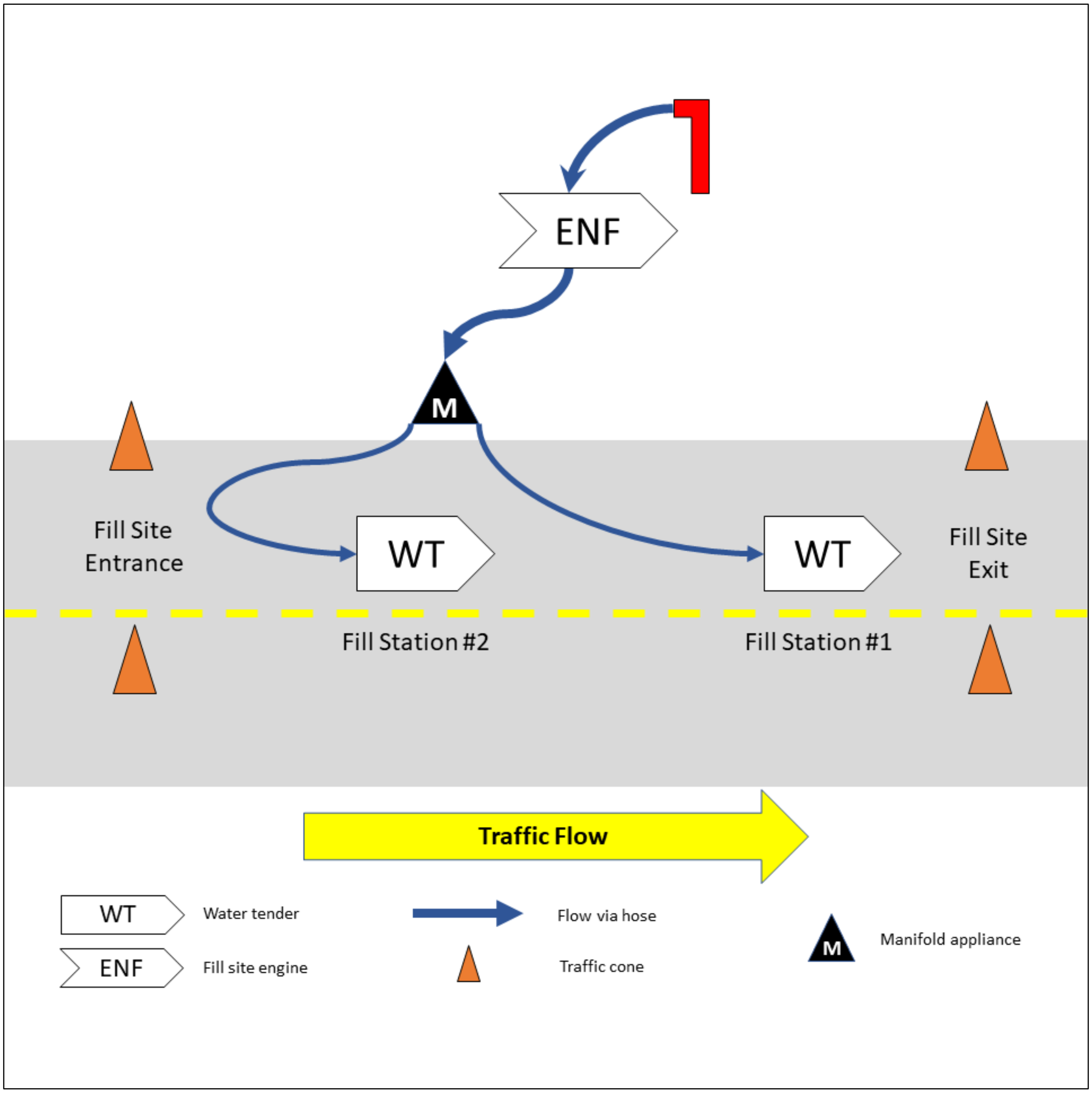


Figure 7. Standard WSTAC fill site layout.

In the rural environment, water sources may be located distally to the desired location for filling water tenders making unidirectional traffic flow difficult to maintain without some planned modifications. For example, a dry hydrant may be located down a long, narrow farm lane some distance from a paved road. Such a situation would require water tenders to not only negotiate a narrow, unpaved lane, but also to perform backing maneuvers to turn around at the hydrant location. Such scenarios emphasize the need to plan fill sites in advance rather than improvising during the incident. In such cases, it may be possible to develop a fill site plan wherein a lay of large diameter hose is used to transfer water from the hydrant, down the lane, and into a manifold for water tender filling, thus bringing the water to the tenders at a safe loading location (Eckman, 1994). Likewise, not every potential water source represents a safe choice for development as a planned fill site. A water main extended down a rural highway may have hydrants placed at regular intervals, but each hydrant is not necessarily a valid basis for a fill site even if it provides a high flow rate. Hydrants that are situated without room for the fill site crew to operate safely separated from roadway traffic should be avoided in favor of hydrants with adequate operational space. This may result in a tradeoff between a potentially longer shuttle and a better designed fill site.

The optimal size of the fill site crew is the matter of some discussion. Eckman (1994) recommends a crew of the following: a fill site officer, a pump operator, a traffic control officer, a safety officer, and an unspecified number of hose handlers, for a total of at least five personnel (he also calls for an unspecified number of crew members to open tank vents, but this is an obsolete requirement today). Figure 8 below shows an example of a three-person fill crew at a training exercise attended by the author. The engine company assigned to the fill site in this case was well-drilled in fill site tasks and could handle the assignment without issue. This is unlikely to be the case for many departments, however, and realistic performance expectations should be maintained. Water shuttle training exercises may convey a false sense of adequacy to many participants when it comes to fill site staffing. At these exercises, there are normally ample hands to cover all fill site tasks. During an actual incident, the fill site will be competing for staffing with fire suppression operations and is likely to have a lower priority. In the rural setting, this may leave a fill site crew with only three personnel, or perhaps only two. This will mean that crew members will need to perform multiple functions and cannot do these simultaneously. A crew member cannot direct water tender movements and connect fill lines at the same time, for example. Low staffing will necessarily increase dwell time at the fill site, and low crew proficiency will compound this. Fire departments should train for realistic conditions of minimal staffing and adjust expectations accordingly.

Figure 8. Fill site operated by a crew of three.

To compensate for low crew staffing and proficiency, every effort should be made to standardize and simplify operations. Reaching agreement on a standard fill port coupling for a county or other mutual aid area would allow standardization of procedures. Adopting a quickconnect or sexless coupling for this standard could further streamline operations (Eckman, 1994). Development and fielding of a standardized complement of equipment for all engines in a mutual aid area likely to be assigned fill site duties would also be valuable.

A myopic focus on reducing the time required to fill a water tender's tank may result in underestimating the time required to perform the necessary preliminary tasks, as noted by Davis (1987). While using two parallel fill lines will indeed reduce the time required to fill the tank, the work of connecting and disconnecting the second fill line incurs additional time costs as well, particularly in a low-staffing environment. In an informal time study at a water shuttle exercise, a member of the WSTAC observed this dynamic first hand. In low-staffing scenarios where all fill lines were connected and disconnected by a single crew member, using two fill lines actually increased the dwell time for a water tender due to the additional time needed for the lone individual to make and break the extra hose connection (E. Collet, personal communication, June 30, 2021).

Dump site operations.

The dump site is the point of delivery for the water tenders' cargo and is typically located proximally to the fire or other incident scene. As is the case with fill sites, it is possible for an incident to have multiple dump sites, but in general, all water is delivered to a single designated point. Generally, the dump site uses one or more portable tanks to receive the water and is supported by one or more engine companies. As a general concept of operations, water tenders transfer water to the portable tanks, while an assigned engine company relay pumps this water to the fire scene for use by attack engines. If multiple tanks are used, water is delivered to support tanks, while the relay engine drafts from a primary tank. In such cases, provision must be made for the operation of jet siphons to transfer water from the supporting tanks to the primary tank.

The jet siphons may be operated by the relay engine, or by additional engines assigned to the task. A multiple tank arrangement is often the final stage of dump site setup, with the site progressing through transitional stages that may include water tenders directly nursing an engine, tenders supplying an engine via a large diameter hoselay and clappered siamese appliance, and single-tank setups (Davis, 1987; Eckman, 1994).

As was the case with fill site design, Davis (1987) offers only limited discussion on the topic of dump site layout but does provide a granular breakdown of tasks necessary to unload a water tender. Paralleling the fill site, Davis divides water tender dwell time at the dump site between the physical offloading time (OT) and the supporting phases of offload preparation and breakdown time (OPT and OBT). Supporting tasks at the dump site include maneuvering water tenders into and out of position to offload and the operation of transfer (dump) valves. While the OT component is entirely dependent on the physical design of the water tender, time required for OPT and OBT components are influenced by apparatus design, layout of the dump site, and ground crew staffing and proficiency. Davis again warns that failure to realistically consider the contributions of OPT and OBT to dump site dwell time will result in unrealistic expectations of shuttle throughput.

Eckman (1994) offers a more detailed discussion on dump site design and operations, and many of his observations remain relevant today. Best practices promulgated by the WSTAC echo many of Eckman's recommendations. The WSTAC promulgates the same general principles for dump sites as it does for fill sites: one-way traffic flow, ground guides, and a pit crew approach. These general rules are believed by the WSTAC to be the best approach to maximizing efficiency and minimizing safety hazards at the dump site. While specific implementation will vary from site to site, they serve as the core basis for site layout and operations (Keller & Collet, 2017). A generic dump site layout incorporating these principles is shown in Figure 9, below.

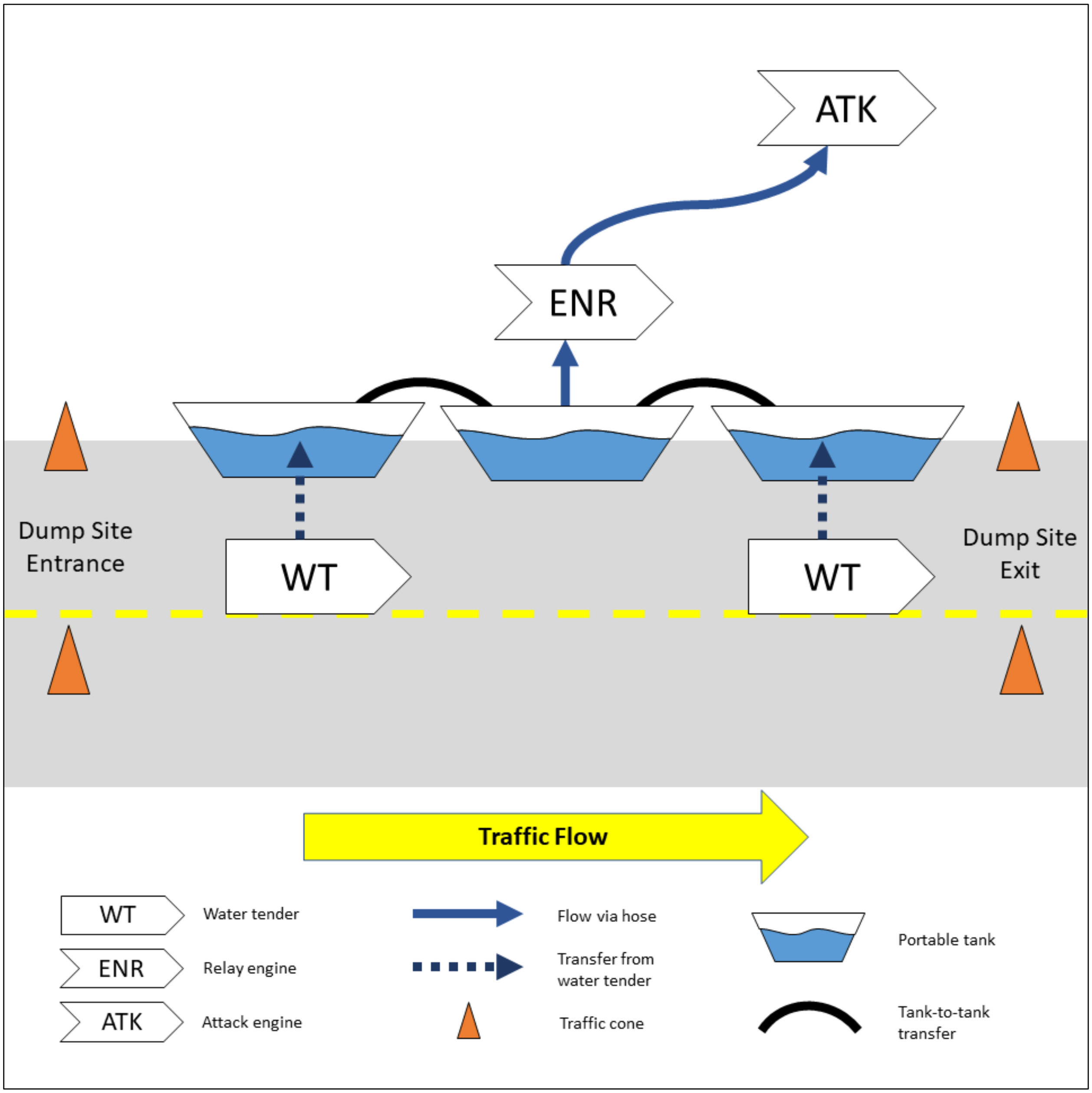


Figure 9. Standard WSTAC dump site layout.

The principle of one-way traffic flow can sometimes be complicated by older or poorly designed water tenders. Although modern water tenders compliant with NFPA 1901 must be capable of offloading to the rear and both sides (NFPA, 2016, para. 18.5.2.1), older apparatus may only be capable of offloading to the rear. Without adaptation, these water tenders require backing maneuvers to unload, an avoidable drag on safety and efficiency that has been discussed for decades. Both Davis (1987) and Eckman (1994) grappled with this problem in their texts. In most cases, these legacy apparatus can be either permanently modified to allow side dumping or equipped with custom fabricated adapter to allow for it (Figure 10). Such adapters are generally simple and low cost, but their use will increase dump site dwell time in two ways. The 90-degree bend required will create more turbulent flow, thus reducing the water tender's effective discharge coefficient *C*, and thereby increasing overall unloading time. Depending on the adapter's design, it may need to be attached and detached with each visit to the dump site, adding to dwell time (Keller, 2021).

Figure 10. Water tender with adapter to allow side dumping.

The layout of the dump site must also accommodate the space requirements of the portable tanks and the supporting relay engine. Portable tanks especially can have a large footprint once deployed. Standard tanks in the commonly-used capacity range of 2,000 – 2,500 gallons have the shape of squares with sides that are 11 to 13 feet long. Because these tanks must be deployed on ground that is as flat as possible, they can take up substantial space needed for other purposes. This is a particular issue for roadside deployments, since the tanks may take up most of the trafficable width of many rural roads, which may have no flat ground at the shoulders. One technological solution for this problem has been the development of portable tanks with narrow profiles. These tanks have the same volume as a traditional square tank but are rectangular in shape and have a width of approximately eight feet. Deployed in line with the engine, and using a 90-degree elbow suction adapter, these tanks can ease congestion in roadside dump sites (Figure 11). Examples include the "Single Lane Type II" tank by Fol-Da-Tank (Fol-Da-Tank Single Lane Tank Type II website, n.d.) and the "Skinny Tank" by Husky (Husky Skinny Tanks website, n.d.). While these tanks have the potential to greatly improve dump site operations in rural settings, the author has not observed widespread uptake or awareness of them among fire department personnel in Ohio. Even when informed about their benefits, in each case fire department leaders have blanched at the expense and are unwilling to replace existing, functional square tanks.

Click or tap here to enter text.

Figure 11. Narrow profile portable tanks.

As with fill site staffing, there is little agreement as to what constitutes optimal or adequate numbers for fill site crew. Also as with fill sites, the dump site is likely to be staffed by a single engine company in most rural areas, and minimal staffing will likely be the rule. Davis (1987) is silent on the subject of staffing. Eckman (1994) recommends the following staffing model for the dump site: a dump site officer, a pump operator, an unspecified number of hose handlers and vent crew members, one or more traffic control officers, and a dedicated safety officer. This level of staffing would be considered luxuriant in most rural settings, where the dump site will be competing for staffing with fire suppression operations and the fill site. The author has observed that a crew of three is a workable minimum, although greater efficiency and safety accrues with additional staffing. Just as is the case with fill site operations, those attending water shuttle training exercises may develop a false sense of what is possible due to the many students on hand to assist with dump site tasks. Fire departments in rural areas would be well served to train with more realistic levels of staffing for dump site crews and adjust operational expectations accordingly. As is the case with fill sites, every effort should be made to simplify and standardize dump site operations across a mutual aid area as a means to compensate for inadequate levels of staffing and proficiency.

Safety considerations at the fill and dump sites.

The fill and dump sites are busy operations occurring in areas of restricted maneuverability. Multiple moving apparatus are mixed with pedestrian workers on the ground. Noise, distraction, poor footing, and lighting issues often complicate operations. Combine this with zones of poor visibility around the apparatus for the water tender driver, and there is great potential for serious mishaps. The risks inherent in fill and dump site operations have been personally observed by the author and other WSTAC committee members, and such risks are briefly mentioned by Eckman (1994) and in the USFA report on water tender operations (USFA, 2003), although only general guidance on mitigation is offered in both cases. Eckman does, however, recommend the assignment of dedicated safety officers to both the fill and dump site if possible.

While safety concerns at the fill and dump site are not well represented in the fire service literature, similar circumstances exist for highway construction work zones and the topic has been addressed by that industry. In a review of the state of research in work zone fatality prevention, Fan, Choe, & Leite (2014) describe an environment at highway work sites that has many similarities to conditions at water shuttle fill and dump sites. The authors recommended the development of internal traffic control plans (ITCP) for each work site as a means of reducing potential mishaps. An ITCP details a traffic flow plan for the site with an emphasis on eliminating the need for backing whenever possible and mandating the use of spotters when backing cannot be eliminated. The development of an ITCP for each potential fill or dump site may seem unduly burdensome for a fire department, but the use of standardized layouts whenever possible would greatly simplify this process. Only sites not suited to a standard design would require specialized planning. Fill and dump sites following a standardized design and using standard procedures would also be more familiar to ground crew and apparatus drivers.

The authors of this study also discuss the importance of developing standardized symbology for use in ITCP documents and site signage (Fan et al., 2014). While this seems like a simple concept, it should be noted that there is likewise no standardized symbology for water shuttle operations. A common symbology would help to standardize not only fill and dump site plans, but also create consistency among training materials and pre-incident planning documents.

Any opportunity to standardize operations and improve clarity would be beneficial in preventing accidents during water shuttle operations.

The authors further warn against the tendency to rely too heavily on technological solutions to safety issues. Innovations such as back-up cameras and proximity sensors are certainly helpful, but they are not foolproof. Such devices should be viewed as adjuncts to fundamental safety controls such as operator training and spotter discipline. A simple, low-tech measure such as using traffic cones to clearly demarcate areas where vehicles may only move under the control of ground guides are highly effective (Figure 12). But such measures require affective change and buy-in among both drivers and ground crew to be effective (Fan et al., 2014).

Figure 12. Traffic control at a dump site operation.

A specific hazard at the dump site is the danger of ground crew becoming pinned between water tenders and portable tank frames. This situation is largely eliminated by mandating side dump layouts, thereby eliminating the need for backing maneuvers. But the situation can still occur during side dump operations. This happens when ground crew need to manually activate dump valves on the side of water tenders and the apparatus has pulled up too far, creating a temptation to squeeze into the gap to reach the operating handle. Eckman (1994) specifically warns against such hazards, and it is part of the reason for his recommendation for a dedicated safety officer at the dump site.

As discussed earlier in the section on water tender design, members of the ground crew should not be climbing on apparatus during operations at the fill site or dump site. Climbing onto the apparatus top, or even onto a tailboard, creates a fall hazard. This hazard is compounded when spilled water creates treacherous footing. As a rule, all ground crew support activities should be done with both feet on the ground. Apparatus that must be climbed onto by ground crew for servicing should be removed from water shuttle operations or modified to eliminate this need if possible.

Other safety concerns at the fill and dump site include environmental conditions and working with pressurized hoselines. Water shuttle operations may be required in any season and at any time of day, therefore some thought should be given to potential environmental hazards. Water spillage at fill and dump sites is ubiquitous, and during winter months this can lead to ice formation and poor footing. Ground crew members should wear safety footwear, and consideration should be given to carrying sand or salt on assigned engines to improve footing. During nighttime operations provisions should be made to provide adequate scene lighting to improve visibility. While members of the fill site crew probably do not need full structural firefighting personal protective ensembles, working with pressurized hoselines and appliances means that the wear of head, eye, hand, and foot protection is warranted. Since fill and dump sites are likely to be located along public roads in many cases, the wear of reflective vests must also be considered (Keller & Collet, 2017).

Queueing Considerations

The phenomenon of water tenders lined up and waiting to be serviced at the fill or dump site is a common occurrence at water shuttles. Although Davis (1987) does not address the subject, Eckman (1994) addresses the issue of water tenders queueing to await service as discussed above (Equation 6). While Eckman does address the impact of this additional time cost on throughput and opines as to reasons that such bottlenecks might occur, he does not provide a means to estimate the amount of waiting time to expect.

Many manufacturing and transportation processes face a similar dynamic of bottleneck formation. Although it has a linear rather than cyclical form, a manufacturing assembly line has similar characteristics to a water shuttle operation. Products move from station to station for processing, with the travel time between stations serving as a sort of temporal buffer to allow time for the next station downstream to become open. When the downstream station is unable to clear earlier units quickly enough, a bottleneck appears just upstream of that station with units queueing to await their turn (McCormick et al., 1989). In the manufacturing industry, much effort has been expended to develop effective control systems to avoid these bottlenecks (Bonvik, Couch, & Gershwin, 1997). For a water shuttle, the travel time between the fill and dump sites can be thought of as a temporal buffer in much the same way as the time between processing stations on an assembly line. As the time to process water tenders through the fill and dump sites increases, the temporal buffer begins to fill up. At some point the buffer is full and water tenders begin to line up waiting to be serviced.

In a study of garment production lines, the authors noted the impact of worker proficiency on the development of bottlenecks at production stations on the line. Differences in operator skill level were found to increase or decrease time required to clear a station by up to 40 percent from a standard value. Amount of staffing was found to have similar impacts, although the effects were not as well quantified. The authors noted that in a production line setting, maximizing throughput for each production station was the key to preventing queueing in the overall process (Cassandras & Ho, 1983). Similar impacts are seen in water shuttle operations, where short-staffed crews or crews with low proficiency simply take longer to process water tenders through the fill and dump sites. Even if these crews are giving a full effort, a lack of proficiency will result in more fumbling and an overall lack of smoothness in task performance. A smaller crew simply has fewer hands available to accomplish the work, meaning that tasks that could otherwise be performed simultaneously must instead be performed sequentially.

In addition to crew staffing and proficiency levels, the impact of resource saturation must also be considered on queueing. Even a short-staffed, low proficiency dump or fill site crew can manage a certain amount of throughput at their station. Their shortcomings only become an issue when the number of water tenders needing service begins to overwhelm their performance capacity. The same is true of adequately staffed, high proficiency crews; the impacts just occur at a higher level of water tender assignments. In a study of container port operations, port throughput shortcomings became apparent as the shipping industry moved to larger vessels requiring more quay cranes for loading and unloading containers. Preventing the queueing of cargo vessels awaiting service was found to be possible by increasing the number of cranes and supporting equipment, and by developing more efficient traffic flow patterns (Roy & de Koster, 2018). Similarly, increasing crew staffing and efficiency is the only way to avoid backlogs at the dump and fill sites as demand for service increases.

Surges in demand for service can also lead to queueing. In a study of congestion at airports, it was found that competition among airlines for access to a limited number of gates during desirable times created bottlenecks, especially when weather further complicated operations. This congestion during peak hours had residual effects, as it tended to continue impacting operations even during less popular hours (Peterson, Bertsimas, & Odoni, 1995). This same situation occurs with road traffic during rush hour. Road networks become severely congested during peak hours, and the effects of this congestion can linger into non-peak hours. The same road network could easily handle the same volume of traffic if it were more evenly spread throughout the day, but focused demand results in transient bottleneck formation (Small, 2015). A similar dynamic can occur during water shuttle operations, particularly at the dump site. If several water tenders arrive to the shuttle simultaneously, all reporting to the dump site, a transient queueing situation could develop as the dump site crew is overwhelmed by the sudden influx of resources. Such a situation could have cascading effects, as the congestion impacts other water tenders already in the shuttle.

Eckman (1994) emphasizes the impact on the overall water shuttle that time spent waiting for service by water tenders can have, and this is supported by observations in the field. While the problem of bottlenecks and queueing is not unique to water shuttle operations, finding exact cognates in other industries seems unlikely. However, there are still valuable insights to be gained in works from these other fields that may point to developing effective methods for estimating potential queueing time during a water shuttle.

Decision Support Systems

A decision support system (DSS), sometimes called an expert system, is an automated tool used by managers to apply a consistent assessment process to various proposed courses of action. The purpose of a DSS is to support a managerial decision-maker and improve their effectiveness by making a large body of information available in a more organized and understandable format. These systems are not intended to replace the decision-maker, but rather to supplement intuition and experience with data presented in a meaningful format. A DSS consists of three basic elements: a database, a model, and a user interface (Rashidi, Ghodrat, Samali, & Mohammadi, 2018).

Development of a DSS for water shuttle operations planning would be helpful to prospective incident commanders by providing realistic estimates of potentially available water supply at crucial points. A mathematical model for tank trucks hauling sewage to a central holding facility was developed by Kuwaiti researchers (Aleisa, 2008). This model formed part of a DSS that helped managers to recognize bottlenecks impacting throughput, allowing for the minimization of queueing to unload. Similar results could be expected for a purpose-designed model for water shuttle operations. Development of a DSS does not necessarily require specialty software. Researchers in Indonesia were able to successfully model a complex system of gasoline delivery to filling stations by a fleet of tank trucks using only Microsoft Excel (Surjandari, Rachman, Dianawati, & Wibowo, 2011). Similarly, development of a DSS for water shuttle planning would not necessarily require major expenditures on specialty software and could be helpful in developing and testing operational plans.

Any DSS developed for water shuttle planning would benefit from the inclusion of GIS functionality but would also require a mathematical component that effectively captures performance characteristics of the water tenders, the dump site, and the fill site. The benefits of such combination systems – called Spatial Decision Support Systems (SDSS) – were noted in the discussion of parallels with the municipal solid waste collection industry above (Kim et al., 2006; Sulemana et al., 2018), and this is true for many VRP situations. In a study of delivery truck routing in Tunisia, efficiency was improved by using a combination of GIS and mathematical algorithms to optimize routes (Faiz, Krichen, & Inoubli, 2014). In a related Tunisian study, the authors were able to use a SDSS to not only identify optimal routing solutions, but to also recommend an optimized fleet in terms of vehicle performance and capacity (Tlili, Faiz, & Krichen, 2013). In a summary of SDSS research, this same Tunisian research group noted that there is no single software solution that will work for all industries. The structure of the GIS model, the related mathematical model, and the degree to which these two components are integrated must be tailored to each industry and specific application (Krichen, Faiz, Tlili, & Tej, 2014).

No model is a perfect replica of reality, and mathematical models should be used to provide insights more than precise numbers (Cassandras & Ho, 1983). The development of a SDSS for planning and assessment of water shuttle operations could help to provide realistic if conservative estimates of likely throughput for the prospective incident commander. It could also help to identify potential inefficiencies in existing or planned operational arrangements. Finally, such a system could be developed using existing software, and would not necessarily require major investments in specialized applications or training for coding proficiency.

Procedures

An evaluative approach was used to answer the project's research questions. The general focus of this research was gathering sufficient information about existing fire apparatus, water supply infrastructure, and road networks to support the development of a two-phase model of water shuttle operations. The two phases are meant to simulate the response (resource concentration) and shuttle (steady state) phases of a water shuttle operation. This model is intended to serve as the basis for a decision support system (DSS) to assist prospective incident commanders to understand what potential water supply is realistically available in the study area.

The response phase of the model uses geospatial information systems (GIS) network analysis techniques to estimate apparatus response times to potential incident assignments. The GIS results are used by spreadsheet tools to determine optimal assignments to different incident roles. Design of shuttle routes was also done using GIS tools, with all calculations needed to estimate final throughput values also done using spreadsheet tools. The overall model may be thought of as residing in a spreadsheet, with the GIS component providing inputs for the calculations. All processes are described in detail in the sections below.

The essential water shuttle throughput calculations use as combination of the methods of Davis (1987), Eckman (1994), and NFPA 1142 (NFPA, 2022). Shuttle throughput is the sum of the throughput of all participating water tenders, calculated as shown in Equation 12, below.

$$Q = \frac{(V \times k)}{(TR + TF + TD + TW)} \tag{12}$$

Where:

Q = Throughput of subject water tender (gpm)

V = Rated capacity of water tender tank (gallons)

k = Coefficient of usable tank capacity (per NFPA 1142)

TR = Route navigation time (minutes)

TF = Fill site handling time (minutes)

TF = Dump site handling time (minutes)

TW = Queueing time (minutes)

As an aid to the reader, a compilation of all variable notation used in the model is provided in Appendix A.

The geospatial aspects of this project were primarily conducted using the ArcGIS Pro platform (ArcGIS Pro Version 2.9), with some supplemental imagery work performed using Google Earth Pro (Google Earth Pro Version 7.3.4.8248). The calculations for both model phases were performed in Microsoft Excel (Microsoft Excel for Microsoft 365 Version 2110). Significant preparatory work was necessary to bring underlying infrastructure data into a usable format. This work was not part of the primary research objectives but was necessary to complete the project and is described briefly in following sections for completeness.

Study Area Characteristics

The study area for this project is the unincorporated area of Harrison Township in Logan County, Ohio (Figure 13). Harrison Township lies to the west of the City of Bellefontaine and is a largely agricultural area characterized by low population densities. This is an area dominated by agriculture comprising 22.84 square miles. As of the 2020 census, the study area has an estimated population of 1,617, with a population density of 70.8 per square mile (U.S. Census Bureau, 2021). The study area includes a total of 694 addressed premises, of which 603 are residential. Structures comprising a large residential summer camp (YMCA Camp Willson) account for 45 of the total premises. The remaining 46 premises are a mix of commercial, agricultural, religious, and other occupancies. Fire protection is provided by the Bellefontaine Fire Department (BFD) under a contract arrangement between the city and the township trustees.

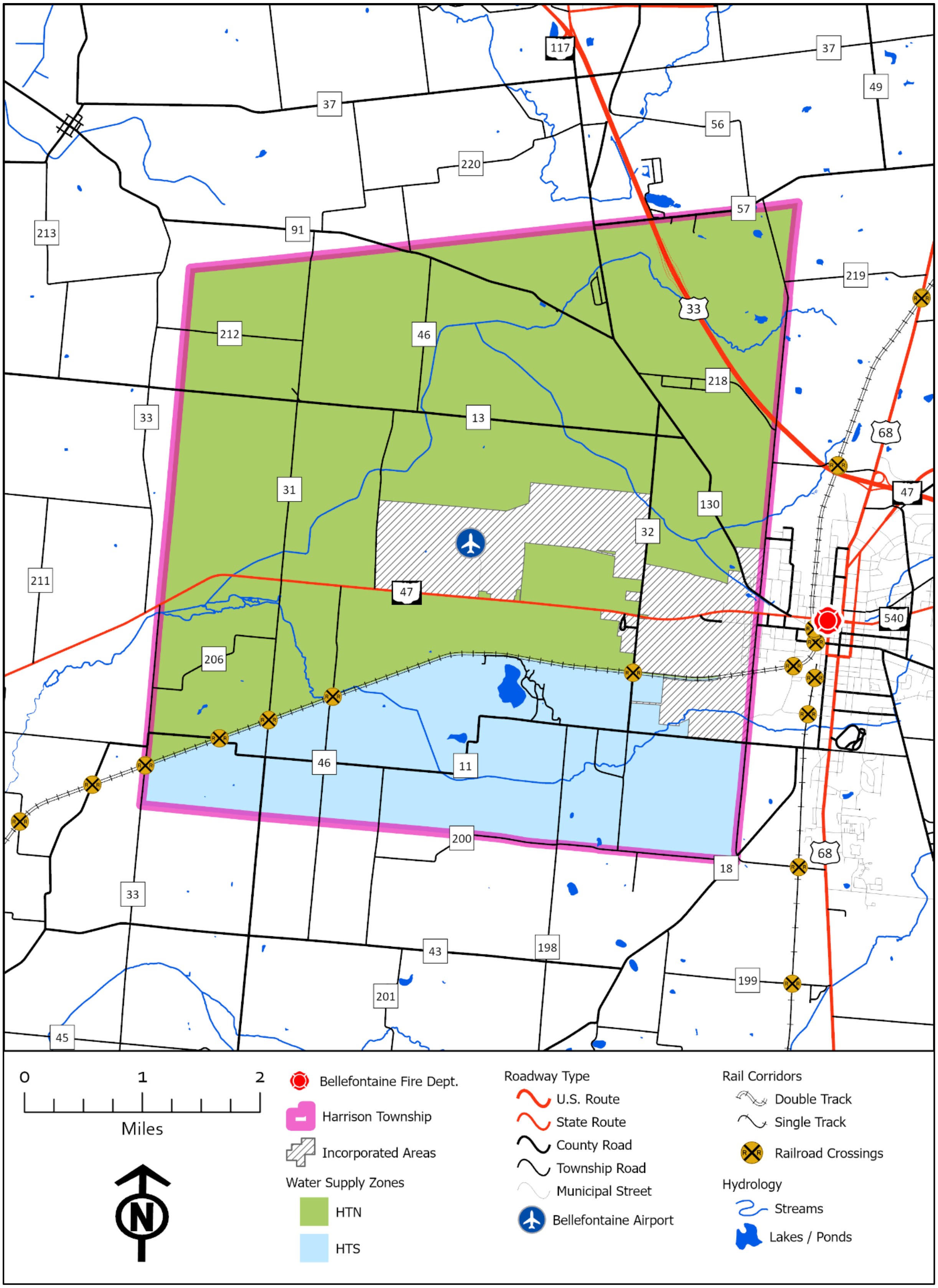


Figure 13. Overview map of study area.

The study area was divided into two water supply zones for planning purposes. The township is traversed by a major double-tracked freight rail corridor: the CSX Indianapolis Line Subdivision, which sees average daily traffic of 60 trains (Ohio Rail Development Commission, n.d.). Within the study area, these trains are moving at slower than normal speed due to the need to negotiate a steep grade and curve in Bellefontaine leaving at-grade crossings frequently blocked for several minutes each hour. Because of this train traffic, the two water supply zones were created on either side of the rail line, with each zone designed to be entirely independent of the other. These zones are designated Harrison Township North (HTN) and South (HTS). The HTN zone is geographically larger, accounting for 450 premises, while HTS contains the remaining 244.

Mutual Aid Area Characteristics

The mutual aid area was intended to capture the pool of likely water tenders and engines available to fill roles in a prospective water shuttle operation in the study area. To ensure maximum resources for consideration in the model, a large area was defined for this purpose. The mutual aid area includes all fire departments located in or covering some part of Logan County. Additionally included were any departments with jurisdictional areas bordering the county even if that department’s response area did not extend into Logan County. The resulting mutual aid area included a total of 23 fire departments, each operating from a single station (Figure 14). Information regarding all fire departments considered in the study is provided in Appendix B.

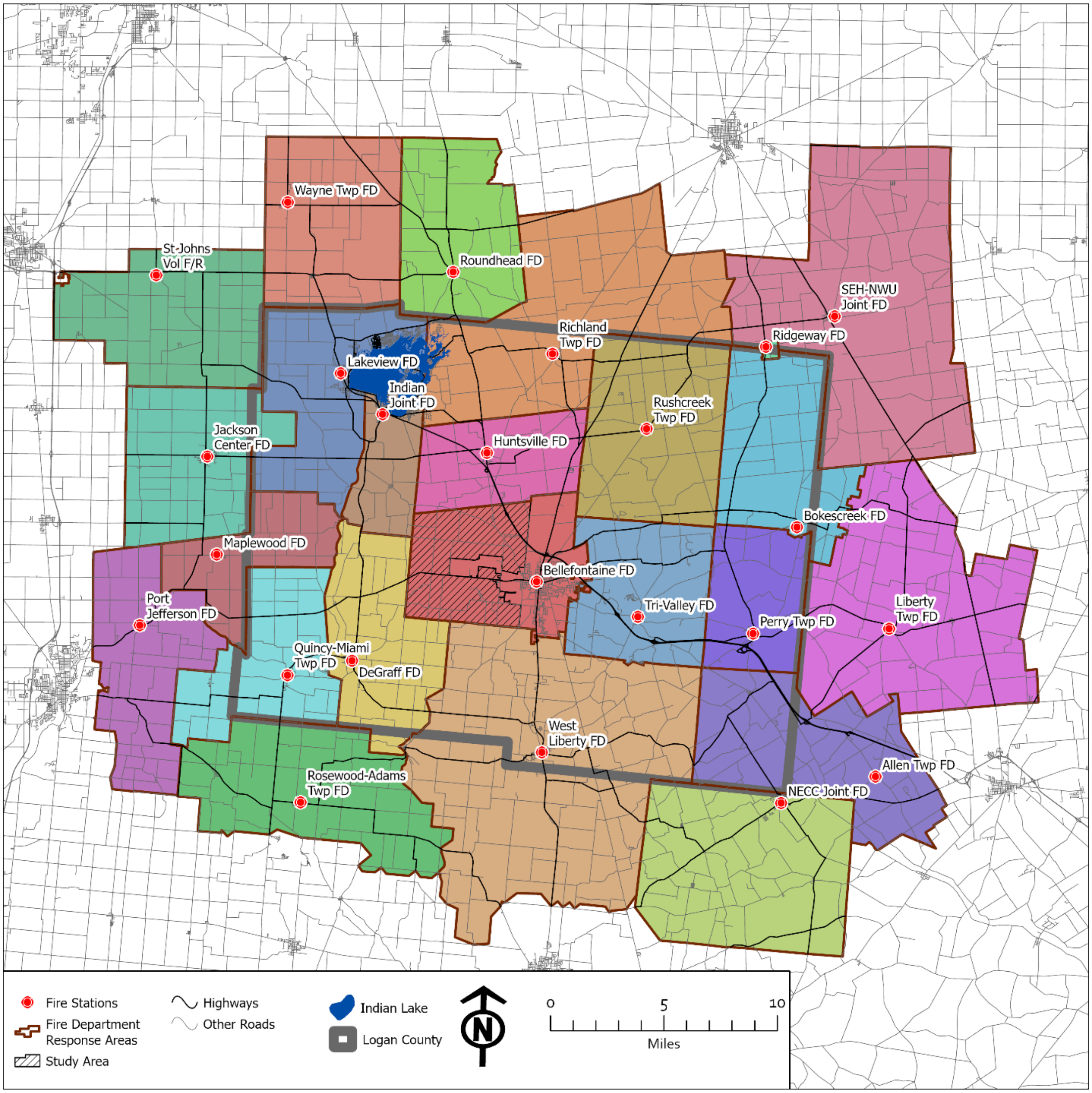


Figure 14. Overview of the mutual aid area.

Preparation of the Road Network

The network of roads in the study and mutual aid areas were characterized at two scales corresponding to the response and shuttle phases. Road centerline geodata were derived from the Ohio Department of Transportation's (ODOT) Location Based Response System (LBRS). The LBRS is a statewide collection of high quality, transportation-related geodata sets maintained by ODOT and available as a public domain resource (ODOT, 2019). This is the data source for road networks used by the Logan County Sheriff's Office dispatch center in their computer assisted dispatch (CAD) system. This is the agency responsible for all emergency dispatching within the study area.

The LBRS roads dataset includes detailed information about each road segment including length, pavement type, and rated speed limit. While detailed information on roadway width is provided for some major highways in the state, road segments within the study area do not include this data. The LBRS roads dataset is highly accurate and topologically integrated across the state. This means that the dataset reflects actual relationships between road segments at intersections making it suitable for use in network analysis software. Because of this, the LBRS roads data were usable without modification for the response phase portion of the model.

For the shuttle phase of the model, a subset of the statewide LBRS roads data was used to develop potential shuttle routes for the study area. This subset included all road segments within the study area along with connecting road segments in a buffer around the study area. The buffer was not a set size but was instead designed to encompass any potential routing solutions even if they passed outside the study area proper.

Because of the lack of data on roadway width, the LBRS roadway segments as provided could not be assessed for their potential to safely support two-way water shuttle traffic. This information was critical for developing shuttle routes. While ODOT-maintained highways have reasonably wide lanes and are designed to safely carry two-way commercial truck traffic, many of the county- and township-maintained roads in the study area are very narrow (Figure 15). These roads are intended to support relatively light traffic with occasional use by agricultural equipment and farm trucks, but not regular commercial traffic. In most cases these roads do not even have striping to separate lanes or mark the pavement edge, they are simply plain asphalt.

Figure 15. Typical township road width conditions.

To fill this information gap, the author developed a remote sensing-based procedure to systematically determine the capacity of the local roads to carry two-way traffic. In June 2020, the author selected six representative county and township road segments within the study area. Visiting these sites, the author measured the drivable roadway width at 37 points where this could be safely accomplished. Measurements were made to the nearest inch using a small measuring wheel (Crescent Lufkin Pro 4-inch Measuring Wheel), with the location of each measurement recorded using a handheld global positioning system (GPS) unit (Garmin GPS 72H). Using the GPS data, the 37 points were converted into a point feature class in ArcGIS Pro and then imported into Google Earth Pro.

Within Google Earth Pro, roadway widths at the 37 points were mensurated on the three most recent, high-quality overhead images available for each site. The same images could not be used for all sites because some were unusable due to tree canopy cover, shadows, or other occluding features. The average mensurated width values at each point were then compared to the measurements taken in the field to assess whether remote sensing methods would be sufficiently accurate. The average absolute difference between the mensurated and field values was 0.24 feet, or 1.16 percent. The author assessed this to be sufficiently accurate for purposes of this study.

Using the “Generate Points Along Lines” tool in ArcGIS Pro, a feature class was created of sample points at 0.25-mile intervals along all road segments in the shuttle area: a total of 245 points. Road segments from ODOT-maintained or designed highways were excluded from this process because they were clearly suitable for two-way traffic. These excluded roadways included a four-lane divided highway (US Route 33), two two-lane state highways (US Route 68 and State Route 47), and a county road that had originally been a state highway (County Road 130, formerly US 33). Any streets in residential areas were also excluded, as they were assumed to be suited to one-way traffic only.

The feature class of sample points was imported into Google Earth Pro for width mensuration. For the 245 sample points, widths were mensurated on three suitable, recent images as described above, with average width values recorded. Within ArcGIS Pro, the sample point network was spatially joined to the road segment features, with a mean value of roadway width generated for each road segment. Using the 12-foot minimum lane width standard from NFPA 1140 (NFPA, 2022), each road segment was assigned a shuttle traffic capacity rating (one-way or two-way). Any segment having a mean width value less than 24 feet was identified as suitable for one-way traffic only, while any segment 24 feet or wider was considered suitable for two-way traffic flow. The author was initially concerned that there would be borderline situations, but this was not the case. All road segments either well exceeded 24 feet wide or were 20 feet or less in width: no segments were close enough to warrant follow-up field measurements.

In addition to roadway width assessments, potential turnaround points were identified along the road network. The prevalence of narrow roads suggested that safe locations to turn apparatus around would likely be useful in developing shuttle routes. Potential turnaround points were classified into two types: those where no backing would be required (type one), and those where a backing maneuver would be necessary (type two). Type one turnaround points (TA1) are facilities where water tenders may be safely turned around without the need for backing or ground crew assistance. Examples include locations with large parking lots, such as churches, stores, or government buildings (Figure 16). Although backing maneuvers are undesirable for reasons of safety, they are difficult to avoid entirely especially in rural areas. While TA1 are preferred, some type two (TA2) options were identified to support route development. These points require the performance of a three-point turn or similar maneuver to turn water tenders around. Examples include farm drive entrances, industrial access roads, and other similar features that would not be damaged by water tender traffic (Figure 17).

Turning maneuvers require time to execute, and this time penalty is included in the route navigation time for the model. The potential time to execute a turning maneuver depends on the configuration of the turnaround point, with backing maneuvers requiring more time to complete. Because empirical data were not available, arbitrary time values were assigned to each turnaround point type: 0.5 minutes for TA1 (no backing) and 1.0 minutes for TA2 (backing required). How these values are used in calculating route navigation time is described in detail in the section on route development, below.

Figure 16. Example of a type one turnaround point (Harrison Township garage).

Figure 17. Example of a type two turnaround point (farm drive).

A total of 30 potential turnaround points were identified in the study area, including 19 TA1 and 12 TA2. Each turnaround point was assigned a provisional identifier consisting of the water supply zone plus a sequential number; for example, “HTN-01.” These points were stored in a “Turnaround Points” point feature class. The work on roadway widths and turnaround points described here was not a part of the study objectives but was a necessary preparatory to support the development of shuttle routes to meet the objectives. The outcome of this preparatory work is shown in Figure 18, below.

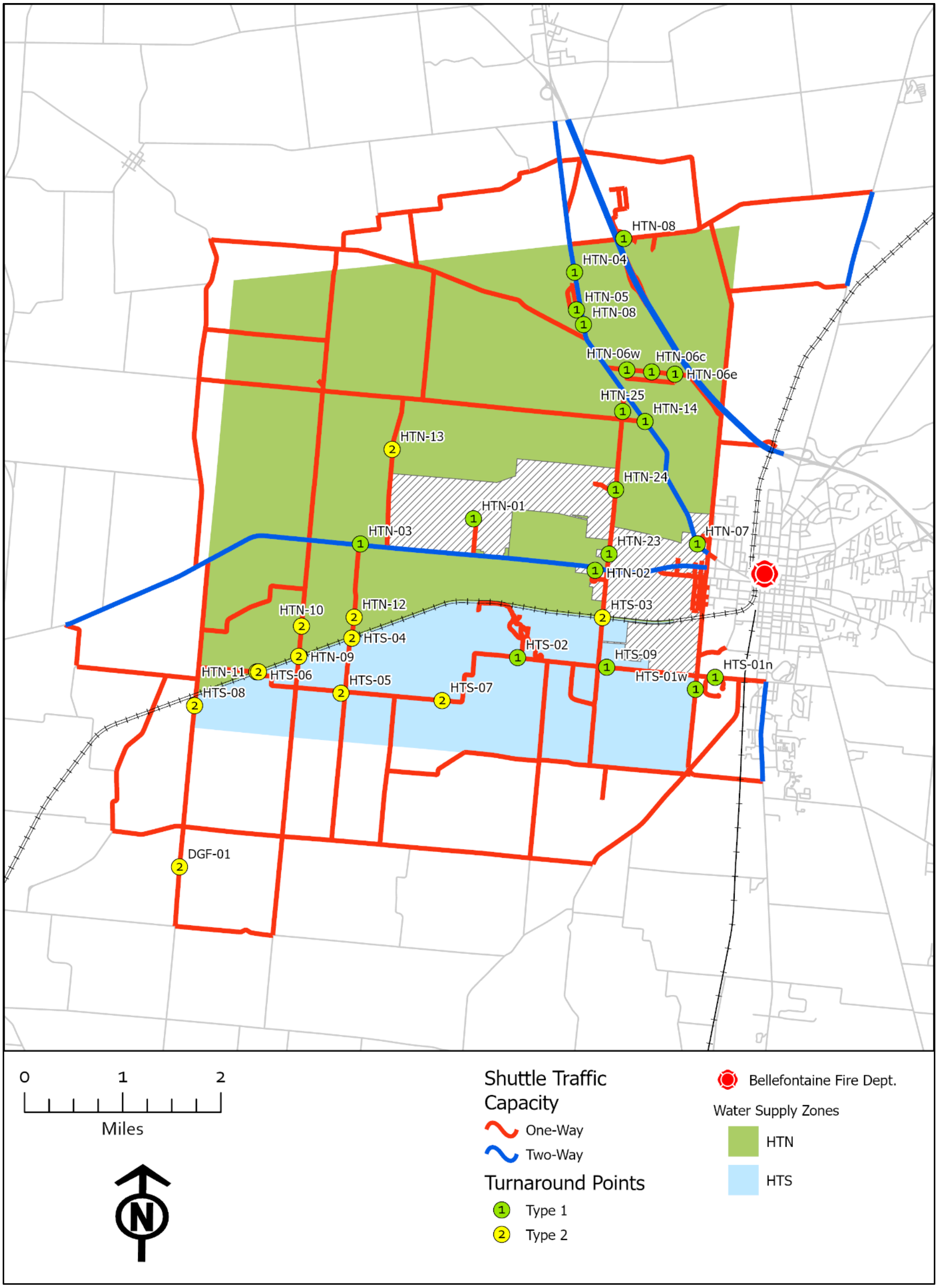


Figure 18. Overview of prepared road segments.

Fill Site Identification

Potential fill sites were identified both within and beyond the study area. Candidate sites included both municipal pressurized hydrants and dry hydrants. Any potential water supply source within a reasonable distance of the study area was considered. A fixed distance was not used, although in the western portion of the study area (distal from the city) distances to some potential fill sites were so great as to be obviously impractical, and these sources were excluded from consideration. Sites were only considered that met a minimum flow requirement of 1,000 gpm and that provided adequate safe working space for fill site operations. The locations of all potential fill sites were used to create a point feature class within ArcGIS Pro for use in geospatial analysis.

Existing dry hydrants considered as potential fill sites totaled ten, including seven deployable bridge-mounted installations and one excavated installation drawing from a lake. Two planned bridge-mounted locations in a neighboring jurisdiction were also considered. The author is working with this fire department on the design and installation of these hydrants and is reasonably confident that they will be installed within the next few years. Each of these dry hydrants has (or will have) a design flow of 1,000 gpm per NFPA 1142 requirements (NFPA, 2022).

Although the study area is not generally served by water mains and hydrants, some portions proximal to the city are on the municipal system. One main runs to the west along State Route (SR) 47, providing service to the Bellefontaine Municipal Airport. Another main runs to the north along County Roads (CR) 32, CR-130, and CR-91 providing service to a large skilled nursing facility, a warehouse facility, and several other commercial properties. Both mains have hydrants at irregular intervals that could serve as the basis of a fill site. A total of 168 municipal hydrants were considered including those on the mains described above as well as all hydrants located on the western side of the city.

No single, definitive data source was available for locating the municipal hydrants, requiring additional preparatory work by the author. The city water department was able to provide complete flow test records for all hydrants as an Excel spreadsheet (.xls). These records did not include hydrant locations in a GIS-ready format. Partial GIS-ready hydrant location data were available from the county CAD system, but many hydrants were missing. Using these two partial sources, Google Earth Pro street-view imagery, and 2019 three-inch resolution aerial imagery from the Ohio Statewide Imagery Program (Ohio Geographically Referenced Information Program, n.d.), the author was able to create a point feature class of municipal hydrants for use in GIS. This feature class was joined to the city's flow test results to allow for assessment of each hydrant as a potential fill site.

All water sources were screened for suitability as a fill site having the WSTAC recommended configuration and an available flow of 1,000 gpm under normal conditions. Desirable fill sites require adequate working space for a supporting engine, water tender traffic flow, and ground crew safety. An overview of all sources considered is provided in Figure 19. Fill sites selected for use were assigned a provisional identifier consisting of the water supply zone, a three-digit road number, and an additional letter if multiple hydrants are on the same road, for example: "HTN-091w." These points were stored in a "Fill Sites" feature class.

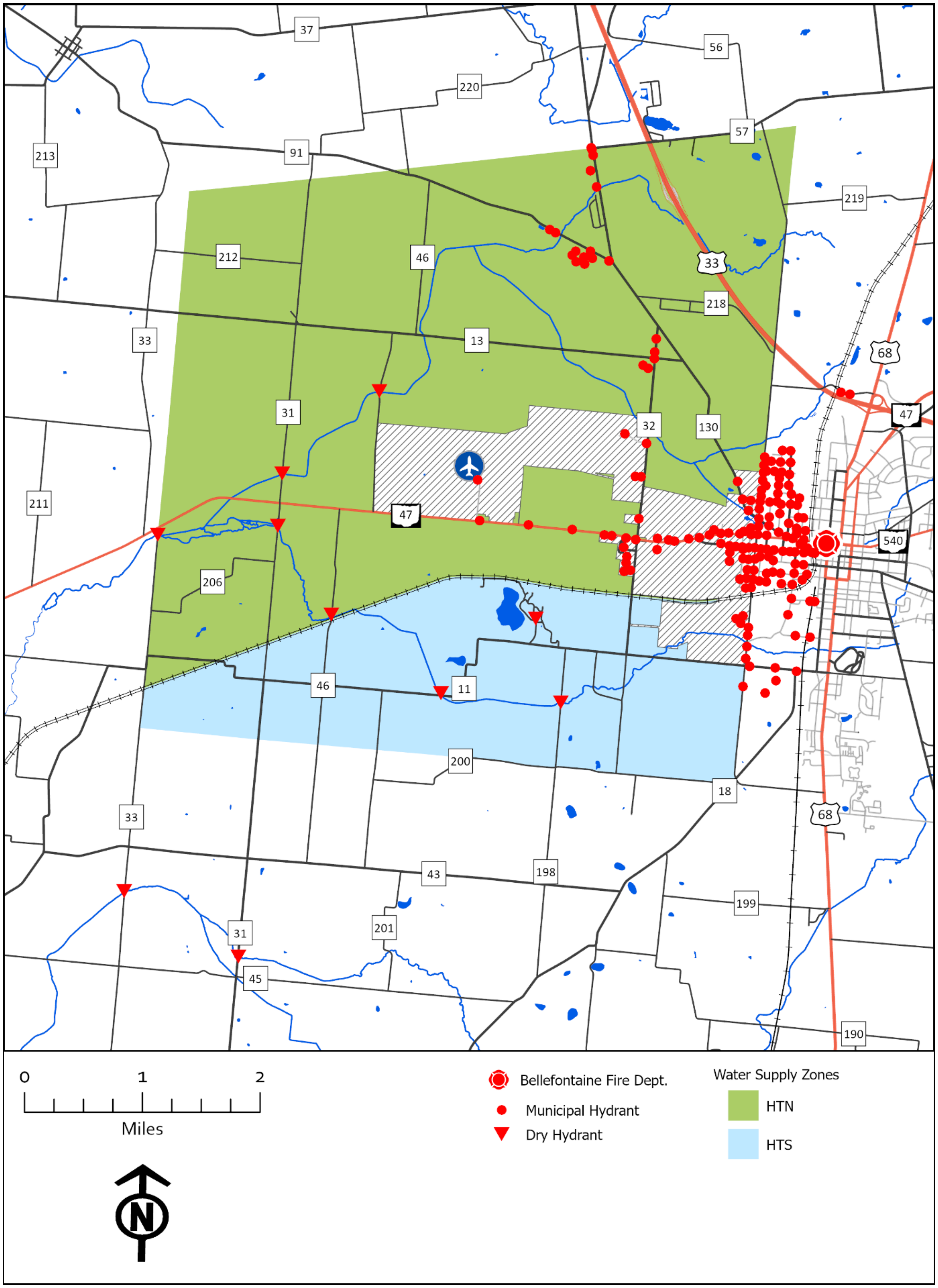


Figure 19. Water sources considered for fill sites.

Identification of Dump Sites

An objective of this study was to determine the potential water shuttle throughput at any location within the study area. To maximize the number of delivery points considered, every addressed premise within the study area was included as a potential dump site. Also included were addressed premises not within the township but located just across the road in places where a roadway ran along the township boundary. This resulted in a total of 741 addressed premises: 694 within the study area, and an additional 47 outside the township but along boundary roads. Dump site locations are shown in Figure 20.

Factors for any premise that would require special planning, such as hazardous occupancies or long rural driveways, were not considered. Such factors were felt to be beyond the scope of this study's purposes but would warrant consideration as the development of the model continues beyond this initial version. Likewise, each site was assumed to be suitable to accommodate a dump site configured to WSTAC recommendations even though this is not the case on the ground. Further detailed assessment of the study area would be required to determine the best locations for dump sites to service all premises of interest.

Dump site locations were obtained from the county CAD system as a GIS-ready point feature class. The address points in this system provide an end-of-driveway location for each premise, rather than the location of specific structures. This accords with WSTAC recommendations for locating dump sites along the public road to avoid clogging the immediate incident scene with support functions. Each dump site was assigned a provisional identifier based on the "Long Street Number" (LSN) field in the CAD data. The LSN value is the street address of the property and is unique to each premise within the county, for example: "3219 N CR 32." These points were stored in a "Dump Sites" point feature class.

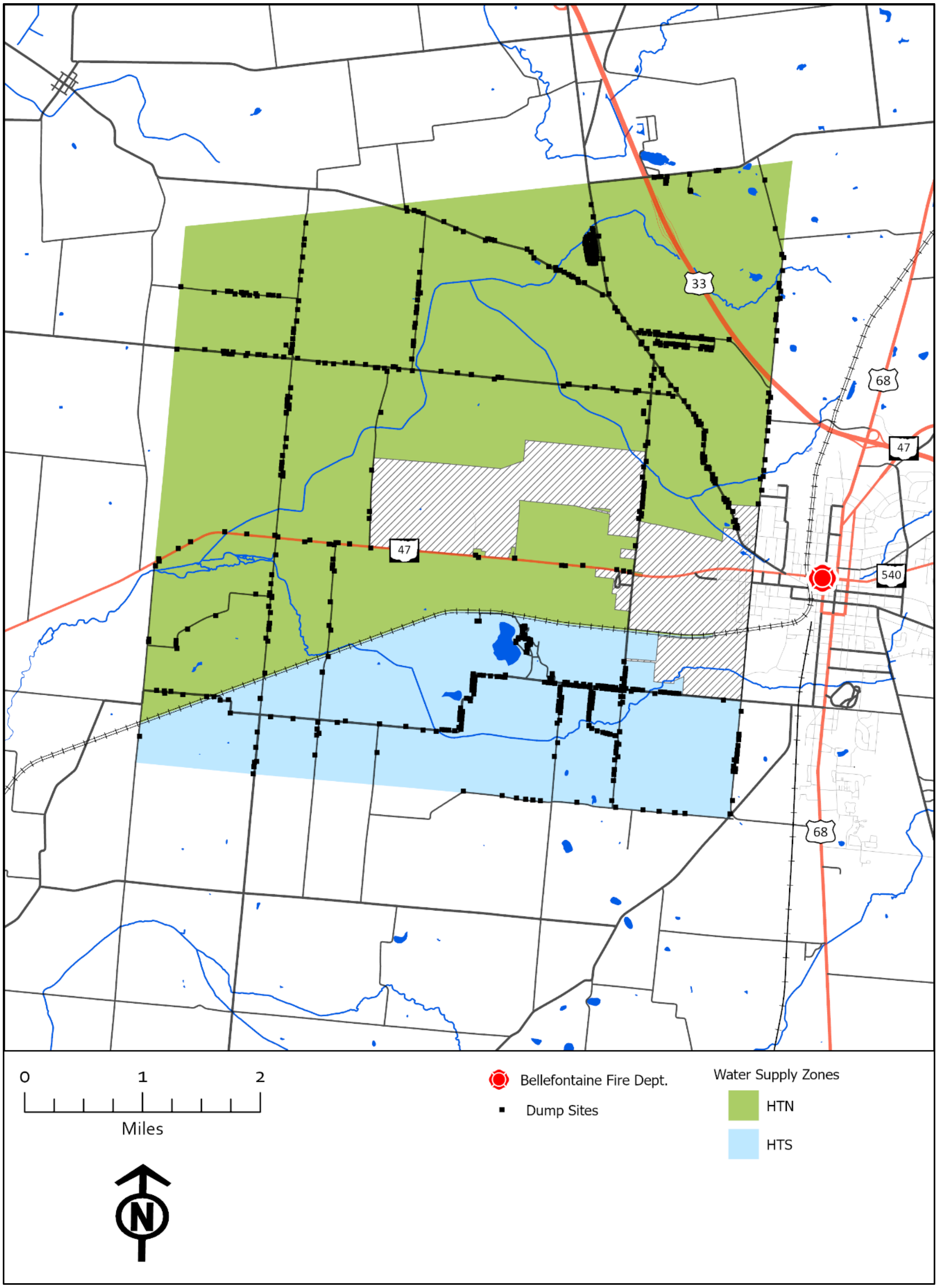


Figure 20. Dump sites selected for the study.

Developing the Shuttle Routes

Potential water shuttle routes were developed using a manual, iterative process using basic GIS functionality in the ArcGIS Pro platform. Routes were designed to connect fill sites to dump sites, using road segments that were assessed for two-way traffic suitability, as described above. The author attempted to use the automated routing tools available in the Network Analyst extension but was unable to achieve desirable results given the desire to prioritize unidirectional loop routes for safety purposes. Using the manual methods described below, a total time of about six hours was required to develop 38 satisfactory routes, enough to cover the entire study area.

The routes were classified as either loop, pendular, or combination following the maritime industry terminology. Because routes could be composed of a mix of road segments suitable for one- or two-way traffic, the three basic route classes were further subdivided to reflect different potential situations, resulting in a total of six classes (Figure 21). Each of these classes requires a different number of turnaround points. Loop routes require no turnarounds, pendular routes require two, and combination routes require one because the loop segment acts as a turnaround. Each class also has a specific formula for calculating effective length. For segments where all traffic flow is in one direction, such as for loop routes, effective length is the same as total length. For pendular sections supporting two-way traffic flow, effective length is two times the total length because water tenders will traverse each segment twice to complete a shuttle. For pendular sections rated for one-way traffic, but forced to carry two-way traffic, effective length is three times the total length as only one water tender can occupy the segment at a time. The additional length is meant to account for the time an opposing water tender is forced to wait for the segment to be clear for travel.

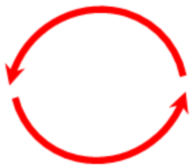
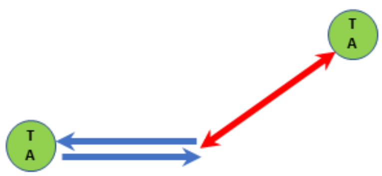
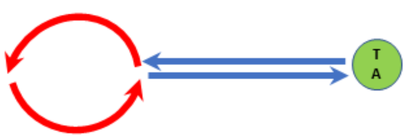
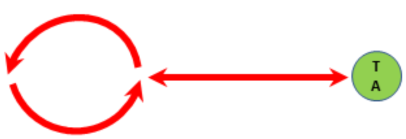
Route Class		Effective Length Calculation	Turnaround Points
	**Loop** All one-way traffic segments	Sum of length for all segments	None
	**Pendular Type 1** All two-way traffic segments	2 x sum of length for all segments	Two
	**Pendular Type 2** Mix of one- and two-way traffic segments	2 x sum of length for two-way segments + 3 x sum of length for one-way segments	Two
	**Pendular Type 3** All one-way traffic segments	3 x sum of length for all segments	Two
	**Combination Type 1** Loop plus two-way pendular section	1 x sum of length of loop segments + 2 x sum of length of pendular segments	One
	**Combination Type 2** Loop plus one-way pendular section	1 x sum of length of loop segments + 3 x sum of length of pendular segments	One

Figure 21. Typology of shuttle routes.

For this study, routes having a loop or pendular type one configuration were used preferentially. These two configurations are the safest options, having either true one-way traffic flow or two-way flow separated into adequate lanes. The other four configurations were used as needed for situations where the preferred options could not be applied.

When determining the relative impact of each route on potential shuttle throughput, the length of the route is not the critical factor: it is the time required to navigate the route that matters. The effective length calculated for each route was converted to an equivalent travel time in minutes assuming an average water tender speed of 35 mph, in keeping with NFPA 1142 methods (NFPA, 2022, para. C.10) and using the following formula:

$$Travel\ Time = Effective\ Length \times \frac{60}{35} \tag{13}$$

Time required to execute directional change maneuvers at turnaround points was also accounted for to produce a final route time (*TR*) value for use in the model's shuttle phase component. For pendular and combination routes, one or two turnaround points from the feature class described above were assigned as appropriate to complete the route. Total route time was calculated as the sum of travel time and turnaround time. Within the model, all participating water tenders experience the same *TR* because they are all moving at the same average speed and using the same turnaround points.

Routes were constructed from LBRS road segments in the GIS environment. These segments form a line feature class, with each segment typically representing a length of roadway between two intersections. Each segment could form a part of multiple routes, so the segments were copied into a new "Route Roadway Segments" intermediate feature class with an attribute field added to identify the route for which each copy of the segment was intended. Routes were developed using a fill site as a start point, then identifying potential loop and pendular type one routes originating from the fill site with a goal of each dump site being reached by at least one route. Multiple routes were identified for each fill site until it became obvious that there would be overlap with another fill site's routes or the edge of the study area was reached. Figure 22, below, shows an example of this process.

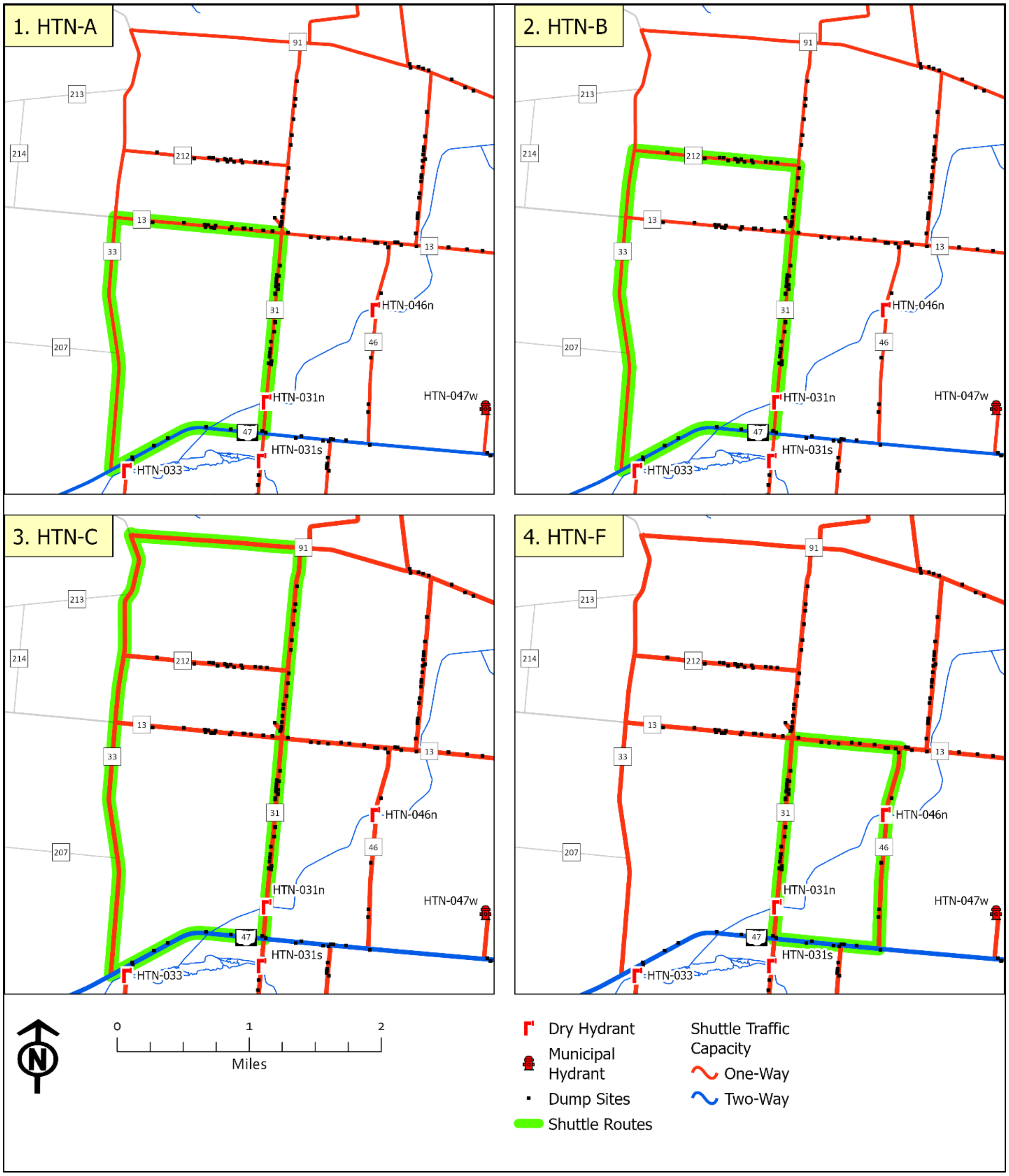


Figure 22. Example of iterative route development.

In the example shown above, the fill site HTN-031n is used as a starting point. A progressive series of loop routes is laid out from the fill site until the edge of the study area is reached, or it becomes obvious that there will be overlap with routes for other fill sites. Each route was assigned a provisional designator consisting of the water supply zone and a successive letter, for example "HTN-A." In the example shown, the routes HTN-A, B, and C can only be serviced by the HTN-031n fill site, whereas the route HTN-F could also be serviced by the nearby fill site HTN-046n. This process was repeated for each fill site until no more routes of the preferred configurations could be generated.

At this point, routes were developed to reach the remaining dump sites that had not been reached by routes of the preferred configurations. In each such case, only one route configuration was possible to reach the remaining dump sites, with the specific configuration driven by the available road segments. In keeping with the concept of wholly independent water supply zones, none of the routes were allowed to cross the rail corridor. This restriction led to the most difficult routing scenarios, forcing the use of backing maneuvers and opposing traffic flow to reach a small portion of the dump sites.

While doubtless the safest option, some loop route configurations were extremely long, and the author felt that these would likely be rejected by fire department leadership. In these few cases, alternative routes using less-desirable configurations were developed to provide an option with a lower time cost albeit with some measure of safety degradation.

Within the intermediate Route Roadway Segments feature class, each segment was identified not only by its intended route, but by traffic flow rating (one- or two-way), and its intended function within the route: part of a loop or pendular section. These attributes allowed calculation of effective length for each segment as shown in Figure 22, above. The intermediate feature class was then dissolved based on the route identifier using the Dissolve tool in ArcGIS Pro. The effective lengths for all participating road segments in a route were summed in the dissolve process, with the total effective length assigned to the route in a new "Shuttle Routes" feature class. To this feature class, two additional attribute fields were added to contain a potential first and second turnaround point (Figure 18), depending on route configuration. The turnaround type (TA1 or TA2) and time penalty for each point were joined from the Turnaround Points feature class. Travel time was then calculated from the effective length using Equation 12, and to this was added any turnaround time penalties, yielding the final navigation time (*TR*) for each route.

A total of 38 potential shuttle routes were developed using this process, with the HTN zone having 27 and HTS having 11. Each route was designed to connect one fill site to multiple potential dump sites. In some cases, additional fill sites are present along the route. In these instances, one fill site is designated as the primary, and any others are considered secondary or backup fill sites.

Assignment of Dump Sites to Shuttle Routes

During the route development process described above, individual roadway segments were often shared by multiple routes. In some cases, dump sites could potentially be assigned to as many as four routes. The dump sites along these shared segments needed to be assigned to just one route to support water shuttle planning based on the routes. Each dump site was assigned to the potential route with the lowest value of *TR* as this was considered an indicator of higher potential throughput, all other things being equal. The assignment process required a multi-step procedure involving ArcGIS Pro and Excel.

A one-to-many spatial join was performed using the Dump Sites feature class as the target, and the Shuttle Routes feature class as the join feature. The join method used was "within a distance" using a 100-foot buffer (to capture address points offset from the roadway). This yielded an intermediate feature class of 1,581 records. The tabular data for this feature class was exported to Excel, and then sorted by dump site identifier and descending *TR* value. Once sorted, the values in the OBJECTID attribute field were replaced with sequential numbers, one through 1,581, in the sorted order and the table was then imported back into ArcGIS Pro (the OBJECTID field cannot be edited in ArcGIS Pro). The "Delete Identical" geoprocessing tool was then run on the re-imported tabular data, using the dump site identifier as the comparison field. This tool modifies the table by eliminating duplicate records, retaining only the copy with the lowest OBJECTID value. In this case, the record for each dump site with the lowest *TR* value was retained. This table was then joined to the Dump Sites feature class, assigning a single route and associated *TR* value to each dump site. A handful of dump sites were missed by the initial spatial join due to being located just outside the buffer, but these were easily assigned to routes manually by comparing assignments for neighboring dump sites.

Fire Department Data

Information relating to location, proficiency, and staffing of Bellefontaine Fire Department and all 23 potential mutual aid departments was gathered to support the model. Each department in this study operates from a single station, and the physical location of all 24 fire stations was verified and recorded in ArcGIS Pro in a "Fire Stations" point feature class.

Each department was assigned values for a series of six staffing and proficiency coefficients. These values were assigned at the departmental level because it is impossible to know ahead of time what specific personnel will be assigned to an incident. The coefficients are meant to represent an overall rating for the organization. The purpose of the coefficients is to modify base times for key tasks based on assessed proficiency of the department having the assignment. The specific use of the coefficients is described in more detail in later sections. The coefficients are:

- Staffing (*kS*): The ability of the department to provide adequate staffing turnout for a fill or dump site assignment
- Water Tender Operations Proficiency (*kWT*): the proficiency of department personnel with regard to driving and operating water tender apparatus
- Dump Site Setup Proficiency (*kDS*): the proficiency of department personnel with respect to initial setup of a standard-configuration dump site
- Dump Site Operations Proficiency (*kDO*): the proficiency of department personnel with respect to operating a dump site
- Fill Site Setup Proficiency (*kFS*): the proficiency of department personnel with respect to initial setup of a standard-configuration fill site
- Fill Site Operations Proficiency (*kFO*): the proficiency of department personnel with respect to operating a fill site

Values of high, moderate, or low were assigned to each coefficient for each department. These descriptive values are converted to the actual coefficient value used to modify times required to perform tasks, where a rating of high equates to 1.00, while moderate and low are 1.25 and 1.50, respectively. Lower proficiency equates to longer times required to perform tasks. Because there are no empirical data to use in assigning these ratings, the author made provisional ratings based on personal experience with the departments. All proficiency coefficient ratings were stored in an Excel table called “FD Factors.” This table is linked to the

GIS data using three-character Logan County dispatch codes for each department as a unique identifier (see Appendix B).

Three departments with some full-time staffing for fire were assigned *kS* values of moderate (1.25), whereas the remaining 21 fully volunteer departments were rated as low (1.50). All departments were assigned an apparatus proficiency (*kWT*) value of moderate (1.25). Two neighboring counties (Shelby and Union) have robust, county-wide water supply procedures and training programs. The five departments based in these counties were assigned values for all fill and dump site coefficients (*kDS*, *kDO*, *kFS*, and *kFO*) of moderate (1.25). The remaining 19 departments, hailing from counties without existing water supply programs, were assigned values of low (1.50) for these coefficients. These are intended to be provisional values for the purpose of this study. The model is designed to allow ready modification of these values should better data become available, such as through training evaluations of department crews.

Water Handling Apparatus Data

Information items necessary for calculations within the model were collected for all water tenders and engines within the study's mutual aid area (Figure 14, above). Other potential water handling apparatus such as aerials and wildland units were not considered. Such apparatus occasionally play a supporting role in water shuttle operations, but any potential contributions to be made by adding them into the model were judged to be marginal.

The author personally visited all 24 fire stations in the mutual aid area between April 2020 and August 2021 to gather the necessary information. The survey forms used for data collection are provided in Appendix C. Measurements of small apparatus components were made to the nearest inch using a conventional tape measure. Larger measurements were made to the nearest 0.1 foot using an AdirPro 16-foot telescoping grade rod. In addition to gathering information specific to the needs of the model, this was also an opportunity to confirm the presence and location of all apparatus of interest in the mutual aid area.

For water tenders, information included those items necessary to determine potential contributions to shuttle throughput, including physical measurements needed to estimate efflux times using Torricelli-derived equations. This included the following elements:

- Tank capacity and material
- Method of operation (conventional or vacuum)
- Configuration and physical dimensions of the water tank
- Configuration and size of the transfer valve (dump chute)
- Fill port diameter and thread
- Presence and capacity of rated fire pump
- Information on other equipment carried, such as portable tanks and water handling appliances related to shuttle operations

For engines, less detailed information was required. Items of interest were those relating to the suitability of the apparatus to serve as a fill site or dump site support engine, including:

- Pump rating
- Primer type (conventional or air primer)
- Number of crew seating positions
- Booster tank capacity
- Supply hose size, coupling thread, and length carried

Data were collected for a total of 34 water tenders and 38 engines. Apparatus were treated according to their most useful likely role as a mutual aid resource supporting a water shuttle, with priority given to water tenders. Hybrid “pumper-tanker” type apparatus were treated as water tenders, even if the owning department referred to them as engines (so long as they were equipped with a large-capacity dump valve). Additionally for all apparatus, year of production and manufacturer were recorded. Each unit was assigned a unique resource identifier consisting to the three-character Logan County dispatch code for the owning department (see Appendix B) followed by the unit's identifier. For example, Bellefontaine Fire Department's water tender is coded as "BFF T-21." Locally, the term "tanker" is still in use, so all water tender identifiers are in the form T-xxx, whereas all engines are E-xxx.

The physical location of all apparatus was captured in ArcGIS Pro using two point feature classes, "Water Tenders" and "Engines." Data elements collected during the apparatus surveys were recorded in Excel for running the necessary calculations using two tables: "WT Factors" and "EN Factors." The GIS and Excel data are linked by the unique resource identifiers.

Sequencing and Assigning Resources

Water tenders and engines were assigned to prospective water shuttle operations based on estimated response times to potential dump or fill sites, depending on the assignment. Response time included both the time required to drive from the unit's home station to its incident assignment, but also any time delay between dispatch and the unit leaving the station. For purposes of this study, it is assumed that all resources assigned to the shuttle are dispatched simultaneously and are operating from a common start time. The model also assumes that all water tenders and engines are available for assignment, and that no apparatus are excluded due to inefficient or unsafe design. Apparatus are assigned based only on their temporal proximity to a prospective incident assignment. Response time estimates were made using origin-destination (OD) matrices developed using the ArcGIS Pro Network Analyst extension.

A total of three OD matrices were generated for the study, generating response time estimates for all 34 water tenders and 38 engines in the mutual aid area:

- OD WT x DS: 34 water tenders to 741 dump sites
- OD EN x DS: 38 engines to 741 dump sites
- OD EN x FS: 38 engines to 22 fill sites

To estimate travel time, a network dataset was generated from the statewide LBRS roads feature class, clipped to a buffer ten miles around Logan County. The road network thus created was more than adequate to encompass all fire stations in the mutual aid area and provide for realistic routing from stations to incident assignments. Travel time for each road segment was calculated as the time required to traverse the segment's length at 90 percent of the posted speed limit for that segment. The impedance attribute for this value was called "minutes_90" in the feature class. It is possible to model very realistic response times that factor in road features such as stop signs, steep slopes, and other impedances. For purposes of this study, this level of detail was deemed unnecessary and too time-consuming. The author has used the method of calculating travel time based on 90 percent of the posted speed limit for past studies and this has been found to return reasonable estimates for rural road networks.

Time delays between dispatch and a unit leaving its station were also developed for all water tenders and engines in the mutual aid area. The author requested response time data for recent years from the Logan County Sheriff's Office CAD system but was refused. Similar requests to the Sheriff's Office dispatch centers of surrounding counties for departments bordering Logan County were also refused. In each case, privacy concerns relating to EMS run data were cited as the reason for refusal. This was even though the author asked specifically for fire runs, and that EMS runs be excluded. The author also asked that location information be excluded, since the only thing needed for each incident were two time stamps: time of dispatch, and time en route. As an alternative, the author investigated using reports from the National Fire Incident Reporting System (NFIRS) for departments in the mutual aid area. The NFIRS data, however, did not include the necessary level of detail.

The author did have on hand an old set of times provided for an earlier study by a prior dispatch supervisor for Logan County. This data set included the dispatch and en route times for all fire and EMS resources dispatched to incidents in Logan County (excluding within the City of Bellefontaine) for the 2013 and 2014 calendar years. Times were provided separately for each unit from each department, including resources dispatched from mutual aid departments outside the county. While this data set was old and incomplete, it did provide a starting point for developing the delay time estimates for this study.

Average delay times for Logan County departments were calculated using the values for all non-EMS units. Ambulances were excluded to avoid skewing the estimates. Not every fire department in the area provides EMS, and even for those that do, these units can respond to an incident with a smaller crew than fire apparatus, and hence a potentially reduced delay. The delays for all non-EMS units were averaged to provide a single value for each department. For several departments outside Logan County, no or very few records of delay data were available. In these cases, an average of all similarly staffed Logan County departments was used to assign a delay value, for example: a volunteer department without delay data is assigned a delay value equivalent to the average of all volunteer departments in Logan County (Appendix D).

For Bellefontaine Fire Department, a different method was used. The department has a normal daily shift staffing of five firefighters, with the ability to call in off-duty personnel and auxiliary (volunteer) members for large incidents. For a fire incident in its own jurisdiction, the department would prioritize staffing engines, with BFD taking the initial attack lead and supporting water supply functions assigned to mutual aid resources. Given this situation, the following delay times were assigned to BFD resources:

- First engine (E-22): 3.0 minutes
- Second engine (E-21): 6.3 minutes
- Water tender (T-21): 10.0 minutes

A summary of dispatch delay times by department is provided in Appendix D.

Using the OD matrix functionality in ArcGIS Pro for response time analysis requires special procedures to include the dispatch delay times. An OD matrix models a route between two points (the origin and destination) that minimizes an accumulating impedance factor, such as travel distance, or travel time in this case. For response time analysis, what would normally be understood as the origin and destination are inverted: the apparatus home station is the destination, while the fill or dump site is the origin. This allows multiple apparatus to be assessed against a single dump or fill site while incorporating a delay time unique to each apparatus.

Some modification is required to the basic locations of the apparatus within the GIS. First, a series of dummy roadway segments ("ramps") are created in the roadway dataset, near each fire station, with one ramp for each individual apparatus. These ramp sections are assigned travel time and distance values of zero so that they do not add to the overall travel time. The point locations of the apparatus from the Water Tenders and Engines feature classes are located at the end of these ramps (rather than at their true location at a fire station). Another point feature class called "Response Delays" is created, with one point placed on each ramp between the apparatus and the actual road network (Figure 23). These points are assigned an attribute value corresponding to the delay time for their associated apparatus and loaded as a point barrier feature in the OD matrix. This process forces the OD solver to generate a route beginning at the fill or dump site and proceeding to the apparatus, passing through the delay point. The travel time values for all road segments traversed are summed with the value for the delay point also added, giving a total response time for that apparatus.

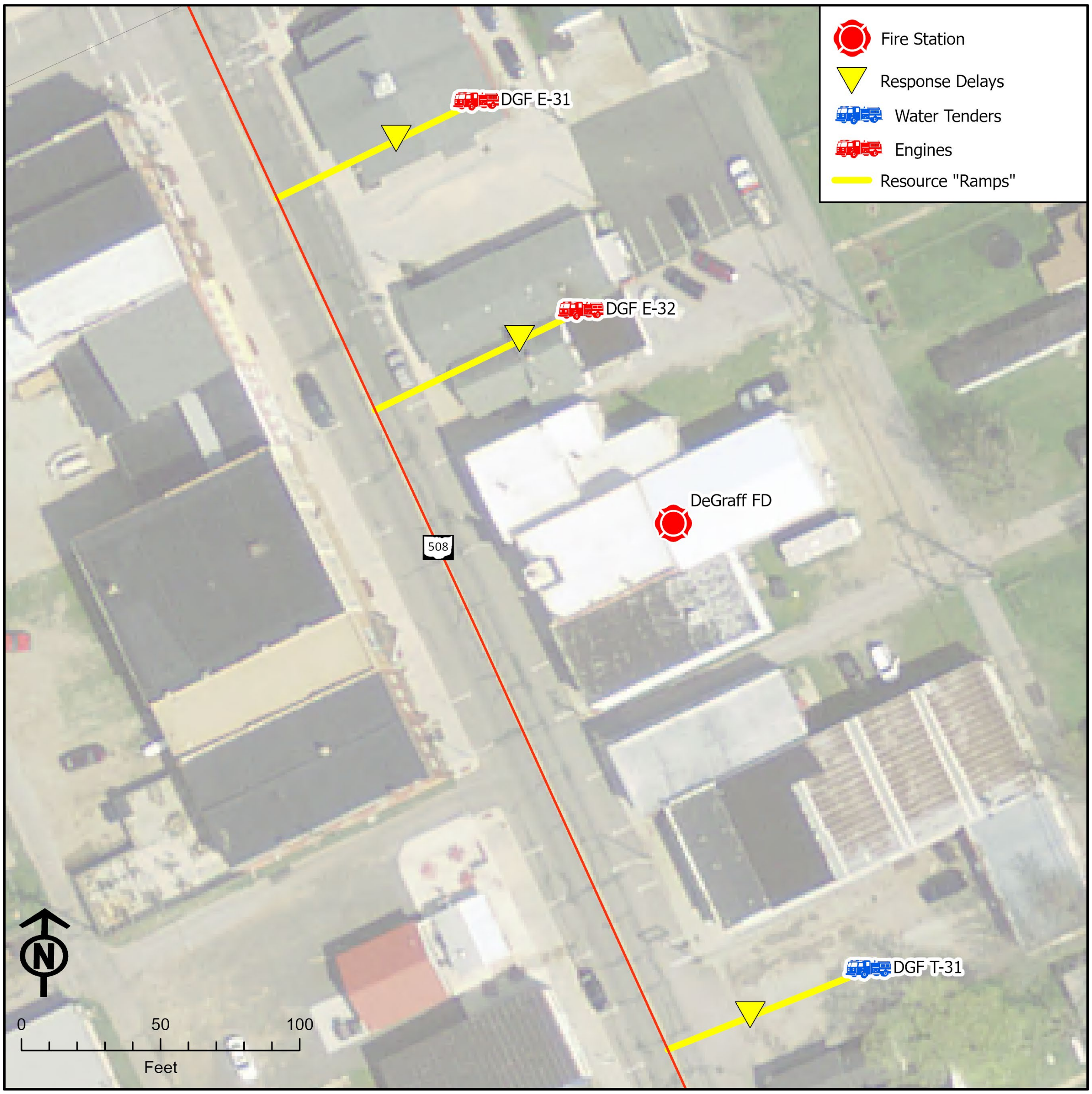


Figure 23. Apparatus data preparation for the origin-destination matrix.

The tabular outputs for each of the three OD matrices generated are imported into tables within the Excel portion of the model for development of assignments. Water tenders are assumed to initially proceed to the dump site upon dispatch to deliver their first load of water. The OD solver identifies the ten water tenders having the shortest response time for each dump site. The raw OD output is imported to an Excel table called "OD WTxDS." This table is then pivoted by shuttle route and water tender using the route to which each dump site is assigned. This reduces the number of potential resource solutions to a more manageable size. Using the pivot table output, each water tender is assigned a rank for each route based on average response time to dump sites on that route. The water tenders having ranks one through ten are then given resource assignments designated WT01 through WT10. A similar process if followed for engines and dump sites, except that only five engines are identified for each route: DS EN01 through DS EN05. Because each route has a primary fill site, the process for fill site engines does not pivot by route with five engines identified for each fill site instead: FS EN01 through FS EN05.

The ten water tenders identified for each route constitute the assignment for water shuttle operations on that route without further consideration. Because engines may fill multiple roles in the shuttle, and because there may be overlap between the engines identified for the fill and dump sites, additional procedures are needed to develop assignments. For this model, the priority of engine assignment is fire attack, dump site, then fill site. The first two arriving engines at dump site, assumed to be proximal to the fire scene, are given attack engine assignments: ATK EN01 and ATK EN02. The third arriving engine is assigned as the dump site (relay) engine: RLY EN03. The two additional engines are not considered for this version of the model. To de-conflict engine assignments between fill and dump site, each of the five engines identified for the fill site are compared in turn to the three that have received dump site assignments (using an "IFS" statement). The first engine that is not already assigned to the dump site is given the fill site assignment: FS EN. Additional engines identified for the fill site are not considered for this version of the model. This process results in the assignment to each route of the following resources: ten water tenders, three dump site engines, and one fill site engine.

Assignment of Base Times

Each fill and dump site has two base times associated with it: setup and maneuver. These base times represent the time needed to perform essential tasks at these sites. In each case the base time is the estimated time required for a proficient and adequately staffed crew to perform the task. The base times are inherent to the site but modified by the proficiency and staffing coefficients described above to yield a final time estimate.

Fill site setup time (*TFS*) is dependent on the type of water source upon which the fill site is based. Water sources were classified into one of three categories for determination of *TFS*, with those requiring more complicated procedures to bring into service having a higher *TFS*. The *TFS* is meant to reflect time needed to perform all actions needed to bring the fill site into service, to include achieving draft, stretching hoses, and any other related tasks. The three *TFS* categories used for this model are:

- Municipal hydrant (3.0 minutes)
- Dry hydrant (5.0 minutes)
- Complex (8.0 minutes)

The "complex" category is used to define sites with unusual characteristics that require excess time to bring into service, such as a site requiring a very long hose lay to service water tenders. Because all dump sites in this study are assumed to follow a common design, the dump site setup time (*TDS*) is universally set at 3.0 minutes. This is meant to reflect the time needed for the dump site engine crew (RLY EN03) to deploy an initial portable tank and make all hose connections necessary to begin relaying water to the attack engines.

Maneuver time is the cumulative time required for a water tender to move into and out of position to be serviced at the fill or dump site once the apparatus has entered the area of control by the fill or dump site ground crew. Based on a safety analysis, it is assumed for the purposes of this model that only narrow-profile portable tanks will be used for dump sites (Appendix E). Dump site maneuver time (*TDM*) is the same for all dump sites at 0.5 minutes, due to an assumed common layout as described above. Fill site maneuver time (*TFM*) depends on the layout of the fill site, with those sites requiring more complex maneuvers by the water tenders having higher values. Fill sites are classified into three categories for *TFM* determination:

Table 1

Fill Site Maneuver Time (TFM) Scenarios.

Scenario	*TFM* (minutes)	Description
Roadside	0.5	Water tenders are serviced directly on the roadway without the need to pull off
Offset	1.0	Water tenders must leave the roadway for servicing, such as being required to pull into a parking lot
Complex	2.0	Water tenders must execute complex maneuvers to position for servicing

Values for all these base times are stored for each fill and dump site in two tables in the Excel component of the model. Fill site data are kept in the “FS Factors” tab, while dump site data reside in the “DS Factors” tab.

Additional base times are inherent in the design of each water tender. These factors include connection times and nursing setup time. As with the base times for fill and dump sites, the water tender base times are modified by the staffing and proficiency coefficients of the assigned crew. Values for these base times are stored with the record for each water tender in the "WT Factors" tab of the Excel component of the model.

The fill site connection time (*TFC*) is meant to capture the time required for the fill site ground crew to connect and disconnect fill lines to the water tender. For purposes of this study, it is assumed that all water tenders will be filled through a single, 2.5-inch connection with NH thread with a fill rate of 528 gpm calculated using Sylvia's (1970) method. This relatively low fill rate is meant to protect poly tanks through standardized procedures. It is also a recognition that, given the low proficiency levels for these skills in the county, a simplified method will likely be safer and ultimately more efficient. Also, for purposes of this study, it is assumed that all water tenders will have sufficient modifications or adapters to allow the use of this standard fill connection by fill site crew operating in a safe manner with both feet on the ground (Appendix E). Given all of this, a standard *TFC* value of 1.5 minutes is used for all water tenders. Provision is made within the Excel component of the model to allow for different *TFC* values if the model is developed further or should the proficiency situation within the county improve.

The dump site connection time (*TDC*) captures the time necessary for the water tender's transfer (dump) valve to be made ready for offloading once the apparatus is positioned at the portable tank. This value varies depending on the design and configuration of each water tender's transfer valve. For purposes of this model, it is assumed that all dump site operations will be conducted without backing maneuvers and with all offloading done to the side (Appendix

E). It is further assumed that where necessary, water tenders that are currently only capable of rear dumping will be equipped with adapter elbows to allow side dumping. Four potential scenarios were used to assign *TDC* values to each water tender (Table 2).

Table 2

Dump Site Connection Time (TDC) Scenarios.

Scenario	*TDC* (minutes)	Description
1	0.0	Transfer valve remotely operated by water tender driver
2	0.2	Dedicated, straight side dumps manually actuated by ground crew
3	0.5	Articulated rear elbow valve, or elbow adapter that can remain safely attached during roadway travel
4	1.0	Elbow adapter that must be removed for route travel and then re-attached by ground crew for each dump site visit

The nursing setup base time (*TNS*) reflects the time required for the water tender operator to connect to a large diameter hose (LDH) lay through a clappered siamese or similar appliance, and then to begin pumping water directly to an attack engine. This model is focused on water shuttle operations, but nursing is often used as a transitional water supply method while the shuttle components are brought into action. The model does not attempt to fully simulate nursing operations, but rather attempts to provide an estimate of when nursing could potentially begin so that a prospective incident commander may better understand the water supply situation.

For purposes of this study, only those water tenders equipped with a fire-rated pump of 500 gpm or greater are considered capable of nursing operations. Apparatus so equipped were all assigned a *TNS* value of 2.0 minutes, with the final value modified by proficiency coefficients. The model assumes that all necessary hose and appliances will have been laid by initial arriving engine crews (ATK EN01, ATK EN02, and RLY EN03) so that the nursing water tender only needs to connect and begin pumping. Calculation of the initial nursing ready time begins with the arrival of the first nursing-capable water tender, described in detail in the section below.

Calculating Response Phase Benchmarks

Key benchmarks in the development of a water shuttle operation include arrival of initial attack resources, bringing the fill site and dump site into action, and establishing transitional nursing capability. These activities are all considered to be a part of the response phase of the model since they are generally prerequisite to the steady state shuttle operation. Corresponding benchmarks for the steady state shuttle phase are described in a later section. As stated previously, for purposes of this study it is assumed that all participating resources are dispatched simultaneously. The response phase benchmarks calculated by the model are shown in Table 3, below.

Table 3

Response Phase Benchmarks.

Benchmark	Location	Significance
Attack On-Scene	Dump site	First attack engine on scene; size up commences
Attack Ready	Dump site	Second attack engine on scene; fire attack commences
Nursing Ready	Dump site	Transitional nursing prepared to commence
Dump Site Ready	Dump site	At least one portable tank deployed; water tender offloading may proceed; relay engine prepared to pump to attack engines
Fill Site Ready	Fill site	Water tender loading may proceed

Each fill site and dump site is assigned a base setup time which is modified by the proficiency and staffing of the engine crew tasked to operate the site, as described in the section above. Calculation of the dump site benchmarks is based on the arrival of resources. The "Attack On-Scene" benchmark is achieved with arrival of the first attack engine (ATK EN01), while the "Attack Ready" benchmark is achieved with the arrival of the second attack engine (ATK EN02). For this model, it is assumed that the first engine will commence size-up of the incident, while the arrival of the second engine will allow commencement of initial fire attack. The dump site setup time (*TDS*) is calculated and added to the time of arrival for the third dump site engine (RLY EN03; the engine assigned to establish and operate the dump site) or the first arriving water tender (WT01), whichever is later (portable tanks are assumed to be carried on all water tenders). The calculation of *TDS* is as follows:

$$TDS = TDS(base) \times kS \ \times kDS \tag{14}$$

Where:

TDS = dump site setup time (minutes)

TDS(base) = base setup time (inherent to dump site)

kS = staffing coefficient (dump site crew home department)

kDS = dump site setup proficiency coefficient (dump site crew home department)

As an example of how the modified base time calculation process works, consider the following scenario: the assignment of staffing a dump site (RLY EN03) organized using a standard design [*TDS(base)* = 3.0 minutes] falls to a volunteer-staffed Logan County fire department (*kS* = 1.5; *kDS* = 1.5). The final value of *TDS* then becomes 6.75 minutes due to the multiplicative nature of the staffing and proficiency coefficients (3.0 x 1.5 x 1.5). This same process is applied to all base times throughout the model, as described in the sections below.

The "Dump Site Ready" benchmark is achieved at the time representing the sum of the arrival of RLY EN03 and the TDS. These calculations are all conducted on the "DS IA" tab of the Excel component of the model.

The final response phase benchmark occurring at the dump site is "Nursing Ready." This benchmark is based on the arrival of the first nursing-capable water tender and the time required to establish nursing capability. The nursing base setup time is assigned to each water tender and modified by the proficiency of the operator, as described in the section above. The calculation of *TNS* is as follows:

$$TNS = TNS(base) \times kWT \tag{15}$$

Where:

TNS = nursing setup time (minutes)

TNS(base) = nursing setup base time (inherent to water tender)

kWT = water tender operations proficiency coefficient (water tender home department)

Calculation of this benchmark assumes that the operator of the first-arriving nursing-capable water tender need only connect to a supply line that has already been laid by earlier-arriving engine crews. The assessed skill of the apparatus operator modifies the base time as a reflection of additional time required to make connections and begin pumping due to lower proficiency levels. These calculations are conducted on the "DS NT" tab of the Excel component of the model.

The "Fill Site Ready" benchmark is achieved when the fill site is fully operational and ready to begin receiving water tenders. This time is calculated as the sum of the time needed for fill site setup (*TFS*) and the time of arrival of the assigned fill site engine (FS EN). The value of TFS is calculated as follows:

$$TFS = TFS(base) \times kS \times kFS \tag{16}$$

Where:

TFS = fill site setup time

TFS(base) = fill site setup base time (inherent to fill site)

kS = staffing coefficient (fill site crew home department)

kFS = fill site setup proficiency (fill site crew home department)

The *TFS* value reflects the time needed to bring a fill site into action, as determined by the site's inherent complexity and as influenced by the skill and staffing level of the assigned engine company. Calculation of *TFS* and the "Fill Site Ready" benchmark is conducted on the "FS IA" tab of the Excel component of the model.

Calculating Dwell Time

Dwell time is the time spent by a water tender while being serviced at the dump and fill site. For each site, the dwell time is a product of the characteristics and interactions of the water tender, the site itself, and the ground crew. Dwell time for any water shuttle scenario will vary for each water tender due to differing performance characteristics among apparatus.

Dwell time at the fill site (*TF*) is the sum of the time required to position the water tender, connect the fill line(s), fill the tank, disconnect the fill line(s), and for the apparatus to leave the fill site ground crew control area. The TF value for each water tender is calculated using the following formula:

$$TF = TFM + TFC + TFF \quad (17)$$

Where:

TF = fill site dwell time (minutes)

TFM = fill site maneuver time (base modified by coefficients)

TFC = fill line connection/disconnection time (base modified by coefficients)

TFF = time required to fill the water tender tank

The *TFM* base value is inherent to the fill site itself but is modified by the proficiency of the water tender driver (*kWT*) as well as the proficiency (*kFO*) and staffing level (*kS*) of the fill site ground crew. The logic here is that a water tender driver with low proficiency will generally require more time to execute the maneuvers necessary to bring the apparatus into and out of position for servicing in an area of limited space. Likewise, the skill of the assigned fill site crew has an impact on how well the ground guides can direct the water tender driver. Lower staffing levels for the ground crew mean fewer hands available to do the work, therefore more time required for personnel to move from one job to another on the site. These impacts are multiplicative, so that the final *TFM* value is calculated as:

$$TFM = TFM(base) \times kWT \times kS \times kFO \quad (18)$$

Where:

TFM = fill site maneuver time (minutes)

TFM(base) = base maneuver time (inherent to fill site)

kWT = water tender operation proficiency coefficient (apparatus home department)

kS = staffing coefficient (fill site crew home department)

kFO = fill site operations proficiency (fill site crew home department)

The final value of *TFC* is similarly determined by the proficiency and staffing of the fill site crew. Because the model assumes that a “pit crew” method will be used at the fill site wherein the driver remains in the apparatus, the proficiency of the driver does not come into play for *TFC*. The value of *TFC* is calculated as:

$$TFC = TFC(base) \times kS \times kFO \tag{19}$$

Where:

TFC = fill site connection time (minutes)

TFC(base) = base connection/disconnection time (inherent to water tender)

kS = staffing coefficient (fill site crew home department)

kFO = fill site operations proficiency (fill site crew home department)

The time necessary to fill the water tender’s tank (*TFF*) is entirely a function of the water tender and the fill rate used; proficiency and staffing levels do not impact this physical process. The fill rate to be used should be determined in advance, taking into consideration the hydraulics of the fill hose layout. As described earlier, a universal fill rate of 528 gpm is used in this model. The value of *TFF* for each water tender is thus simply the rated capacity of the tank divided by

528, with the assumption that all water tenders arrive at the fill site entirely empty and will depart entirely filled.

Dwell time at the dump site (*TD*) is calculated similarly to the fill site but instead considering the processes required for offloading water tenders. The value of *TD* is calculated as follows:

$$TD = TDM + TDC + TDD \qquad (20)$$

Where:

TD = dump site dwell time (minutes)

TDM = dump site maneuver time (base modified by coefficients)

TDC = dump site connection/disconnection time (base modified by coefficients)

TDD = time required to empty the water tank

Maneuver considerations at the dump site closely parallel those at the fill site. The water tender must be carefully positioned close enough to a portable tank to allow offloading, but not so close as to damage the tank. As with *TFM*, the proficiency of the driver and ground crew, as well as ground crew staffing, all play a role in determining the final time as follows:

$$TDM = TDM(base) \times kWT \times kS \times kFO \qquad (21)$$

Where:

TDM = dump site maneuver time (minutes)

TDM(base) = base maneuver time (inherent to dump site)

kWT = water tender operation proficiency coefficient (apparatus home department)

kS = staffing coefficient (dump site crew home department)

kFO = fill site operations proficiency (dump site crew home department)

Connection time at the dump site (*TDC*) encompasses those actions necessary to position the transfer valve (dump chute) for offloading, to operate the valve, and to stow the valve or any adapters as needed. Water tenders vary widely in this respect with some having electronically actuated valves operated from the cab, while others require the manual attachment of locally fabricated elbows. For automated systems, the base time is set at zero since it is assumed that the time needed for the driver to operate the system is negligible. For all other systems, a variable base time is assigned to the water tender reflective of the complexity of operation. As with *TFC*, the driver is considered to not be directly involved in this procedure (except for automated systems with a base value of zero), so the base time is modified by the proficiency and staffing of the dump site crew as follows:

$$TDC = TDC(base) \times kS \times kDO \tag{22}$$

Where:

TDC = dump site connection time (minutes)

TDC(base) = base connection/disconnection time (inherent to water tender)

kS = staffing coefficient (dump site crew home department)

kDO = dump site operations proficiency (dump site crew home department)

The time necessary to empty the water tender's tank is inherent to the design of each water tender and is not impacted by proficiency or staffing. The model uses Torricelli-derived equations to estimate total efflux time for each water tender, based on the shape of the tank, the size of the dump aperture, tank height, and flow path of the transfer valve (dump chute). Water tenders were classified as one of five common tank shapes (Figure 6), and the appropriate equation as described in the literature review was applied: Equation 9 is used for rectangular tanks, Equation 10 for circular, and Equation 11 for elliptical. For rectangular tee tanks, Equation 9 is applied to the upper and lower sections of the tank, and the results are summed. For elliptical tee tanks, Equation 11 is used for the top section with Equation 9 used for the bottom trough.

Values for the discharge coefficient *C* were assigned based on the likelihood of turbulent flow generated by the water tender's transfer valve (dump chute) design. A lack of empirical data led the author to assign two basic values for this study. For designs in which the water follows a straight path directly out of the tank, a value of 0.9 was used. For designs in which the water must follow an angled path (such as elbow adapters), a value of 0.6 was used to reflect the higher turbulence.

The NFPA 1142 standard notes that conventional, gravity-dumped water tenders are assumed to lose up to ten percent of their rated capacity during transit due to spillage (NFPA, 2022, para. C.10). This is accounted for in the model's calculation of *TDD*. For each water tender, efflux time is calculated for the full tank and this value is then converted to a gpm rate. The gpm rate is then applied to the effective volume of the tank as specified by NFPA 1142 (90 percent of the rated capacity) to yield a final *TDD* for conventional water tenders. For vacuum type water tenders, the author was unable to determine an acceptable mathematical method for estimating *TDD* values. Instead, actual time figures were obtained from the owning department for use as the *TDD* for vacuum apparatus.

All dwell time calculations are conducted in the Excel component of the model. Fill site dwell time calculations (*TF* and constituent elements) are located on a "WS FS" tab, while similar calculations for the dump site are on a tab named "WS DS." Calculations of *TFF* and *TDD* for each water tender are located alongside records for each apparatus on the "WT Factors" tab.

Calculating Queueing Time

As water shuttle operations grow in complexity, water tenders are commonly forced to line up to await servicing at the fill and dump sites. This additional time spent waiting to complete each cycle of the shuttle is captured in the model as queueing time (*TW*) and is a function of the number of water tenders, the handling capacity of the fill and dump sites, and the temporal buffering capacity created by the route time (*TR*).

As a first step, the fill and dump sites are assigned a capacity value: *Kf* and *Kd*, respectively. This is an integer value representing the number of water tenders that may be simultaneously serviced by each site. The author has observed very proficient organizations capable of simultaneously processing two water tenders at a fill site ($Kf = 2$), and three at a dump site ($Kd = 3$). However, in the case of this study area, where proficiency is known to be generally low, *K* values of one were universally assigned to all fill and dump sites.

The calculation of *TW* in this model treats route navigation time (*TR*) as a temporal buffer holding water tenders that are not being serviced at the fill or dump sites. As the number of water tenders in the shuttle exceeds the combined handling capacity of the fill and dump sites, the temporal buffer begins to fill, eventually forcing water tenders to queue for service. The value of *TW* is calculated as follows:

$$TW = \frac{\{THm \times [nWT - (Kf + Kd)]\} - TR}{nWT} \tag{23}$$

Where:

TW = Queueing time (minutes)

THm = Mean handling time (*TF* + *TD*) for all participating water tenders

nWT = Number of participating water tenders

Kf = Fill site handling capacity

Kd = Dump site handling capacity

TR = Route navigation time

Within the model, the value of *TW* is zero until the temporal buffering of navigation and dwell time is exceeded, typically when the number of water tenders (*nWT*) exceeds the total handling capacity (*Kf* + *Kd*). Negative values are automatically set to zero in the model calculations. After that, the value of *TW* increases each time a new water tender arrives to join the shuttle. The degree of increase at each step is dependent upon the performance characteristics of the participating water tenders because the value of *THm* may go up or down depending on the average efficiency of all apparatus. The value of *TW* is applied equally to the cycle times of all participating water tenders, with the amount applied increasing with each additional tender added to the shuttle. Consider the simplified hypothetical scenario presented in Table 4 below:

Table 4

Example of Queueing Time (TW) Calculation.

Step	*nWT*	*TF*	*TD*	*TH*	*THm*	*TW*
WT01	1	4	3	7	7.0	0.0
WT02	2	3	3	6	6.5	0.0
WT03	3	5	4	9	7.3	0.0
WT04	4	3	4	7	7.3	1.2
WT05	5	4	4	8	7.4	2.4
WT06	6	3	4	7	7.3	3.2
WT07	7	6	7	13	8.1	4.4
WT08	8	3	3	6	7.9	4.7
WT09	9	4	4	8	7.8	5.0
WT10	10	3	4	7	7.8	5.2

Note. Constant values used in calculations include *TR* = 10, *Kf* = 1, and *Kd* = 1.

In the example above, *TW* does not begin to accumulate until the fourth water tender arrives (WT04), after which it increases with each additional tender. This was the point at which the buffering capacity of the handling and navigation time is exceeded. The value of TW increases sharply with the arrival of an inefficient tender at step WT07. This demonstrates the differential impacts attending to variations in water tender handling characteristics. All calculations of TW are conducted in the Excel component of the model on the “WS TW” tab.

Calculating Shuttle Phase Benchmarks

As with the response phase, the estimation of the time that certain key events in the water shuttle operation are achieved is provided for the prospective incident commander. In the shuttle phase, the benchmarks concern achievement of key water delivery rates to the incident scene. For this study, the standard delivery rates of NFPA 1142 are used: 250, 500, 750, and 1,000 gpm

(NFPA, 2022, table 4.6.1). The benchmarks are referred to in the model as BM250, BM500, BM750, and BM1000 and provided as an elapsed time from initial dispatch. As previously indicated, the model assumes that all assigned resources are simultaneously dispatched and are thus operating from a common temporal baseline.

In reality, certain events must necessarily precede others in a water shuttle operation. Notably, the offloading of water cannot proceed until the portable tanks are deployed and ready to receive it. Because of this, the response phase “Dump Site Ready” benchmark must be achieved prior to any of the water deliver benchmarks. The model is designed to check for this situation, and in the case where a water delivery benchmark would have been achieved prior to the dump site being ready, the water delivery benchmark is increased to match the value for “Dump Site Ready.” Calculation of all water shuttle flow rates and times is performed in the “WS Calcs” tab of the Excel component of the model, while the benchmark calculations are conducted in the “WS Times” tab.

Summary of Model Design

This project is built on a two-phase model of a proposed water shuttle operation, using the actual apparatus and infrastructure available for the study area. A diagrammatic representation of the model is shown in Figure 24, below.

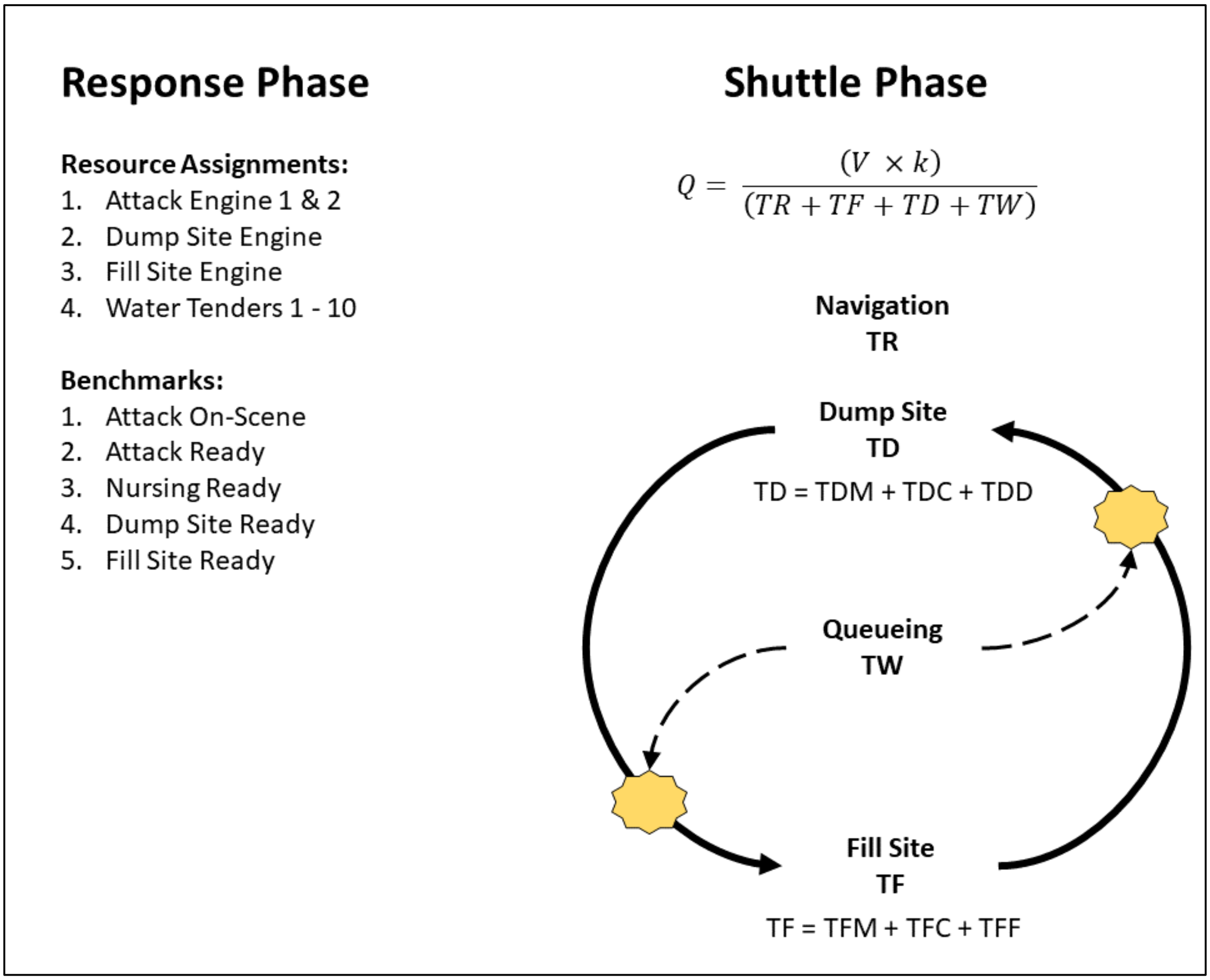


Figure 24. Overview of model structure.

The model is designed to provide a spatial decision support system (SDSS) allowing a prospective incident commander to understand when key water supply benchmarks are likely to be achieved at any location within the study area. The model can also serve as a planning tool. In this capacity, it can be used to test the effectiveness of different combinations of apparatus, or to gage the impact of proposed water supply development projects.

Results

The final product of this research project yielded the results intended: a workable model of water shuttle throughput estimation. This model can serve as both the core of a decision support system, and as an aid to planning improvements in apparatus, equipment, and infrastructure for alternative water supply. Specific results are presented below, organized according to the project's five research questions.

Water Handling Apparatus Inventory

A total of 34 water tenders and 38 engines were inventoried at the 24 fire stations in the mutual aid area. There was tremendous diversity among this apparatus fleet in terms of age, design, and manufacturer. Summary data for these apparatus is presented in several tables below. The data collected here answers the first research question: What water handling apparatus (engines and water tenders) are available for use in the study area, and what are their locations and performance characteristics?

Throughout the tables, each apparatus is referred to by a provisional identifier consisting of a three-character code representing the owning department (Appendix B), and the department's own unit identifier. As an example, Bellefontaine Fire Department's Engine 21 (E-21) is "BFF E-21," a unique identifier for that apparatus that is used throughout the study. A few "pumper-tanker" apparatus are considered engines by their home departments, but for purposes of this study they are treated as water tenders so long as they are equipped with a large capacity dump valve.

Of the 24 fire departments for which data were collected, all had at least one water tender. Ten of the departments had two water tenders. Table 5, below, provides a summary of basic information for the water tenders.

Table 5

Water Tender General Characteristics.

Unit	Tank capacity (gallons)	Design	Manufacturer	Year of manufacture
ATF T-601	3,600	vacuum	Firovac	2006
BCF T-121	1,600	conventional	E-One	1996
BCF T-122	2,000	conventional	unknown	unknown
BFF T-21	1,800	conventional	KME	1996
DGF T-31	2,000	conventional	locally fabricated	2001
HVF T-51	1,300	conventional	locally fabricated	1995
IJF T-101	2,000	conventional	Smeal	2009
JCF T-562	3,000	conventional	S & S	1994
JCF T-565	2,100	conventional	unknown	1990
LTF T-292	2,000	conventional	unknown	1994
LVF T-61	1,800	conventional	Smeal	1996
MTV T-22	3,500	conventional	U.S. Tanker	2007
MWF T-861	1,500	conventional	Pierce	1986
MWF T-862	1,500	conventional	Pierce	1989
NEC T-321	1,500	conventional	Pierce	2014
PJF T-963	3,000	conventional	Pierce	2020
PTF E-42	2,000	conventional	Sutphen	2018
PTF T-41	1,800	conventional	unknown	1992
QVF E-72	2,000	conventional	Sutphen	1974
QVF T-71	1,400	conventional	Rosenbauer	2007
RCF T-91	1,800	conventional	U.S. Tanker	2000
RHD T-1002	3,200	conventional	locally fabricated	2000
RTF E-12	2,000	conventional	KME	2005
RTF T-11	2,000	conventional	KME	2000
RWD T-161	1,800	conventional	Sutphen	1980

RWD T-164	2,000	conventional	Sutphen	1998
RWF T-82	3,000	conventional	Rosenbauer	2007
RWF T-83	2,000	conventional	Rosenbauer	2017
SJF E-6041	2,500	conventional	Smeal	2001
SJF T-6042	1,800	conventional	Midwest	2009
TVF T-141	2,200	conventional	U.S. Tanker	2005
TVF T-142	1,500	conventional	unknown	1986
WLF T-111	3,000	conventional	Sutphen	2017
WTF T-943	2,000	conventional	Good Hope	1994

Only one vacuum-type water tender was identified in the mutual aid area, with the remainder being of conventional, gravity-dump design. The average tank capacity was found to be 2,124 gallons. In terms of the resource typing standard adopted by the Ohio Fire Chiefs' Association for intrastate mutual aid assignments (Keller & Browne, 2016), the surveyed fleet represents the following (based on tank capacity alone):

- Type 1 (≥ 3,000 gallons): seven (20.6%)
- Type 2 (≥ 2,400 gallons): one (2.9%)
- Type 3 (≥ 1,800 gallons): 19 (55.9%)
- Type 4 (≥ 1,000 gallons): seven (20.6%)

The water tenders were found to have a variety of manufacturers. Three were known to be locally fabricated or converted from other uses. For five units, the manufacturer could not be determined, but it was clear that they were not locally fabricated. The remaining 26 were built by recognizable fire apparatus manufacturers, although not all were still in business. The most common manufacturer with five units was Sutphen, which is unsurprising given that Logan County is located nearby that company's headquarters.

The average age of the water tenders was found to be 20.9 years. The oldest unit that could be definitively dated was built in 1974, while the newest was built in 2020. No date could be found for one unit, and for several of the oldest units, the author was somewhat skeptical of the date provided.

Information regarding the water handling characteristics for each unit were also collected. This information was collected with an eye toward meeting the needs of model calculations, rather than attempting an encyclopedic collection of every unique attribute. A summary of factors affecting fill and dump time estimates is provided in Table 6, below.

Table 6

Water Tender Water Handling Characteristics.

Unit	Tank shape	Tank material	Side dump configuration	Adaptable fill ports
ATF T-601	vacuum	not poly	straight, remote	1
BCF T-121	rectangular	poly	angled, not affixed	2
BCF T-122	elliptical	poly	angled, not affixed	2
BFF T-21	rectangular	not poly	angled, not affixed	2
DGF T-31	rectangular	not poly	angled, not affixed	1
HVF T-51	rectangular	not poly	angled, not affixed	1
IJF T-101	rectangular	poly	straight, remote	2
JCF T-562	elliptical	not poly	straight, manual	2
JCF T-565	elliptical	not poly	angled, affixed	2
LTF T-292	elliptical	not poly	angled, not affixed	2
LVF T-61	rectangular	poly	angled, not affixed	2
MTV T-22	rectangular	poly	straight, manual	1
MWF T-861	rectangular	not poly	angled, not affixed	1
MWF T-862	rectangular	poly	angled, not affixed	1
NEC T-321	rectangular	poly	angled, affixed	1

PJF T-963	rectangular	poly	straight, remote	2
PTF E-42	rectangular tee	poly	angled, affixed	2
PTF T-41	rectangular tee	poly	angled, not affixed	2
QVF E-72	rectangular	not poly	angled, not affixed	1
QVF T-71	rectangular	poly	angled, not affixed	2
RCF T-91	elliptical	not poly	straight, manual	2
RHD T-1002	elliptical	not poly	angled, not affixed	1
RTF E-12	rectangular	poly	angled, not affixed	1
RTF T-11	rectangular	poly	angled, not affixed	2
RWD T-161	rectangular	not poly	angled, not affixed	1
RWD T-164	rectangular tee	poly	angled, not affixed	2
RWF T-82	rectangular	poly	straight, manual	2
RWF T-83	rectangular tee	poly	angled, affixed	1
SJF E-6041	rectangular tee	poly	angled, affixed	2
SJF T-6042	rectangular	poly	angled, affixed	1
TVF T-141	elliptical	not poly	angled, not affixed	1
TVF T-142	elliptical	not poly	angled, not affixed	1
WLF T-111	rectangular tee	poly	angled, affixed	2
WTF T-943	rectangular	not poly	angled, affixed	2

The shape of the tank was critical for using the model's Torricelli-derived methods for estimating efflux times. Tank geometry was variable, with rectangular configurations the most common. No tanks with a circular or elliptical tee configuration were encountered. The distribution of tank shapes was:

- Rectangular: 19 (55.9%)
- Elliptical: eight (23.5%)
- Rectangular tee: six (17.6%)

- Vacuum: one (2.9%)

The material of tank construction was important in determining an appropriate rate and pressure for filling operations, given the restrictions inherent in tanks of poly construction. The majority of tanks were of poly construction, with 19 water tenders so configured. Excluding the single vacuum unit, this represents 57.6% of the surveyed fleet. With the exception of the vacuum unit, the newest water tender with a non-poly tank entered service in 2005, while the oldest poly unit entered service in 1992, although it was unclear whether this unit had been retrofitted with a poly tank at some point.

The configuration and size of the transfer (dump) valve was also needed for the Torricelli equations. A variety of dump valve configurations was encountered, and these were placed into one of the four categories used to assign the dump site connection time (*TDC*) for each apparatus. The configuration was also used to assign a value for the discharge coefficient (*C*) for use in the Torricelli equations.

Three water tenders (8.8%) had straight dump valves that could be operated remotely from the cab, yielding the lowest *TDC* value of 0.0 minutes and a *C* value of 0.9. Four units (11.8%) had straight dump outlets that required manual operation by the ground crew, resulting in the same *C* value, but a *TDC* value of 0.3 minutes. Eight units (23.5%) had angled dump valves that could remain affixed during road travel, yielding a *TDC* value of 0.6 minutes. These chutes had an articulated design, allowing them to pivot to any angle at the rear of the apparatus. The remaining 19 water tenders (55.9%) were designed to only dump to the rear, and thus for offloading to the side would require an elbow adapter that could not remain affixed during road travel. These units were assigned a *TDC* value of 1.2 minutes. Both types of angled dump arrangements were assigned a value of 0.6 for the *C* coefficient.

Size, number, coupling, and arrangement of fill ports was very diverse across the surveyed fleet of water tenders. In keeping with the model assumption of all filling occurring via a common 2.5-inch NH connection at the rear of the apparatus, the fill port arrangements were categorized according to how many available connections could be adapted to this standard. Eighteen units (52.9%) had two acceptable fill ports, while the remaining 16 (47.1%) had only one.

In addition to the information presented in the tables above, the dimensions of the tanks were collected for use in the Torricelli equations. When combined, this information allowed for the calculation of estimates for offloading time (*TDD*) and rate. Under the assumptions of the model, all water tenders will be filled at a common rate of 528 gpm, so only fill time (*TFF*) was calculated, not fill rate (Table 7).

Table 7

Estimated Fill and Offload Times for Water Tenders.

Unit	Fill time (*TFF*, minutes)	Offload time (*TDD*, minutes)	Offload rate (gpm)
ATF T-601	6.8	4.5	800
BCF T-121	3.0	1.4	996
BCF T-122	3.8	1.1	1,665
BFF T-21	3.4	1.2	1,359
DGF T-31	3.8	1.4	1,278
HVF T-51	2.5	1.0	1,203
IJF T-101	3.8	0.8	2,212
JCF T-562	5.7	1.4	1,983
JCF T-565	4.0	1.2	1,583
LTF T-292	3.8	1.0	1,874
LVF T-61	3.4	1.2	1,359

MTV T-22	6.6	1.8	1,731
MWF T-861	2.8	1.2	1,158
MWF T-862	2.8	1.2	1,158
NEC T-321	2.8	0.9	1,517
PJF T-963	5.7	1.2	2,248
PTF E-42	3.8	1.9	959
PTF T-41	3.4	1.6	996
QVF E-72	2.7	1.0	1,257
QVF T-71	3.8	1.3	1,362
RCF T-91	3.4	1.0	1,605
RHD T-1002	6.1	4.2	683
RTF E-12	3.8	1.6	1,124
RTF T-11	3.8	1.6	1,110
RWD T-161	3.4	1.3	1,219
RWD T-164	3.8	1.4	1,252
RWF T-82	5.7	1.8	1,481
RWF T-83	3.8	2.6	702
SJF E-6041	4.7	2.0	1,129
SJF T-6042	3.4	1.1	1,425
TVF T-141	4.2	1.1	1,844
TVF T-142	2.8	1.4	978
WLF T-111	5.7	2.8	959
WTF T-943	3.8	1.7	1,081

Note. Offload time for vacuum unit ATF T-601 provided by owning department, not calculated.

The average estimate for water tender fill time (*TFF*) is 4.0 minutes, with a range of 2.5 to 6.8 minutes. Because the model uses a standard fill rate, the value for *TFF* is a direct function of tank capacity: larger tanks take longer to fill. The potential performance of units with multiple fill ports or without the restrictions of a poly tank is discounted. Using a more flexible filling scenario would allow for improved performance by many of the units.

Average offload rate was estimated to be 1,332 gpm, ranging from 683 to 2,248 gpm. This yields an average offload time (*TDD*) estimate of 1.7 minutes, with a range of 0.9 to 4.7 minutes. Without empirical data for comparison, it is impossible to say with certainty whether these represent realistic estimates for offload times and rates. The values are within ranges normally observed by the author during water shuttle training evolutions, however.

Data on pumps and portable tanks was also collected for all water tenders. From the standpoint of the model, pumps were of interest only with regards to nursing operations. For this reason, pumps on water tenders were classified into two categories: those capable of supporting nursing, and those not. A pump rating of 500 gpm was used as a minimum value to support nursing. Portable tanks were inventoried by capacity (gallons) and shape (square, narrow profile, or other). A summary of this ancillary equipment inventory is provided in Table 8, below).

Table 8

Summary of Water Tender Ancillary Equipment.

Unit	Nursing capable pump?	Number of portable tanks	Tank capacity (gallons)	Tank configuration
ATF T-601	yes	1	2,000	square
BCF T-121	no	1	1,500	square
BCF T-122	no	1	1,500	square
BFF T-21	yes	1	2,100	square
DGF T-31	no	2	2,000 / 1,800	both square
HVF T-51	no	1	2,000	square
IJF T-101	yes	1	2,100	square
JCF T-562	yes	1	3,000	square

JCF T-565	no	2	2,500 / 2,100	both square
LTF T-292	yes	1	1,000	square
LVF T-61	no	1	2,000	square
MTV T-22	yes	1	3,500	square
MWF T-861	yes	1	2,000	square
MWF T-862	yes	1	2,000	square
NEC T-321	yes	1	1,500	narrow profile
PJF T-963	yes	1	3,000	square
PTF E-42	yes	1	2,000	square
PTF T-41	no	1	1,500	square
QVF E-72	yes	1	1,000	square
QVF T-71	yes	1	2,100	square
RCF T-91	yes	1	2,000	square
RHD T-1002	no	0*	n/a	n/a
RTF E-12	yes	0	n/a	n/a
RTF T-11	yes	1	2,500	square
RWD T-161	no	2	2,000 / 2,000	both square
RWD T-164	yes	1	2,500	square
RWF T-82	yes	1	3,000	square
RWF T-83	yes	1	2,000	square
SJF E-6041	yes	1	2,500	square
SJF T-6042	yes	1	2,000	square
TVF T-141	yes	1	2,200	square
TVF T-142	no	1	1,500	square
WLF T-111	yes	1	3,000	square
WTF T-943	no	1	2,100	square

Note. Unit RHD T-1002 does not carry its own portable tank, instead it is carried on the department's engine; the tank is 1,800 gallons and square in shape.

Twenty-three of the water tenders (67.6%) had rated fire pumps of 500 gpm or better, and thus were capable of nursing operations for purposes of this model. The remainder either carried no pump, a portable pump, or had a mounted pump of insufficient capacity. No attempt was made to inventory additional tools or appliances useful for nursing operations due to the lack of any standard operating procedures for guidance.

All but two of the water tenders carried at least one portable tank, and three units carried two tanks on board. In only one case was a narrow profile tank carried, all other tanks were of the traditional square configuration. Portable tank capacity was generally related to the capacity of the water tender's tank but was considerably less in some cases.

With respect to which water tenders were actually used in the model, the author collected more apparatus information than was strictly necessary. Of the 34 water tenders surveyed, just 23 were used to fill the WT01 through WT10 assignments for one or more routes (Figure 25). It was unclear prior to running the model which water tenders would actually come into play, so the author intentionally took an expansive approach to data collection to avoid missing any potentially useful units. While not needed this study specifically, the data collected for the water tenders that were not needed was useful in gaining an understanding of local apparatus and equipment conditions and could be used in future expansion of the model to other areas.

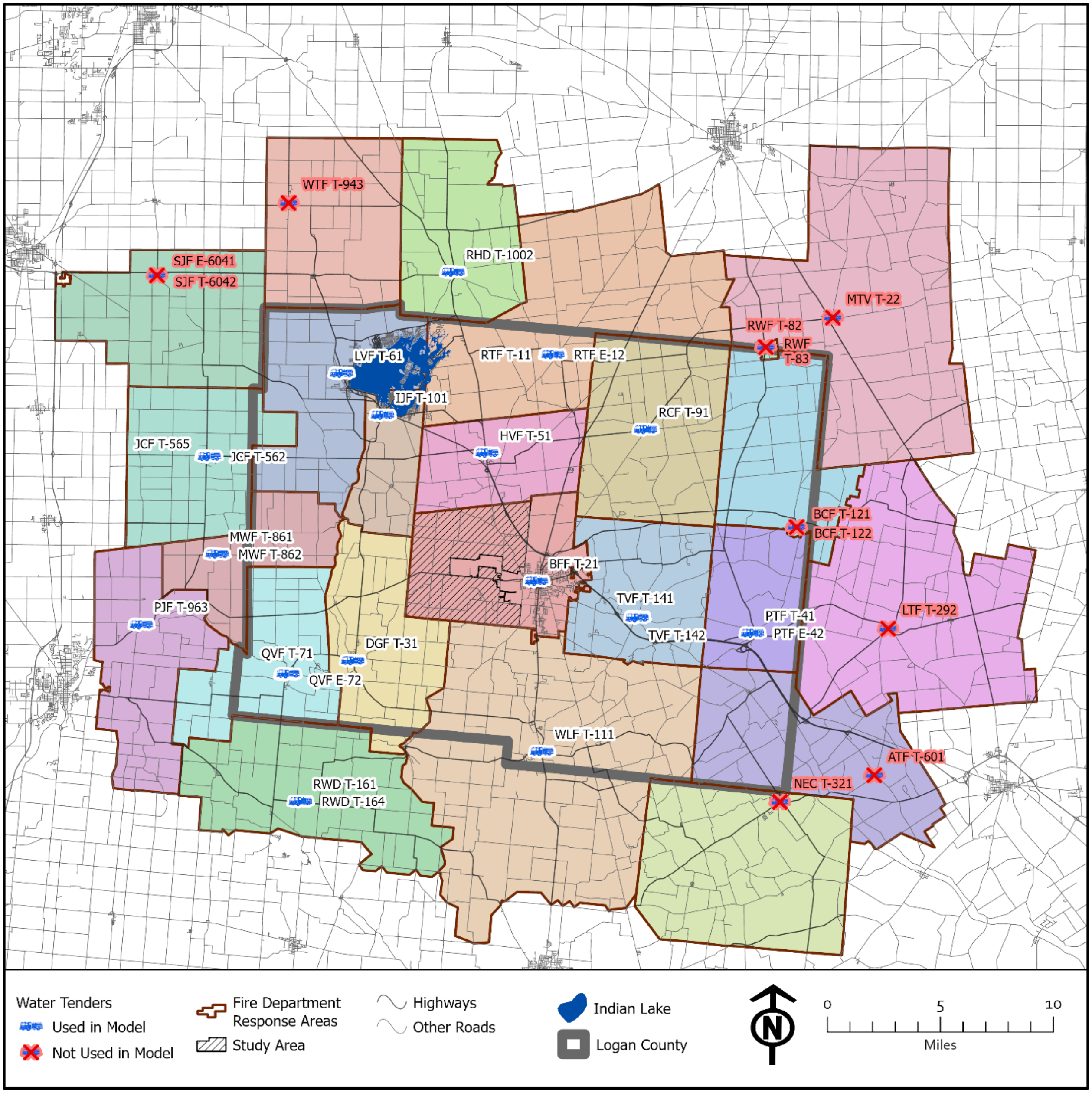


Figure 25. Water tenders actually used in the model.

A total of 38 engines were surveyed at the 24 fire stations. Data elements collected for these units were intended to assess the suitability of each apparatus for the role of a fill or dump site engine. Because combination "pumper-tanker" units were classified as water tenders, one department had no units that were surveyed as engines (SJF). In one case, a combination “rescue-pumper” was encountered; it was inventoried as an engine for purposes of this study (ATF). Summary information on the engines surveyed is provided in Table 9, below.

Table 9

Engine General Characteristics.

Unit	Pump rating (gpm)	Manufacturer	Year of manufacture	Primer type
ATF E-601	1,500	Sutphen	2017	air
ATF R-601	1,250	HME	1998	conventional
BCF E-121	1,250	HME	1997	conventional
BCF E-122	1,250	Luverne	1994	conventional
BFF E-21	1,250	KME	1998	conventional
BFF E-22	1,500	Smeal	2003	conventional
DGF E-31	1,000	Grumman	1990	conventional
DGF E-32	1,250	Smeal	2008	conventional
HVF E-51	1,250	Boardman	1994	conventional
HVF E-52	1,000	Grumman	1991	conventional
IJF E-101	1,250	Smeal	2000	conventional
IJF E-102	1,000	Grumman	1989	conventional
JCF E-563	1,500	Smeal	2002	conventional
LTF E-291	1,250	Smeal	2002	conventional
LTF E-293	1,500	Sutphen	2009	air
LVF E-61	1,000	Grumman	1989	conventional
LVF E-62	1,500	Smeal	2009	conventional
MTV E-24	1,500	Sutphen	2014	air
MWF E-863	2,000	KME	2012	conventional
NEC E-321	1,000	Grumman	1987	conventional
NEC E-322	1,250	Smeal	1999	conventional
PJF E-962	1,250	Pierce	1992	conventional
PJF E-964	1,250	HME	2004	conventional

PTF E-41	1,500	Sutphen	2013	air
QVF E-71	1,250	E-One	1997	conventional
RCF E-91	1,250	Smeal	2005	conventional
RCF E-92	1,000	Pierce	1982	conventional
RHD E-1001	1,000	Boardman	1994	conventional
RTF E-11	2,000	KME	2004	conventional
RWD E-161	750	Grumman	1991	conventional
RWD E-163	1,500	Smeal	2007	conventional
RWF E-81	1,250	Rosenbauer	2010	air
TVF E-141	1,500	Sutphen	2010	conventional
TVF E-142	1,000	Smeal	1995	conventional
WLF E-111	1,250	Pierce	2005	conventional
WLF E-112	1,000	Grumman	1984	conventional
WTF E-941	1,000	Grumman	1988	conventional
WTF E-942	1,250	Rosenbauer	2009	conventional

In most cases, fire departments had two engines: this being the case for 15 of the 24 departments. Due to overlap in some cases with "pumper-tanker" units and with quint apparatus partly filling the engine role in some organizations, this is not a clear-cut metric but more a matter of semantics. A total of four aerial apparatus (ladders and quints) were encountered (BFF, IJF, JCF, MTV). While these apparatus could theoretically fill the role of an engine in the model, especially in the attack roles, they were not inventoried at this stage of development of the model.

The surveyed engine fleet represents a broad sweep of technological development in automotive fire apparatus. The average engine age was found to be 21.2 years, older than the water tender fleet. The oldest unit still in service was 39 years old, entering the fleet in 1982. The newest unit had entered service in 2017. The presence of so many old engines is likely the result of units kept in reserve service, although the distinction between front-line and reserve status was not clear in some organizations. The most common manufacturer was Smeal with 10 units (25.6%). Classic Grumman FireCats were also well represented with eight units (20.5%) still prowling around local fire stations. Hometown manufacturer Sutphen was a distant third, representing just five units (12.8%) in the surveyed engine fleet. The remainder of units were produced by a variety of manufacturers, most of which remain in business.

Most of the surveyed engines had pumps rated at 1,250 gpm, accounting for 16 of the total (41.0%). The remainder were evenly split, with 11 (28.9%) of lower capacity (1,000 and 750 gpm) and the same number of greater capacity (1,500 and 2,000 gpm). The lower capacity pumps were found on engines that were greater than 25 years old in each case, while all of the pumps of greater capacity were found on apparatus less than 20 years old. Primer design was also noted for each engine, differentiating between conventional and air primers. It was thought that this may be of use for future development of the model, since air primer equipped units may be a better choice for fill sites with dry hydrants. A total of five engines were equipped with air primers (13.2%), the oldest of which was a 2009 model.

Additional information collected for engines included factors felt to be helpful in deciding which units might be the best choices for fill or dump site assignments. Although engines were not differentiated for these roles with this version of the model, this is a likely avenue for future development. These additional items are shown in Table 10, below.

Table 10

Engine Additional Characteristics.

Unit	Crew capacity	Tank capacity (gallons)	Supply hose size (inch) & coupling	Supply hose carried (feet)
ATF E-601	4	1,000	5.0 Storz / 3.0 NH	1,250 / 600
ATF R-601	5	750	5.0 Storz / 3.0 NH	300 / 600
BCF E-121	6	500	3.0 NH	500
BCF E-122	6	1,000	3.0 NH	100
BFF E-21	4	750	5.0 Storz	1,050
BFF E-22	6	750	5.0 Storz	800
DGF E-31	2	1,000	2.5 NH	1,200
DGF E-32	5	1,000	5.0 Storz / 2.5 NH	500 / 1,200
HVF E-51	5	1,000	5.0 Storz / 3.0 NH	500 / 700
HVF E-52	2	1,000	5.0 Storz	300
IJF E-101	3	1,000	5.0 Storz / 3.0 NH	800 / 600
IJF E-102	3	1,000	3.0 NH / 2.5 NH	600 / 600
JCF E-563	6	700	5.0 Storz	1,000
LTF E-291	6	1,000	5.0 Storz / 3.0 NH	1,000 / 500
LTF E-293	6	1,000	5.0 Storz / 3.0 NH	1,000 / 500
LVF E-61	3	1,000	5.0 Storz	1,000
LVF E-62	5	1,000	5.0 Storz	800
MTV E-24	5	1,000	5.0 Storz	1,800
MWF E-863	6	750	5.0 Storz / 3.0 Storz	1,000 / 500
NEC E-321	2	750	3.0 NH	700
NEC E-322	5	1,000	3.0 NH	1,200
PJF E-962	6	1,000	5.0 Storz / 3.0 NH	1,000 / 1,000
PJF E-964	6	900	5.0 Storz / 3.0 NH	1,000 / 1,000
PTF E-41	5	1,000	5.0 Storz / 3.0 NH	900 / 500
QVF E-71	5	1,250	2.5 NH	2,500

RCF E-91	6	1,200	5.0 Storz	500
RCF E-92	3	1,000	5.0 Storz	500
RHD E-1001	2	750	2.5 NH	500
RTF E-11	8	500	5.0 Storz / 3.0 NH	800 / 800
RWD E-161	5	1,250	2.5 NH	1,200
RWD E-163	5	1,250	3.0 NH	1,200
RWF E-81	5	1,500	5.0 Storz / 2.5 NH	1,000 / 1,000
TVF E-141	6	1,000	5.0 Storz / 3.0 NH	250 / 500
TVF E-142	5	1,000	2.5 NH	500
WLF E-111	5	1,000	2.5 NH	1,000
WLF E-112	3	1,000	2.5 NH	1,000
WTF E-941	3	1,000	4.5 Storz	250
WTF E-942	3	1,250	4.5 Storz	500

Note. Type your note content here.

Crew capacity, defined as the number of belted riding positions, was noted for each engine. This was collected with an eye toward screening out some engines for assignment to the fill or dump site role based on limited crew size. Such screening was not conducted with this initial model version but would be helpful as the model is developed further. Units capable of carrying a crew of four or more would be best suited to staffing fill or dump sites, assuming all spots are filled when leaving the station. Twenty-seven (71.0 %) of the surveyed engines had a crew capacity of four or greater, with one capable of seating a crew of eight (referred to by its department as “the school bus”). Four older units only had two belted positions, and seven had only three.

Capacity of each unit’s (booster) tank was also recorded. While not used in this version of the model, this data was gathered in hopes of developing a module for tracking cumulative on-scene water in a future version. The majority of engines had a tank capacity of 1,000 gallons: 22

units (57.9%) had this capacity. Six units (15.8%) carried more than 1,000 gallons, while ten units (26.3%) carried less. Those units with tanks of 1,000 gallons or greater meet the NFPA 1901 capacity requirement for water tender (NFPA, 2016, para. 7.5), but each one lacked a dump valve to allow for rapid offloading, so they were not considered water tenders for purposes of this study.

Information on supply hose carried by each engine was recorded as a potential screening mechanism for assignments, but also to gain a sense of what the dominant sizes and couplings are in the local fire community. There was tremendous variation, reflecting the diverse philosophies and preferences of 24 entirely independent fire departments. A majority of engines carried at least some amount of 5.0-inch Storz large diameter hose (LDH), with 23 units so equipped (60.5%). An additional two engines carried 4.5-inch Storz LDH lines, while the remaining 13 engines (34.2%) carried only 2.5- or 3.0-inch NH supply hose.

As was the case with water tenders, the author collected more apparatus data than necessary: only 12 of the 38 engines surveyed were actually used in the model to fill either a dump site or fill site role for one or more routes (Figure 26). While not immediately useful, the data gathered was helpful in understanding the local engine fleet and could be useful for future expansion of the model to other areas.

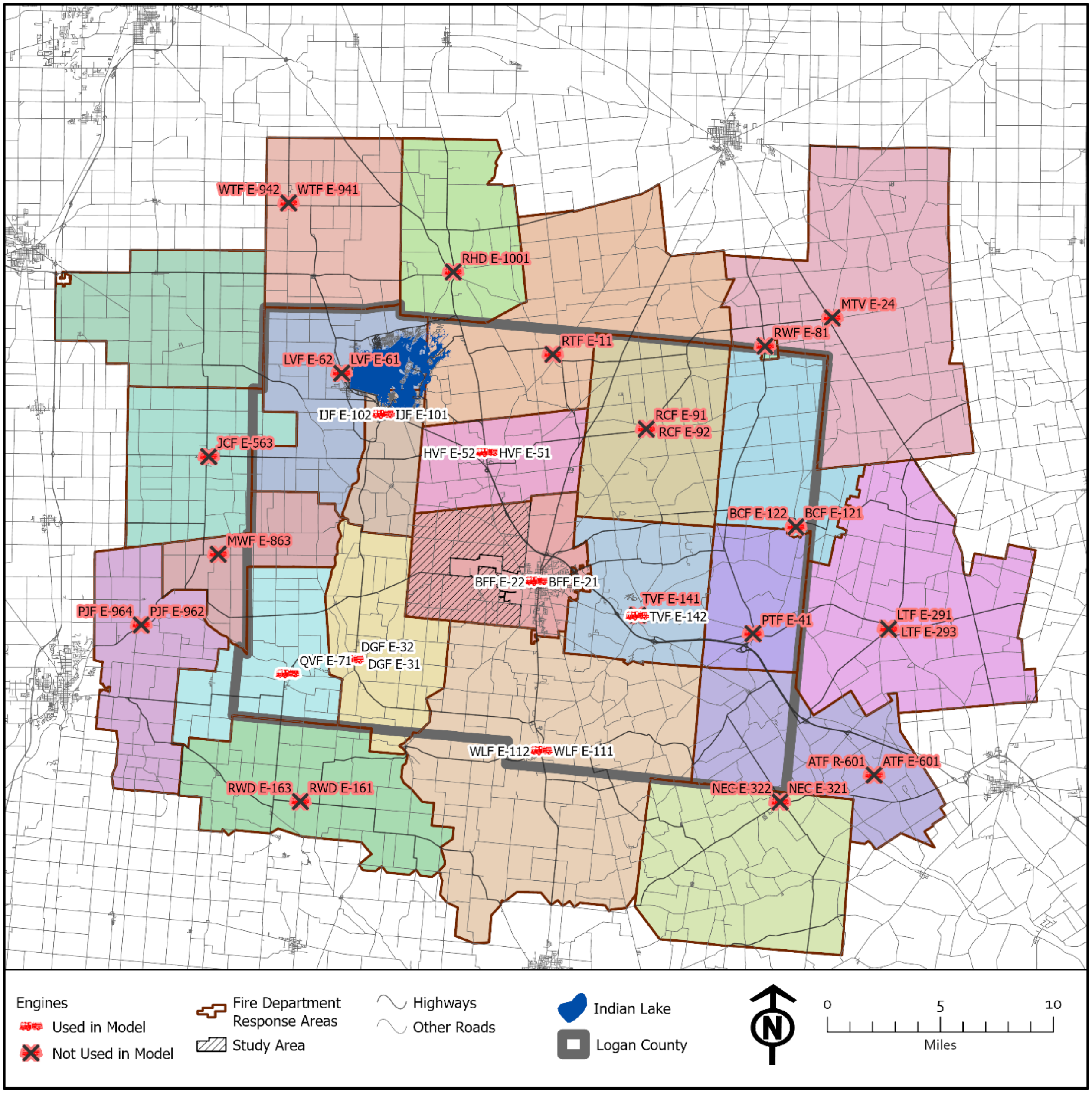


Figure 26. Engines actually used in the model.

Each fire department was also surveyed for the presence of appliances necessary for establishing either a fill or dump site: jet siphons, low-level strainers, and manifolds. No effort was made to determine on which apparatus these items are carried, how many were available, or any information about size, age, or manufacturer. Instead, this information was gathered to develop a general sense of what water handling equipment was available in the mutual aid area and what items may need to be purchased for integrated operations. A summary of this data is provided in Table 11, below.

Table 11

Inventory of Ancillary Appliances.

Fire Department	Low-level strainer	Jet siphon	Manifold
ATF	yes	yes	yes
BCF	yes	yes	no
BFF	yes	no	yes
DGF	yes	yes	no
HVF	yes	no	no
IJF	yes	yes	yes
JCF	yes	yes	yes
LTF	yes	yes	yes
LVF	yes	yes	yes
MTV	yes	no	yes
MWF	no	no	no
NEC	yes	yes	no
PJF	yes	yes	yes
PTF	yes	yes	no
QVF	yes	yes	no
RCF	yes	no	no
RHD	yes	no	yes

RTF	yes	yes	yes
RWD	yes	yes	yes
RWF	yes	yes	yes
SJF	yes	yes	yes
TVF	yes	yes	yes
WLF	no	no	no
WTF	yes	no	no

Of the 24 fire departments surveyed, only 11 (45.8%) owned at least one of each of the three appliances. Most departments owned at least one low-level strainer, with 22 (91.7%) reporting ownership. Sixteen departments (66.7%) reported owning at least one jet siphon, while 14 (58.3%) claimed ownership of at least one manifold.

Fill Site Inventory

A total of 22 fill sites were identified for potential use with the model. These sites were screened for a minimum available flow of 1,000 gpm and acceptable physical characteristics to ensure safe and efficient working conditions for the fill site crew. All ten dry hydrants considered (eight existing and two planned) were deemed suitable; not surprising given that dry hydrants are generally designed to be used as a water shuttle fill site. Twelve municipal hydrants of the 168 considered were assessed as suitable fill sites. The 22 fill sites used as the basis for route development are shown in Figure 27, below. The data collected here answers the second research question: What potential water supply sources (fill sites) are available for the study area and what are their flow potentials?

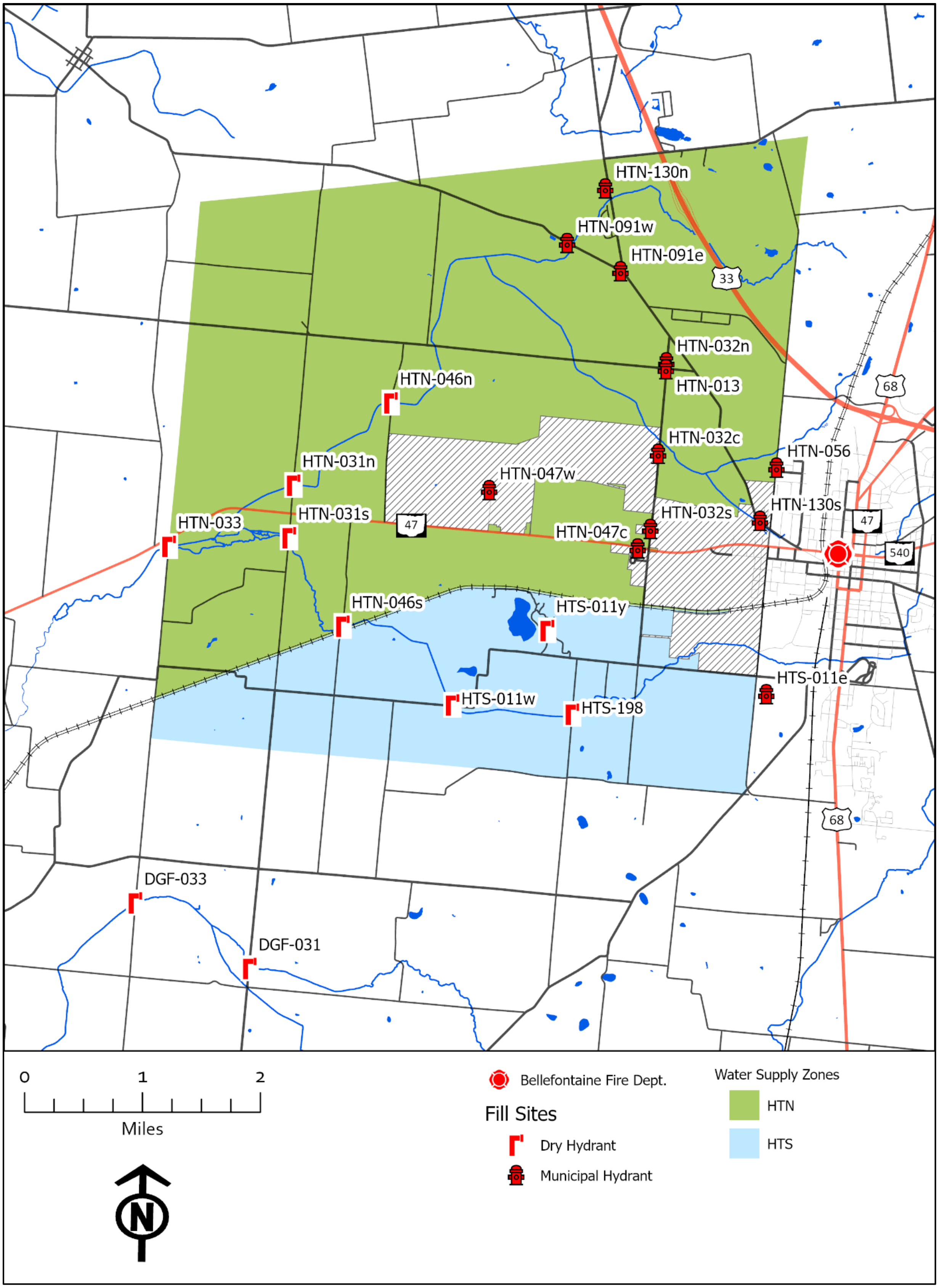


Figure 27. Fill site locations.

Besides flow rate, fill sites were classified into several categories for assignment of model time factors. For the setup base time (*TFS*), fill sites were classified according to their source of water supply and its perceived difficulty of bringing into action: municipal hydrants, dry hydrants, or complex scenarios. For the maneuver base time (*TFM*), fill sites were classified according to the assessed difficulty of moving water tenders into and out of position for servicing: roadside, offset, or complex. Summary fill site information is provided in Table 12, below.

Table 12

Fill Site Inventory.

Fill site	Type	Flow rate (gpm)	*TFS* base (minutes)	Maneuver scenario	*TFM* base (minutes)
DGF-031[1]	dry hydrant	1,000	5.0	roadside	0.5
DGF-033[1]	dry hydrant	1,000	5.0	roadside	0.5
HTN-013	municipal hydrant	2,066	3.0	roadside	0.5
HTN-031n	dry hydrant	1,000	5.0	roadside	0.5
HTN-031s	dry hydrant	1,000	5.0	roadside	0.5
HTN-032c	municipal hydrant	1,752	3.0	roadside	0.5
HTN-032n	municipal hydrant	2,026	3.0	offset	1.0
HTN-032s	municipal hydrant	1,989	3.0	roadside	0.5
HTN-033	dry hydrant	1,000	5.0	roadside	0.5
HTN-046n	dry hydrant	1,000	5.0	roadside	0.5
HTN-046s	complex / dry hydrant	1,000	8.0	complex	2.0
HTN-047c	municipal hydrant	1,948	3.0	offset	1.0
HTN-047w	municipal hydrant	2,021	3.0	offset	1.0
HTN-056	municipal hydrant	1,326	3.0	roadside	0.5
HTN-091e	municipal hydrant	1,989	3.0	roadside	0.5
HTN-091w	municipal hydrant	1,476	3.0	roadside	0.5

HTN-130n	municipal hydrant	1,834	3.0	offset	1.0
HTN-130s	municipal hydrant	1,055	3.0	roadside	0.5
HTS-011e	municipal hydrant	1,923	3.0	roadside	0.5
HTS-011w	dry hydrant	1,000	5.0	roadside	0.5
HTS-011y[2]	dry hydrant	1,000	5.0	complex	2.0
HTS-198	dry hydrant	1,000	5.0	roadside	0.5

Notes. 1. Planned installation in neighboring jurisdiction. 2. Excavated installation in lake.

Sixteen of these fill sites were used in the route development process for the northern water supply zone (HTN), while six were used for the southern zone (HTS). The six fill sites for HTS include two planned sites located in a neighboring jurisdiction (DGF), but well sited to provide coverage for parts of the study area. During the route development process, three of the prospective fill sites were found to be superfluous: HTN-031s in the north zone, and HTS-011y and DGF-031 in the south zone. These sites were not needed because the routes were better covered by other sites. This left a total of 19 fill sites that were actually used for route development in the model. Because some of the routes developed were also superfluous, an additional fill site was excluded from the final model: HTN-013. This left a total of 18 fill sites used to generate the final model outputs. The excluded fill sites could be used as secondary or alternative points of water supply as the model is further developed, but for purposes of this study, only one fill site was assigned to each route.

Shuttle Routes Developed

Shuttle routes were developed to connect each potential dump site with at least one fill site. Thirty-eight potential routes were developed for consideration. The results of this process presented below answer the project's third research question: What are the potential water shuttle routes linking sources of water supply with premises within the study area?

For the route development process, 30 potential turnaround points were identified to support pendular and combination route design. These points include any potentially usable site within or immediately around the study area, such as parking lots and improved farm drives. A total of 20 turnaround points were identified for the northern zone, and 10 for the southern zone. Summary information for the turnaround points is provided in Table 13, below.

Table 13

Turnaround Point Inventory.

Turnaround point	Type	Time penalty (minutes)	Description
DGF-01	TA2	1.0	improved farm drive at fill site DGF-033
HTN-01	TA1	0.5	Bellefontaine airport parking lot
HTN-02	TA1	0.5	Logan County Children's Services parking lot
HTN-03	TA1	0.5	Harrison Township building parking lot
HTN-04	TA1	0.5	Nash Finch warehouse parking lot
HTN-05	TA1	0.5	Ohio Valley Court mobile home park loop drive
HTN-06c	TA1	0.5	Shady Knolls subdivision center drive
HTN-06e	TA1	0.5	Shady Knolls subdivision east drive
HTN-06w	TA1	0.5	Shady Knolls subdivision west drive
HTN-07	TA1	0.5	Wayside Estates mobile home park loop drive
HTN-08	TA1	0.5	Stites Grocery parking lot
HTN-09	TA2	1.0	CSX railroad service drive, S CR 31 north side

HTN-10	TA2	1.0	improved farm drive at 879 S CR 31
HTN-11	TA2	1.0	CSX railroad service drive, CR 11 west side
HTN-12	TA2	1.0	residential drive, 741 S TWP 46
HTN-13	TA2	1.0	improved farm drive at fill site HTN-046n
HTN-14	TA1	0.5	roadway triangle
HTN-23	TA1	0.5	Jubilee Mennonite Church parking lot
HTN-24	TA1	0.5	IEG Plastics facility parking lot
HTN-25	TA1	0.5	Logan Electric Cooperative parking lot
HTS-01n	TA1	0.5	Southview Park, north entrance
HTS-01w	TA1	0.5	Southview Park, west entrance
HTS-02	TA1	0.5	YMCA Camp Willson
HTS-03	TA2	1.0	CSX railroad service drive, S CR 32 south side
HTS-04	TA2	1.0	CSX railroad service drive, S TWP 46 south side
HTS-05	TA1	0.5	Gretna Brethren Church parking lot
HTS-06	TA2	1.0	CSX railroad service drive, CR 11 east side
HTS-07	TA2	1.0	improved farm drive at fill site HTS-011w
HTS-08	TA2	1.0	improved farm drive at 1473 S TWP 33
HTS-09	TA1	0.5	Church of Christ parking lot

Of the 30 potential turnaround points identified, 20 were used in the potential routes that were developed. For routes in the northern water supply zone (HTN), a total of 14 were used including nine TA1 and five TA2. A total of six were used for routes in HTS, all of which were TA2.

A total of 38 shuttle routes were identified for potential use in the model: 27 in the northern zone, and 11 in the southern zone. Of these routes, 18 were of the favored loop or pendular type one configurations, while the remaining 20 were a mix of less favorable pendular and combination route configurations. Navigation time for each route (*TR*) was calculated based on its configuration, as detailed in the procedures section. Summary information for the shuttle routes is provided in Table 14, below.

Table 14

Shuttle Route Inventory.

Route	Fill site	Configuration	Turnaround points	*TR* (minutes)	No. assigned dump sites
HTN-A	HTN-031n	loop	none	10.2	15
HTN-B	HTN-031n	loop	none	11.9	27
HTN-C	HTN-031n	loop	none	15.2	0
HTN-D	HTN-047w	pendular type 2	HTN-01/HTN-02	6.9	8
HTN-E	HTN-047w	pendular type 2	HTN-01/HTN-03	6.9	3
HTN-F	HTN-031n	loop	none	8.0	43
HTN-G	HTN-047c	loop	none	13.0	2
HTN-H	HTN-032n	loop	none	1.5	13
HTN-I	HTN-091w	loop	none	10.3	58
HTN-J	HTN-091w	loop	none	14.0	0
HTN-K	HTN-130n	combination type 2	HTN-04	2.9	65
HTN-L	HTN-130n	pendular type 1	HTN-04/HTN-08	2.8	4
HTN-M1	HTN-091e	combination type 2	HTN-08	5.3	15
HTN-M2	HTN-091e	combination type 2	HTN-08	4.5	46
HTN-N	HTN-130s	combination type 2	HTN-07	6.8	46
HTN-O	HTN-056	loop	none	8.2	19
HTN-P	HTN-130n	loop	none	10.5	27
HTN-Q	HTN-130n	combination type 2	HTN-04	4.9	4
HTN-R	HTN-033	loop	none	6.2	23
HTN-S1	HTN-033	combination type 2	HTN-09	10.8	1
HTN-S2	HTN-033	combination type 2	HTN-10	9.2	7
HTN-T	HTN-033	combination type 2	HTN-11	11.8	7

HTN-U	HTN-046s	pendular type 3	HTN-03/HTN-12	5.3	11
HTN-V	HTN-046n	combination type 2	HTN-13	12.0	14
HTN-W	HTN-013	loop	none	7.7	0
HTN-X1	HTN-032s	pendular type 3	HTN-23/HTN-24	4.4	14
HTN-X2	HTN-032c	pendular type 3	HTN-24/HTN-25	5.1	12
HTS-A	HTS-011e	loop	none	4.3	16
HTS-B	HTS-011e	loop	none	6.9	21
HTS-C	HTS-198	loop	none	5.3	21
HTS-D	HTS-198	loop	none	5.2	69
HTS-E	HTS-198	combination type 2	HTS-03	8.8	9
HTS-F	HTS-011w	loop	none	9.3	99
HTS-G	HTS-011w	pendular type 3	HTS-04/HTS-07	9.9	4
HTS-H	HTS-011w	pendular type 3	HTS-06/HTS-07	12.3	3
HTS-I	HTS-011w	combination type 2	HTS-07	10.4	5
HTS-J	HTS-011w	combination type 2	HTS-07	12.1	9
HTS-K	DGF-033	pendular type 3	DGF-01/HTS-08	10.5	1

Of these potential routes, three were screened out during the dump site assignment process: HTN-C, HTN-J, and HTN-W. In each case, these were loop routes with long navigation times that could be readily replaced by routes of less favored configuration, but with better values for *TR*.

The final 35 routes serviced an average of 21.2 dump sites each, with a range from just one for routes HTN-S1 and HTS-K, to 99 for route HTS-F. In the case of route HTS-F, many of the 99 potential dump sites are structures on the campus of YMCA Camp Willson, a large summer camp facility. This number is reflective of the many small structures in the relatively compact camp property. The routes servicing only a handful of premises were the most challenging to design. These represented scattered farm and residential properties that were not picked up as “low hanging fruit” by the obvious loop route configurations and required complex pendular or combination routing solutions.

Potential Water Delivery Rates

Using the inputs from the preceding results, the model was able to generate estimates of potential water delivery rates to all premises within the study area. These results answer the fourth research question: What is the potential water delivery rate to each premise within the study area? As originally envisioned, individual estimates would be provided for each of the 741 potential dump sites in the study area. As the model was developed, however, it became clear that this was an unnecessary level of detail. All dump sites serviced by a given route have the same estimate, since the entire route must be traversed regardless of where the premise is located along it. Because of this, water delivery estimates are couched in terms of routes rather than individual premises. The outcome is the same since all premises (dump sites) are assigned to just one route.

Results presented in Table 15, below, show the accumulation of flow for each route as additional water tenders arrive and join the shuttle. Potential flow rates are annotated in terms of the cumulative contribution of each water tender as it joins the shuttle, where Q01 is the flow produced by the first water tender (WT01), Q02 is the combined flow of WT01 and WT02, and so on through Q10, which represents the combined flow of all ten water tenders potentially assigned to any route.

Table 15

Estimated Potential Water Delivery Rates (gallons per minute).

Route	Q01	Q02	Q03	Q04	Q05	Q06	Q07	Q08	Q09	Q10
HTN-A	87	140	213	251	280	327	362	398	475	528
HTN-B	81	129	202	239	267	311	345	379	453	504
HTN-D	74	134	204	280	341	372	423	456	502	528
HTN-E	87	156	210	258	282	324	364	405	478	522
HTN-F	83	182	225	251	299	344	382	420	470	513
HTN-G	59	106	201	240	266	310	350	379	420	467
HTN-H	91	245	282	316	382	443	506	528	528	528
HTN-I	54	142	207	247	297	344	392	427	466	516
HTN-K	82	219	262	303	357	393	450	509	528	528
HTN-L	82	220	263	304	338	385	444	510	528	528
HTN-M1	70	187	236	294	342	396	452	512	528	528
HTN-M2	74	197	243	302	352	408	464	527	528	528
HTN-N	64	146	230	259	316	378	428	479	528	528
HTN-O	60	136	190	246	307	357	408	452	505	528
HTN-P	53	140	204	239	282	312	360	405	469	509
HTN-Q	72	191	244	284	334	368	424	489	528	528
HTN-R	90	161	214	264	288	328	369	446	490	528
HTN-S1	74	130	189	233	300	328	376	421	458	497
HTN-S2	79	140	197	243	265	326	363	401	450	494
HTN-T	70	124	184	226	291	324	357	404	446	478
HTN-U	95	170	220	271	296	363	404	447	500	528
HTN-V	50	131	204	241	285	330	363	406	456	518
HTN-X1	74	198	252	331	361	415	468	523	528	528
HTN-X2	71	189	245	276	335	390	445	523	528	528
HTS-A	137	230	266	324	375	422	480	521	528	528
HTS-B	121	201	246	299	346	378	423	477	528	528

HTS-C	130	225	272	301	358	392	460	507	528	528
HTS-D	131	226	273	301	359	393	461	518	528	528
HTS-E	111	185	250	275	326	356	416	459	511	528
HTS-F	78	187	243	268	319	348	385	433	477	528
HTS-G	76	135	234	275	331	359	407	452	498	528
HTS-H	69	122	182	224	288	316	362	405	441	477
HTS-I	75	132	231	272	326	354	402	446	484	522
HTS-J	70	123	182	249	301	345	387	418	454	491
HTS-K	74	132	190	234	302	349	393	428	466	500
Average	84	180	235	275	323	366	415	464	499	523

For all routes, a minimum estimated shuttle throughput of 250 gpm is attainable. A final throughput of 500 gpm is attainable for most routes, although even the routes that do not quite reach 500 gpm do come very close to this flow. On average, the 250 gpm flow is achieved at the WT04 level, while the full complement of ten water tenders is required to reach 500 gpm (although it is effectively reached at WT09 with 499 gpm). For 21 of the 35 routes, the limiting factor is the 528 gpm fill rate at the fill site. Because the overall water delivery rate cannot exceed the fill rate, these routes are limited by this ceiling, generally hitting it at the WT09 level or earlier. These routes would achieve higher maximum flow rates if a higher fill rate were used.

Benchmarks

While knowing the absolute estimated throughput for a shuttle is important, perhaps more important is knowing at what time key flow benchmarks are likely to be achieved. Such benchmarks can inform operational decisions by the prospective incident commander. In addition to estimating potential throughput rates, this study also sought to estimate time of occurrence for key events in a hypothetical water shuttle operation: arrival of initial attack resources, readiness of the fill and dump sites, ability to commence transitional nursing, and achievement of specific water delivery rates. These results answer the fifth and final research question: How long will it take to reach water delivery benchmark rates (e.g., 250 or 500 gallons per minute) for each premise within the study area?

The seven specific benchmarks estimated for each route were:

- Attack On-Scene (arrival of ATK EN01 at dump site/incident)
- Attack Ready (arrival of ATK EN02 at dump site/incident)
- Nursing Ready (arrival of first nurse-capable water tender at dump site, plus *TNS*)
- Dump Site Ready (arrival of RLY EN03 and WT01 at dump site, plus *TDS*)
- Fill Site Ready (arrival of FS EN at fill site, plus *TFS*)
- BM250 (achievement of 250 gpm throughput)
- BM500 (achievement of 500 gpm throughput)

Additionally, the model was designed to calculate values for throughput benchmarks BM750 and BM1000. Since no shuttle route reached these flow rates, the benchmarks were not calculated. Benchmark estimates by route are shown in Table 16, below.

Table 16

Benchmarks by Shuttle Route (minutes from dispatch).

Route	Attack On-Scene	Attack Ready	Nursing Ready	Dump Site Ready	Fill Site Ready	BM250	BM500
HTN-A	13.1	17.8	20.2	23.3	26.5	23.3	24.6
HTN-B	13.3	17.3	19.8	22.7	26.5	22.8	23.9
HTN-D	8.8	15.8	23.3	26.2	26.8	26.2	26.2
HTN-E	12.3	17.9	23.2	23.5	22.2	23.5	25.6
HTN-F	12.8	18.4	21.7	24.5	28.8	24.5	24.7
HTN-G	7.5	14.5	21.9	25.5	25.7	25.5	n/a
HTN-H	7.9	14.9	21.1	21.8	21.8	21.8	22.3
HTN-I	10.3	16.5	20.6	22.2	21.3	22.5	23.8
HTN-K	9.8	14.9	19.6	20.3	21.4	20.7	22.2
HTN-L	9.7	14.4	19.1	19.9	21.4	20.3	21.7
HTN-M1	8.8	15.9	21.2	21.9	20.5	21.9	22.2
HTN-M2	9.0	16.0	20.7	20.5	20.5	20.5	22.7
HTN-N	6.5	13.5	20.9	23.0	24.6	23.0	24.4
HTN-O	7.3	14.3	21.8	23.2	24.7	23.2	23.2
HTN-P	9.6	15.5	20.1	21.0	21.4	21.0	22.2
HTN-Q	10.3	13.5	18.2	19.0	21.4	19.3	21.7
HTN-R	14.2	16.3	22.4	21.9	27.7	21.9	24.4
HTN-S1	14.8	16.6	24.1	22.2	27.7	22.3	25.3
HTN-S2	14.2	17.1	23.5	22.7	27.7	22.7	24.8
HTN-T	14.9	15.0	22.4	20.1	27.7	22.9	n/a
HTN-U	12.8	17.9	23.4	23.5	32.8	23.5	24.8
HTN-V	12.4	16.4	19.5	22.3	26.5	22.3	23.6
HTN-X1	8.9	15.9	23.1	23.8	25.0	23.8	24.3
HTN-X2	8.4	15.4	21.7	22.4	23.2	22.4	24.0
HTS-A	8.1	15.1	19.1	22.0	22.5	22.0	23.8

HTS-B	8.8	15.8	21.0	23.9	22.5	23.9	24.7
HTS-C	9.4	16.4	21.6	24.5	27.8	24.5	24.9
HTS-D	10.0	17.0	21.5	24.4	27.8	24.4	25.3
HTS-E	9.2	16.2	21.7	24.6	27.8	24.6	24.9
HTS-F	11.4	18.4	23.5	25.6	27.3	25.6	25.7
HTS-G	13.7	17.3	24.6	22.9	26.7	22.9	25.4
HTS-H	15.0	15.6	23.0	21.2	26.7	22.3	n/a
HTS-I	13.9	16.6	24.3	22.2	26.7	22.2	25.7
HTS-J	14.8	15.8	23.5	21.4	26.7	21.5	25.2
HTS-K	14.2	14.2	21.9	21.1	26.8	22.5	24.4
Average	10.4	16.3	21.4	23.0	24.9	23.1	24.1

Notes. Throughput benchmarks BM250 and BM500 could not occur before Dump Site Ready achieved; three routes did not achieve 500 gpm throughput and have no BM500 value.

For the study area on average, initial size-up could begin at 10.4 minutes, with initial attack commencing at 16.3 minutes. Transitional nursing becomes available for water supply less than eight minutes later at the 21.4-minute mark. Within 6.8 minutes of initial attack commencing, the average shuttle solution delivers 250 gpm to the incident scene, with 500 gpm achieved just one minute later. These results are for the "average" route in the study area.

Results for individual routes vary, with some of the routes varying considerably from the mean values, as determined by distance from supporting fire stations, route configuration, and performance characteristics of assigned resources. Estimates for commencement of size-up by the first on-scene engine ranged from 6.5 to 15.0 minutes, with initial attack capability achieved at 13.5 to 18.4 minutes. Initial water supply secured via transitional nursing is possible at 18.2 to 24.6 minutes. The dump site is brought into action between 19.0 and 26.2 minutes, while the fill site is brought into action between 20.5 and 32.8 minutes. Water delivery via shuttle reaches 250 gpm between 19.3 and 26.2 minutes, with 500 gpm between 21.7 and 26.2 minutes. Estimates for benchmark achievement by premise (dump site) are displayed graphically in Figures 28 through 34. Results are displayed in these graphics by premise rather than route due to the overlap of road segments among routes, which makes an interpretable display of results by route unworkable.

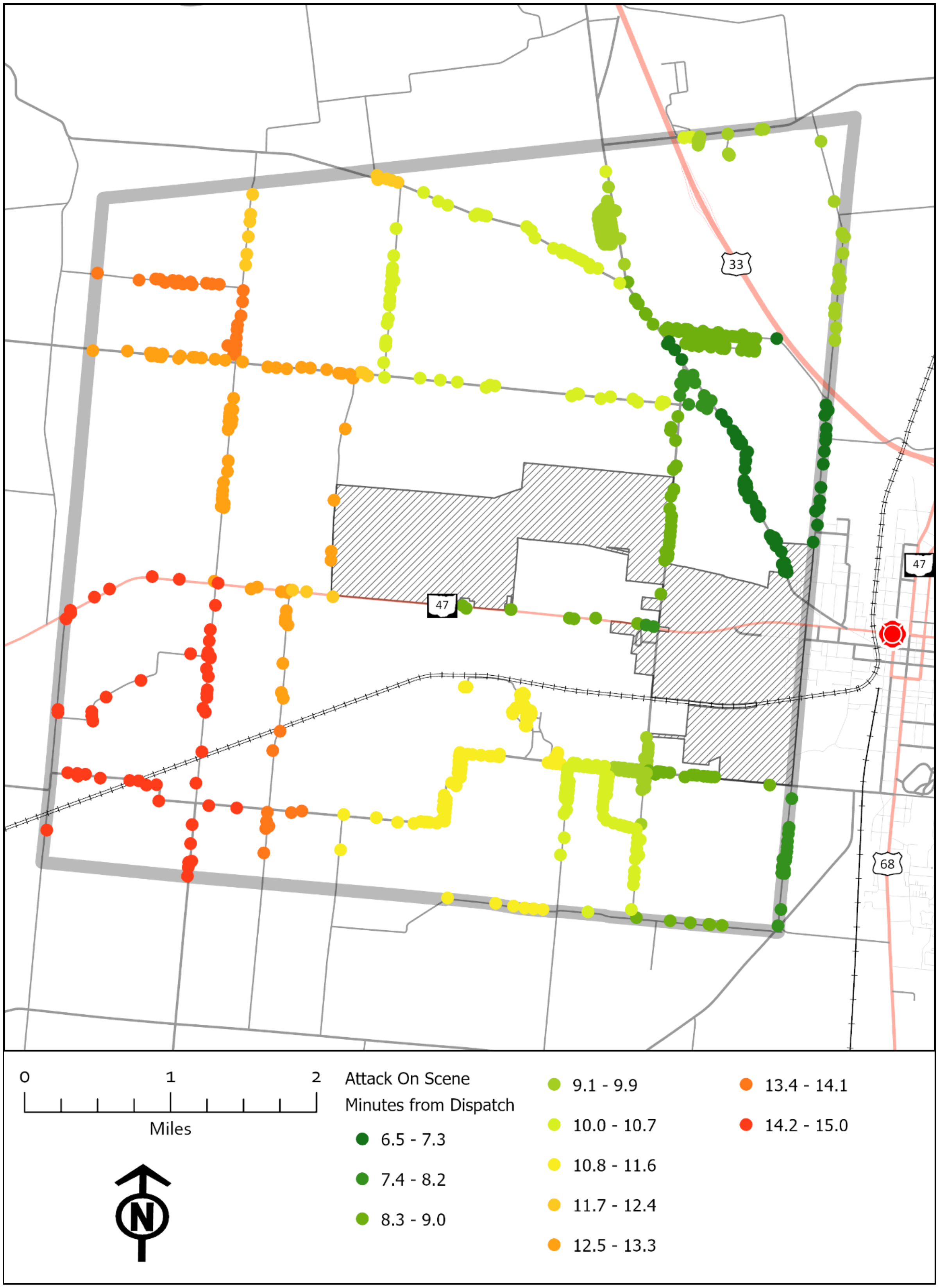


Figure 28. Benchmark: Attack on-scene by premise.

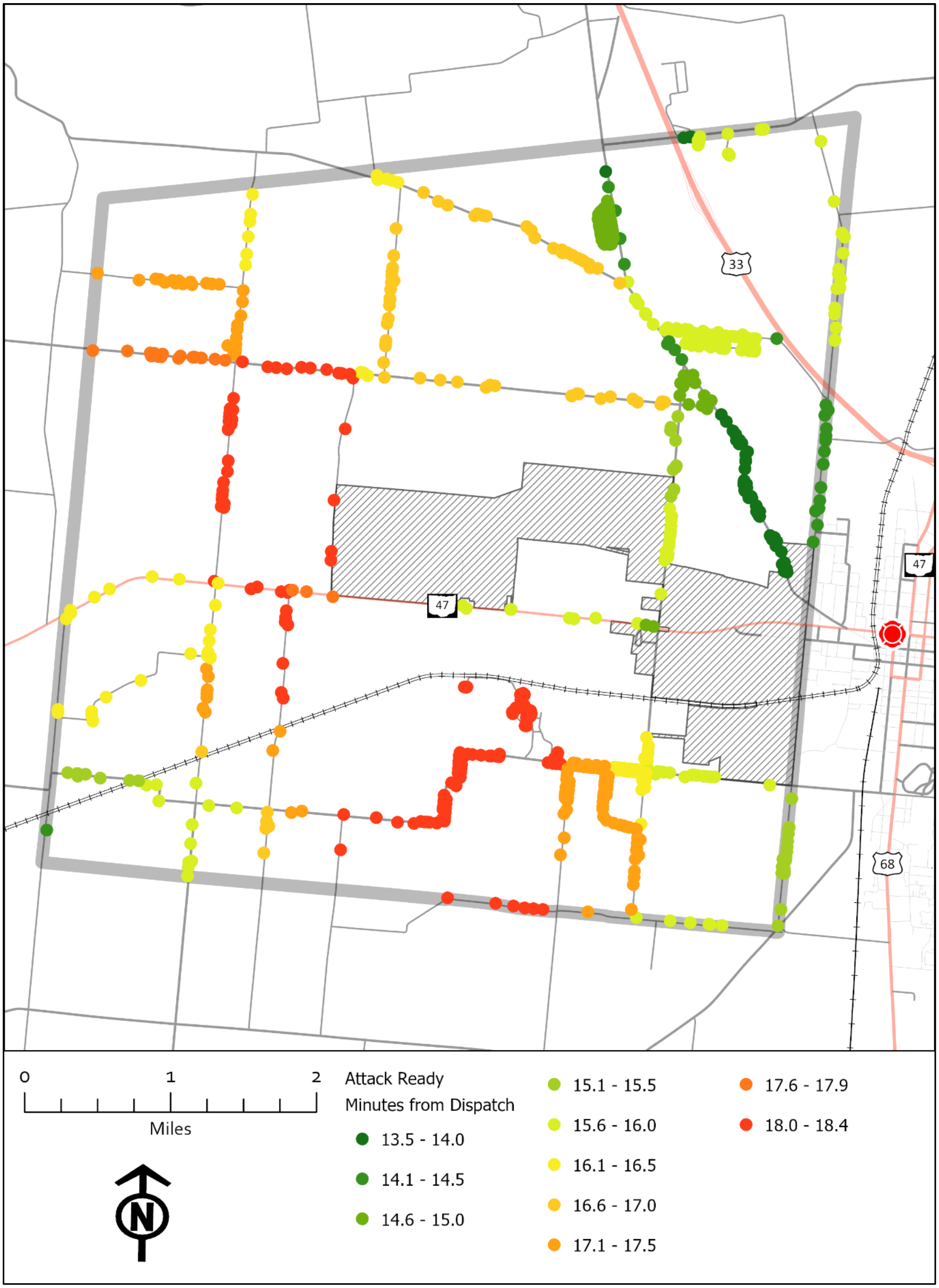


Figure 29. Benchmark: Attack ready by premise.

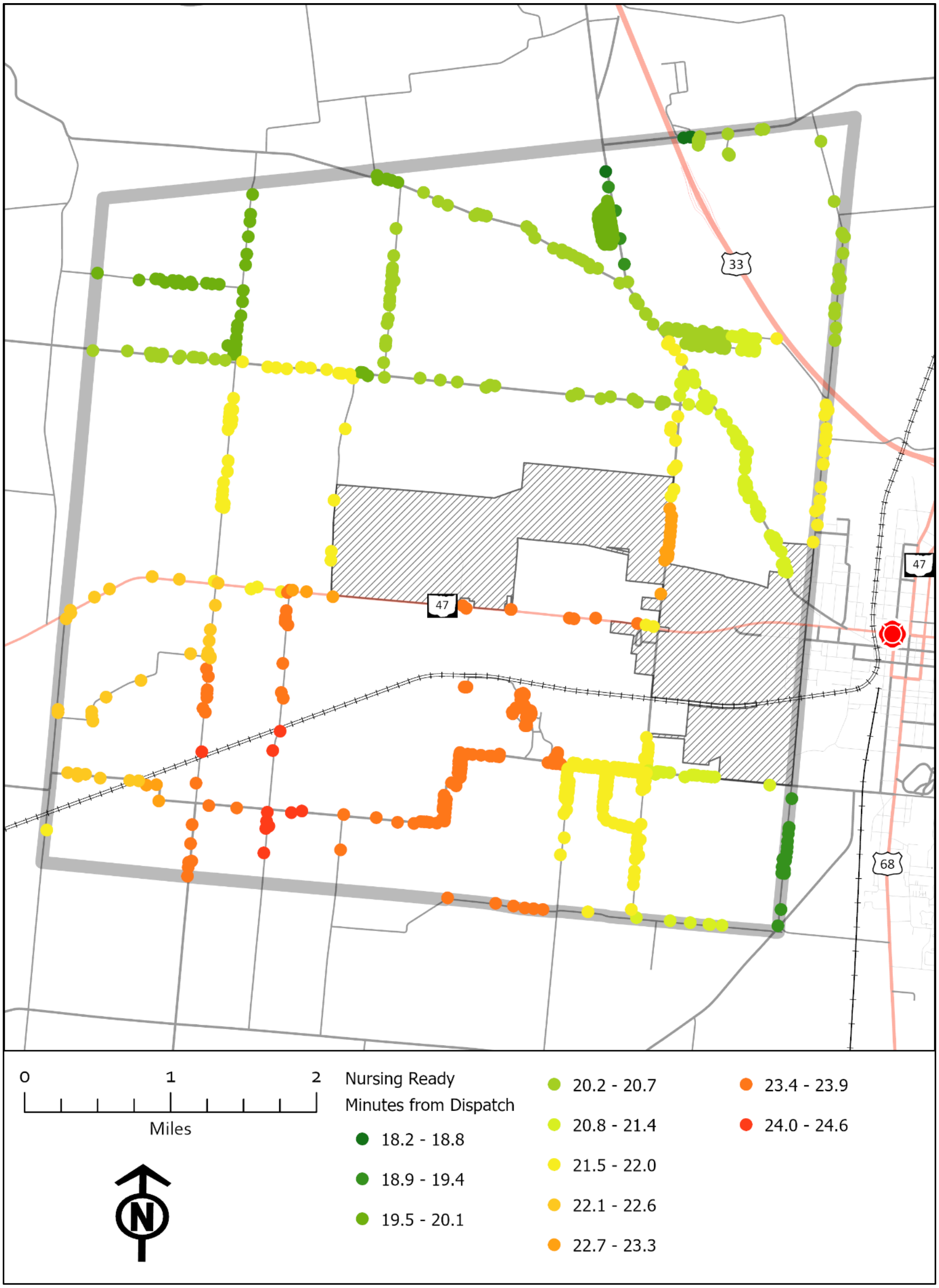


Figure 30. Benchmark: Nursing ready by premise.

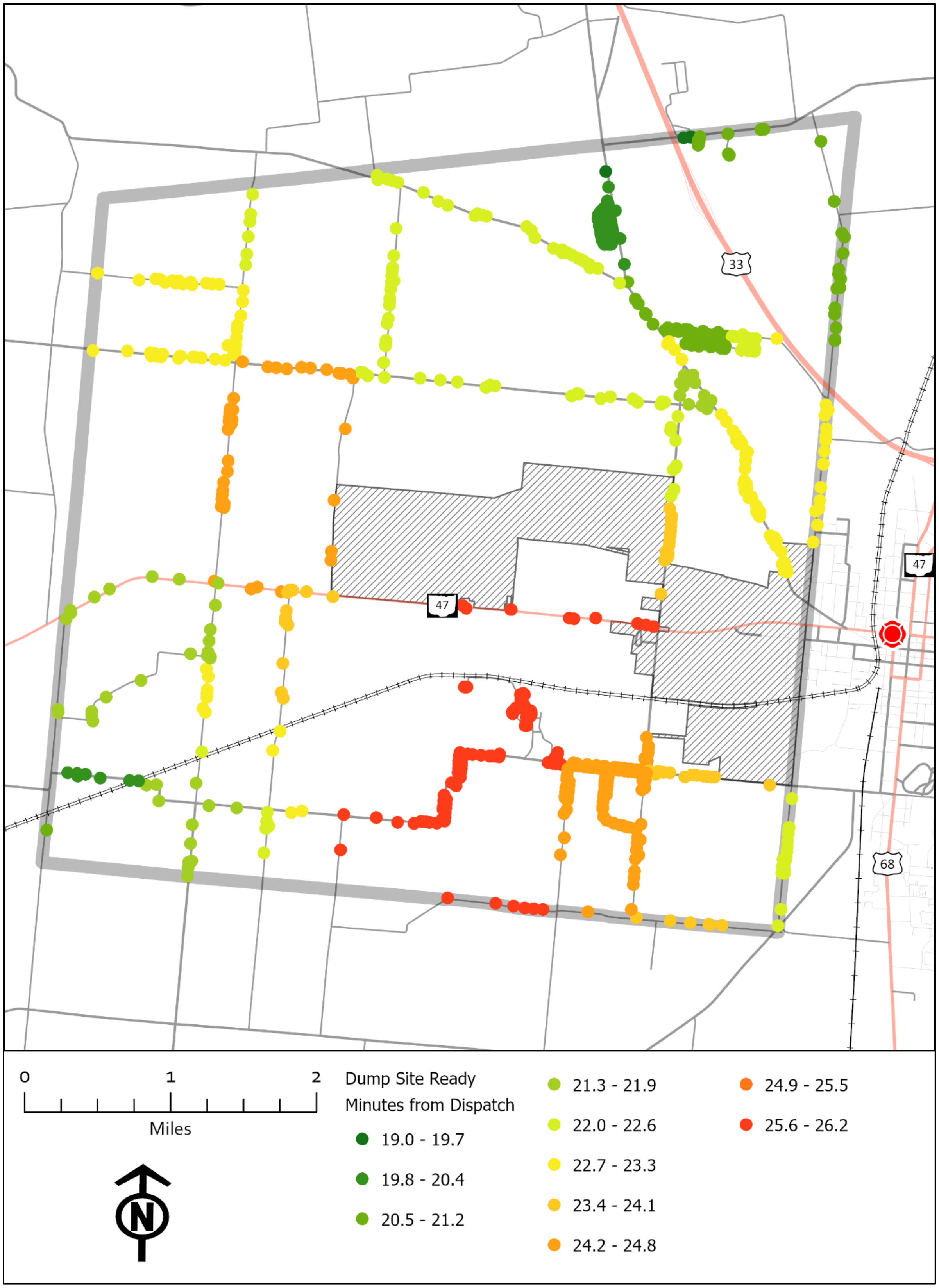


Figure 31. Benchmark: Dump site ready by premise.

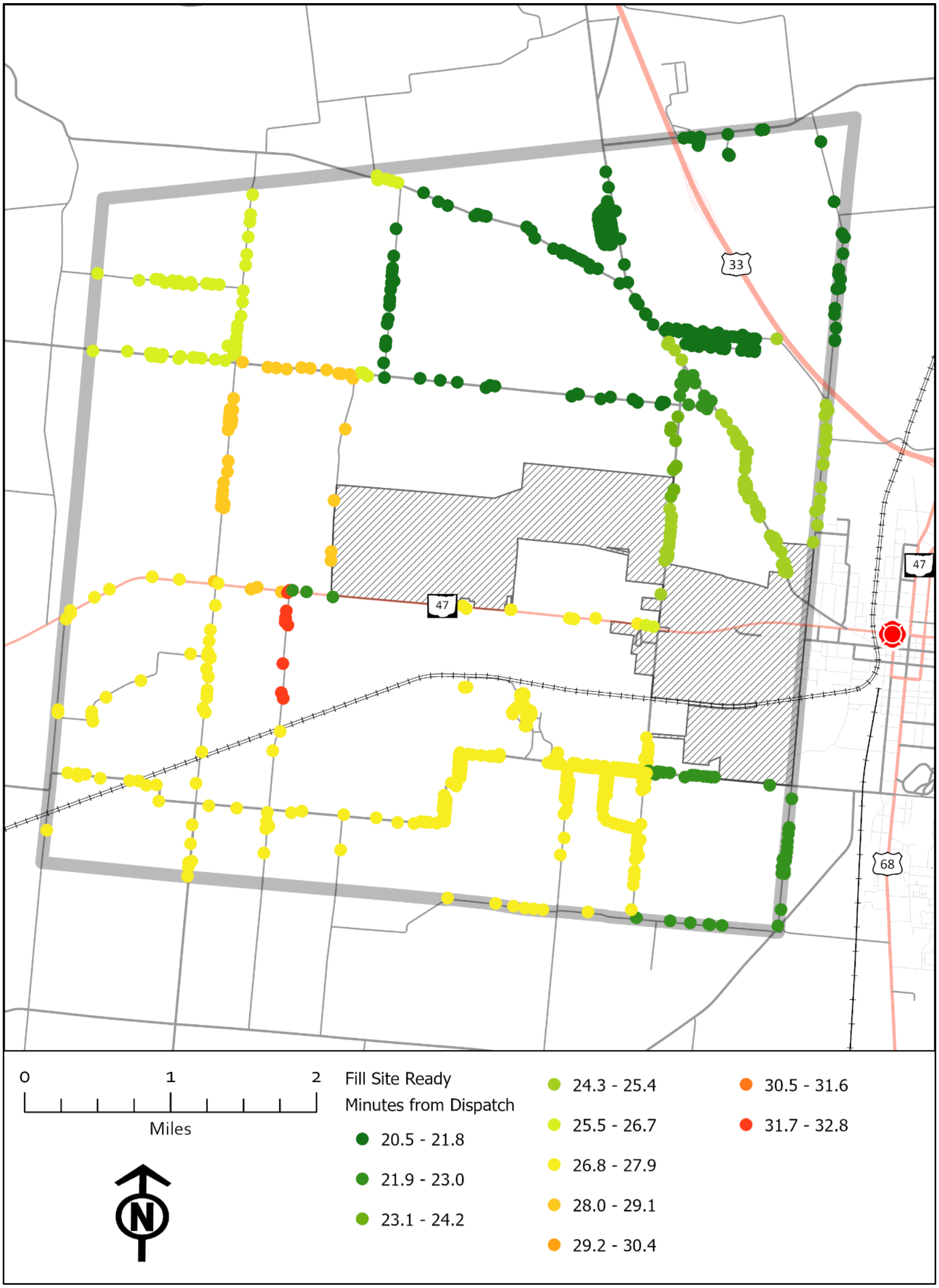


Figure 32. Benchmark: Fill site ready by premise.

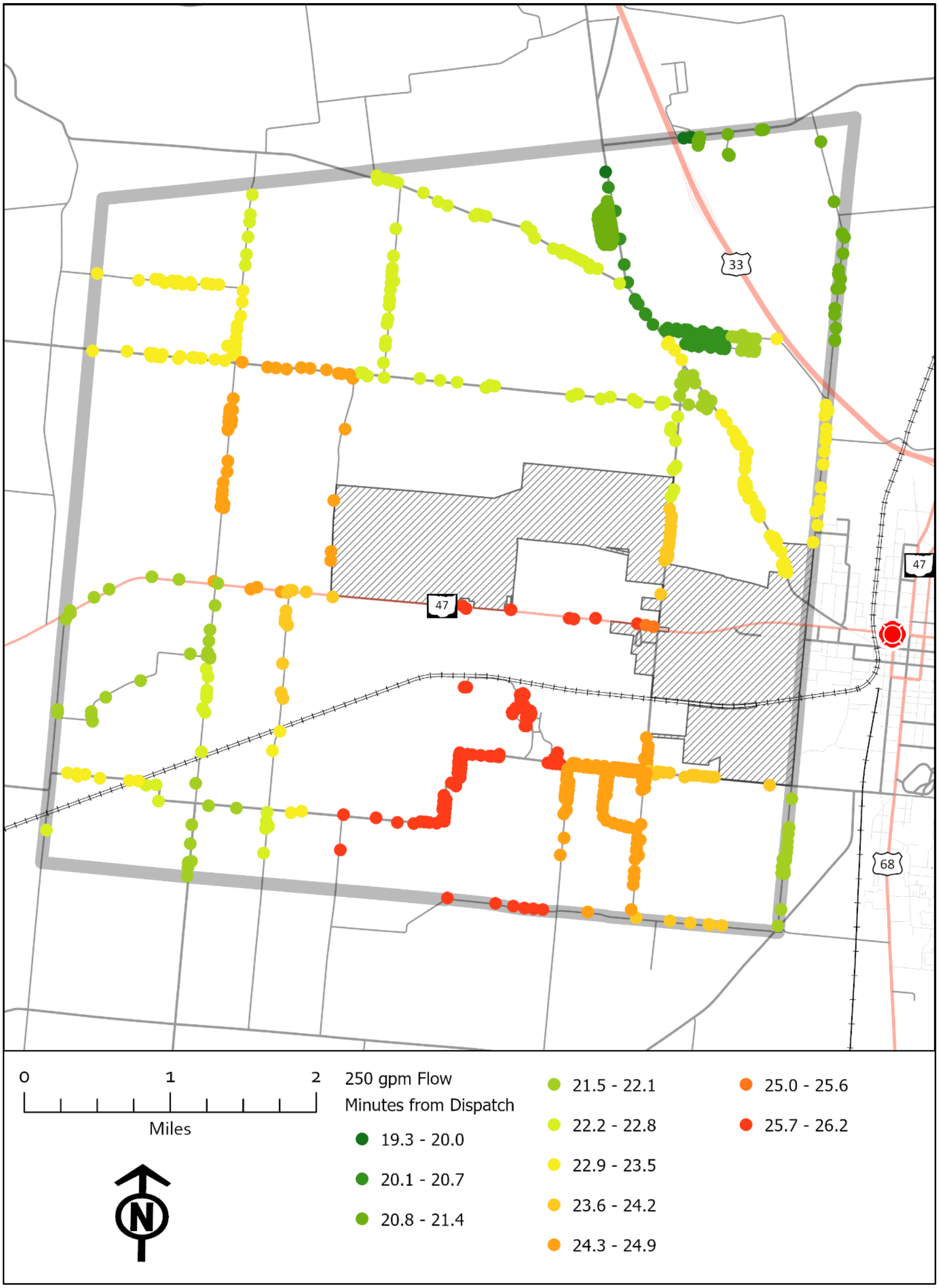


Figure 33. Benchmark: 250 gpm throughput achieved.

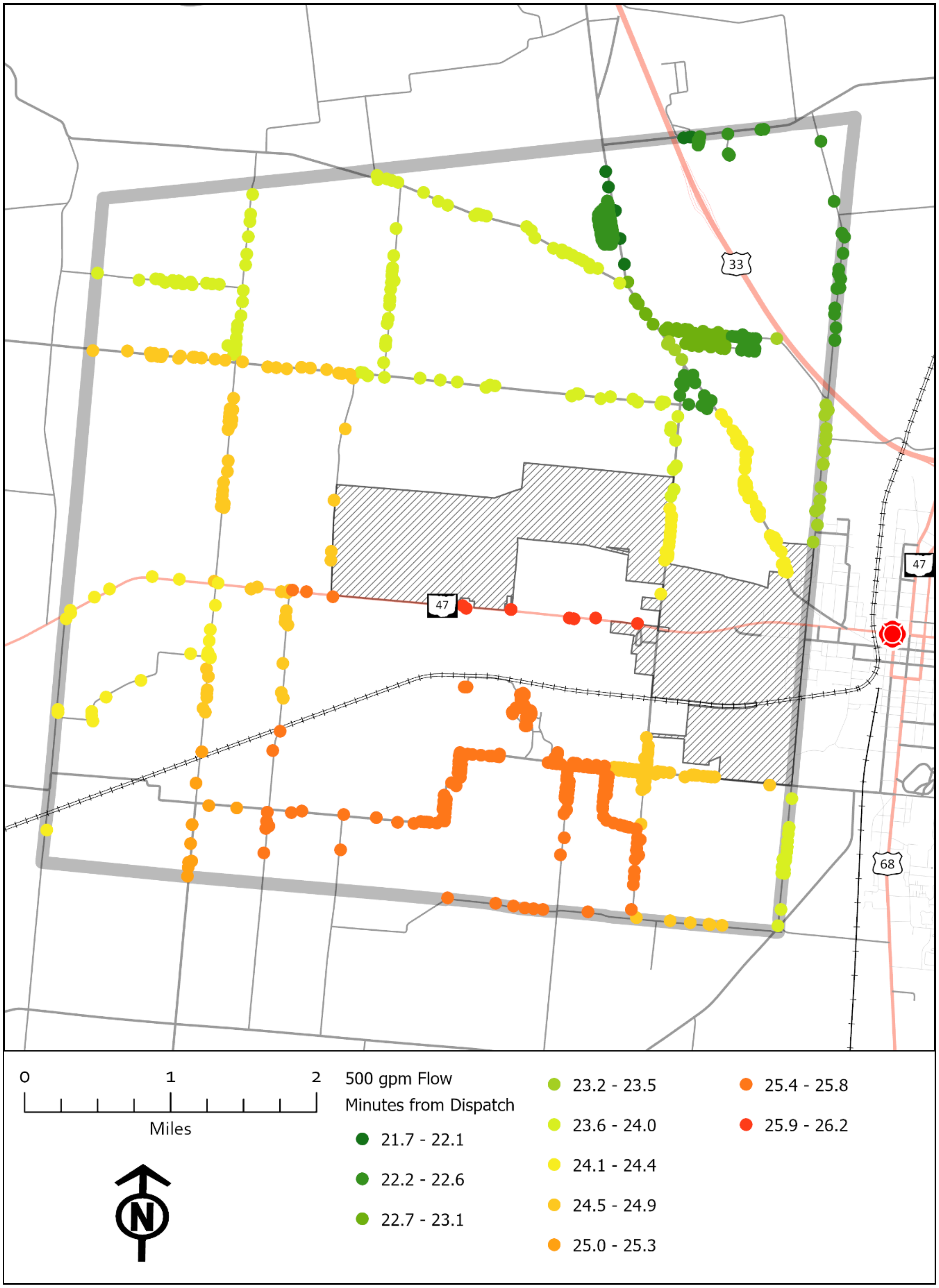


Figure 34. Benchmark: 500 gpm throughput achieved.

Discussion

No model is a perfect replica of reality, but a well-designed model can nonetheless provide a better understanding of reality: "…the main purpose of an analytical model is insight and not numbers" (Cassandras & Ho, 1983, p. 151). The results of the model presented here should not be interpreted as exact results to be expected, but rather as reasonable, conservative estimates of potential outcomes. The author believes that the research project was successful as a first iteration proof of concept and will serve as a useful foundation for further development of the methods described. This project was well suited to the author's role as rural operations coordinator within the Bellefontaine Fire Department (BFD), with major duties including development of rural water supply and liaison with mutual aid fire departments.

Water Handling Apparatus and Equipment Inventory.

The study's first research question sought to characterize the existing water tenders, engines, and appliances within the BFD's mutual aid area. The author cast a wide net in collecting apparatus and equipment data from the BFD and 23 potential mutual aid fire departments. This effort represented the first comprehensive survey of water handling capabilities in Logan County and the surrounding areas. In fact, other than basic lists of apparatus by function, no comprehensive apparatus inventory had ever been completed in the county. The data on apparatus not specifically required for this study may prove useful if this same process is repeated for development of water shuttle solutions for other parts of the county.

While this part of the study was essentially just a basic inventory, insights were still to be found. The author was not surprised to find that the average age of both the water tender and engine fleets exceeded 20 years. The author was also not surprised at the universal lack of standardization present in the area. Ohio's legal structures practically invite this situation. By not allowing any kind of county- or regional-level coordinating authority, numerous small fire departments persist in rural areas, each one competing for limited funding and personnel, and unnecessarily duplicating services and equipment (Ohio is home to nearly 1,200 entirely independent fire departments).

In discussion with a fire chief from a neighboring volunteer department, the author was told of plans to design and purchase an engine with the express intent that it remain in active service for forty years. Well-intentioned but short-sighted efforts to cut costs such as this, along with conversion of commercial tank trucks to water tenders, lead to firefighters needlessly exposed to hazards. These older and conversion apparatus can miss generations of safety improvements as technology and manufacturing processes improve. Likewise, these apparatus are often simply poorly designed from a performance standpoint. This is especially the case for water tenders, where older and conversion apparatus hail from an era when the state of the art for maximizing throughput was less developed.

As a case in point, the water tender pictured in Figure 35 was converted from a dairy tank truck and is an active unit for department in the mutual aid area. The truck chassis was manufactured in 2000, but the tank body was of unknown vintage and had been remounted at least once. While no doubt cheaper than a purpose-built fire apparatus, it is unknown if the safety features of this apparatus are up to the task of a fire department water tender. From a performance standpoint, the sole outlet for the tank is a seven-inch circular orifice that requires a pipe extension to clear the back bumper. While the tank is large (3,200 gallons), this volume is rendered less useful by the lack of a means to rapidly offload it. This represents the most extreme example inventoried for this study, but several other units encountered were not much better.

Figure 35. Water tender conversion from dairy tanker.

In another discussion, a different local chief was surprised to learn of the existence of large diameter hose (LDH), a technology with which he was unfamiliar. This is indicative of the general lack of coordinated standard operating procedures (SOPs) within the county, which leads to uncoordinated training and equipment purchasing. This in turn leads to confusion at the incident scene, as the author has personally experienced.

As with any model, the one presented in this study was grounded on at least some assumptions. Among the assumptions for this study were that several particularly glaring safety issues relating to apparatus would be resolved. These included relatively low-cost and easily affected apparatus modifications, such as installing new fill ports or pipe extensions to allow all fill operations to be conducted from ground level. Assumed apparatus fixes relating to the dump site included the adoption of narrow profile portable tanks and the purchase of adapter elbows to allow all offloading operations to occur to the side and thus eliminate backing maneuvers. These safety-related items were considered by the author to be potentially achievable in the near term. All major existing items relating to apparatus were retained as they currently exist, as capital expenditures such as new apparatus or stations were felt to be beyond what is reasonably achievable in the near term.

With refinement, the model results could be used to provide justification for regional grant applications to remedy the safety issues identified. Substituting hypothetical well-designed apparatus for existing poorly designed units to compare relative performance could form part of the justification for an apparatus replacement grant, especially if coupled with safety deficits in the old unit.

While the topics of vacuum versus conventional water tenders and optimal tank capacity for tenders are often the subject of deeply held opinions, there is little empirical data to support the merits of any of the various stances. By running the model with various combinations of vacuum and conventional tenders, and with apparatus of varying tank capacity, it would be possible to discern optimal, data-driven solutions for the conditions of a given area's topography, roads, and staffing conditions.

The inventory itself was a useful exercise, because as previously stated, no comparable effort has ever been made in the area. The results of the inventory will be used to produce a map of water handling apparatus with performance data annotations for distribution to all participating departments. The director of the Logan County Emergency Management Agency (EMA) has also expressed interest in the inventory and performance data collected for this project. For future runs of the model, the author intends to exclude apparatus that are particularly old, unsafe, or inefficient. This will allow for the development of dispatch plans that only include the apparatus best suited to accomplish the mission safely and efficiently.

One aspect of this study that required significant unexpected effort was the problem of estimating efflux rates and times for water tenders. While this may seem like a minor issue, the time required to offload a water tender's cargo is a major constituent of dwell time at the dump site. This time is normally directly measured in the field using the method outlined in NFPA 1142 (NFPA, 2022, para. C.10) or a similar procedure. The author did have field estimates from past training events on hand for a small number of the apparatus surveyed, but the list was far from complete. None of these estimates provided documentation of the methods used, rendering them somewhat suspect as well as incomplete. Simply using a standard rate such as 1,000 gpm for all water tenders would have failed to reveal potential performance differences between apparatus. The dearth of dependable data led the author to seek out mathematical methods for efflux estimates.

The Torricelli-derived methods used for the model yielded results that were within ranges normally observed. Without verification using field measurements, however, it is difficult to say with certainty that the results are fully reflective of reality. The author has had no luck convincing local fire departments to commit to water tender performance testing exercises, so the Torricelli-based methods will likely need to be validated elsewhere. Should these methods be successfully validated and refined, they could be useful for rapidly estimating water tender offload performance throughout the fire service.

Acceptable rate and pressure for filling water tenders was another aspect of the project that incurred additional effort. The issue of poly tank fill rate limitations is a topic of some interest amongst the author's fellow WSTAC members, although, in the author's experience, it is not widely recognized outside of specialist groups like the committee. After broaching the topic with a local fire officer, the author received the response "Oh, that's why we keep busting those seams." The fact that the damage will most likely accrue to a mutual aid water tender belonging to a neighboring department would seem to make the issue even more important to address.

The imposition of both a rate and pressure limitation by the tank manufacturers makes this a difficult problem to manage at a real-world fill site, where flow meters and pressure gages are not always readily available to the crew. The fact that the 1,000 gpm flow rate maximum from the manufacturer seems to be in conflict with the NFPA 1901 minimum 1,000 gpm fill rate capability for water tenders also complicates this issue. When discussing the issue with fellow WSTAC member Ed Collett, it was suggested that Sylvia's (1970) formula for calculating open-butt flows could be the basis for a solution, since the tank filling process is essentially an open-butt flow.

The lack of standardization of supply hose size and couplings carried on area engines presents an issue for the development of county-wide water supply SOPs. While the majority of engines carried 5.0-inch Storz hose, a non-negligible minority of departments cling to 2.5- and 3.0-inch NH hose for water supply. Standardizing on LDH would allow for more seamless integration of resources during water shuttles and any other water supply mission but will require significant persuasion to convert some departments. The inventory of other equipment – portable tanks, low level strainers, jet siphons, and manifolds – showed both great variety and a general state of neglect. These tend to be infrequently used, low priority items of equipment for most area departments. Wholesale replacement of square portable tanks with narrow profile models would allow for safer and more efficient dump site operations but convincing a department to willingly replace an obsolete – but still functional – tank would be difficult. This is perhaps another avenue for a regional grant where an argument for replacing these obsolete items with standardized models could be made based on safety and efficiency improvements.

The survey and inventory of water handling apparatus and equipment was an enlightening experience for the author. The information obtained was both essential to the study's model, but also useful in its own right as the first comprehensive compilation of this data.

Inventory and Characterization of Fill Sites.

The second research question involved identifying potential fill sites for the study area and characterizing their flow rates. As with the water handling apparatus question discussed above, this involved an inventory process of potential sites. Unlike the apparatus question, it required screening of sites for suitability; narrowing down 178 potential sites to the final 22 considered for the model.

As briefly touched on above, the eight existing and two planned dry hydrant sites were all retained for initial consideration (although two were later found to be superfluous during route development). This is not surprising given that all of these dry hydrants were installed to improve water supply to areas beyond the municipal system and that they were purposely designed to serve as water shuttle fill sites (Figure 36).

Figure 36. Bridge-mount dry hydrant in the study area.

A standard flow rate of 1,000 gpm was used for all dry hydrants, corresponding to their design flow rate and average streamflow rates at the bridge sites. Future iterations of the model could also include variable flow rates to represent seasonal low streamflow or drought conditions as the hydrologic estimates for these flow rates are available. The author felt that attempting to include such a level of variability would make this initial version of model too complex to fulfill its proof-of-concept function.

The City of Bellefontaine municipal hydrant system was a more complex issue for the author, who is typically focused on alternative water supply sources. As described in the procedures section, quality location data was not readily available, and required significant additional effort to produce and link to flow test data. Although 168 potential municipal hydrants were considered, many of these could be easily screened out as falling in residential neighborhoods where water shuttle traffic would be unacceptable. This left mostly those hydrants located along lengthy water mains reaching out into the unincorporated township to service critical facilities. The author was initially concerned that these long mains might lack sufficient flow to serve as a workable source of water supply. This was not the case, however, as many of the hydrants on these mains had better flow than those located on the established urban grid. This is likely due to the fact that the extended mains are much newer than those in the older parts of the city, and so are built to higher standards and have a lower degree of constriction due to mineral deposits. All of the hydrants on these mains readily exceeded the 1,000 gpm flow requirement.

Even with adequate available flow, not all of these hydrants were suitable for a fill site. The mid-main hydrants are located primarily with water system maintenance in mind rather than fire protection needs, leaving many of these poorly placed for safe fill site operations. Specifically, many of these hydrants are located very close to busy rural roads without a significant shoulder or any other hard surface upon which to set up a fill site. The final 12 municipal hydrants selected as potential fill sites were mostly located in parking lots of different facilities. This had the additional advantage of providing a co-located turnaround point where needed. Not all of these hydrants were ideal, but all were workable. Some were older installations with obsolete outlet designs (Figure 37), but in each case flow was adequate and the availability of adequate safe working space for fill site operations was a deciding factor.

Figure 37. Municipal hydrant on edge of system.

One unexpected outcome of the project was the elimination of a planned bridge-mount dry hydrant installation following analysis of initial model results. This site had been designed to provide a fill site in the southern zone, but its location had been selected without considering the potential of municipal hydrants as fill sites. Model results showed that the route including the planned dry hydrant was adequately served by two existing municipal hydrants, allowing cancellation of the installation.

Lack of empirical data forced the author to assign setup and operational base time values for fill sites based on observations of water supply training exercises. While not made up from whole cloth, these values would be improved by the development of more reliable estimates. Such estimates would ideally come from repeatable time and motion studies of firefighters repeatedly performing the tasks but could also potentially be derived from analysis of existing videos of water shuttle training and operations.

Shuttle Routing.

The project's third research question sought to identify the combination of routing solutions that could most efficiently link all 741 potential dump sites in the study area to at least one fill site. Routes of the loop or pendular type one configuration were felt to be the safest options for shuttle traffic, so these configurations were prioritized where feasible. Routes of the favored configurations were found to be capable of servicing 457 (61.7%) of the dump sites, while routes of less favorable configurations were needed to service the remaining 284 (38.3%).

The blanket statement that only loop routes should be used for water shuttles is sometimes heard. One major takeaway from the routing process was that such a universal rule is impractical in application. While there are many compelling safety reasons that favor loop configurations, there are sometimes equally compelling safety reasons that prevent them, such as the need to avoid routing across a major rail corridor. Equally important to consider are operational realities. Loop routes may be the safest configuration, but if very long loops are considered impractical due to their length by prospective incident commanders, other options must be considered.

Loop routes might have accounted for an additional unknown number of premises except that when some of the longer routes were previewed to officers of the author's department, they were rejected as unworkable. Alternative routes of less favorable pendular or combination configurations were developed to meet these concerns. Because these were not one-for-one substitutions, it is not known exactly how many premises might have been assigned to the rejected loop routes. Figure 38 shows an example of this, where the long loop routes HTN-C and HTN-J were rejected in favor of the alternative route HTN-V with a combination type two configuration.

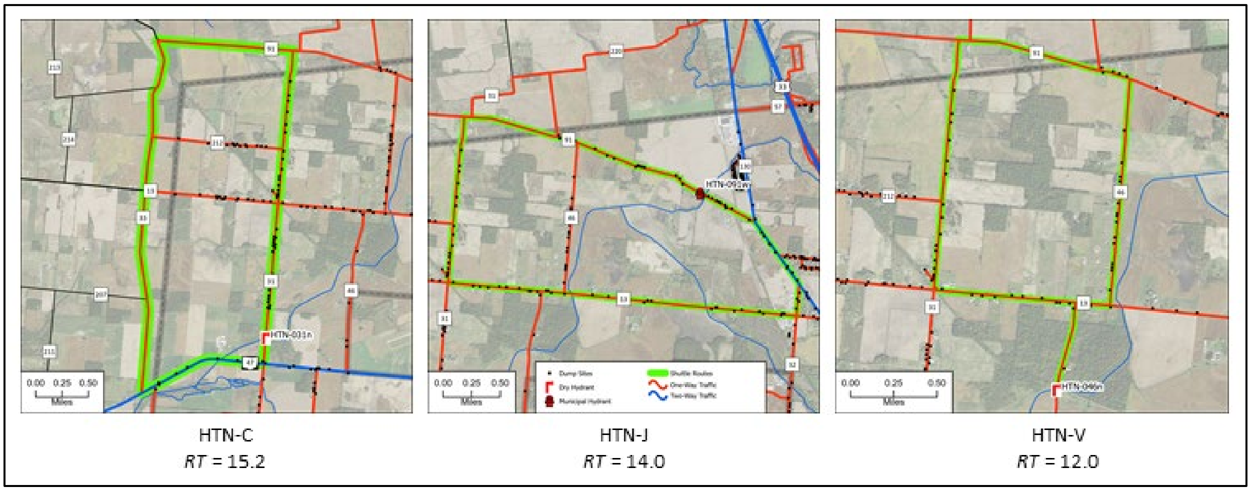


Figure 38. Alternative routing example.

In the case shown above, the loop routes HTN-C (based on fill site HTN-031n) and HTN-J (based on fill site HTN-091w) were rejected due to perceived excessive length, i.e., high *RT* values. The alternative route HTN-V (based on fill site HTN-046n) with a lower *RT* value was developed as a substitute. HTN-V is a combination route with a large loop component, but that also includes a pendular section of about 0.5 miles in length (south end of the route) needed to access the fill site. This pendular section involves a narrow township road suitable for one-way shuttle traffic only, meaning that water tenders will need to ensure the section is clear for travel before proceeding onto it. This presents a potential collision exposure if drivers fail to check before proceeding. It also incurs a time penalty as the tenders are forced to wait for clearance.

There are several potential approaches to mitigate the hazard exposures posed by pendular sections incapable of safely supporting two-way traffic flow, such as that described above. The first would be to eliminate the need for water tenders to travel the pendular section. This could be accomplished by laying LDH from the fill site to the junction of the pendular and loop sections. This would entail a need for additional personnel and apparatus as well as significantly longer setup time. A second method would be the development and enforcement of traffic control procedures to coordinate water tender use on the pendular section. Coordination could be achieved by an assigned traffic control officer, or – more likely given local staffing limitations – by the drivers of the water tenders themselves communicating via radio. For purposes of this study, the author assumed that a relay would be impractical, and that some form of traffic coordination would be used to mitigate the hazard.

In some cases, the only possible routing solution was one with a suboptimal and potentially hazardous traffic flow. These situations required the use of a pendular type three configuration, the least favorable of all due to its consisting entirely of pendular routing on roadways incapable of safe two-way flow. Fortunately, most such cases involved only a handful of isolated or awkwardly situated premises. An example of this is route HTS-H, shown in Figure 39, below.

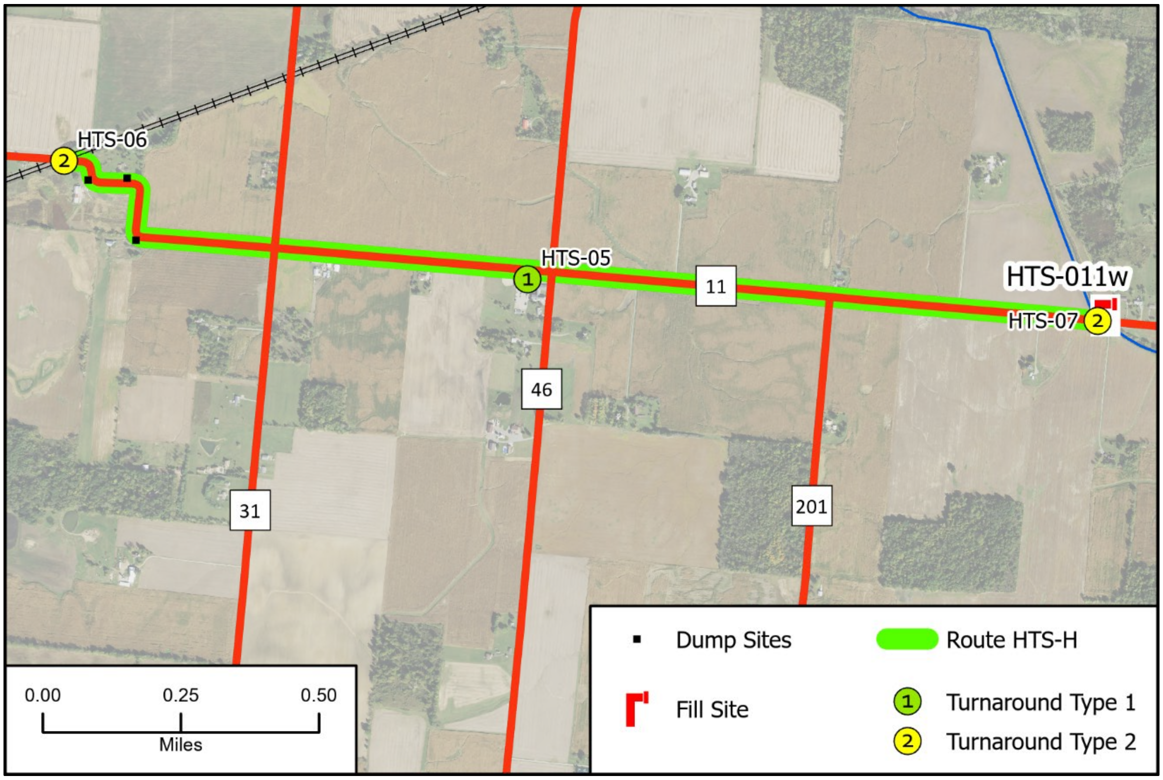


Figure 39. Suboptimal routing example.

In the case of route HTS-H, three premises at the west end of the route were left unserviced by any route of a more favorable configuration owing to the requirement that no routes cross the rail corridor. The only feasible solution was a roughly two-mile route on narrow roadway segments of County Road 11. Two turnaround points were required, one at each end, and both requiring backing maneuvers (TA2). Turnaround point HTS-06 is a railroad service drive, while HTS-07 is a farm drive co-located with the route's fill site, dry hydrant HTS-011w. One feature of this route that could help to mitigate traffic coordination issues is the presence of Gretna Brethren Church at the approximate midpoint. This facility, identified as a type one turnaround point (HTS-05) during the planning process, has a large parking lot. This could ease traffic coordination since the route can be managed as two sub-routes for water tenders, with the church serving as a safe short-term staging area for water tenders awaiting clearance to proceed.

In one case, the choice to use a less favorable routing solution was based on operational considerations. Loop route HTN-W was based on municipal hydrant fill site HTN-013 and had been designed to service an approximately 1.5-mile section of County Road 32N. With several large commercial occupancies on this section of road, it was felt that the proposed route's *RT* value of 7.7 minutes was too long. Two pendular type three routes were developed to service the target area as an alternative: HTN-X1 and X2, both also based on municipal hydrants. Route HTN-X1was based on fill site HTN-032s and has an *RT* value of 4.4 minutes, while HTN-X2 is based on HTN-032c and has an *RT* value of 5.1 minutes. The presence of several large commercial parking lots allowed these pendular routes to use only type one turnaround points. While this eliminated the backing hazard, the issue of two-way traffic flow on a narrow road can only be mitigated by traffic coordination procedures and discipline (Figure 40).

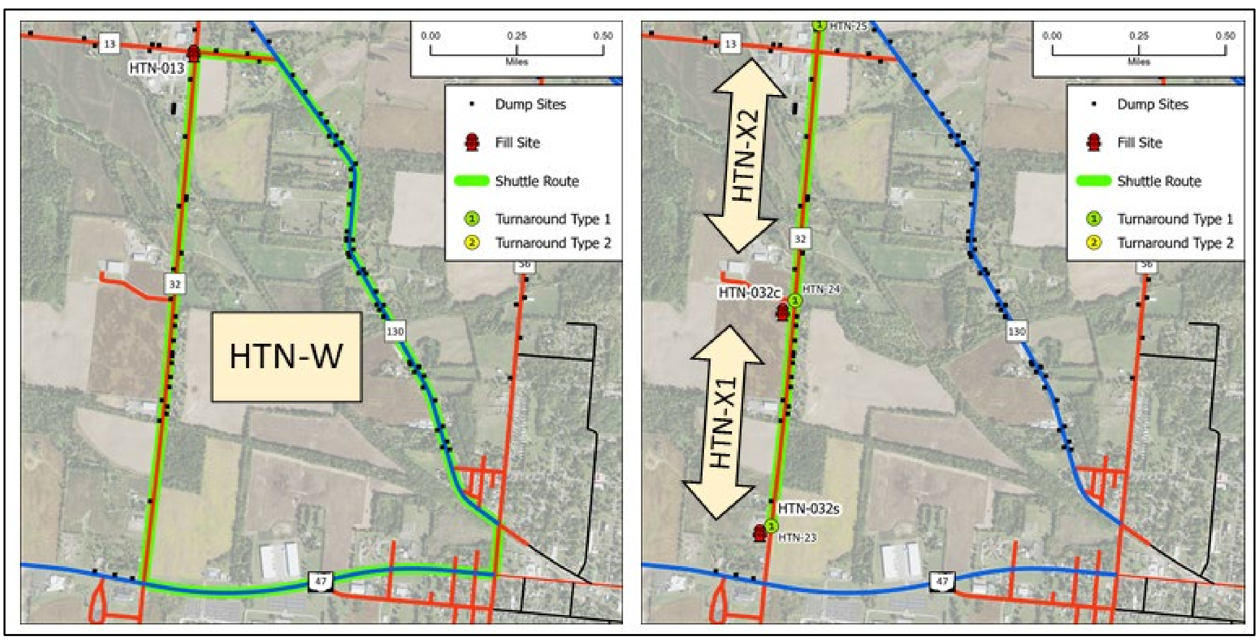


Figure 40. Alternative routing for operational concerns.

The process of route development was time-intensive in no small part due to the need for significant preparatory work, specifically the need to characterize road segment widths and identify potential turnaround points. Both items were important for route development because they are needed to address known safety issues attendant to water tender operations.

Trafficable roadway width was identified as the key factor in determining the ability of a road segment to safely support two-way shuttle traffic. Width data was available from the Ohio Department of Transportation (ODOT) for state highways but was not needed because these roads are known to be designed for two-way truck traffic and safely carry significant volumes of it every day. For local roads, this was not the case. Roadway width data simply did not exist for county and township roads, and the author was forced to devise a methodology to characterize these roads' capacity for bidirectional shuttle traffic. Mensuration of road surface widths from aerial imagery, validated by ground truth samples, was found to be an effective way to rapidly classify local roads.

Awareness among local apparatus operators about the potential for rollover incidents on narrow roads with unpaved shoulders is not well developed. Many of these drivers have a false sense of security on local roads from operating farming equipment that is less prone to rollovers, such as combines and spray rigs, especially during the harvest season when unpaved road shoulders are relatively hard. During large parts of the year, soil moisture is high, and these same shoulders are too soft to support water tender wheels that have left the paved roadway. Developing the necessary discipline to follow traffic plans appropriate for local roads will require a concerted training effort.

Addressing the issue of backing maneuvers at turnaround points required further effort but was aided by the author's knowledge of the local area. The available commercial parking lots were already known, and additional sites (such as farm drives) were readily identified before and during the route development process. Pre-identifying as many turnaround points with no need for backing (TA1) as possible, and designing routes incorporating them, helps to eliminate some of the backing hazard. Developing a safety-first mindset wherein water tender drivers do not perform backing maneuvers without a spotter (or at least dismounting to do a walkaround first) is the only way to address the unavoidable need for backing at some of the remote turnaround points.

For this study, each route was based on a single fill site. Each premise – or at least high-risk occupancies – would be better served by having a secondary or backup source of water supply. In some cases, more than one fill site was present along a route so that a secondary source of supply was readily available. Ideally, any secondary fill site would be designed to cover known risks to the primary site. For example, a primary dry hydrant site should have a municipal hydrant as a secondary or backup site, and vice versa. In this way, a drought impacting the dry hydrants would not impact the municipal hydrants, and a water main break would not impact the dry hydrants. In cases where multiple fill sites are not present along a route, secondary water supply could be supplied by assigning a secondary route with its own fill site to the target premises.

Planning 35 unique shuttle routes for a township-sized area is one thing, convincing water tender drivers to use them during a shuttle is another matter entirely. In the author's estimation, it is highly unlikely that temporary signage could be placed to direct drivers, or that assistants will be available to read maps and give directions from the officer's seat. Of great use would be the integration of the routes, along with audible turn-by-turn directions, into some mobile application for hands-free use by water tender drivers. Apparatus mounted mobile data terminals are uncommon in the county, but most departments in the area use the Active 911 application (active911.com), with members using the application via their personal devices. If possible, the integration of the shuttle routes with audible directions into this application would seem to represent an optimal solution.

Water Shuttle Throughput.

Quantification of potential water delivery rates to each premise in the study area was the focus of the project's fourth research question. Apart from a few critical alterations to address safety concerns, the author made every effort to develop estimates in a "come as you are" fashion with infrastructure, apparatus, staffing, and proficiency depicted as they presently exist. This led to the generation of what are believed to be representative – if conservative – throughput estimates.

The scenarios used in this model present a span of control challenge for the water supply officer (WSO). A water delivery rate of 250 gpm – the minimum required by NFPA 1142 (NFPA, 2022, para. 4.6.3) – is achievable for all routes with five or fewer water tenders, a manageable number. Reaching the recommended minimum rate of 500 gpm for residential areas (para. A.4.4) requires at least eight water tenders for all routes and is not always attained with the full complement of ten tenders. For the WSO already managing a fill and dump site, a large number of water tenders from different departments will be difficult to manage without first forming them into one or more strike teams or task forces. Using this intermediate management level would pose its own problems, due to lack of qualified personnel to serve as strike team / task force leaders and a general lack of familiarity and proficiency with using the Incident Command System (ICS).

While most water supply studies focus on one or a few target hazards and build solutions specific to those facilities, this study had the advantage of quickly generating solutions for all premises in the study area. Many departments would be unable to dedicate the time necessary to develop water shuttle plans for individual residences or even groups of structures. With throughput estimates based on routes, this study allows all premises along a route to be treated as a group. Water delivery estimates for any new construction in the study area will already be available since it is unlikely that any new roads will be built in this area and these structures will fall along routes with existing plans.

Likewise, these route-based estimates allow planning for water supply for unaddressed areas between the identified premises. Wildland fires in the area are generally fought using mobile engine tactics, and the assigned brush trucks require periodic refilling to stay in the fight. The throughput estimates for a route would be just as useful for supporting water delivery to a refill point for a brush truck swarm during a large grass fire as they would be for a barn fire.

Target hazards within the study area that are likely to require exceptional water delivery rates (beyond 500 gpm) will require additional site-specific planning. Such sites include YMCA Camp Willson, a large residential summer camp complex. This facility is already protected by an existing, on-site dry hydrant installation for stationary pumping. This on-site supply could be reinforced by shuttle-delivered water with a plan derived from the route-based estimates modelled in this study.

Another challenging target hazard in the study area is the CSX freight rail corridor. The rail line was used to demarcate independent water supply zones, but the train traffic itself presents the primary hazardous materials exposure for the township. Most of the rail corridor lies in roadless areas that are not trafficable to fire department apparatus. This study at least provides estimates for potential water delivery rates to the at-grade road crossings along the line, with the possibility of two parallel shuttles supplying a derailment or other incident, one on either side of the corridor.

As mentioned in the fill site discussion section, above, reliable estimates for setup and operating base times do not exist. This required the author to allow experience to guide the assignment of reasonable estimates for these times for actions at both the fill site and dump site. The author does believe that the base times used for the study are reasonable. There is a general lack of appreciation as to just how long it does take to accomplish these tasks, especially in the staffing-constrained environments of most rural areas. This is due in part to misconceptions formed at large water supply training events, where many students are available to accomplish the needed tasks. Running a fill or dump site with two or three personnel will necessarily be less efficient than doing so at a training event where a dozen students are assigned to the same job. While the times used here are believed to be reasonable, development of validated baseline estimates for these activities through time and motion studies or some other method would result in more accurate throughput estimates.

By using an intentionally low fill rate of 528 gpm for the model, the throughput estimates are necessarily lower than they potentially could be. Because it is physically impossible for the final water delivery rate to exceed the rate of fill, this represents a hard constraint for some routes. For other routes, the effects of this low fill rate cascade through the calculations, limiting the potential outcome in less obvious ways. For current proficiency conditions in the mutual aid area, this low fill rate was deemed necessary and reasonable by the author. However, it is hoped that through development of county water supply SOPs and increased proficiency through training, that higher fill rates could be allowed. An increased fill rate would not only directly reduce the water tender fill time (*TFF*) but would also tend to reduce queueing time (*TW*) as tenders are processed more quickly through the fill site, thereby reducing overall cycle time, and increasing throughput. This would not be a direct, linear improvement, however, since increasing the fill rate will likely require the use of two fill lines, increasing the fill site connection time (*TFC*) while reducing *TFF*, although it is expected that an overall time reduction would always be realized.

Operational Benchmarks.

This study's fifth and final research question sought to place the throughput estimates discussed above into a time-phased framework of benchmarks. This is where the present study departs from other studies of water supply familiar to the author. In many water supply studies, the focus lies with the final throughput estimates, with little thought given to the time necessary to arrive at the estimated delivery rates. In the author's experience, the scale of buildup time required to assemble the final water shuttle is often underestimated by fire departments. Water shuttle operations require large numbers and variety of apparatus, equipment, and personnel. In the rural setting, these resources will be converging on the incident from widely scattered locations, resulting in long ramp-up times before the final throughput is achieved.

Eckman (1994) hints at the use of such benchmarks for planning but lacked the GIS tools to make the necessary estimates. The NFPA 1142 standard addresses minimum water delivery rates and the minimum durations they should be maintained but does not stipulate when they must be achieved. The NFPA 1720 deployment standard provides benchmarks for initial attack but does not specifically address water supply (NFPA, 2020, para. 4.3.2), but the related *Fire Suppression Rating Schedule* of the Insurance Services Office (ISO) does stipulate a 15-minute benchmark for achievement of 250 gpm flow (ISO, 2012, para. 611.E).

Based on the model estimates, the ISO water delivery benchmark for 250 gpm is not predicted to be met for any of the routes. While not the focus of this study, the model also predicts that the NFPA 1720 initial attack benchmark (six personnel on-scene within 14 minutes) is also not met for any of the routes, assuming that the minimum staffing requirements for that standard are met with the arrival of the second attack engine ("Attack Ready" benchmark). If the premises are taken individually rather than as part of a route, the NFPA 1720 is predicted to be met for 50 of them (6.7%). If the time estimates are rounded to the nearest minute, this number increases to 76 (10.3%). This is still not the desired outcome but is less bad than the alternative.

An inability to meet recognized response and water supply benchmarks is the case for many rural areas across the country, owing to lack of staffing and funding, and compounded by long response distances. This situation is intuitively understood by department leadership and elected officials regarding the study area. Without the benchmark estimates developed using the model, however, there would be no reliable baseline times from which to plan improvements. The shortfalls revealed by the model can provide a starting point for planning new water supply sources, designing more efficient apparatus, developing common SOPs, improving proficiency through training, and securing the funding to pay for all these things. The graphical products produced using the model outputs in ArcGIS Pro will be particularly helpful for educating the cognizant elected officials.

An advantage of having a model such as this one is the ability to conduct sensitivity analysis: changing one factor while holding all other factors constant to discern where the greatest potential for improvement lies. This is a tremendous advantage over the informed guesswork that is currently used. While the model results are not an exact reflection of reality, they are reasonable enough to serve as a basis for planning and funding decisions.

The model does have several limitations as mentioned previously. Notably, the model uses a simplified initial attack scenario for development of the benchmarks, including very simplified processes to represent transitional nursing and relay pumping from the dump site to supply attack engines. These simplifications were necessary due to a lack of existing county (or even department) SOPs for these water supply tasks. It is hoped that the results of this study can be used to spark discussion on the development of county-level water supply SOPs through the only coordinating body available: the Logan County Fire Chiefs' Association.

The model also assumes that all resources needed for the water shuttle will be dispatched simultaneously. This concept has been met with resistance when presented to local fire leaders. There is an understandable reluctance to automatically dispatch ten water tenders and four or more engines to a reported structure fire without the benefit of confirmation from an initial size up of the incident scene. To not automatically dispatch the planned resources would only serve to delay establishment of water supply even more; an undesirable scenario given that the 250 gpm ISO benchmark is already not met. A compromise solution may be to automatically dispatch at least the first five water tenders (WT01 through WT05), while only putting the remaining five on alert for dispatch. This would place at least some resources en route, while simultaneously causing outlying volunteer stations to summon drivers to the station for potential response. Such a compromise would place the benchmarks further out of reach but would be less bad than awaiting positive confirmation before dispatching any water supply resources.

An interesting phenomenon in the results was the fact that the 500 gpm benchmark is achieved for most routes within two minutes of achieving 250 gpm, even though at least five additional water tenders are needed to make this increase in many cases. The author believes that this has to do with the placement of fire stations across the mutual aid area. While stations are not located on any kind of systematic grid, they are not also entirely randomly situated. This leads to a convergence of response times as travel distance increases from the study area (Figure 41).

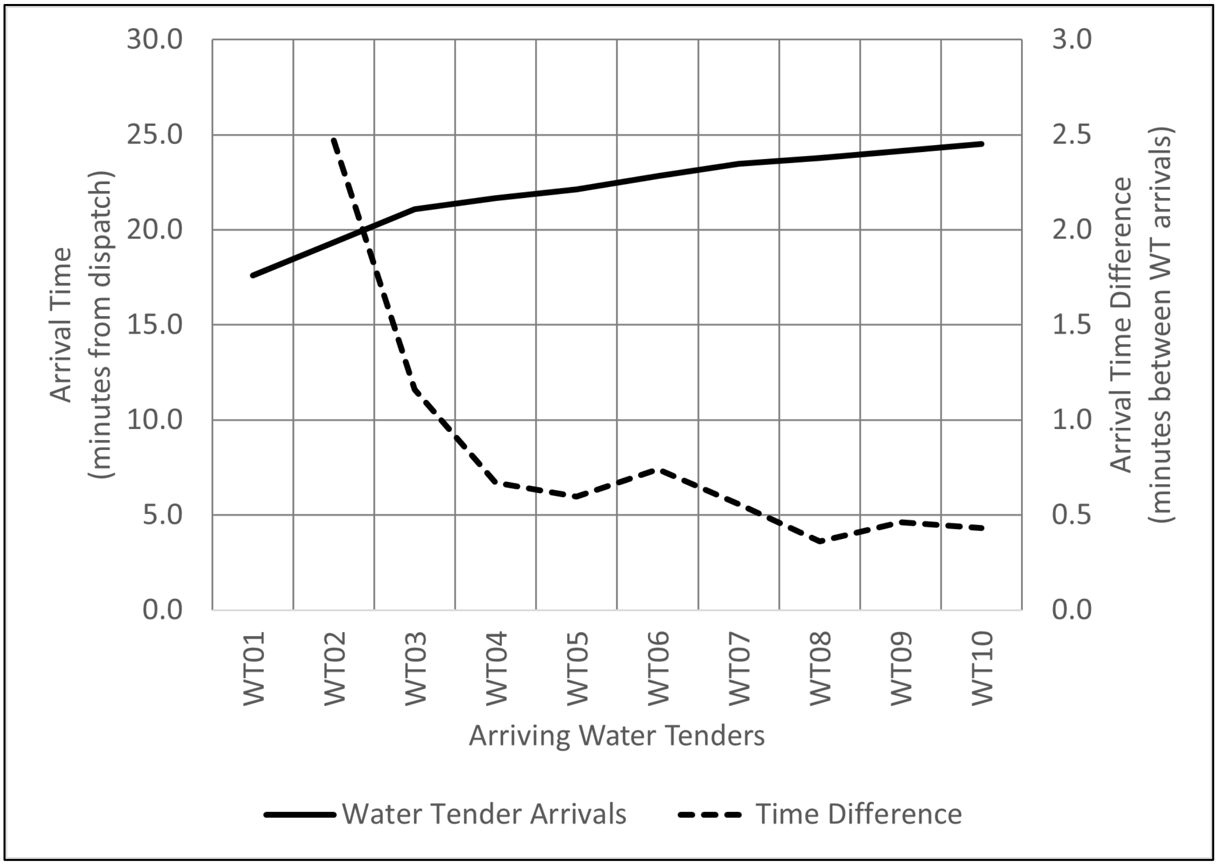


Figure 41. Water tender arrival time differences.

For later-arriving water tenders, after WT03, the difference in arrival times is reduced to about 0.5 minutes. The response times are still long, but water tenders WT03 through WT10 all arrive within a five-minute window on average: 20-25 minutes from initial dispatch (assuming all are dispatched simultaneously).

Project Conclusions.

On September 15, 2015, the main lodge of the Mad River Mountain Ski Resort in eastern Logan County was destroyed in a massive fire. Crews from 15 fire departments in Logan and three surrounding counties were required to contain the blaze and prevent damage to exposures (Tipple & Dunham, 2015). While a ski resort in Ohio may seem odd, this small resort is a major tourist draw for the area, with residents of the Columbus metro area making the short drive to practice for trips to Colorado and elsewhere. While the lodge has since been rebuilt, the loss of tax revenues for the county during the winter of 2015-2016 was significant. This incident required a major water shuttle operation to supply aerial apparatus, and the Logan County fire service was revealed to be not up to the task – embarrassingly so. In fact, the water shuttle was only eventually organized thanks to the intercession of officers from neighboring Union County.

This incident threw Logan County's lack of water supply SOPs and equipment standardization, as well as a general lack of water supply proficiency, into stark relief. While capital purchases of equipment and apparatus will require long-term effort, one thing that can be immediately addressed is the lack of SOPs. Neighboring Union County to the east and Shelby County to the west both have mature, county-wide water supply systems and procedures in place. Logan County sits between them with our many uncoordinated fire departments all acting in isolation. Development of water supply SOPs, including all the tasks needed for a water shuttle, ought to be a priority for Logan County's fire service leaders. Because the existing systems for Union and Shelby Counties differ, whatever is developed for Logan County will need to be interoperable with both systems. Once common SOPs are in place, planning for coordinated training and purchasing can begin.

The proof-of-concept demonstrated by this project can serve as a basis to guide creation of these SOPs. While the results presented here are focused on a small study area, the model is readily adaptable to any other area. Given time to develop the underlying geospatial data elements, the author could conduct a countywide analysis without additional modifications to the model structure. In fact, this model is usable for any rural area and any other fire department could make use of it. While some level of GIS capability facilitates running the model, the Excel component may be run separately using inputs derived from methods other than the GIS-based ones described here.

The author does believe that, given sufficient time and coding expertise, the entire model could have been contained within a GIS framework, with the Excel components replicated within the ArcGIS Pro environment. If this were to be achieved, it would be possible to evolve the entire framework into a web-based platform. In such a case, users would need to provide the necessary apparatus and infrastructure inputs but would require no specialized GIS skills.

It is the author's intention to use the results of this study to inform water supply planning efforts for Bellefontaine Fire Department's rural coverage area. The author also intends to extend this assistance to other fire departments throughout the county. It is the author's hope that the model developed here will be of use to rural fire departments generally, and that it will do some small part to help improve the safety and efficiency of water shuttle operations.

Recommendations

The following recommendations are based upon the findings of this study and the associated literature review:

1. Expand the water supply analysis to the rest of Logan County's rural areas. The author will gather the necessary additional information to systematically run the same analysis for the rest of Logan County, township-by-township. The author expects this process to require an additional year of effort. Once complete, the results will be shared via the county fire chiefs' association to better inform interdepartmental planning and dispatch procedures.
2. Begin the process of developing common, countywide standard operating procedures (SOPs) for water supply. The author will advocate within the county fire chiefs' association for the creation of a water supply working group charged with developing consensus SOPs for all county departments. Once adopted, these SOPs will serve as the basis for coordinated training and purchasing recommendations relating to water supply.
3. Validate model assumptions. The author will work via the Ohio Fire Chiefs' Association Water Supply Technical Advisory Committee (WSTAC) to gather empirical data necessary to validate certain aspects of the model. The author will seek to validate the Torricelli-based estimates of efflux times. The author will also work to develop reliable, standardized estimates of setup and operation base times at the fill and dump sites.

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Appendix A

Compilation of Notation Used in Study

Table A1.

Model Notation Summary.

Variable or Coefficient	Name	Description
kDO	Dump site operations proficiency coefficient	Modifies dump site base handling times according to assigned fire department's assessed proficiency at these tasks
kDS	Dump site setup proficiency coefficient	Modifies dump site base setup time according to assigned fire department's assessed proficiency at this task
kFO	Fill site operations proficiency coefficient	Modifies fill site base handling times according to assigned fire department's assessed proficiency at these tasks
kFS	Fill site setup proficiency coefficient	Modifies fill site base setup time according to assigned fire department's assessed proficiency at this task
kS	Staffing coefficient	Modifies dump and fill site base times according to assigned fire department's assessed ability to respond with optimal crew staffing
kWT	Water tender driver/operator proficiency coefficient	Modifies dump and fill site base maneuver and nursing setup times according to assessed driver/operator proficiency of fire department providing a given water tender
K	Handling capacity	Number of water tenders that can be simultaneously serviced at the dump and fill sites; sum of Kd and Kf

Kd	Dump site handling capacity	Number of water tenders that can be simultaneously serviced at the dump site
Kf	Fill site handling capacity	Number of water tenders that can be simultaneously serviced at the fill site
Q	Total shuttle throughput	Sum of water delivery throughput for all water tenders participating in a shuttle (gallons per minute)
Qn	Shuttle throughput	Water delivery throughput for water tender *n* within a shuttle (gallons per minute)
T	Total shuttle cycle time	Total time required for a given water tender to complete one full shuttle cycle; sum of TR, TF, TD, and TW; specific to each water tender
TD	Dump site handling time	Total time required for a given water tender to be serviced at the dump site; sum of TDC, TDD, and TDM; specific to each water tender
TDD	Water tender unload time	Time required for a given water tender's tank to be unloaded at the dump site (efflux time); a characteristic of the water tender
TDC	Dump site connection time	Base time required for preparing a water tender's transfer (dump) valve for offload operations; a characteristic of the water tender
TDM	Dump site maneuver time	Base time required for a water tender to maneuver into and out of unloading position at the dump site; a characteristic of the dump site
TF	Fill site handling time	Total time for a given water tender to be serviced at the fill site; sum of TFC, TFF, and TFM; specific to each water tender

TFC	Fill site connection time	Base time required for fill line(s) to be connected and disconnected to a given water tender at the fill site; a characteristic of the water tender
TFF	Water tender load time	Time required for a given water tender's tank to be filled at the fill site; a characteristic of the water tender
TFM	Fill site maneuver time	Base time required for a water tender to maneuver into and out of loading position at the fill site; a characteristic of the fill site
TR	Navigation time	Total time required for a water tender to travel the roadway segments between the dump and fill sites (both unloaded and loaded segments) at the designated shuttle speed; a characteristic of the route
TW	Queueing time	Total time a water tender will spend queueing to be serviced at the dump and fill sites during each shuttle cycle; a characteristic of the overall shuttle operation, assigned to each water tender equally

Note. All time factors are in minutes unless otherwise specified.

Table A2.

Notation for Water Tender Performance Equations.

Variable or Coefficient	Name	Description
a	Semi-major axis	One-half of the width of an ellipse; for Torricelli-derived equations
A	Aperture area	Cross-sectional area of the unloading aperture (dump chute); for Torricelli-derived equations
b	Semi-minor axis	One-half of the height of an ellipse; for Torricelli-derived equations
C	Discharge coefficient	Coefficient of turbulent flow at the aperture; for Torricelli-derived equations
g	Acceleration due to gravity	Physical constant for Torricelli-derived equations (32.2 ft/s^2)
h	Tank height	Height of tank or tank section; for Torricelli-derived equations
k	Usable tank capacity	Coefficient applied to water tender tank volume to account for spilled or unusable water volume; per NFPA 1142
l	Tank length	Length of tank or tank section; for Torricelli-derived equations
S	Tank surface area	Cross-sectional area of surface of water within a tank
t	Efflux time	Total time to drain a tank; for Torricelli-derived equations (s)
w	Tank width	Width of tank or tank section; for Torricelli-derived equations

Note. All length and area factors are in feet unless otherwise specified.

Appendix B

Mutual Aid Area Fire Departments

The table below provides a summary of the 24 fire departments that formed the potential mutual aid study area for this project. The mutual aid area represents all fire departments with jurisdictional coverage of some part of Logan County, Ohio, some of which have overlapping coverage within the county, but are based in a neighboring county. The mutual aid area also includes any departments with jurisdictional areas bordering but not entering Logan County. This area was intended to represent the maximum likely mutual aid pool for Bellefontaine Fire Department.

Each of the departments in the table is a fully independent entity, organized as a municipal or township fire department, or as a multi-jurisdictional joint district. Ohio law does not provide for over-arching, county-level or regional fire authorities, meaning that all mutual aid coordination is accomplished via memoranda of understanding (MOU), generally brokered by county fire chiefs' associations. Each department in this study operates from a single station.

Table B1.

Fire Department Summary Information.

Dispatch Code	Name	Home County	Staffing for Fire
ATF	Allen Township Fire Department	Union	Full-time
BCF	Bokescreek Township Fire Department	Logan	Volunteer
BFF	Bellefontaine Fire Department	Logan	Full-time
DGF	DeGraff Fire Department	Logan	Volunteer
HVF	Huntsville Fire Department	Logan	Volunteer

IJF	Indian Joint Fire District	Logan	Volunteer
JCF	Jackson Center Fire Department	Shelby	Volunteer
LTF	Northwestern Joint Fire District	Union	Full-time
LVF	Lakeview Fire Department	Logan	Volunteer
MTV	Southeast Hardin-Northwest Union Joint Fire District	Hardin	Volunteer
MWF	Maplewood Fire Department	Shelby	Volunteer
NEC	Northeast Champaign County Joint Fire District	Champaign	Volunteer
PJF	Port Jefferson Community Fire Company	Shelby	Volunteer
PTF	Perry Township Fire Department	Logan	Volunteer
QVF	Quincy Fire Department	Logan	Volunteer
RCF	Rushcreek Township Fire Department	Logan	Volunteer
RHD	Roundhead Fire Department	Hardin	Volunteer
RTF	Richland Township Fire Department	Logan	Volunteer
RWD	Adams Township-Rosewood Fire Department	Champaign	Volunteer
RWF	Ridgeway Fire Department	Hardin	Volunteer
SJF	St. John’s Fire and Rescue	Auglaize	Volunteer
TVF	Tri-Valley Joint Fire District	Logan	Volunteer
WLF	West Liberty Fire Department	Logan	Volunteer
WTF	Wayne Township Fire Department	Auglaize	Volunteer

Note. Some departments have hybrid staffing with full-time coverage for emergency medical services (EMS) only, coupled with traditional volunteer fire coverage; staffing indicated above is as it pertains to fire response.

Appendix C

Apparatus Data Survey Forms

Water Tender Data Collection Form

Fire Department	Station	Apparatus Identifier
Manufacturer	Year	
Rated Tank Capacity (gallons)	Water Tender Design	☐ Vacuum: performance must be determined by testing ☐ Conventional: continue below

Tank Configuration (as viewed from rear)

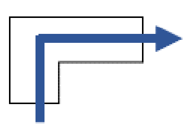
Tank Shape	Rectangular	Circular	Elliptical	Rectangular Tee		Elliptical Tee	
Dimensions to Collect	Height Width Length	Height Length	Height Width Length	Upper Section Height Width Length	Lower Section Height Width Length	Upper Section Height Width Length	Lower Section Height Width Length

Height	Width	Length	Height (lower)	Width (lower)	Length (lower)

Dump Outlet Configuration

Outlet Shape	Square	Circular	Rectangular	
Dimensions to Collect	Height	Diameter	Height	Width

Side Dump Configuration

☐ Straight Path	
☐ Angled Path	

Pump Configuration

Pump	☐ Fire-Rated ☐ Portable ☐ None
Rating (gpm)	

Fill Configuration

Tank Material	☐ Poly ☐ Non-Poly
Rear Fill Port #1 Diameter	
Rear Fill Port #2 Diameter	

Water Handling Equipment

Portable Tank Configuration	☐ Single-Lane ☐ Square
Portable Tank Capacity (gallons)	
Other Appliances	☐ Low-Level Strainer ☐ Manifold ☐ Jet Siphon

Engine Data Collection Form

Fire Department	Station

Engine #1

Apparatus Identifier	Manufacturer		Year
Pump Rating (gpm)	Primer Type ☐ Air Primer ☐ Conventional		No. Crew Seating Positions
Booster Tank Capacity (gal)	Supply Line Size	Supply Line Coupling	Supply Line Length

Engine #2

Apparatus Identifier	Manufacturer		Year
Pump Rating (gpm)	Primer Type ☐ Air Primer ☐ Conventional		No. Crew Seating Positions
Booster Tank Capacity (gal)	Supply Line Size	Supply Line Coupling	Supply Line Length

Engine #3

Apparatus Identifier	Manufacturer		Year
Pump Rating (gpm)	Primer Type ☐ Air Primer ☐ Conventional		No. Crew Seating Positions
Booster Tank Capacity (gal)	Supply Line Size	Supply Line Coupling	Supply Line Length

Appendix D

Mutual Aid Department Response Delays

Table D1.

Fire Department Response Delays.

Dispatch Code	Name	Delay Time (minutes)	Staffing for Fire
ATF	Allen Township Fire Department	4.1	Full-time
BCF	Bokescreek Township Fire Department	5.3	Volunteer
BFF	Bellefontaine Fire Department	3.0, 6.3, 10.0	Full-time
DGF	DeGraff Fire Department	7.8	Volunteer
HVF	Huntsville Fire Department	9.5	Volunteer
IJF	Indian Joint Fire District	6.2	Volunteer
JCF	Jackson Center Fire Department	7.0	Volunteer
LTF	Northwestern Joint Fire District	5.2	Full-time
LVF	Lakeview Fire Department	7.0	Volunteer
MTV	Southeast Hardin-Northwest Union Joint Fire District	7.0	Volunteer
MWF	Maplewood Fire Department	8.1	Volunteer
NEC	Northeast Champaign County Joint Fire District	7.0	Volunteer
PJF	Port Jefferson Community Fire Company	7.0	Volunteer
PTF	Perry Township Fire Department	5.1	Volunteer
QVF	Quincy Fire Department	7.9	Volunteer
RCF	Rushcreek Township Fire Department	8.8	Volunteer
RHD	Roundhead Fire Department	7.0	Volunteer

RTF	Richland Township Fire Department	7.0	Volunteer
RWD	Adams Township-Rosewood Fire Department	5.5	Volunteer
RWF	Ridgeway Fire Department	6.0	Volunteer
SJF	St. John's Fire and Rescue	7.0	Volunteer
TVF	Tri-Valley Joint Fire District	8.1	Volunteer
WLF	West Liberty Fire Department	5.4	Volunteer
WTF	Wayne Township Fire Department	7.0	Volunteer

Note. Times for BFF are for first-, second-, and third-responding units.

Appendix E

Water Shuttle Safety Analysis

As with any fire service operation, a water shuttle carries potential risks to participating firefighters. Developing mitigation measures to reduce these risks is best accomplished through use of a systematic process. The risks inherent to a water shuttle operation are amenable to exposure control analysis using the National Institute for Occupational Safety and Health (NIOSH) hierarchy of controls (National Institute for Occupational Safety and Health [NIOSH], 2015). The NIOSH hierarchy comprises five steps, in order of descending effectiveness:

1. *Elimination*. This is the removal of the hazard altogether. A relevant example would be removal of the need for the water shuttle in the first place, which could be accomplished by aggressive fire prevention efforts.

2. *Substitution*. This is the use of an alternative process with less risk exposure. A relevant example would be expanding municipal water main and hydrant networks to eliminate the need for a water shuttle.

3. *Engineering controls*. This is the use of design features or technology to reduce risk to firefighters and equipment. These measures are automatic and require no firefighter input or activation. A relevant example would be the installation of governors on water tenders to reduce excessive speed.

4. *Administrative controls*. These are rules, regulations, and procedures that, when followed, are intended to separate firefighters and equipment from known risks. These controls are not automatic and require active firefighter compliance to be effective. A relevant example would be a requirement that water tenders move only under the control of a ground guide in congested areas.

5. *Personal protective equipment (PPE)*. This is the last line of defense for firefighters, and the least effective control measure. This includes items typically worn by the firefighter to provide some measure of protection from known hazards when all the above controls have been unsuccessful. A relevant example would be requiring the wear of safety footwear during water shuttle operations to protect the feet and reduce slip, trip, and fall accidents.

In the case of water shuttles, elimination and substitution are beyond the scope of the operational level. Elimination through fire prevention efforts is an ongoing effort by most fire departments and is never completely effective. This means that there will always be some number of fires in rural areas, and alternative water supply methods will be needed to combat them. Likewise, substitution is ongoing in many jurisdictions through the gradual expansion of municipal water main systems. While this will eventually be helpful, the installation of new hydrants occurs on a timescale that is not relevant to immediate operations.

This means that for water shuttle operations safety, the planner is left with the three bottom tiers of the hierarchy: engineering and administrative controls, and PPE. Each of these methods requires strong fireground leadership in order to be effective. Many firefighters will view these measures as impediments to efficiency and may be non-compliant or attempt to disable automatic controls. Training, coaching, and modeling of appropriate behavior by leaders, as well as active enforcement at the incident scene, will be essential to mitigate risk. A matrix analysis of potential engineering, administrative, and PPE control measures for common water shuttle risk exposures is provided in the tables below. The tables reference the following standards:

- NFPA 1901 Standard for automotive fire apparatus (NFPA, 2016)

- NFPA 1911 Standard for the inspection, maintenance, testing, and retirement of in-service emergency vehicles (NFPA, 2017)

Table E1.

Safety Analysis: Route Operations.

Risk Exposure	Potential Mitigating Controls
Rollover due to excessive speed / failure to negotiate curves	EC: ensure electronic stability control systems are used EC: install speed governor on water tenders AC: set and enforce maximum speed limits AC: develop water tender driver training program
Rollover due to inadequate road width / right wheels leaving pavement	EC: lower water tender center of gravity AC: plan and enforce one-way routing AC: develop water tender driver training program
Driver ejection during rollover accident	AC: set and enforce mandatory seat belt use policy AC: develop water tender driver training program
Collision with other vehicles	EC: ensure electronic stability control systems are used AC: plan and enforce one-way routing AC: set and enforce maximum speed limits AC: develop water tender driver training program
Liquid surge / slosh hazards	EC: ensure water tenders are properly baffled AC: set and enforce policy forbidding moving partially filled water tenders AC: develop water tender driver training program
Accident due to mechanical failure	EC: ensure all apparatus meet minimum NFPA 1901 design standards AC: ensure all apparatus meet minimum NFPA 1911 preventive maintenance standards
Driver fatigue / inattention	AC: ensure relief drivers are available for long-duration incidents AC: ensure supervisors monitor drivers for signs of fatigue

Note. EC = engineering control; AC = administrative control; PPE = personal protective equipment.

Table E2.

Safety Analysis: Fill Site Operations.

Risk Exposure	Potential Mitigating Controls
Injuries due to pressurized hose lines	EC: pressure relief valves on manifold EC: use locking couplings where available EC: ensure all apparatus meet minimum NFPA 1901 design standards AC: set and enforce maximum pump pressure PPE: mandate wear of helmets, eye protection, safety footwear and work gloves by fill site ground crew
Runover / backover / pinning accidents	EC: design fill site layouts for one-way traffic flow to eliminate need for backing EC: ensure all water tenders can be filled from rear; retrofit old apparatus as needed AC: set and enforce policy preventing apparatus movement unless under control of a ground guide AC: ensure adequate scene lighting is provided during low visibility periods AC: develop fill site operations training program and standard operating procedures (SOPs) PPE: mandate wear of high-conspicuity vests or other reflective outerwear
Slip / trip / fall accidents	EC: ensure all fill connections are accessible by personnel standing on the ground; retrofit old apparatus with adapters as needed AC: set and enforce policies forbidding climbing on apparatus tailboards AC: ensure sand, salt, or grit are spread to improve traction during freezing weather AC: ensure adequate scene lighting is provided during low visibility periods PPE: mandate wear of safety footwear

Note. EC = engineering control; AC = administrative control; PPE = personal protective equipment.

Table E3.

Safety Analysis: Dump Site Operations.

Risk Exposure	Potential Mitigating Controls
Injuries due to pressurized hose lines (relay engine and tank-to-tank transfer)	PPE: mandate wear of helmets, eye protection, safety footwear and work gloves by fill site ground crew
Runover / backover / pinning accidents	EC: design dump site layouts for one-way traffic flow to eliminate need for backing EC: ensure all water tenders can offload from side; retrofit old apparatus with adapters as needed EC: ensure all water tender dump valves can be operated without need for personnel between apparatus and tank EC: use narrow profile (single lane) portable tanks AC: set and enforce policy preventing apparatus movement unless under control of a ground guide AC: ensure adequate scene lighting is provided during low visibility periods AC: develop dump site operations training program and standard operating procedures (SOPs) PPE: mandate wear of high-conspicuity vests or other reflective outerwear
Slip / trip / fall accidents	AC: set and enforce policies forbidding climbing on apparatus tailboards AC: ensure sand, salt, or grit are spread to improve traction during freezing weather AC: ensure adequate scene lighting is provided during low visibility periods PPE: mandate wear of safety footwear

Note. EC = engineering control; AC = administrative control; PPE = personal protective equipment.