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Abstract

This dissertation examines the resiliency, efficiency, and environmental impact of barge shipments within the upper Ohio River basin, contrasting findings relevant to this region with assumptions and findings of broader national studies and providing alternative assessment methods. The unique attributes of this region's inland waterways infrastructure and usage patterns are dominated by the shipment of coal; mines and powerplants with heavy and inflexible dependence on barge shipments; and the constrictions of the waterway infrastructure. Acknowledging these attributes allows for a more accurate assessment in the future of risks due to infrastructure failure and opportunities for efficiency gains. Research goals were set in three major areas: assessing the impact of an extended loss of commercial river navigation due to catastrophic infrastructure failure; assessing current and potential new efficiency metrics for inland waterways freight movement, both in terms of vessel movements and the infrastructure itself; and quantifying and assessing air emissions from regional commercial river traffic.

The first research goal was to assess the impact of an extended loss of commercial river navigation due to catastrophic infrastructure failure. The objectives of this research goal were to develop a failure scenario; to develop methodologies to identify at-risk commodity shipments, feasible alternate modes of transportation, supply chain options, and shipping costs; and to develop a methodology to assess the potential closure of facilities impacted by infrastructure failure. A hypothetical failure scenario was assessed for a year-long closure of the Monongahela River between Charleroi and Elizabeth in 2010. For this scenario, the potentially displaced volume of coal shipments from mines to powerplants for a hypothetical river shutdown in 2010 was estimated at 7.0 million tons. The resilience of the impacted facilities, the feasibility of their shipping alternatives, and their ability to re-organize into new markets were assessed, showing

heavy predicted impacts for facilities within the hypothetical failure zone, minimal impacts on facilities located below the failure zone, and mixed impacts above the failure zone that depend on facility-specific shipping mode alternatives. Lost revenues were estimated for facilities that close due to an inability to adapt, as well as the replacement cost of towboats and barges trapped by a catastrophic and sudden failure. The aggregate costs to these facilities as a result of a year-long closure in 2010 were estimated at $0.56-1.7 billion.

The second research goal was to assess commonly used and potential new efficiency metrics for the inland waterways. Objectives of this goal included the development of methodologies to identify, characterize, and differentiate between vessel and commodity trips; to assess efficiency metrics currently used by USACE and develop improved metrics; and to conduct stochastic time studies of commodity trips to quantify efficiency gains from infrastructure improvements. The vessel and commodity trip analyses provide a unique assessment of the inefficiencies created by the infrastructure bottlenecks within the region. Data from USACE's Lock Performance Monitoring System and the Energy Information Administration's Survey 923 were used to characterize and rank the vessel and commodity trips made in 2010 in terms of frequency, tonnage, and ton-miles. Such rankings can be used to prioritize optimization projects and to assess usage patterns. The analyses of various efficiency measures commonly used for the inland waterways were conducted in light of the particular constraints of operation within the upper Ohio River basin. These upriver locks differ in size, requiring vessel operators to optimize the type and configuration of barges used within the region, and causing the regional profile to differ from fleet and flotilla profiles generated at a national level or for other regions. Consideration of these differences allows for more accurate analysis of usage patterns, with implications for efficiency considerations of time and fuel consumption. Stochastic modeling of historical usage patterns allows for the comparison of time requirements with different flotilla configurations and with different infrastructure configurations. A scenario analysis on a typical regional shipment between a coal mine and powerplant was used to demonstrate the method. Results show that completion of a long delayed lock reconstruction project will reduce the time required, and thus the cost and fuel, to move commodities across the region. The savings for a 15-jumbo barge tow moving 200 miles across the study area was estimated to be 17% as a result of completion of the Lower Mon Project.

The third research goal was to quantify and assess the regional impact of commercial river traffic on air quality. The specific objectives of this goal were to develop a methodology for calculating emission loadings; and to develop a methodology to assess the impact of vessel emissions on regional air monitors. An estimation of particulate emissions from the vessels' diesel engines is presented, showing total releases of PM2.5 to be about 360 tons in 2010 across 600 river miles of the upper Ohio River basin, on the same order of magnitude as the major point source releases reported in Allegheny County, and about 25% of releases from a typical 1,700 MW regional powerplant. A screening analysis estimates PM2.5 concentrations attributable from towboats passing through the Liberty-Clairton non-attainment region, predicting that these emission levels would be orders of magnitude below the detection limits of the region's air monitors, and would be dwarfed by the point source impacting those monitors.

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I. Introduction

The inland waterways in the United States serve a critical role in the movement of commodities. Over 2.2 billion tons were shipped on the inland waterways in 2012 [1]. The motivation for this dissertation centers on concerns about the condition of the inland waterway infrastructure and the potential for failure and extended delays, as well as an incomplete picture about how the waterways perform and are used. This infrastructure, managed by the U.S. Army Corps of Engineers (USACE), is paid for by a dysfunctional array of funding mechanisms [2]. Key to obtaining appropriate funding levels is the Corps' analysis of benefits and costs associated with the inland waterways. The National Resources Council (NRC) has challenged USACE to expand its benefit cost analysis scope [3]. The President's Council on Environmental Quality has similarly broadened the scope of the criteria used to assess water resource projects, including the Corps' navigation projects [4]. In response to the challenge of improving the Corps' assessment tools, this dissertation presents methodologies that can be used to more accurately assess resiliency, efficiency and costs associated with the inland waterways.

Research goals were set in three major areas: assessing the impact of an extended loss of commercial river navigation due to catastrophic infrastructure failure; assessing current and potential new efficiency metrics for inland waterways freight movement, both in terms of vessel movements and the infrastructure itself; and quantifying and assessing air emissions from regional commercial river traffic.

Research Goal 1 was to assess the impact of an extended loss of commercial river navigation due to catastrophic infrastructure failure. The objectives of this research goal were to develop an infrastructure failure scenario (Objective 1.1); to develop methodologies to identify at-risk commodity shipments (Objective 1.2); to develop methods for the identification of feasible alternate modes of transportation and supply chain options (Objective 1.3); to develop a methodology to assess the viability of new submarkets formed by the river closure (Objective 1.4); and to develop a methodology to assess the potential closure of facilities impacted by infrastructure failure (Objective 1.5). Section II describes the methodology and findings for this research goal and objectives.

Research Goal 2 was to assess commonly used and potential new efficiency metrics for the inland waterways. Objectives of this goal included the development of methodologies to identify, characterize, and differentiate between vessel and commodity trips (Objective 2.1); to assess efficiency metrics currently used by USACE and develop improved metrics (Objective 2.2); and to conduct stochastic time studies of commodity trips to quantify efficiency gains from infrastructure improvements (Objective 2.3). The analyses of vessel and commodity trips are presented in Section III (Objective 2.1), while the efficiency metrics analyses and stochastic modeling are described in Section IV (Objectives 2.2 and 2.3).

Research Goal 3 was to quantify and assess the regional impact of commercial river traffic on air quality. The specific objectives of this goal were to develop a methodology for calculating emission loadings (Objective 3.1); and to develop a methodology to assess the impact of vessel emissions on regional air monitors (Objective 3.2). Section V presents the findings of the third research goal and objectives.

Much work precedes this thesis on modeling the transport of commodities. The complexity of the national freight network requires extensive use of simplifying assumptions, resulting in understanding at the broadest level of the economy, and misrepresentation at the regional level.

Regional granularity supports the robustness of regional infrastructure investment decision making. Understanding how infrastructure is used at the local level improves the accuracy of benefit and cost analyses used to allocate constrained funds. Further, the ongoing debate about the appropriate funding levels and mechanisms for the inland waterways, acknowledged by the Congress and the Administration by the May 2014 reauthorization of WRDA, often covers the topics of efficiency and delays. The issues associated with the operation of the inland waterways at the upper stretches of the network are different from the issues closer to the coastal ports. In addition, shipping on the Ohio River System (ORS) is dominated by regional movements of coal. The costs and time constraints for coal transits differ from other commodities in ways that can be considered in the assessment of the value and efficiencies of the inland waterways. These concepts are explored in throughout this dissertation.

II. Estimating Economic and Resilience Consequences of Potential Navigation Infrastructure Failures on the Lower Monongahela River[1]

A. Introduction

> **Research Goal 1**: Assess the impact of an extended loss of navigation due to catastrophic infrastructure failure

The motivation for this research was the concern about the reliability of the inland waterway infrastructure. This infrastructure, managed by USACE, allowed for the shipment of 2.2 billion tons of commodities in 2012 [1]. More narrowly, this study was motivated by the extended delay in the completion of a major USACE project to replace the antiquated components of the three lower Monongahela River lock and dam facilities in southwestern Pennsylvania with two modern facilities [5] and the potential for failure of the aging components and resultant extended loss of navigation (discussed in detail in II.D).

The analysis focused on coal shipments from mines to powerplants; coal shipments account for three quarters of the commodity tonnage shipped on the region's rivers [6]. Of particular interest was the resilience of the regional "coal-to-utility network" in response to an extended loss of navigation through a key stretch of river. Numerous regional and national studies have previously examined various aspects of commodity transport and congestion using geographic information system (GIS) tools and national databases, making general assumptions about the impact of river failure on commodity movements [7] [8]. This analysis looked in more detail at actual transport through the at-risk locks, and assesses local and regional impacts, particularly with respect to potential infrastructure failure and the abilities of regional coal mines and powerplants to adjust to a long-term system constraint.

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[1] Published in part. Gwen Shepherd DiPietro, H. Scott Matthews, Chris T. Hendrickson. "Estimating economic and resilience consequences of potential navigation infrastructure failures: A case study of the Monongahela River." Transportation Research Part A: Policy and Practice. Volume 69. November 2014. Pages 142-164.

The specific objectives to address this research included: to develop and infrastructure failure scenario (Objective 1.1); to develop methodologies to identify at-risk commodity shipments (Objective 1.2); to develop methods for the identification of feasible alternate modes of transportation and supply chain options (Objective 1.3); to develop a methodology to assess the viability of new submarkets formed by the river closure (Objective 1.4); and to develop a methodology to assess the potential financial impact of closure of facilities impacted by infrastructure failure (Objective 1.5). Figure 1 provides an overview of the data sources, intermediate analyses and research objectives for this section.

The contributions of this research lie in extending the current body of work which assesses and models (i) the commodity transportation network, (ii) the integrated energy system (focused on the coal-to-utility network), and (iii) impacts of and vulnerability to catastrophic infrastructure failure. The specific application is to failure within the inland waterways, but the findings are applicable to broader transportation infrastructure analyses. Tools are developed to identify mine and powerplant accessibility constraints that may compromise components of the integrated energy system. Consideration of these vulnerabilities allows for a methodology to assess resilience and to quantify losses at facilities that may not be able to remain in business without access to barge transport.

Section II.B reviews key prior studies and concepts relevant to this work. Section II.C provides background information that characterizes the river infrastructure in the study area and the commodities that are shipped through the region. Section II.D describes the infrastructure failure scenario assessed (Objective 1.1). Section II.E identifies at-risk coal shipments that were barged through the potential failure zone in 2010 (Objective 1.2). Section II.F presents methods to predict feasible responses to an unexpected and prolonged closure of a portion of the

Monongahela River (Objective 1.3). Section II.G explores the likelihood that new markets could successfully emerge above and below the failure zone, allowing the impacted facilities to remain operational (Objective 1.4). Section II.H quantifies the financial impacts to the mines, powerplants, and barge shipping operations due to displacement of their coal shipments (Objective 1.5). Conclusions are presented in Section II.I.

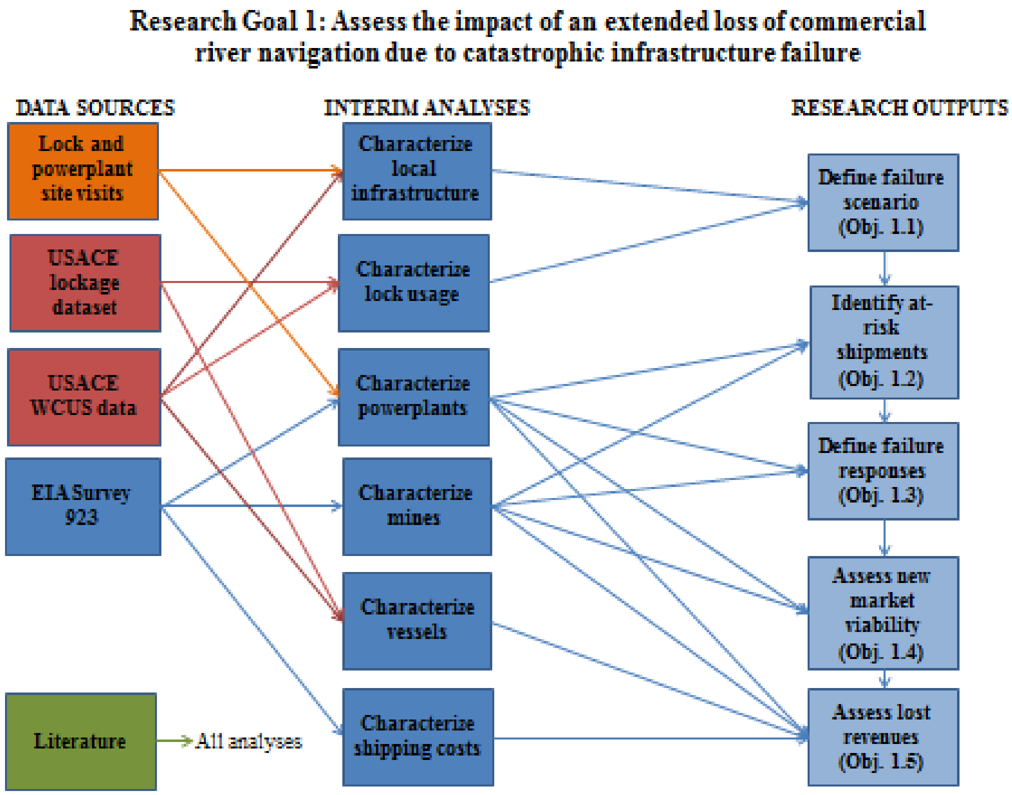


Figure 1. Research Goal 1 Flow Diagram

B. Prior studies and key concepts

Extensive work precede this analysis that develop increasingly sophisticated approaches to modeling the transport of commodities with differing levels of focus on economic theory [9], traffic flow modeling, queuing modeling, agent-based modeling [10], and optimization. These analyses differ in terms of whether they assess normal, unperturbed conditions; short-term disruptions [11] [12] [13] [14]; or long-term catastrophic disruptions [15]. Some assess broad commodity flows using input/output models [16] [12] [14], while others focus more narrowly on specific commodities of importance to a specific region [17]. In all of these analyses, a tension exists between what can be modeled under appropriate simplifying assumptions, and the interest in incorporating a robust set of parameters and potential outcome sets. The ultimate need for robustness in these types of analysis has several drivers. First, efficient infrastructure investment decision making in a resource-constrained world requires robust accounting of the costs and benefits of proposed projects. In the specific case of the inland waterways infrastructure, Congress requires USACE to conduct extensive analyses to document the need for all major infrastructure projects, including the rehabilitation of aging locks and dams [18]. Second, national security concerns have increasingly driven more sophisticated failure and resiliency analyses - in assessing both the potential infrastructure vulnerabilities that could lead to system failures, as well as the resiliency of the broader systems to continue to function in the wake of catastrophic losses [19] [20] [21] [22]. Third, the transportation sector accounts for 32% of U.S. greenhouse gas emissions [23], and the development of sensible and effective strategies to move this sector to a lower level of negative impacts requires an accurate accounting of costs and benefits [10].

Resilience is generally understood to mean the "capacity to adapt to changing conditions without catastrophic loss of form or function," with a more refined definition suggested by Park et al. [24] to be "an emergent property of what an engineering system does, rather than a static property the system has." In the context of the commodity distribution system that supplies coal to powerplants, resilience (or the lack thereof) applies to the physical infrastructure that facilitates movement (e.g., the locks and dams of the inland waterways), as well as to the entities that represent the supply and demand forces in the system (the mines and powerplants), and more broadly the integrated energy system. Park et al. [24] go on to characterize resilience as the "persistence of relationships" where fundamental basic influence relationships are maintained. Applying these concepts to the coal-to-utility system when subjected to failure of a key infrastructure component, we agree that the generic relationship between fuel supplier and electricity generator will remain intact (the lights will stay on), but the nodes will shift. This research demonstrates the capacity of the coal-to-utility system to utilize a variety of suppliers, re-organizing into new sub-markets (above and below the potential failure zone), as discussed in Section II.G. Section II.G also explores the possibility that not all nodes will remain in the altered system if the new sub-markets are reorganized in a way that maximizes profit (rather than the retention of facilities in the system). Finally, the research explores the potential fragility or marginal nature of some of the nodes as an important component of an accurate assessment of the impact of catastrophic failure (Section II.H).

The range of potential responses of these entities to an extended river outage differs as a function of their accessibility to the coal-to-utility market. Jenelius [11] discusses accessibility as a key component in road network vulnerability analysis, and the concept is useful in this waterway network as well. Geurs and van Wee [25] explore different accessibility measures for land-use and transportation strategies, as well as the inaccuracies that can arise in analyses with incomplete accessibility measures. For the mines and powerplants, their vulnerability to catastrophic infrastructure failure is a direct function of their accessibility to the coal-to-utility market (i.e., their location, shipping patterns, available shipping alternatives, and alternative raw material sourcing flexibility). Understanding the probable impacts of failure requires consideration of these factors.

A number of proof-of-concept modeling exercises have explored different ways to simulate the movement of commodities on the inland waterways. To demonstrate these models, simplifying assumptions are frequently used to allow the developers to validate the underlying equations and theory. For example, models might assume inelastic demand for transportation services, where the movement of the commodity is assumed to be a given; other alternatives, such as waiting for a port to re-open or cancelling the shipment, might be ignored [11] [16]. Models that focus on understanding the incremental cost associated with shifting transportation modes in response to a port closure might assume that rail or truck is always a feasible alternative to disrupted barge shipments, both in terms of accessibility and capacity [12] [7] [8]. Broad analyses of the value of the inland waterways might assume closure of an entire waterway, requiring the complete displacement of all barge traffic to alternative modes [7] [26] [8]. These assumptions serve their purpose in allowing for the exploration of modeling advances and screening impacts. However, to characterize impacts for the purposes of infrastructure investment decision making, the modeling needs to continue to evolve to better approach the constraints of reality [3] [27]. This national priority was clearly stated in the 2013 update to the Principles and Requirements for Federal Investments in Water Resources:

> In consideration of the many competing demands for limited Federal resources, it is intended that Federal investments in water resources as a whole should strive to maximize public benefits, with appropriate consideration of costs. Public benefits encompass environmental, economic, and social goals, include monetary and non-monetary effects and allow for the consideration of both quantified and unquantified measures. [4]

As will be shown below, examination of reported shipments between coal mines and powerplants in 2010 shows that simplistic assumptions of blanket switching to alternative transportation modes is not appropriate given the geographical and infrastructure constraints that these entities operate under.

C. Regional inland waterways infrastructure and commodities

Pittsburgh, located at the junction of three major rivers, has an industrial history that is profoundly intertwined with its waterways. Hundreds of millions of tons of finished and raw materials move in and out of the region's mills, powerplants and mines, relying on a sophisticated web of infrastructure in, beside, above and below the rivers. The focus of this dissertation is a particular layer of infrastructure, the locks and dams used to make the rivers navigable, and their role in the integrated energy system and broader commodity flow system.

In 1791 and 1792, the Pennsylvania Assembly passed legislation funding the first formal improvements to the Pennsylvania waterways, including removing obstructions, stabilizing shorelines, dredging channels, and digging connecting canals and portages. Pittsburgh's first set of locks and dams were completed in the 1840s to improve navigation on the lower Monongahela [28].

Over the past 170 years, the river infrastructure has been improved and redesigned repeatedly in response to the city's growth, heavy river use, and the needs of advancing transportation technology. Today, USACE's Pittsburgh District operates nine navigation locks and dams on the Monongahela River, eight on the Allegheny River, and six on the Ohio River (Figure 2) [29], in addition to 16 flood control and multi-purpose reservoirs with a combined capacity of over 3.7 billion cubic meters (3 million acre feet) [30]. There is a high level of connectivity between the upper and middle Ohio River Basin. USACE’s Huntington District covers the middle ORB, from the Hannibal locks down through the Meldahl locks above Cincinnati, and includes three locks on the Kanawha River.

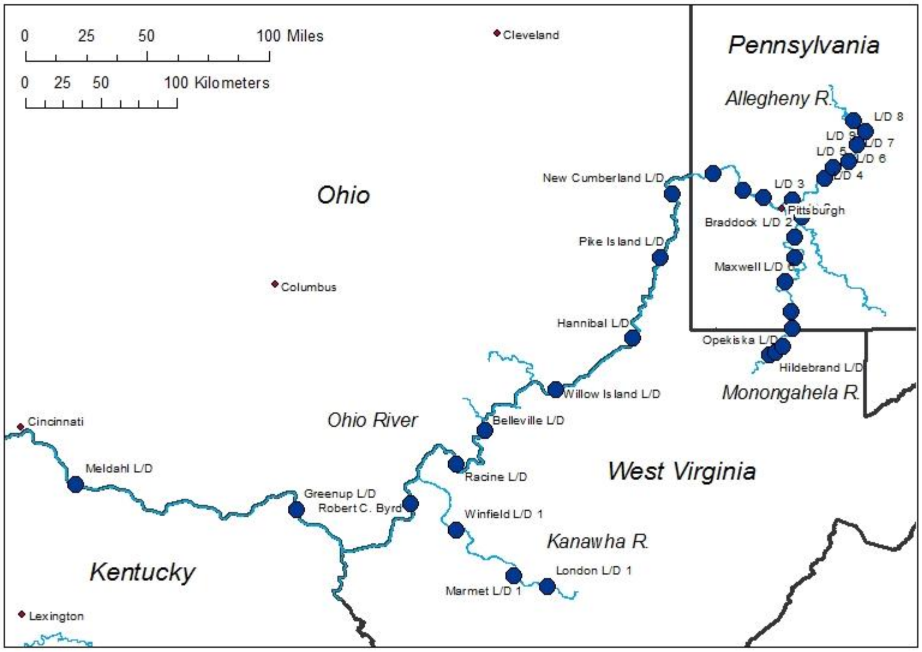


Figure 2. Locks and dams in the Pittsburgh and Huntington Districts, 2010.

The 23 locks and dams in the Pittsburgh District are of varying sizes. The up-river facilities tend to be smaller, single-chamber locks, while the down-river facilities can accommodate much larger barge tows, with the added capacity and backup of auxiliary chambers (see Table 1) [30].

Table 1. Lock dimensions, Pittsburgh District, 2010

River	Lock names (kilometers/miles from confluence)	Main chamber (meters, feet)	Auxiliary chamber
Ohio	Hannibal (203/126), Pike Island (135/84), New Cumberland (87/54)	34m x 366m 110' x 1,200'	34m x 183m 110' x 600'
	Montgomery (51/32), Dashields (19/12), Emsworth (10/6)	34m x 183m 110' x 600'	17m x 34m 56' x 110'
Monongahela	Braddock (18/11)	34m x 219m 110' x 720'	17m x 110m 56' x 360'
	Elizabeth (39/24)	17m x 219m 56' x 720'	17m x 110m 56' x 360'
	Charleroi (66/41)	17m x 219m 56' x 720'	17m x 110m 56' x 360' (closed)
	Maxwell (98/61)	26m x 219m 84' x 720'	26m x 219m 84' x 720'
	Grays Landing (132/82) and Point Marion (146/91)	26m x 219m 84' x 720'	None
	Morgantown (174/102), Hildebrand (184/108), Opekiska (196/115)	26m x 183m 84' x 600'	None
Allegheny	All eight locks	17m x 110m 56' x 360'	None

Source: USACE [29]

Typical Barge Sizes:
Standard: 26’ x 175’
Stumbo: 26’ x 195’
Jumbo: 35’ x 195-200’

The dimensions of the lock chambers limit the configuration of tows that can pass through the lock. The 34-meter (110 foot) widths of the Ohio locks, as well as the main chamber at Braddock on the Monongahela, allow for tows of 11-meter (35-foot) wide "jumbo" barges that are three barges abreast. Above Braddock, the Elizabeth and Charleroi locks (as well as all of the locks on the Allegheny) can only accommodate single wide configurations of jumbo barges, or double width configurations of the smaller "standard" and "stumbo" barges (8 meter (26 feet) wide). Similarly, the length of the lock chamber serves as a capacity constraint; the three largest locks in Table 1 are 366 meters (1,200 feet) long, accommodating tows up to four barges deep. Large tows of jumbo barges must be broken into smaller tows or pushed through in stages (double or triple locking). The constriction of the lock capacities is particularly tight at Charleroi where the auxiliary lock has been closed since 2004 due to an ongoing and delayed construction project. Above Charleroi, six more modern up-river locks can accommodate double widths of jumbo barges.

The construction project at Charleroi is part of USACE's "Lower Mon Project" (LMP). The LMP was first authorized in the 1992 Water Resources Development Act (WRDA), calling for a new dam at Braddock, new, larger locks at Charleroi, and Elizabeth's elimination [5]. In 1995, detailed design and construction planning was completed, resulting in a cost estimate of $750M with a 2004 completion date. Work to replace the nearly 100-year-old fixed crest dam at Braddock with a gated dam was completed in 2004. Work at Charleroi began in 2002, but Federal budget constraints are stretching the project well beyond the initial 2004 completion target. As of 2014, USACE estimated it will take $2.7B to complete the work by 2028 [31]. The May 2014 revision and reauthorization of WRDA, renamed the Water Resources Reform and Development Act (WRRDA) [32], is expected to ameliorate some of the funding roadblocks, although contracting constraints and appropriation concerns remain. Assuming funding continues to be slow, completion could be delayed till the 2030s at a higher overall cost [5].

The LMP will improve the capacity of the upper Ohio River basin by removing bottlenecks at the outdated locks at Elizabeth and Charleroi. Upon completion of the new twin 26 m x 219 m (84'x720') Charleroi locks, and removal of Elizabeth's locks and dam, the 48 km (30 mile) pool of unimpeded navigation between Braddock and Charleroi [5] will allow for faster transit across this stretch of waterways.

D. **Risk of infrastructure failure**

The delay in completing the LMP exposes the Monongahela River navigation system to extended risk of failure of the antiquated components still in place. River transportation is reliant on the ability of USACE to keep the antiquated Elizabeth and Charleroi facilities functioning. USACE's 5-year work plan identifies additional maintenance costs of over $3M/year at both Charleroi and Elizabeth to keep these facilities functional until the project is completed. USACE recently completed a $3 million repair to the Elizabeth lock gates and valves [33]. The 2013 Lower Mon Factsheet, summarized in Table 2, lists a number of risks associated with the viability of these facilities [5].

Objective 1.1: Develop an infrastructure failure scenario

Table 2. Major risks associated with long-term viability of Elizabeth and Charleroi locks

Locks and Dam 3 – Elizabeth	Locks and Dam 4 – Charleroi
Primary lock's filling and emptying flume is structurally deficient – both roof and walls have severely deteriorated concrete	Only one operational lock chamber (Age - 80 years)
Auxiliary lock's components are on poor condition and are subject to frequent failure	Downstream guide wall beyond capacity
DSAC I Dam – repair in 2007-2008 expected to last 5-10 years (Age - 105 years)	DSAC II Dam – Stilling basin inadequate
	Lock walls founded on timber piles – wall movement
	Serviceability – wall anchorages (wall armor, corner protection, etc.)
	Resource constraints of piecemealing construction (batch plant, work area, etc.)

Source: USACE [5]

While each of these risks threatens navigation, failure of the Elizabeth dam has particularly severe implications. The Dam Safety Action Classification System (DSAC) is used by USACE to "to provide consistent and systematic guidelines for appropriate actions to address the dam safety issues and deficiencies of USACE dams" [34]. Elizabeth's Class I DSAC status is used for "urgent and compelling" conditions "where progression toward failure is confirmed to be taking place under normal operations and the dam is almost certain to fail under normal operations within a time frame from immediately to within a few years without intervention; or, the combination of life or economic consequences with probability of failure is extremely high." The emergency repairs conducted on the Elizabeth dam in 2007-2008 are now approaching the end of their expected lifetime. Charleroi's Class II DSAC status, "high urgency," is assigned to dams "where failure could begin during normal operations or be initiated as the consequence of an event."

Failure of the Elizabeth dam would result in loss of pool below Charleroi. Loss of the hydraulic pressure provided by the pool could cause the fragile downstream guide wall and lock walls at Charleroi to collapse, a scenario identified by USACE Pittsburgh District engineers during tours of the Charleroi locks [35]. Locks at both Elizabeth and Charleroi would be out of commission as a result, with repairs taking many months to restore navigation. Main gate failures, a somewhat less traumatic type of failure, can take many months to repair, as evidenced by the eight-month repair period at the Columbia River's John Day lock [36]. The probability of this failure scenario, cascading dam and lock wall collapse, can only increase given the known issues with these particular facilities and ongoing aging and deterioration, unless additional piecemeal repairs or completion of the LMP occur.

The bounds of this hypothetical failure scenario were discussed with USACE Pittsburgh staff during several site visits [35]. The consensus was that (1) the Braddock lock and dam would withstand the surge from a sudden and catastrophic dam failure at Elizabeth; (2) the Charleroi Dam would withstand the loss of its lower pool; (3) it would be possible to secure the upper lock gates at Charleroi to maintain pool above Charleroi; and (4) upper Monongahela navigation above Charleroi would be maintained.

Under this scenario, navigation is assumed to remain possible below Elizabeth in the vicinity of the mouth of the Youghiogheny River (approximately Mile 15), and above Charleroi (Mile 42). (Assuming no damage to the Braddock Dam, the lower pool would be restored on a priority basis to protect the industrial and municipal water intakes below the failed Elizabeth dam.) The development of the scope of the failure scenario represents an alternative to assumptions made in prior analyses that have assumed closure of the entire course of a waterway.

As with all modes of infrastructure, there are many ways, large and small, that locks and dams can fail. USACE is positioned to rapidly address routine issues associated with filling flumes, lock gates, runaway barges, etc. Catastrophic failures such as the loss of a dam, however, cannot be remediated quickly, resulting in cascading impacts over the course of the river closure. The scenario is artificially set to reflect failure for all of 2010, a crude estimate of how long it might take to restore navigation. Setting the scenario length to one year of closure allows for a simplified use of the survey data, as well as the assessment of a closure extended beyond those seen to date [9]. Impacts from a longer closure would be similar to those presented in this section while remaining reflective of the extensive work that would needed to restore navigation after catastrophic failure. A shorter remediation period would minimize impacts, and perhaps allow entities to avoid closure.

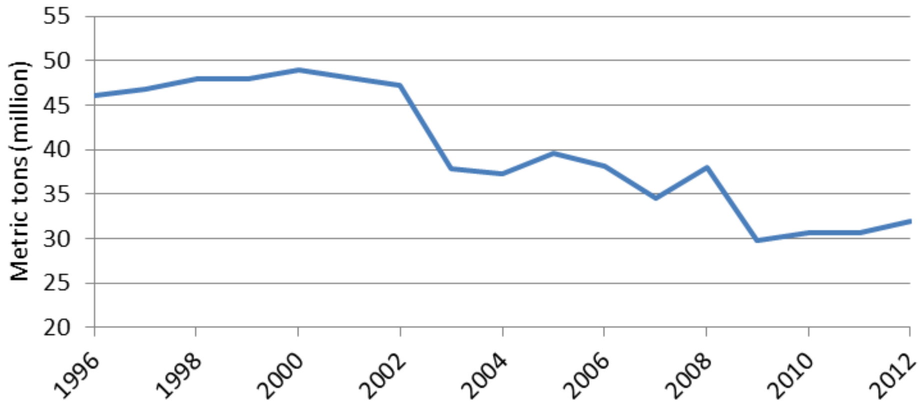
The extended outage scenario examined here has not happened, and hopefully will be avoided. However, the inland waterway has experienced major unscheduled maintenance and disaster outages:

- 52-day closure of the Greenup Locks and Dams on the Ohio, 2003 [37]
- 67-day closure of the Mississippi River between the Upper and Lower St. Anthony Falls Lock and Dams due to the collapse of the I-35 bridge in Minneapolis (re-opened for limited commercial barge traffic after 37 days) [38]
- 22-day closure of Locks 12-25 on the Upper Mississippi River due to flooding [39].

The risks of the failure scenario evaluated in this dissertation exist at various other aged components of the Nation's inland waterways system. The funding constraints are felt throughout the U.S. inland waterways [2]. The Olmstead Project, a two-for-one project on the lower Ohio River, is significantly bigger than the LMP and similarly delayed. Within the Pittsburgh District alone, USACE has done significant rehabilitation of the Emsworth dams to prevent catastrophic failure [40].

Pittsburgh Regional Commodity Flow

USACE compiles extensive data on commodity movements on the inland waterways, available through the Waterborne Commerce in the United States (WCUS) website [1]. These statistics are derived from monthly Vessel Operator Reports (VOR) (i.e., ENG Form 3925 and 2925B) and data collected at locks via USACE’s Lock Monitoring Performance System (LPMS), available through USACE’s Navigation Data Center (NDC) [41]. WCUS shows that the inland waterways system processed 2,200 million metric tons (2,500 million tons) nationwide in 2012. The Port of Pittsburgh, encompassed by the Pittsburgh District, is the 17th busiest port in the Nation, handling 31.9 million metric tons (35.2 million tons) in 2012 [41]. Unlike the coastal ports, the inland Port of Pittsburgh does not handle containers or foreign shipments [42] [6]. The Port is defined by the 200 miles of navigable rivers across a 12 county area, and includes about 200 river terminals and barge industry service suppliers [43]. Figure 3 shows the trends in commodity tonnage handled on Pittsburgh's rivers since 1996. The downward trend, stabilized over the past four years, indicates that the rivers are capable of carrying a significantly higher volume of commodities.



Source: USACE [6]

Figure 3. Barge tonnage through the Port of Pittsburgh over time.

The predominant product shipped through the Port of Pittsburgh is coal, accounting for over 75% of the materials handled on the rivers in 2011 [6]. Table 3 provides an overview of the major commodity categories tracked by USACE[2]. The second largest category, "Crude Materials, Inedible Except Fuels," includes 1.8 million tons of sand and gravel, 1.5 million tons of limestone, and 0.4 million tons of gypsum. Primary iron and steel products account for 0.9 million tons barged.

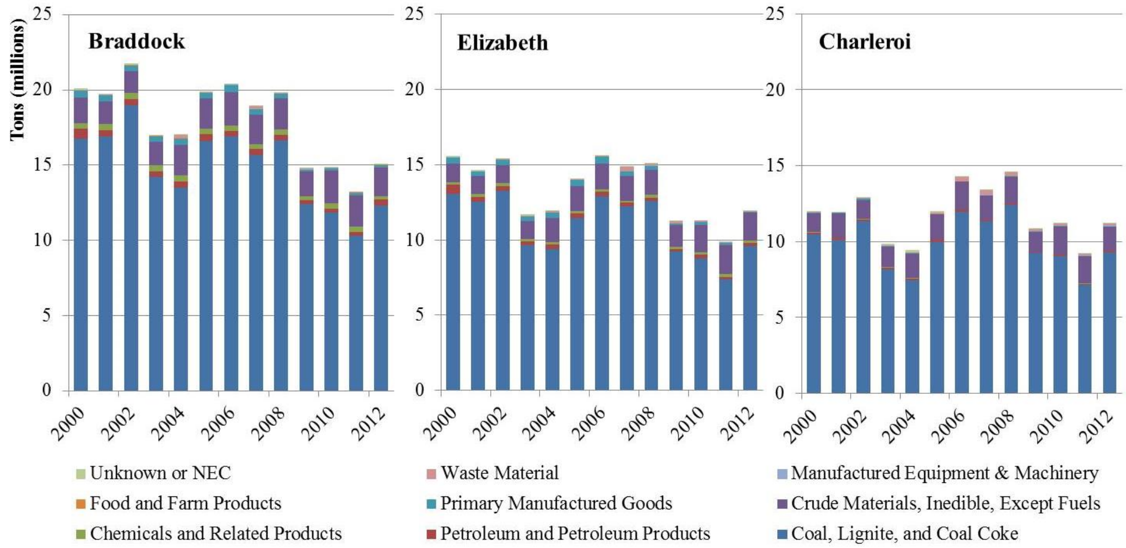
[2] Note: USACE uses its own unique commodity codes, the Waterborne Commerce Statistical Codes, which are closely tied to the Harmonized System of commodity codes used by the World Customs Organization, with a focus on commodities expected to be transported on the waterways [1] [134]. The WCSC do not correlate directly to the U.S. Department of Transportation's commonly used Standard Classification of Transported Goods (SCTG).

Table 3. Port of Pittsburgh commodities barged, 2011

	Metric tons (million)	% of total
Total Coal, Lignite and Coal Coke	23.1	75.4
Total Crude Materials, Inedible Except Fuels	4.71	15.3
Total Primary Manufactured Goods	1.14	3.7
Total Petroleum and Petroleum Products	1.10	3.6
Total Chemicals and Related Products	0.59	1.9
Total Food and Farm Products	0.008	<0.1
Total All Manufactured Equipment, Machinery	0.003	<0.1
All Commodities	30.7	
Source: USACE [6]		

The Port of Pittsburgh is predominantly a regional port. Within the Ohio River System (ORS), which encompasses USACE's Pittsburgh, Huntington, and Louisville Districts, 80% of trips start and end within the region [1].

Within the Port of Pittsburgh, the locks at Braddock, Elizabeth, and Charleroi handled 13.7, 10.8, and 10.2 million metric tons (15.1, 11.9, and 11.2 million tons) of commodities in 2012, respectively [44]. Focusing on Braddock, coal and coke represent 81% of the commodities locked in 2012, showing a higher prevalence of coal shipments than seen across the broader Port. Figure 4 shows the distribution of commodities over the past two decades that have been locked through the Braddock, Elizabeth, and Charleroi facilities [6]. The coal mines of southwestern Pennsylvania and northwestern West Virginia use docks on the upper Monongahela to reach coal-fired power utilities and coking plants. There are a number of power generation and coke production plants located on the rivers of the Pittsburgh District that utilize coal barged from both local and distant mines. Given the predominance of coal shipments, the primary focus of this analysis is the movement of thermal coal from coal mines to coal-fired utilities.



Source: USACE [44]

Figure 4. Commodity tonnage barged on Lower Monongahela River, 2000-2012

Inland waterways shipment data are also presented in the context of the national freight network from the U.S. Department of Transportation (USDOT) Bureau of Transportation Statistics' (BTS) Commodity Flow Survey (CFS) [45] and Oak Ridge National Laboratory's Freight Analysis Framework (FAF) [46]. The CFS is a sample survey of shippers conducted every five years, designed to serve as a primary source of national and state-level data on domestic freight shipments. The FAF is a tool which compiles a variety of shipping, economic and geographic data for the analysis of commodity movements (including the CFS). Upon examination, the WCUS provides much more detailed and accurate information on inland waterways shipments at the regional level. Table 4 presents extracts of shipments from Ohio to Pennsylvania from the WCUS, EIA (coal shipments from mines to powerplants, discussed further in the following section), FAF and CFS. For this extract, WCUS shows 2.7 million tons barged from Ohio to Pennsylvania in 2007, most of which was coal [47]. The CFS reports no water shipments from Ohio to Pennsylvania. The FAF only reports 0.001 million tons shipped by water for the same origin and destination (O/D), with other modes matching well with the CFS (upon which it draws). This gap is a good example of the CFS's inability to provide consistent coverage outside of a "small number of rather large geographic regions" [48] [49]. The gap in CFS and FAF coverage of waterways shipments is further illustrated by considering data collected by the U.S. Department of Energy's (USDOE's) Energy Information Administration (EIA) Survey 923 (EIA-923), which includes data about the amount and source of fuel purchased by each utility, and primary and secondary modes of transportation used to move the fuel to the utility [50]. Analysis of the EIA data for 2012 shows that there were 3.6 million tons of coal shipments in 2012 from Ohio mines to Pennsylvania powerplants, 2.3 million of which were shipped via river. The WCUS coal barge shipments in 2012, at 4.1 million tons are larger, as expected, reflecting all coal shipments, including shipments to coking facilities in the Pittsburgh region.

Further concerns with use of the FAF for regional analysis arise when the FAF system is queried only for coal shipments between Ohio and Pennsylvania, showing only truck shipments of 0.27 million tons (no other modes reported). In addition to the river shipments documented by the WCUS and EIA datasets, the EIA also documents rail shipments of OH/PA coal of 0.99 million tons, whereas FAF shows no rail shipments of coal.

Table 4. Comparison of datasets for freight shipped from Ohio to Pennsylvania (million tons)

Data source	Mode	Commodity	2012	2007
WCUS	River	Chemicals excluding Fertilizers	0.07	-
	River	Coal, Lignite, and Coal Coke	4.2	2.3
	River	Sand, Gravel, Shells, Clay, Salt, and Slag	0.82	0.23
	River	Unknown and Not Elsewhere Classified Products	0.017	0.16
	Total	**All commodities**	**5.0**	**2.7**
EIA	River	Coal	2.4	NA
	Rail	Coal	0.99	NA
	Truck	Coal	0.23	NA
	Total	**Coal**	**3.6**	**0.67**
FAF	Water	All commodities	0.0011	0.0010
	Rail	All commodities	1.8	1.8
	Truck	All commodities	15.3	14.5
	Air (include truck-air)	All commodities	0.0012	0.00095
	Multiple modes & mail	All commodities	0.35	0.35
	Pipeline	All commodities	0.063	0.056
	Other and unknown	All commodities	0.29	0.28
	Total	**All commodities**	**17.9**	**17.0**
	Truck	Coal	0.27	0.24
CFS	Water	All commodities	NA	0
	Rail	All commodities	NA	1.7
	Truck	All commodities	NA	14.0
	Air (include truck-air)	All commodities	NA	S
	Multiple modes & mail	All commodities	NA	0.30
	Pipeline	All commodities	NA	S
	Other and unknown	All commodities	NA	S
	Total	**All commodities**		**16.1**

Sources: USACE [1], EIA [50], Oak Ridge National Laboratory [46], BTS [45]

E. Identifying at-risk coal shipments

> **Objective 1.2**: Develop methodologies to identify at-risk commodity shipments

A river O/D table was developed linking barged coal transactions in 2010 between 211 U.S. mines and 94 U.S. powerplants, giving tonnage barged and total tonnage shipped from the mines to each utility (see Appendix 1 for an extract of this matrix for the linked Ohio, Pennsylvania, and West Virginia mines and powerplants). The River O/D table was derived from the EIA-923, which includes coal transactions across all modes of transportation for over 750 mines and 480 utilities in 2010, as well as other transactions for natural gas, diesel fuel oil and other fuel types [50].

A regional model was developed from the River O/D table to assess the potential impact on the powerplants and mines of infrastructure failure at Elizabeth and Charleroi. The River O/D table was combined with other public sources to create a model of thermal coal movements between mines and powerplants. Latitude and longitude coordinates for each mine and utility were extracted from data maintained by the U.S. Environmental Protection Agency (USEPA) [51] and the Mine Safety and Health Administration (MSHA) [52]. USACE data was also extracted for the mile number of docks controlled by the utilities and mines [29]. See Appendix 2 and Appendix 3 for summaries of the mines and powerplants of interest, respectively.

A key assumption in the model development was the assignment of docks and river miles to the coal mines. Some mines actually own and operate their own docks, which were readily identifiable in the USACE dock dataset (e.g., the Cumberland Mine dock at Mile 81.5 on the Monongahela). Other mines are controlled by operating companies that have river loading capacity that is used by multiple mines (e.g., Consol's Alicia transloading facility at Mile 58 on the Monongahela). Some mine operators identify their river loading facilities' locations on their websites. One mine operator responded to an email request for clarification regarding the loading docks used for two of their strip mines. Less certain mine river loading assignments were made after examining satellite images for loading operations [53]. Where clear determinations could not be made from these methods, docks assigned in the Velocity Suites (Coal Transaction Analyst) software were used [54]. The Velocity Suites source was found to be inaccurate for some facilities, predicting rail deliveries for mines and powerplants known to have no connection to the national rail system. As a result, this source was used cautiously.

Starting with the four Monongahela River powerplants, linkages to each of the mines that supplied these powerplants with coal in 2010 were characterized in terms of their functionality after failure at Elizabeth/Charleroi. Similarly, linkages to the 15 coal mines that barge their product from the Monongahela were coded, with transits that pass through the failure zone coded as not feasible (these linkages included 16 powerplants located on the Ohio or further downstream). A final layer of connections was then added to code shipments to the non-Monongahela River powerplants from other mines that had not otherwise been included in the model. The resultant regional model thus included 36 powerplants linked to 129 mines, with direct impacts predicted at the subset of facilities summarized in Table 5. Figure 5 shows the distribution of most of these facilities, omitting the Powder River Basin (PRB) mines and marginally connected powerplants located further down the Ohio and Mississippi River.

The resulting model links powerplants and mines, allowing for an assessment of the importance of reliance on barge movements on the Monongahela, as a function of tonnage barged, location of mine and utility docks, and documented availability of alternative transportation modes.

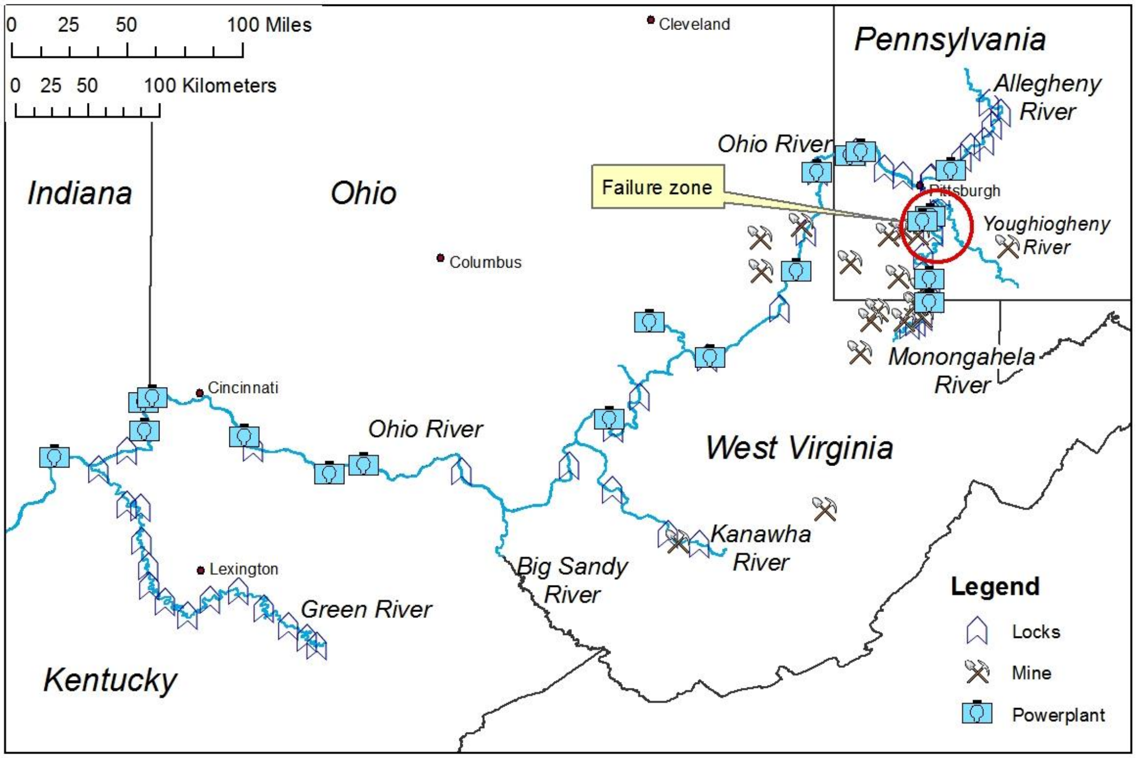


Figure 5. Potentially impacted powerplants and coal mines using barge coal delivery

Table 5. Profile of facilities modeled as directly impacted by infrastructure failure scenario at Elizabeth and Charleroi locks, 2010

Mines:	Count	Total coal production (million tons)
Above failure zone	15	43
Within failure zone	0	0
Below failure zone	11	270
Subtotal	26	320
Power plants:		Total electricity generation capacity (MW)
Above failure zone	2	2,900
Within failure zone	2	880
Below failure zone	16	21,000
Subtotal	20	24,000

Figure 6 depicts the impacted mines and powerplants in terms of the expected functionality of their coal shipments and receipts, as well as their geographic placement with respect to the failure zone. 6.4 million metric tons (7.1 million tons) of coal shipments/receipts would have been displaced by the Elizabeth/Charleroi failure scenario. These displacements represent the direct impacts of river closure. The specific impacts to individual powerplants and mines are described in Appendix 3 and Appendix 7, respectively. As will be discussed further below, additional secondary impacts, including subsequent mine and powerplant closures and losses to towboat and barge owners, are of interest.

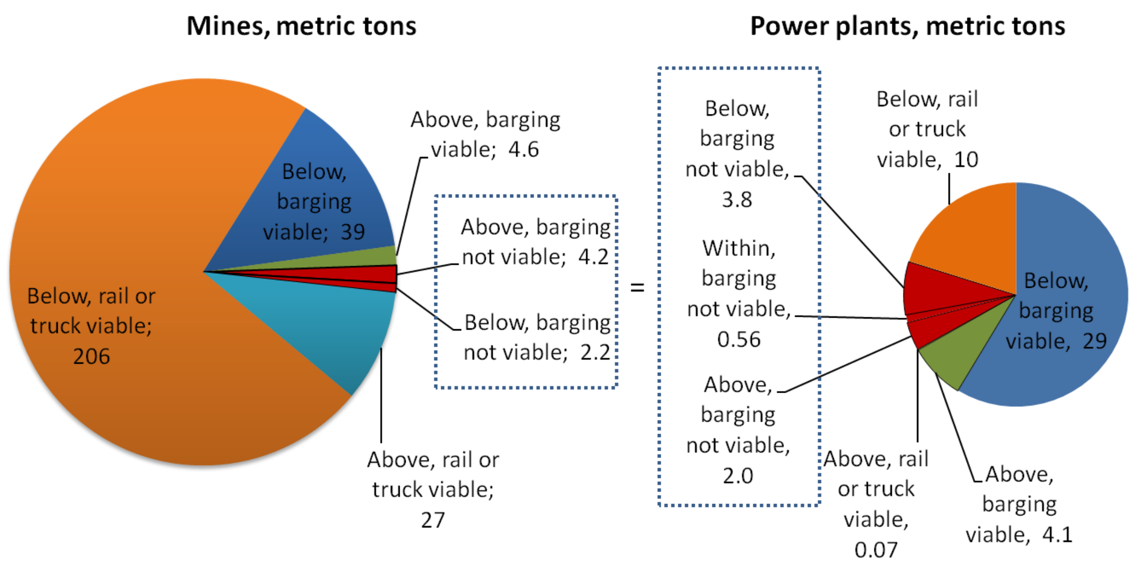


Figure 6. Functionality of thermal coal mine and powerplant transits, 2010

This analysis focuses on the powerplants and coal mines potentially impacted by the Monongahela River failure scenario, and the 6.4 million metric tons (7 million tons) of thermal coal barge shipments that would not be feasible in a year-long river outage. The impacts of failure at Charleroi and Elizabeth, however, would also extend to several major steel and coke-making facilities located on the Monongahela, as well as the metallurgical coal mines that barge to these facilities. As shown in Figure 4, overall shipments through the Elizabeth lock in 2010 totaled 10.2 million metric tons (11.3 million tons), 8.0 million metric tons (8.7 million tons) of which were coal. The 1.6 million metric tons of coal not accounted for by the 6.4 million metric tons of thermal coal tracked in the EIA 923 survey may be metallurgical coal used for coking at the US Steel Clairton coking facility located between the Elizabeth and Braddock locks [55], or coal used for other industrial applications [56]. The Port of Pittsburgh Commission identifies ten river terminals on the Monongahela, four of which are located within the failure zone and thus would be directly impacted by a river outage [43]. There are towboat operators and barge carriers who would also be directly impacted (five major docks within the impact zone), as well as a variety of other businesses that service the region's river freight industry or rely on the river pool provided by the Elizabeth dam. Examination of USACE's navigation maps shows three municipal water intakes and seven industrial water intakes within the failure zone, as well as 13 private marinas, six municipal docks and two state fish commission docks [57]. See Appendix 4, Appendix 5, and Appendix 6, respectively, for additional details. Other potential impacts not quantified here include recreational boating, movement of lime and limestone to upriver utilities, as well as the shipment of coal combustion residuals to disposal sites. Kruse, et al (2007, amended 2009) discusses a wide range of potential impacts.

F. Potential responses to infrastructure failure

Objective 1.3: Develop methodologies to identify feasible alternate modes of transportation and supply chain options

An extended outage of navigation on the Monongahela River would have a profound impact on the industries that rely on barge transportation. The range of potential responses of these entities to an extended river outage differs as a function of their accessibility to the coal-to-utility market. Assessing disruptions to the inland waterway has some parallels to assessments of roadway disruptions in that the mines may respond in a variety of ways [58]: some may be completely thwarted, some may be partially blocked, and others scarcely impacted at all. In road networks, the possible responses to a disruption have been summarized as: (1) cancelling the trip, (2) postponing the trip, (3) choosing another destination, (4) choosing another mode, (5) choosing another route [59]. This type of framework has been used in a combined travel demand model (CTDM) to estimate long-term equilibrium network conditions due to network disruptions [60]. USACE's Navigation Economic Technologies Program (NETS) has conducted a number of surveys and interviews of shippers in the wake of several extended lock closures to assess the impacts of and response functions to closures [61]. An extensive interview with a utility impacted by the 2003 closure of the Greenup lock identified tiered priorities in the face of a river closure: stockpile as much as possible (assuming suppliers can step up production) and wait until closure is over (relevant for planned closures); divert to alternative modes (assuming excess capacity exists); shift coal sources to avoid closed infrastructure; close plants that cannot receive coal and re-dispatch remaining plants or purchase power off the grid [37]. In response to a catastrophic failure of river infrastructure, a barging mine may consider these same responses, as discussed further below and then applied to the facilities potentially impacted by a closure at Charleroi and Elizabeth.

1. Shift transport mode from barge to rail

Some prior studies have made the simplifying assumption that all disrupted barge shipments could be shifted to rail [12] [7]. In the specialized coal-to-utility network, however, this is not always possible. In a study focused on the Illinois waterway, Folga [21] noted that "shifting to an alternative mode may not be feasible in the short-term because of the characteristics of the cargo or the physical absence of a practical alternative."

A number of mines and powerplants do not have any access to the national rail system. Bray [18] discusses the operating limitations of powerplants: "utility companies are set up to operate as they are now because of vested infrastructure, and to orient their businesses more to rail transportation would be very expensive." Drawing from shipper surveys, Bray goes on to describe specific powerplant limitations: no access to rail, dependence on bridges with limited weight capacity, favorable barge back haul rates being unavailable for rail. These limitations can be seen in the powerplants of interest in this study. Figure 7 depicts the Fort Martin powerplant that relies entirely on barge deliveries of its coal [62]. The map view shows that a railroad bounds the plant site, but provides no service to the site (as evidenced by the lack of a spur). The response scenarios for the barge-only mines and powerplants cannot include a ready shift-to-rail option.

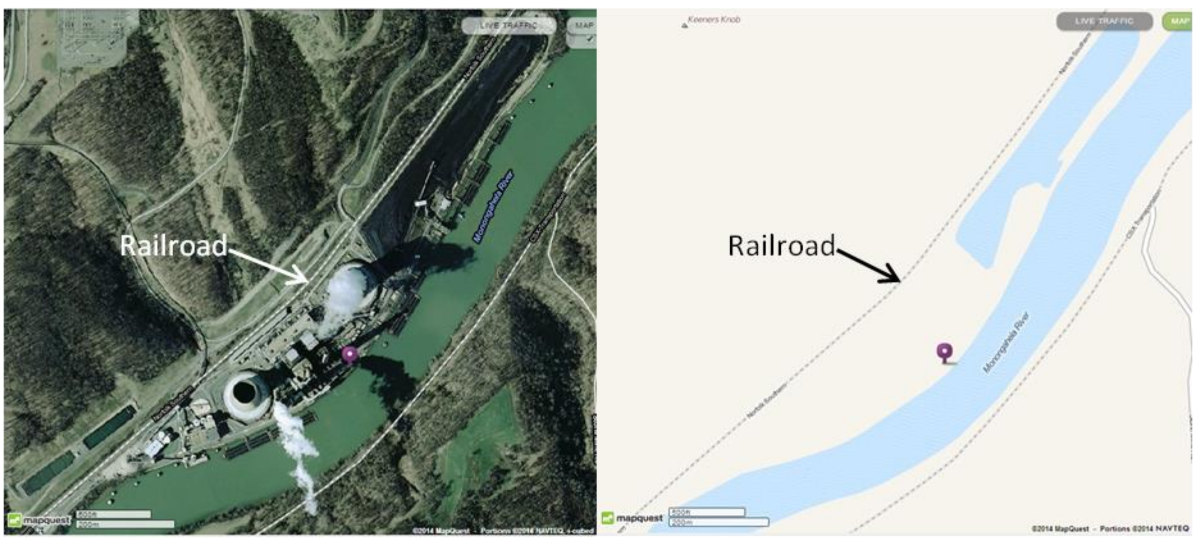


Figure 7. Satellite and map images of the Fort Martin powerplant in Maidsville, WV, a barge-only powerplant

Several researchers have used USACE's dock database [29] to determine whether rail access exists at a site [22] [21]. The Corps' data is primarily derived from on-site surveys, which are no longer being conducted (the last survey covered the Houma, LA region, conducted in 2008) [63]. For example, the dataset indicates that Fort Martin, depicted above in Figure 7, has "one surface track serving plant at rear; connects with Norfolk Southern Railway." This no longer appears to be the case.

Theoretically, a barge-only facility might build a rail spur. The narrow river valleys in the study area, however, limit the land available for this type of expansion, which would need to accommodate at least a unit train of 125 cars and the railcar-loading equipment at the mine, or the offloading equipment needed to move the railed coal into the powerplant. EPA describes the costs associated with adding rail service to mine-mouth powerplants in its Integrated Planning Model to include:

> "a) a rotary dump railcar unloader capable of handling unit train coal shipments, which is estimated to cost about $25 million installed (in 2011$), b) at least three miles of loop track, which would allow for one trainload of coal to be unloaded, and a second trainload of coal to simultaneously be parked on the plant site preparatory to unloading, and c) at least one mile of additional rail spur track to connect the trackage on the plant site with the nearest railroad main line."

EPA estimates the minimum investment needed to add rail service at $37 million (in 2011$) [64]. For the purposes of the analyses described in this dissertation, the alternative of building rail access was not considered feasible given the land constraints of the study area, the cost associated with installing the required rail and equipment, and the time needed to implement such a project (particularly if land purchases or environmental permitting were required) given the assumed year-long river outage.

2. Rely more on rail (when available)

Some of the impacted powerplants have both rail and barge access. Campo [22] described *five physical and operational* factors that limit transits that rely on both rail and river: lack of terminals and suitable locations, lack of transshipment capability, excess terminal capacity, limited railroad access to transshipment terminals, and environmental laws. Wang [13] describes the capacity of transloading facilities as a limitation as well. Discussions with powerplant operators revealed that rail access does not guarantee sufficient rail off-loading capacity to run operations totally from rail deliveries. For example, the geographically constrained riverside location of these plants may allow for a rail spur, but not a rail loop. Thus such a site can accommodate one coal train on site which must be fully off loaded and then backed out onto the main line before another train can be admitted to the plant. If the plant also lacks access to sufficient siding to allow for staging of the "next" train, the logistical challenges of keeping the plant fully fueled increase. Further, an extended outage would cause regional ripple effects, with unexpected increased demand for rail creating shortages [37].

3. Shift to truck

Prior analyses have sometimes assumed that truck transport is used if rail is not available [21]. This may be appropriate for limited shipments (time or volume), however the logistics associated with a mode shift from barge to truck are not feasible for a long-term displacement. A single "stumbo" barge holds 1,085 tons [65], while a highway tractor-trailer truck's capacity is 25 tons. As an example, the Hatfield's Ferry powerplant in Masontown, PA burned 4 million tons of coal in 2010. Supplying this volume by truck instead of barge would require offloading 438 trucks per day, or a new truck every three minutes, 24 hours per day, 365 days per year to deliver this volume of coal. Thus truck delivery will be highly infeasible. The feasibility of this option is further limited in that (1) the plants and mines must have the requisite truck off-loading and loading equipment, (2) sufficient excess truck fleet capacity must exist to step into a sudden need, and (3) the roads and bridges between the mines and powerplants must have the requisite load-bearing ratings and capacity to bear this load.

4. Transload and rail around failure zone

Mines that barge through the failure zone may have the option to use rail to avoid the failure zone. Mines that currently use a combination of rail and barge to reach the barge-only powerplants might be able to re-route to a transloading dock above the failure zone. Barge-only mines could only physically reach the barge-only powerplants by adding transloading to rail around the failure zone, rail past the failure zone, then transloading back to barge for delivery to the plants. The costs associated with these additional transfers and rail shipments are significant and may make this alternative infeasible.

Limitations on increased use of these segments of rail might include the transloading capacity, equipment availability, and track ratings [18]. Transloading from rail to barge costs $1.50/ton and rail switching to short line rails if needed can cost $2 per ton ($2011) [66]. The cost of rail itself adds about $15/ton for shipments within Pennsylvania. For perspective, the average total cost of coal for powerplants with impacted barge transits is $57 per ton ($2010) (see section II.G); transloading around the failure zone thus might increase coal costs by a third.

5. Plant closure

Having acknowledged the significance of the mode shift constraints, what alternatives remain? If a powerplant must receive all or most of its coal by barge, what will happen if barge deliveries are disrupted for an extended (say, year-long) period of time? One alternative not commonly considered in prior studies is the possibility that a facility's accessibility to its market is so tailored to its geography that it is unable to adapt to a catastrophic constriction of its key infrastructure. Such a plant thus would no longer be a functional participant in the coal-to-utility network and conceivably would face closure.

In 2007, the I-35W bridge over the Mississippi River collapsed. A study of traffic reactions to this catastrophic failure showed that one third of previous trips using the bridge disappeared [67]. The study authors postulated that these trip reductions may have been due to changes in destination and trip consolidation, and to a lesser extent changes in mode. We would add to this list the possibility that entities that had trips that were completely tied to a transit across the bridge might close in response to an inability to make that critical transit.

The inability to adapt to catastrophic infrastructure losses is a function of many factors, one of which is proximity to the failure zone. Barge-only facilities within the failure zone would have extremely limited options. Facilities outside the failure zone that partially rely on shipments through the failure zone have many more options.

Another key adaptability factor is the resource base of the facility itself. We postulate here that facilities at the end of their useful lives (as evidenced by low capacity factors, dropping production rates, or closures since 2010 in the absence of infrastructure failures) will simply close sooner rather than expend additional resources needed to cope with a constrained transportation network. Facilities within the study area known to have closed since 2010 include 6 powerplants (Elrama, Mitchell (PA), Hatfield's Ferry, AES Beaver Valley, R.E. Burger, Willow Island, and Tanner's Creek) and 2 mines (Mine 84 and Yellowbush) (see Appendix 8 for details and references). We suggest a simple approach to quantifying this loss (aka unmet demand) in Section II.G.

(For barge-only facilities with significant remaining useful lives, their approach might be to run down their stockpiles and/or shift to lower levels of production until navigation is restored.)

6. Assessing mode shift opportunities

Mode shift opportunities have been modeled in a variety of ways, simplistic and sophisticated. The simplest models assume that shifts will occur when the costs of the alternative mode become lower than the current mode. Bray used the results of an extensive shipper survey to explore the maximum willingness to pay for shipping in the context of mode shifting, concluding that "[t]ransportation decisions are often highly integrated with choices regarding other inputs. They are also highly integrated with other supply chain costs such as loading and unloading or storage costs" [18].

The potential responses (mode shift, closure, supplier shift, etc.) of the powerplants and thermal coal mines to failure at Elizabeth and Charleroi are deduced largely from data extracted from the EIA-923 survey [50], with additional information gleaned from satellite images [53] [62]. The EIA-923 survey provides a valuable tool for determining the accessibility of specific mines and powerplants to the coal-to-utility network. Power plants report the primary and secondary transportation methods used to move coal from mine to powerplant. The primary mode is defined to be "the method used to transport the fuel over the longest distance from point of origin [the mine] to consumer." The secondary mode is reported when "more than one method of transportation is used in a single shipment" for the "second longest method used to transport the fuel to consumer." Additional modes are not reported [68]. Nine modes of transport are used in the survey. The top eight combinations of these modes (out of 29 reported combinations) are presented in Table 6. 90% of all shipments are limited to single mode of transportation, with about 10% being shipped by "river-only."

Table 6. Major transport modes reported for shipment of coal to powerplants, industry-wide and for selected upper Ohio River Basin plants in 2010

Transport mode	Codes	Metric tons (millions)	% of total	Hatfield's Ferry	Fort Martin	Bruce Mansfield	W.H. Sammis
Railroad only	RR	507	62.7%			0.5	2.5
Truck only	TR	84.5	10.5%		0.00009	0.04	
River only	RV	79.3	9.8%	3.5	2.5	5.2	1.3
Tramway or conveyer only	TC	47.1	5.8%				
Railroad/river	RR RV	28.7	3.6%			0.03	
	RV RR	1.41	0.2%			0.05	
Railroad/truck	RR TR	26.7	3.3%				
	TR RR	1.48	0.2%				
Source: derived from EIA [50]							

Table 6 shows the reported transport codes for the four largest powerplants in the immediate study area. These results show the full dependence of the Monongahela River powerplants (Fort Martin and Hatfield's Ferry) on barge transport, and the more varied modes used by the two Ohio River powerplants (Bruce Mansfield and W.H. Sammis). Thus the EIA-923 provides a useful tool to assess the accessibility of the powerplants (as well as the mines) to a range of transportation modes. Additional confirmation can be derived by examining additional years of EIA-923 data, and by examination of satellite images (see Figure 7).

Noting that the FAF shows a significant use of trucks for Pennsylvania coal shipments to Pittsburgh, one reviewer of the paper submitted to journal for this section asked whether shifts to truck therefore aren’t feasible. Continuing the FAF/WCUS/EIA analysis described in section II.C, the datasets were queried for coal deliveries from Pennsylvania (at the state level) to the Pittsburgh Combined Statistical Area (CSA), defined by the U.S. Census as an 8 county region centered on Pittsburgh (and referred to by the Census as the Pittsburgh-New Castle CSA) [69]. Table 7 shows a similar disconnect between the FAF and EIA data as described previously. The FAF shows no river shipments of coal for the designated O/D, while the EIA shows 0.5 million tons barged to the 11 powerplants within the CSA in 2010. Also, the EIA shows a significant decline in shipments between 2010 and 2012, reflecting significant changes in operating status and fuel sources for 8 of the 11 powerplants; in contrast the FAF shows an increase in coal shipments to the CSA over the 2007-2012 timeframe. Although the WCUS O/D tallies reported in the NDC do not allow for examination of movements at the regional level, the Pennsylvania to Pennsylvania WCUS shipments show a similar decline as seen in the EIA data, with 14.8 million tons barged within the state in 2007, and 8.9 million shipped in 2012. The FAF appears to be over counting coal shipments from Pennsylvania to the Pittsburgh CSA by an order of magnitude, even after considering that several million tons are shipped to industrial manufacturing sites (e.g., cokers) not covered by the EIA-923.

Table 7. Comparison of datasets for coal shipped from Pennsylvania to the Pittsburgh CSA (million tons)

Data source	Mode	Commodity	2012	2010	2007
EIA	River only	Coal	0.16	0.55	NA
	Rail only	Coal	0.043	0.29	NA
	Truck only	Coal	0.29	0.60	NA
	Mixed modes	Coal		1.3	
	Total	**Coal**	**0.49**	**2.8**	
FAF	Rail	Coal	13.0	NA	11.8
	Truck	Coal	14.3	NA	13.5
	Other and unknown	Coal	0.064	NA	0.061
	Total	**Coal**	**27.4**	**NA**	**25.4**
Source: EIA [50]**, Oak Ridge National Laboratory** [46]					

The EIA-923 allows for the close examination of the eleven powerplants within the Pittsburgh CSA over a five year period (prior EIA data did not include transportation data). Table 8 summarized the transport modes used by these plants. Note the declining number of plants, total deliveries, and rail deliveries (including bimodal deliveries that include rail). Despite the contraction of the coal-fired utility industry, the barge deliveries were fairly stable, and consistently higher than 2009 levels.

Table 8. Shipments (million tons) by transport mode to Pittsburgh CSA powerplants

Year	Count	Total Coal Deliveries	RR	TR	RV	RR/RV	RR/TR	RV/TR
2009	11	13.1	2.09	0.687	6.35	1.50	0.014	0.550
2010	11	13.6	3.28	1.25	7.40	1.05	0.187	0.373
2011	10	12.0	2.33	0.634	7.44	0.36	-	1.26
2012	7	9.54	0.380	0.518	8.36	-	-	0.281
2013	5	8.60	0.508	0.642	7.16	-	-	0.292
Source: EIA [50]								

Looking specifically at truck shipments, one plant relies heavily on truck shipments, with no river shipments (New Castle Plant, Lawrence County), while two plants took no truck deliveries (G.F. Weaton and Hamilton) (see Table 9). Several plants show changing dependence on truck over time, ranging from 0 to 25% truck deliveries; Bruce Mansfield took no truck shipments in several years, and 0.3 million tons in two years. (One limitation of the EIA data is that the transport data are provided in terms of the longest mode segment; for trips with two modes, it is not possible to tell from the data which mode was used for the final delivery to the plant. The bi-modal data are noted but not included in this analysis.)

The data allow for a rough estimation of the number of trucks each facility handled per day, assuming 365 days of delivery, and 25 tons per coal truck. Armstrong and New Castle depend heavily on truck delivery, taking 45 trucks/day in 2010 (and less than half that level in other years). Facilities that routinely handle significant shipments of truck deliveries have invested in the infrastructure needed to efficiently process a high level of trucks. A plant that is designed to receive its coal at a dock, with smaller amounts occasionally delivered by truck, cannot be expected to quickly develop the infrastructure to dramatically increase its truck deliveries. As previously discussed in Section II.F.3, the Hatfield's Ferry powerplant would have required 438 trucks/day, 365 days/year to deliver the coal it burned in 2010. This theoretical truck delivery rate is an order of magnitude higher than the highest daily truck rate observed in the study areas over the past five years.

Table 9. Truck deliveries to Pittsburgh CSA powerplants, 2009-2013

Plant ID	Name	Trucked shipments (tons)					Max Trucks/day
		2009	2010	2011	2012	2013	
3181	Mitchell Power	33,000	29,700	0	49,900	75,900	8.3
3098	Elrama Power Plant	53,500	7,850	26,100	453	NA	5.9
7286	Richard Gorsuch	192,000	145,000	NA	NA	NA	21.1
2872	Muskingum River	0	199,000	156,000	0	0	21.8
3178	Armstrong Power	155,000	413,000	240,000	26,200	NA	45.2
6094	Bruce Mansfield	0	41,400	0	306,000	283,000	33.5
10676	AES Beaver Valley	806	4,590	NA	NA	NA	0.5
50130	G F Weaton	0	0	NA	NA	NA	0
3138	New Castle Plant	223,000	412,000	211,000	136,000	116,000	45.2
8226	Cheswick	29,700	0	0	0	167,000	18.3
2917	Hamilton	0	0	0	NA	NA	0
NA – indicates the facility took no coal deliveries by any mode that year Source: EIA [50]							

The previous discussion focuses on the specific question raised by the reviewer about the FAF results for coal deliveries from Pennsylvania mines to Pittsburgh powerplants. A broader examination of the powerplants potentially impacted by the catastrophic loss of navigation at Elizabeth and Charleroi gives similar results (see Table 10). One large powerplant on the Ohio, Cardinal Power, depends on truck deliveries from three local coal mines for about a third of their fuel, averaging 76-145 trucks per day over the 2009-2013 period; no other plant in the study area handles more than an average of 34 trucks per day. The majority of Cardinal's coal is delivered by barge, consistent with most of the rest of the study area plants.

Table 10. Transport modes for study area powerplants, 2009-2013

Overall summary	Count	Total (million tons)	RR	TR	RV	TC	RR/RV	RR/TR	RV/TR
2009*	38	113.6	9%	1%	56%	0.3%	10%	0%	0.7%
2010	38	107.9	14%	2%	73%	2%	9%	0.2%	0.3%
2011	36	99.75	13%	1%	74%	1%	9%	0%	2%
2012	33	92.66	10%	2%	77%	2%	8%	0%	1%
2013	32	90.97	10%	2%	84%	1%	3%	0%	0.3%

*Does not add to 100% due to missing transport codes for 25% of shipments
RR- railroad; TR-truck; RV-river; TC-tramway or conveyer
Source: EIA [50]

7. Change supply chain

Analysis of the EIA data over the 2009-2012 period shows that powerplants have some flexibility in their access to coal sources [50]. The potentially impacted powerplants each generally rely on a limited set of mines from year to year for the majority of their fuel, but also access a wide number of additional and different mines in any given year for the balance of their fuel.

- Over the course of four years, all of the powerplants used at least 10 unique mines, with an *average* of 21 unique mines (see Table 11).
- Each powerplant had a smaller subset of base mines that they used at least three of the four years, averaging 27% of the total number of mines they used over the four years. These "go-to" mines provided 73% of the coal consumed by these powerplants over the four years.

Thus the powerplants and mines maintain a complex and shifting web of transactions. The ability of the powerplants to supplement their base coal contracts (their go-to mines) with a variety of non-base mines appears to provide resilience and flexibility to their logistics chains, with the non-base mines serving as a spot market. The expectation then is that the loss of access to certain mines as a result of the failure scenario of concern would not be devastating to the powerplants in terms of availability to coal and continued access to the coal "spot market." This conclusion coincides with the overall conclusions of USACE's study of the impact of closing the Monongahela River to barged steam coal shipments [8].

Table 11. Impacted study area powerplant and coal mine linkages, 2009-2012

	Total tons (million) of coal used 2009-2012	Number of unique mines used 2009-2012	Percentage of mines used 3-4 times in 4 years	Percentage of coal from mines used 3-4 times in 4 years
Bruce Mansfield	26.5	19	42%	89%
Cumberland	24.2	20	20%	79%
J. M. Stuart	23.9	15	40%	89%
Clifty Creek	19.1	11	27%	56%
Hatfield's Ferry	15.9	26	27%	75%
W. H. Sammis	15.5	36	14%	65%
Miami Fort	13.9	39	36%	92%
Mountaineer	13.7	38	16%	69%
W. H. Zimmer	11.9	30	33%	83%
Fort Martin	9.78	26	42%	81%
Muskingum River	8.81	29	17%	59%
East Bend	7.53	26	27%	71%
Killen Station	6.86	15	33%	83%
Cheswick	4.06	11	18%	79%
Tanners Creek	3.99	10	30%	41%
Mitchell	1.68	26	12%	55%
Average	11.0	21	27%	73%
Source: derived from EIA [50]				

8. Impacts and response classifications for powerplants and mines

The powerplants and mines assessed fall into five general classes (see Table 5). The range of potential impacts and failure scenario responses for these five categories are discussed briefly below and in more detail in Appendix 8.

- Powerplants on the Monongahela River above the failure zone
- Powerplants within the Monongahela River failure zone
- Non-Monongahela River powerplants burning coal sourced from Monongahela River loading coal mines
- Monongahela River loading coal mines

- Non-Monongahela coal mines fueling Monongahela River powerplants.

Table 12 summarizes the potential responses of the impacted mines and powerplants to catastrophic river closure at Elizabeth and Charleroi. Facilities within or above the failure zone will bear more significant impacts than the downriver mines and powerplants. Facilities with barge-only access to the supply chain are also much more susceptible to significant impacts. Models that incorrectly assume all facilities can shift to rail shipments significantly underestimate the significance of infrastructure failure to these facilities. The response options listed are subjective projections of the authors; the actual options available to the facilities may be different given the full range of factors that determine a site's viability and transportation alternatives at any point in time.

Table 12. Summary of potential responses of powerplants and mines to catastrophic Monongahela River closure at Elizabeth and Charleroi Locks

Category	Number	Dependency on barging	Level of direct disruption	Response options
Power plants above failure zone	2 large	Very high	30-35% of 2010 coal deliveries would not have been feasible	• Replace with local coal • Re-route around failure zone • De-rate • Closure (Hatfield's Ferry)
Power plants within failure zone	2 small	Very high	100%	• Closure (Elrama and Mitchell)
Power plants below failure zone burning Mon. loaded coal	3 small	High	>50%	• Replace with feasible barged coal • Increase rail shipments • Closure (Beaver Valley and RE Burger)
	6 medium to large	High	<50%, but >200,000 tons	• Replace with feasible barged coal • Increase rail shipments • Closure (Tanners Creek)
	7	Low to moderate	<30%, <150,000 tons	• Replace with feasible barged coal • Increase rail shipments
Mon. loading mines	1 large	High	>60%	• Increase barge shipments to local powerplants • Re-route around failure zone • Closure (Cumberland)
	2 small	High	Low	• Continue barge shipments to local powerplants • Closure (Mine 84)
	2 strip mines	High	Moderate	• Truck to alternate docks
	4 marginal	Low to high	None to low	• No change for most shipments • Increase rail and truck shipments
	2	Low to moderate	None	• No change
	4	Low to moderate	<10%	• No change for most shipments • Shift to rail • Shift to non-impacted powerplants
Non-Mon mines fueling Mon powerplants	4 PRB	Low to moderate	<1%	• Insignificant impact
	2	Moderate to high	<1%	• Insignificant impact
	3	High	15-40%	• Shift to non-impacted powerplants • Closure (Yellowbush)
	2	Moderate to high	Moderate	• Shift to rail • Shift to non-impacted powerplants

G. Market-wide response to potential failure

Objective 1.4: Develop methodologies to assess the viability of new submarkets formed by infrastructure failure

A probable response to a prolonged outage due to infrastructure failure is the emergence of reorganized coal-to-utility markets above and below the failure zone. A supply and demand analysis was conducted to determine whether the regional market could feasibly re-organize into separate markets above and below the failure zone, while recognizing that many of the mines above the potential failure zone will continue to be able to reach powerplants below the failure zone by rail, truck, or alternate docks. The new market above the failure zone would be significantly smaller and more constrained than the new market below the failure zone.

The specific question of interest is whether sufficient supply and demand for coal remains after river failure and subsequent plant shut downs to "make" new markets. The key assumption driving this analysis is that extended river closure at Charleroi/Elizabeth will be a sufficient disruption to some powerplants and mines that they will stop operating, and thus be removed from the coal-to-utility network. Given the interdependency in this system, we explored the potential ripple effects of such postulated closures.

To address this market stability question, the five grouping of mines and powerplants discussed above were characterized in terms of (1) total tonnage shipped or received by all modes of transportation, (2) barged tonnage that would have been displaced by a river outage, and (3) the likelihood of closure in response to the outage (see Table 12). Four scenarios were considered:

- Scenario 1, the baseline scenario, assumes the direct closures of six powerplants, and two mines thought to be "marginal" and thus expected to close directly in response to the catastrophic loss of key river infrastructure (see prior section's discussion of Plant Closure). These closures include the two powerplants within the failure zone (Elrama, Mitchell) and other facilities that have subsequently closed (AES Beaver Valley, R.E. Burger, Willow Island, and Tanner's Creek; Yellowbush Mine and Mine 84)

- Scenario 2 assumes the baseline direct closures plus the closure of the Hatfield's Ferry powerplant. First Energy has announced the closure of this facility in late 2013 [70]. Thus closure in response to the additional complications of operating in a constrained river delivery system seems reasonable.

- Scenario 3 assumes that the Cumberland Mine closes in addition to the baseline closures. This Monongahela-loading mine barges all of its output to its customers. Loss of access to its customers below the failure zone, combined with increased competition for contracts with the remaining Monongahela powerplants, could conceivably change the financial viability of this mine.

- Scenario 4 reflects a cascading scenario, where both Hatfield's Ferry and the Cumberland Mine close, as well as two other barge-only Monongahela mines (Crawdad #1 and Prime #1) and the baseline facilities.

For each scenario, the projected excess coal supply from the remaining mines and lost supply from the remaining powerplants was calculated and compared for the reorganized markets above and below the failure zone.

A supply and demand analysis of these impacted facilities is presented in Table 13. As described in Section II.E and Figure 6 and reported again in the first four columns of Table 13, 6.4 million metric tons out of a total 283 million metric tons of coal shipments from impacted mines would not have been feasible in 2010 as a direct result of closure of the Monongahela River at the failure zone. Stated from the perspective of the powerplants, those same 6.4 million metric tons delivered to impacted powerplants (out of a total of 50 million metric tons, delivered) would not have been feasible as a result of the year-long modeled river closure.

The impacts would have been particularly acute for both of the powerplants and the large mine located above the failure zone that are primarily dependent on barge transport and would essentially be "trapped" by river closure; the impacted mines are identified as a discrete "barge only" subcategory in Table 13. The barge-only mine above the failure zone would have had 3.0

million metric tons out of a total 6.4 million metric tons of coal shipments disrupted by the modeled year-long river closure.

As discussed in II.F.8, it is reasonable to assume that certain facilities will close in response to a catastrophic river infrastructure failure. Closure of mines means a reduction in the regional coal supply; powerplant closure is a reduction in regional demand. The 5^{th} column of Table 13 shows that 0.65 million metric tons of coal would have been withdrawn from the market due to the assumed baseline mine closures, and 3.1 million metric tons of demanded coal would have been canceled due to the assumed baseline powerplant closures. The 6^{th} column describes the portion of the baseline closure facilities shipments that were barged through the failure zone, and thus were counted in the 4^{th} column of not feasible barged shipments from impacted facilities. Removal of these facilities from the regional mine-to-powerplant network reduces the regional supply of coal by only 2% (0.65 of 28 million metric tons of mined coal) and reduces the regional demand of coal from the baseline closure of powerplants by 6% (3.12 of 50 million metric tons). The modeled cancellation of barged shipments for these baseline closure facilities accounts for 21% of the displaced 6.4 million metric tons.

This withdrawal of supply and demand would impact linkages between powerplants and mines that otherwise would have been feasible despite a river closure; the final column in Table 13 describes these secondary impacts. The model shows 0.6 million metric tons of secondary lost sales to mines located below the failure zone because of baseline powerplant closures, and 0.33 million metric tons of secondary lost deliveries to powerplants located below the failure zone due to baseline mine closures. Consideration of these secondary impacts is relevant to the assessment of the remaining supply and demand balance above and below the failure zone.

Table 13. Supply and demand in new submarkets of coal shipments after modeled 2010 infrastructure failure at the Elizabeth and Charleroi locks, Monongahela River (million metric tons)

	Impacted facilities			Baseline (direct) closures		Secondary lost shipments from closed but feasible links (barged)
	Total shipments (all modes)	Total barged shipments	Barged shipments, not feasible	Total (all modes)	Barged, not feasible	
Mines (coal supply):						Lost demand
Above failure zone (with access to rail)	28	2.2	1.2	0.012	0.012	0.00
Above failure zone (barge only)	6.8	6.6	3.0	0.0	0.0	0.00
Below failure zone	248	42	2.2	0.64	0.11	0.60
Subtotal	283	51	6.4	0.65	0.12	0.60
Power plants (coal demand):						Lost supply
Above failure zone	6.15	6.09	2.0	0.00	0.00	0.00
Within failure zone	0.72	0.56	0.56	0.72	0.56	0.00
Below failure zone	43.1	33.1	3.8	2.4	0.77	0.33
Subtotal	50	40	6.4	3.12	1.32	0.33

In the scramble to remain operating in the aftermath of a catastrophic and extended river closure, it is reasonable to assume that the mines and powerplants would attempt to form new markets to reflect the new challenge of moving coal cost effectively, particularly above the failure zone. Several powerplants and the "barge only" mines lack the near-term ability to shift coal transport to rail to circumvent the failure zone; these facilities would need to find a way to continue to ship/receive coal by barge or face closure. Table 14 summarizes the new markets that could form in response to an extended river closure, incorporating the supply/demand losses of the facilities above and below the failure zone. Negative net supplies indicate a shortfall within the new markets. This analysis assumes full exchangeability of the coal within this mine-to-utility network, which ignores the powerplants' needs to balance their fuel mixes to match their boiler and environmental permit constraints. Consideration of these constraints would further complicate the ability of the new markets to adapt to the loss of navigation through Elizabeth and Charleroi. Discussion of these results is provided below.

Table 14. Barged coal supply analysis by submarkets (above and below failure zone)

	Scenarios (million metric tons barged)			
	1: Baseline closures	2: Baseline + Hatfield's Ferry closures	3. Baseline + Cumberland closures	4. Baseline + Hatfield's Ferry + barge-only Mon mine closures
Facilities above failure zone				
Power plant lost supply	-2.03	-0.75	-3.24	-0.80
Mine (with rail access) excess barge supply	1.16	1.33	1.16	1.33
Mine (barge only) excess supply	3.03	5.18	0.05	0.14
Net supply above failure zone	2.16	5.75	*-2.03*	0.67
Facilities below failure zone				
Power plant lost supply	-3.39	-3.39	-3.39	-3.39
Mine (with rail access) excess barge supply	1.13	1.13	1.13	1.13
Mine (barge only) excess supply	1.57	1.57	1.57	1.57
Net supply	-0.68	-0.68	-0.68	-0.68
Net system wide coal	1.48	5.06	-2.71	-0.018

In Scenario 1, where the marginal powerplants and mines with high dependency on barge traffic through the failure zone close, the market above the failure zone has the potential to re-organize adequately to keep the two powerplants operating. In other words, the 2.0 million metric tons of unmet demand at those powerplants created by the inability of Ohio River coal mines to barge up through the failure zone could be offset by the 4.2 million metric tons of excess supply available at the Monongahela mines that could not be barged down through the failure zone. Key observations of the Scenario 1 results include:

- Marginal powerplants and mines close (1.9 million metric tons of barged demand and 0.65 million metric tons of barged supply, respectively).

- Remaining Monongahela powerplants: The lost barged supply (2.0 million metric tons) for these powerplants could be fully powered by the displaced barged coal available above the failure zone (4.2 million metric tons).

- Barge-only Monongahela mines: The viability of the Scenario 1 submarkets is dependent on whether these barge-only mines (with 3.0 million metric tons of displaced coal) can secure contracts for a significant amount of that unmet 2.0 million metric tons of barged demand with the remaining Monongahela powerplants and absorb the remainder by reducing output. It is not expected that these mines could cost-effectively transload the remainder of their excess supply from barge to rail to compete against those Monongahela mines with established rail access for contracts to powerplants below the failure zone. The outlook for these mines under Scenario 1 is not encouraging.

- Monongahela mines with rail access: These mines, with 1.1 million metric tons of displaced barged coal, are competitors of the barge-only mines, and thus would compete to supply the lost barged supply for the Monongahela powerplants, as well as for the 0.6 million metric ton projected shortfall of supply to powerplants below the failure zone. With their established rail and barge alternatives, they will have a cost advantage over the barge-only mines.

- Below the failure zone: A slight shortfall in supply (-0.68 million metric tons) would result in the market below Elizabeth; this shortfall could be readily addressed by excess supply from those Monongahela mines with rail access, or slight increased production below the failure zone. The impact below the failure zone is unchanged for the remaining three scenarios (which remove additional facilities only from above the failure zone).

- Overall, more demand is removed from the combined markets than supply as a result of river closure, resulting in an excess supply of 1.5 million metric tons after if the market reorganizes successfully without additional closures. Much of the excess supply, however, is from barge-only Monongahela mines that would be "trapped" above the failure zone. While this represents less than 1% of the total volume of coal produced by the impacted mines, if the trapped Monongahela barge-only mines are unsuccessful in joining the re-organized markets, their closure may occur, as modeled in Scenario 3 and 4.

Scenario 2 considers the added impact of closure of the Hatfield's Ferry powerplant, which in fact had occurred by the time of completion of this dissertation. As shown in Table 14, closing Hatfield's Ferry in response to the river failure would have resulted in an excess of 5.7 million metric tons of coal that otherwise would have been barged through the region. Additional Scenario 2 observations:

- Marginal powerplants and mines close.
- Remaining Monongahela powerplant: Fort Martin could be fully powered by the remaining barged coal available above the failure zone.
- Barge-only Monongahela mines: Closure of Hatfield's Ferry would have a significant additional impact on these "trapped" mines, increasing their surplus barged coal 70% to 5.2 million metric tons; 25% of Cumberland Mine and half of the Crawdad and Prime No. 1 mines' customer base would have been lost in this scenario. While transloading to rail to reach customers below the failure zone would be physically possible, it may not be cost-effective for these mines. Permanent or temporary closure is more likely under this scenario than in Scenario 1.
- Monongahela mines with rail access: These 11 mines can be expected to cost-effectively shift their excess supply from the river to rail (or truck). Their excess supply would only increase by 0.2 million metric tons by closure of Hatfield's Ferry.
- System wide, closure of Hatfield's Ferry would create an excess supply of 5.1 million metric tons of coal. This glut may force additional mine closures in the constrained market above the failure zone.

Scenario 3 considers the impact of closure of the Cumberland Mine, in addition to the baseline closures. This large mine shipped coal over 4.8 million metric tons of coal in 2010 to the 13 powerplants below the failure zone and the two powerplants on the Monongahela. Impacts include:

- Marginal powerplants and mines close.
- Remaining Monongahela powerplants and mines: These powerplants would need to find an additional 2.0 million metric tons of barged coal to remain fully powered. It is reasonable to assume that the remaining Monongahela mines (with total production of 34 million metric tons in 2010) would step up to this unmet demand with a 6% increase in production.
- System wide, closure of the Cumberland Mine would result in an additional 4.2 million metric ton barged shortage over the baseline scenario.

Scenario 4 represents a cascading series of closure in which the Hatfield's Ferry powerplant (as in fact has already occurred without a river outage) and the three barge-only Monongahela-loading mines then close (Cumberland Mine, Crawdad No. 1, and Prime No. 1):

- Marginal powerplants and mines close.
- Remaining Monongahela powerplant: Fort Martin's 0.80 million metric ton shortfall can be met fully by the surplus barged coal from the remaining mines, leaving an excess of 0.6 million metric tons of coal.
- Barge-only Monongahela mine: One remaining barge-only mine (Washington County Strips) would be competing to meet Fort Martin's shortfall. This strip mine, however, has some flexibility to truck its output to alternative docks below the failure zone for barge transloading.
- Monongahela mines with rail access: These five mines, with 1.4 million metric tons of displaced barged coal, are assumed to have crowded out their barge-only competitors in this scenario, and would be competing among themselves to supply the lost barged supply for the Fort Martin, as well as for the 0.6 million metric ton projected shortfall of supply to powerplants below the failure zone. Three of the five mines were owned by the same company in 2010. All five mines had robust rail connections to the broader market below the failure zone.
- System wide, closure of both Hatfield's Ferry and the barge-only mines would result in an insignificant barged shortfall over the baseline scenario.

H. Estimating financial impacts of closure

Objective 1.5: Develop a methodology to assess the potential financial impact of closure of facilities impacted by infrastructure failure

The previous section explored impacts in terms of logistics and the projected successfulness of reorganized markets above and below the failure zone. This section builds on those scenarios, characterizing the revenue losses and displacements associated with facility closures, specifically in terms of revenue and employment losses to those powerplants and mines that might close, and the revenues lost by the barge shipping industry due to displaced coal movements. The revenue losses assume a one-year long river closure at Elizabeth and Charleroi, after which time revenue streams to the impacted entities could be resumed.

Revenues are used as the metric of interest as an upper bound of the financial impacts of plant closures. A more detailed financial model would yield a more accurate assessment of losses associated with plant closures, differentiating (for example) between cost of materials, wages, and profits. With the exception of the cost of delivered coal, the data used for this analysis do not support this level of detail; development of a detailed financial model is left to future modeling.

This analysis recognizes that these private losses will be offset largely in the broader economy by stepped up electricity generation (and revenues) and fuel production elsewhere in the grid; however the localized impacts where facilities close will be real and painful.

Prior models have estimated the cost of failure in terms of increased travel costs due to delays and mode shifts. Jenelius also describes the cost of "unsatisfied demand" where the perturbed system is not able to move product to customers [11]. The valuation of unsatisfied demand, according to Jenelius, is "still an open question, however, or a matter of political decisions," and quantified unsatisfied demand as a fraction of total demand. In the examination of this particular case for the inland waterways, an alternative valuation is proposed: the value of revenues displaced at facilities that are expected to close in the face of failure of critical infrastructure.

Consideration of the closure potential is a valid means for assessing where the impacts of a disruption may be most severe [58]. Chulkov's application of social net present value to port technology investment decision making also identifies lost revenue as a cost of port closure [9].

This analysis does not attempt to quantify all of the financial impacts associated with a catastrophic loss of infrastructure, but instead is focused on an impact area not fully explored in prior analyses – what are the financial impacts associated with firms that cannot adapt to the loss of critical infrastructure.

1. Revenue losses at closed coal mines

Table 15 summarizes the revenue losses associated with a one-year coal mine closure for each of the four scenarios characterized above, ranging from $45 million to $509 million ($2010). These losses were estimated from the EIA-923 dataset by calculating the value of the shipments from specific mines to specific utilities (reported as fuel cost, $/MMBtu, and combined with reported average heat content, MMBtu/ton, and quantity, ton). The publicly reported valuations represent the total cost of the coal, including transportation costs. To isolate the loss of revenue to the mines, these total coal valuations were adjusted to estimate freight-on-board (FOB) costs. (Actual FOB costs are collected in the EIA-923, but are withheld from the public datasets used for this analysis.) Transportation costs, based on state-to-state (barge and truck) or coal basin-to-state (rail) rates ($/ton) reported by EIA were subtracted from the total coal prices to give rough estimates of FOB coal prices [71]. In a limited number of cases, fuel costs were not reported in the public dataset, and were extrapolated from similar transits (mode and length). Similarly, missing transport costs for specific O/D combinations were extrapolated from similar transits or prior years, as available (see Appendix 9).

Note that these estimated revenue losses are direct private costs to the owners of the mines. They do not include the additional indirect costs associated with shuttering a mine or powerplant. This analysis does not attempt to calculate net costs to society of changes in utility fuel sources due to river infrastructure failure. Also, these estimated revenue losses assume a year-long closure, after which the river is assumed to be re-opened and mine or powerplant operations could resume. The actual length of the river closure would affect the scale of the losses, as would the feasibility of the facilities to re-open with the river.

Table 15. Potential revenue losses by barging coal mines modeled to close in response to catastrophic river closure at Elizabeth and Charleroi locks under year-long failure scenarios (2010$)

	Total 2010 Production at Impacted Mines (million metric tons)	Baseline Value ($million, FOB, 2010)	Lost 2010 revenue at closed mines ($million, FOB)		
			Baseline (Scenario 1) and Scenario 2	Baseline + Cumberland Mine closure (Scenario 3)	Baseline + closure of Hatfield's Ferry and barge-only Mon mine closures (Scenario 4)
Closed Mines			*Yellowbush Mine 84*	*Yellowbush Mine 84 Cumberland*	*Yellowbush Mine 84 Cumberland Crawdad No. 1 Prime No. 1*
Mines above failure zone	35.2	1,240	1.1	337	465
With transport alternatives	28.5	772	1.1	1.1	1.1
Barge only	6.83	471	0	336	464
Mines below failure zone	248	2,820	44.2	44.2	44.2
With transport alternatives	228	1,890	0	0	0
Barge only	20.4	924	44.2	44.2	44.2
Mine Subtotal	$283	$4,060	$45.3	$382	$509
Source: Production and valuation derived from EIA [50]					

2. Revenue losses at closed powerplants

Using EIA data for electricity prices by state in 2010 in conjunction with the net electricity generated by each of the impacted powerplants [50] [72], the revenues potentially lost by these owners at the closed powerplants under the four modeled year-long Scenarios were calculated, as summarized Table 16. Folga used a similar approach for powerplants forced to close due to a loss of water intake for their cooling water supply [21].

Table 16 also provides (in brackets) the cost of delivered coal as reported by these facilities in the EIA-923 survey. Accounting for the cost of coal allows for the subsequent addition of lost revenues of mines and powerplants without double-counting the coal.

These lost revenues represent direct private costs to the powerplant owners, and are not a quantitative assessment of the net impact to society, as electricity generation (and revenues) will shift to other power generators and other fuel sources. The catastrophic infrastructure failure scenario is not expected to cause immediate shutdowns at the directly impacted powerplants - stock piled coal will allow for continued operation in the near term and grid-wide transitions to alternative power mixes [21]. The timing of the failure thus would drive the length of time that the powerplant remains operating while drawing down its stockpiles. EIA tracks the utility stockpiles in terms of tonnage and the average number of burn days that the stockpiles can support [56]. Stockpiles peak seasonally in early spring before the cooling season, and again at slightly lower levels in early fall before the heating season [56]. Generally the average burn days fluctuate between 65-75 days, with higher levels seen in 2012 as the industry adjusted to increasing availability of competing natural gas, and lower levels in the first half of 2014 [56].

Table 16. Potential revenue losses by barging powerplants modeled to close in response to catastrophic river closure at Elizabeth and Charleroi locks under year-long failure scenarios ($2010)

	Total 2010 Production from Impacted Plants (million MWh)	Baseline 2010 Value ($million)	Lost 2010 revenue at closed powerplants [cost of delivered coal] ($million)	
			Baseline (Scenarios 1+3)	Baseline + additional closures (Scenario 2+4)
Closed powerplants			Elrama Mitchell Beaver Valley R.E. Burger Willow Island Tanner's Creek	Elrama Mitchell Beaver Valley R.E. Burger Willow Island Tanner's Creek Hatfield's Ferry
Power plants above failure zone	15.3	$ 1,400	$ 0 [0]	$925 [$232]
Power plants within failure zone	1.49	$153	$153 [40]	$153 [40]
Power plants below failure zone	115	$ 10,300	$503 [149]	$503 [149]
Subtotal	132	$ 11,800	$ 656 [189]	$ 1,580 [421]
Source: Production and valuation derived from EIA [50]				

3. Revenue losses to barge shippers

Shipping costs are substantial for large quantity, high-density commodities such as coal. Closure of the river due to infrastructure failure will cause the displacement of many millions of tons of shipment. Assuming the grid remains fully functional, which seems reasonable given the availability of coal stockpiles at the utilities and extensive redundancies within the grid, the shipments that are impossible due to river closure would be replaced by other shipments elsewhere. The direct impact to the individual shippers will be a function of their ability to supply those replacement shipments, an analysis which is beyond the scope of this dissertation and the available data. A worst case scenario, however, simply assesses the lost shipping revenues from the cancellation of the shipments that (1) become impossible because they need to pass through the failure zone, (2) are from mines that close, and (3) are to powerplants that close, resulting in estimated lost shipping revenues of $47-69 million (see Table 17). Shipping costs were determined as described above in Section II.H.1 for the lost mine revenue calculations [50]. The largest impacts would be on those shippers who service the mines above the failure zone.

Table 17. Potential revenue losses from cancelled barge shipping due to catastrophic river closure at Elizabeth and Charleroi locks under year-long failure scenarios (2010$)

Shipping Origin	Total 2010 Shipping Revenue, no failure, all modes	Baseline (Scenario 1)	Baseline + Cumberland Mine closure (Scenario 3)	Baseline + closure of Hatfield's Ferry and barge-only Mon mine closures (Scenario 4)
Lost revenue - not feasible barge shipments ($million)				
Mines above failure zone	590	31.4		
Mines below failure zone	5,670	11.0		
Lost revenue - cancelled feasible barge shipments from closed mines ($million) (not including shipments to closed pp)				
Mines above failure zone		0	14.4	7.71
Mines below failure zone		1.65	1.65	1.65
Lost revenue - cancelled feasible barge shipments to closed powerplants ($million)				
Mines above failure zone		0	0	14.1
Mines below failure zone		2.76	2.76	2.76
Total	6,260	46.8	61.2	68.6
Source: Valuation derived from EIA [50]				

As with the revenue losses at impacted powerplants, these shipping revenue losses reflect the direct private losses to specific shipping firms over the course of a one-year river closure. Given society's unrelenting demand for electricity, fuel shipments will continue, albeit not via barge through the failure zone. The net shipping cost to society, not estimated here, would be a function of where the replacement electricity is generated, what specific fuel sources are used, and selecting the most cost-effective shipping modes available between the replacement powerplant and fuel source.

For those mines with access to both rail and barge, it is possible to assess the magnitude of the increased shipping costs associated with moving their barge shipments to rail in response to a loss of passage through Elizabeth/Charleroi. Comparing barge shipping rates across the region with rail rates for the same O/D pairings shows that rail rates are $2-20/ton more expensive than comparable barge rates (see Appendix 10). However, as discussed previously in the mode shifting discussion and as Wang noted, "the interfaces between the rail and barge networks are limited, and there are real costs to the shipper for making this modal change, which are not all captured in the freight rates" [13].

4. Value of trapped vessels

Barge and towboat owners also are exposed to the risk of being trapped within the failure zone. Such entrapment might result in losses ranging from total losses of the vessels, to temporary grounding until the pool could be re-established at the downstream Braddock Dam. The size of such losses can be estimated from the number of vessels and barges that typically move through the potential failure zone on an average day [73], with replacement values estimated by USACE [74] and CPI-adjusted to 2010 costs. The daily lockage profiles were taken from a dataset of lockages through USACE’s Pittsburgh District for 2010; each record in the dataset identifies the timestamp, lock number, vessel number and number of barges locked. Additional data on vessel size as measured by engine rating were taken from a USACE dataset characterizing registered towboats [75].

If failure were to occur on a day with average traffic through the failure zone, seven or eight vessels would have locked through the three locks bounding or in the failure zone. On average, the replacement value of these vessels and their barges would be on the order of $32-38 million. On the highest traffic day, there might have been twice as many vessels moving in the region, doubling the potential losses. See Table 18.

This analysis provides a very rough approximation of the potential magnitude of vessel and barge losses; these represent indirect private costs. Some of these vessels would have only moved through one lock (e.g., larger towboats that typically do not travel higher than Braddock) and may have moved out of the failure zone. Others would have been in transit across the entire zone (e.g., tows moving from the Monongahela mines to the Ohio River powerplants) and also may be trapped by a sudden failure. In addition, moored vessels and barges, as well as harbor-duty towboats, are not visible in USACE lockage dataset used to construct this analysis, yet would also be trapped and possible damaged by river infrastructure failure.

Table 18. Replacement value of vessels and barges trapped in potential failure zone at Elizabeth and Charleroi locks (2010$)

	Braddock	Elizabeth	Charleroi
Total number of lockages in 2010	3,355	5,299	5,455
Barges per lockage, average	6.1	2.9	3
Daily number of lockages, average	9	15	15
Daily number of lockages, maximum	20	31	26
Daily number of unique vessels locked, average	7	8	8
Daily number of unique vessels locked, maximum	13	16	15
Average towboat power (hp)	2,261	1,684	1,532
Replacement value per vessel ($million)	2.9	2.1	1.9
Replacement value of average daily number of vessels locked ($million)	18.8	17.0	16.3
Barge replacement ($million)	19.5	14.6	15.6

5. Aggregated lost revenues associated with thermal coal shipments due to infrastructure failure

In summary, the private cost of extended river closure due to catastrophic infrastructure failure at Elizabeth and Charleroi will be significant, particularly for those mines, powerplants, and vessel owners in the near vicinity of the failure zone. The aggregate revenue losses due to the closure of mines and powerplants that may not be able to adapt to the loss of navigation are estimated to range from $560 to $1,700 million in 2010$ over a year-long river closure (see Table 19). Additional indirect costs for vessel and barge losses are about $35 million. Of course, there are other significant costs not tallied here for those impacted facilities that continue to operate in the post-failure markets.

From a broader social perspective, these lost revenues will be transferred to other powerplants and fuel producers, as the region's demand for electricity will be unchanged. The transfer of these revenues is of no comfort to the local economies that depend on and benefit from the closed facilities. These estimated aggregate private costs due to facility closures in response to a year-long river closure are on the same order of magnitude as USACE’s estimate of the total cost of the Lower Mon Project ($2.7 billion).

Table 19. Displaced revenues from thermal coal mine and powerplant closures due to year-long infrastructure failure (2010 $ million)

	Scenarios			
Impact Category	1: Baseline closures	2: Baseline + Hatfield’s Ferry closures	3. Baseline + Cumberland closures	4. Baseline + Hatfield’s Ferry + barge-only Mon mine closures
Mines	$ 45	$ 45	$ 382	$ 509
Power plants	$ 656	$ 1,580	$ 656	$ 1,580
Cost of coal, delivered	$ (189)	$(421)	$(189)	$(421)
Shipping	$ 47	$ 47	$ 61	$ 69
Sum (million)	$ 559	$ 1,251	$ 910	$ 1,737

The costs summarized above focus on the powerplants and mines that could close in response to a prolonged loss of navigation through Elizabeth and Charleroi. To the extent that these values include revenues from closed mines that supplied closed powerplants, these results include some double counting of impacts. The remaining mines and powerplants would also incur costs (not quantified here) associated with procuring alternative shipping or shifting to new positions within the regional coal-to-utility network.

Additional costs would be borne by the disruption of shipments of metallurgical coal and other commodities not assessed in this analysis.

- Metallurgical coal may account for another million tons of shipments through Elizabeth, although there are no publicly available data to quantify these shipments or their origins and destinations. To the extent that these shipments are from barge-only mines, additional mine closures could result.

- Certainly a significant vulnerability is the U.S. Steel coking facility at Clairton (mile 19-22) which receives significant feedstock by river and relies on the river for its process water.

- There is also a significant movement of limestone and lime through Elizabeth, totaling over 1.4 million metric tons in 2010, much of which is expected to be shipped to the upper Monongahela River coal-fired utilities that rely on lime for the operation of their air pollution control devises. Disruption of these shipments could increase the likelihood that these plants would close in response to catastrophic failure at Elizabeth and Charleroi. These key shipments warrant further investigation.

- The current market equilibrium differs from the modeled 2010 scenarios due to the actual closure of the Mitchell, Elrama and Hatfield’s Ferry powerplants. This demonstrated methodology could be extended readily to different time frames or regions. The Emsworth lock and dam faces similar vulnerabilities.

I. Conclusions

A careful examination of actual transit alternatives in response to a significant river infrastructure failure shows that impacts are highly localized to the failure zone, with particularly significant impacts on the river segments that become isolated from the remainder of the inland waterways. A failure further down river would impact more industries, but would result in more symmetric and larger new submarkets that would, by the nature of their size, be more resilient.

Impacts would be much more significant for those facilities with accessibility limited to only one mode of transportation. Facilities with active access to multiple modes of transportation (barge, rail and truck) are better positioned to cope with the catastrophic loss of major infrastructure such as a lock (or bridge or rail spur). This resilience gives them the flexibility to shift transport modes. Without this flexibility, facilities that are completely reliant on barge transport may be forced to close.

Most powerplants and mines participate in a fairly extended supply network, providing resilience in the face of loss of a specific supplier/customer. The ability of powerplants to supplement their base contracts with coal from a variety of non-base mines provides resilience and flexibility to the logistics chain. Thus for those powerplants that are not within the failure zone nor fully dependent on barge coal delivery, loss of access to certain mines as a result of the failure scenario of concern could be managed by their continued access to the coal "spot market."

The impacts to the powerplants and mines that would be stranded above the failure zone, as well as the owners of the towboats and barges servicing these facilities, would be significant and perhaps catastrophic from a business feasibility perspective. The aggregate private cost of a year-long infrastructure failure to the facilities that cannot adapt and close is comparable in magnitude to USACE’s estimated cost for the ongoing and long delayed project to replace that infrastructure.

The modeled failure scenario assumes that certain powerplants and mines would close in response to the disruption caused by a prolonged river closure at Elizabeth and Charleroi. Many of these plants have in fact closed since 2010. The viability of facilities in the face of major infrastructure failure is closely related to their fundamental financial position. Facilities that are approaching the end of their useful lives, or that face other constraints on their profitability (such as pending environmental regulations may close rather than absorb additional costs associated with shifting transportation modes or with competing in a newly constrained market.

This section focused on impacts to coal mines and their powerplants customers who used the Monongahela River for transport of 6.4 million metric tons of thermal coal in 2010. Other commodities of interest shipped through the potential failure zone include an estimated million tons of metallurgical coal and 1.4 million metric tons of limestone and lime. Insufficient public data exist to assess the potential impact of the displacement of these metallurgical coal shipments, but could be expected to be similar in nature to the thermal coal impacts modeled in this section. The limestone and lime shipments are likely being delivered to the upper Monongahela powerplants and local cement plants, and thus the disruption of these shipments would further complicate the viability of these facilities in the face of a river closure.

In conclusion, the contributions of this section of this dissertation are several. We have demonstrated the importance of assessing the actual accessibility of impacted plants to multiple modes of transportation, as well as a novel methodology for determining facility-specific transportation mode accessibility. We have added the overall viability of plants as a criterion to whether they would be able to adapt to the loss of critical infrastructure, and suggested a methodology for quantifying their removal from the coal-to-utility network. We have assessed the feasibility of formation of new sub-markets in response to an extended closure of an important stretch of river. We have suggested a methodology to assess the loss of towboats and barges and their valuation as a result of a sudden catastrophic loss of pool. These contributions provide additional tools for the full assessment of the value of maintaining the inland waterways infrastructure.

III. A Methodology to Estimate Commodity Trips and Shipping Costs on the Inland Waterways[3]

A. Introduction

Research Goal 2: Assess current and potential new efficiency metrics for the inland waterways
Objective 2.1: Develop methodologies to identify, characterize, and differentiate between vessel and commodity trips

The purpose of this research was to characterize the efficiency of commercial river traffic on the upper Ohio River system, using new methodologies to assess trips made by vessels, as well as full trips needed for commodity shipments (which often include consecutive vessel-trips). The methods developed in this research used as inputs USACE's Lock Performance Monitoring System (LPMS) data (described in Section II.C [76]), as well as the EIA-923 survey (described in Section II.D [50]).

The motivation for this work was to extend the existing toolset used to assess the Nation's inland waterway infrastructure. The analyses described here provide useful additional characterizations of the ways the rivers are used, illustrating applications of valuable data sources that have not been used extensively for these applications to date, as well as the importance of regional patterns. More approaches and datasets provide an opportunity for data validation and greater accuracy. The intent was to provide a better assessment of waterway performance to inform improved investment and operational decision making.

The USACE [76] and Energy Information Administration (EIA) [50] data support a wide variety of analyses of commodity movement through the region. This chapter is organized around the following analyses, and as illustrated in Figure 8:

[3] Submitted for consideration. Gwen Shepherd DiPietro, Chris T. Hendrickson, H. Scott Matthews. "A Methodology to Estimate Commodity Trips and Shipping Costs on the Inland Waterways." Transportation Research Record. August 2014.

- Characterization of the vessel trips visible by linking the individual lockages of vessels, allowing for an assessment of typical trip lengths and frequencies, as well as the tonnage and ton-miles for these trips

- Characterization of commodity trips from EIA data for coal, the predominant commodity in the study area

- Assessment of regional shipping costs from EIA coal data.

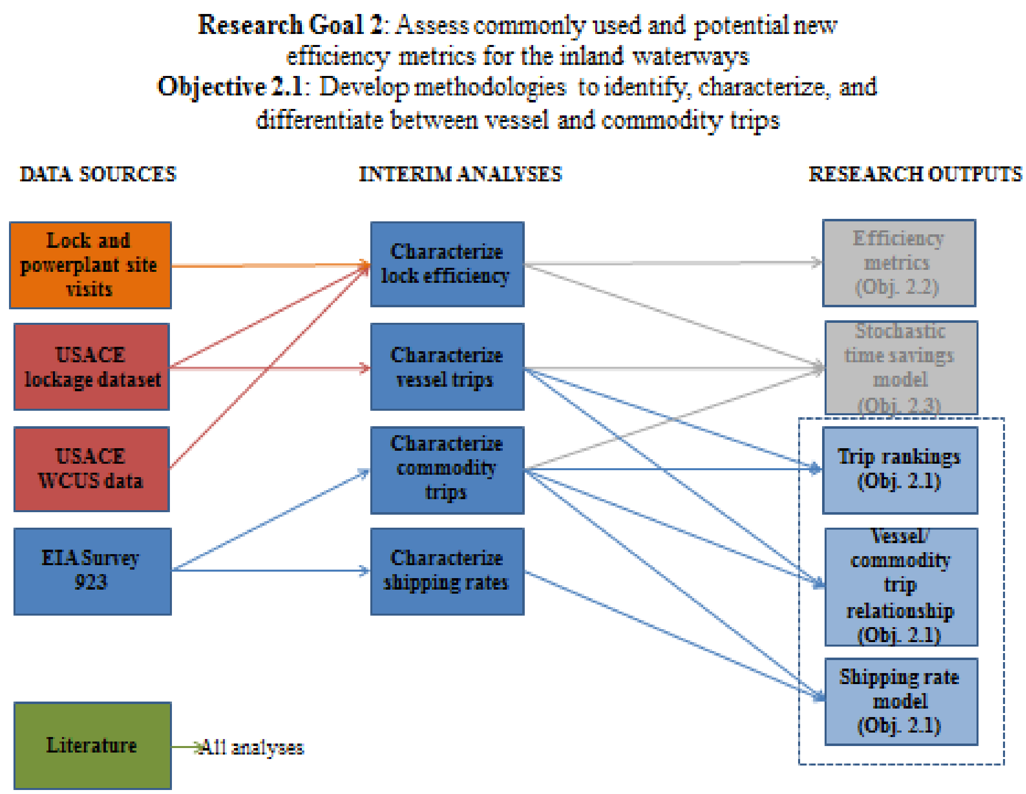


Figure 8. Research Goal 2, Objective 2.1 Flow Diagram

B. Background

The study area for this research is USACE's Pittsburgh District [77] and neighboring down-river Huntington District [78] (see Figure 2). In general, the locks and commodity volumes handled decrease with proximity to the heads of navigation (see Table 20) [41]. This trend does not necessarily hold for the annual number of lockages logged – the oldest locks in the system (OH1, OH2, OH3, MN23, and MN24) have high lockage rates due to the need for barge flotillas to be locked through in phases, or in "cuts" that fit in their smaller sizes.

Table 20. USACE Pittsburgh and Huntington District lock profiles

Lock	Lock ID	Year Opened	Miles from Pittsburgh confluence	2010 Commodity Tonnage	2010 Lockages
Emsworth	OH1	1921	6.2	15.3	4,866
Dashields	OH2	1929	13.3	16.4	4,134
Montgomery	OH3	1936	31.7	18.2	4,696
New Cumberland	OH4	1959	54.4	26.3	3,469
Pike Island	OH5	1965	84.2	30.0	4,251
Hannibal	OH71	1973	126.4	42.3	3,876
Willow Island	OH72	1972	161.7	41.8	3,620
Belleville	OH21	1969	203.9	44.6	3,909
Racine	OH22	1967	237.5	45.6	4,097
R.C. Byrd	OH26	1993	279.2	50.4	4,669
Greenup	OH24	1959	341.0	56.4	5,944
Meldahl	OH25	1962	436.2	57.7	4,954
Braddock	MN22	1905	11.2	14.8	3,360
Elizabeth	MN23	1907	23.0	11.3	5,304
Charleroi	MN24	1932	41.5	11.2	5,459
Maxwell	MN25	1963	61.2	10.2	2,617
Grays Landing	MN27	1993	82.0	4.6	1,265
Point Marion	MN28	1994	90.8	4.5	1,249
Morgantown	MN29	1950	102.0	0.2	172
Hildebrand	MN30	1960	108.0	0	0
Opekiska	MN31	1964	115.4	0	0
Allegheny L&D2	AG42	1934	6.7	1.2	1,250
CW Bill Young	AG43	1934	14.5	1.2	1,203
Allegheny L&D4	AG44	1927	24.2	0.99	1,407
Allegheny L&D5	AG45	1927	30.4	0.82	1,156
Allegheny L&D6	AG46	1928	36.3	0.01	22
Allegheny L&D7	AG47	1930	45.7	0.01	20
Allegheny L&D8	AG48	1931	52.6	0.007	8
Allegheny L&D9	AG49	1938	62.2	0	0
Winfield	KA1	1997	297.0	19.9	2,592
Marmet	KA2	2008	334.0	14.6	2,792
London	KA3	1933	349.0	3.5	4,001
Source: USACE [41]					

1. Using LPMS lockage data to assess vessel trips

USACE reports a variety of national, regional, port, and lock statistics regarding the flow of commodities on the inland waterway. These statistics are based on data logged in the LPMS for every lockage in the system, and essentially represent a full census of lockages. Geographically this dataset is limited to those vessel movements that pass across USACE's locks – thus it provides no data on transits on the lower Mississippi or the Great Lakes. USACE also tallies data from the Vessel Operator Report (VOR) regarding tonnage, commodities, and origin and destination by vessel. The VOR contains proprietary data that are only publically released in aggregate form (i.e., the annual Waterborne Commerce of the United States (WCUS) Waterways and Harbors report) [1]. The VOR reports are not limited to transits through locks, and thus cover the full national waterways. The LPMS data are available in limited form for the most recent 24-hour period at the Corps Locks website and released upon request for older data [79].

A detailed assessment of the movement of vessels and barges in the study area has been assembled from LPMS data provided via request by the Corps of Engineers Institute for Water Resources (CEIWR) for 2010 [76] (the VOR data were not provided). The raw public LPMS data include the lock number of each lockage, the vessel locking by name and Coast Guard identification number, number of barges processed, as well as timestamps for arrival at the lock, beginning, and ending of lockage. There were 66,382 records of lockages through the 23 locks in the Pittsburgh dataset, and 39,996 lockage records through the nine locks in the Huntington dataset. For the purposes of a regional analysis that is centered on the upper reaches of the inland waterways, the LPMS provides a strong profile of underway transits.

The raw LPMS dataset did not include tonnage, types of barges, types of lockages, or specific commodities. Additional data characterizing the registered vessels and physical structures of interest (lock dimensions, tributary confluences, and lock milepoints, bridges, and docks) were downloaded from the Navigation Data Center (NDC) website.

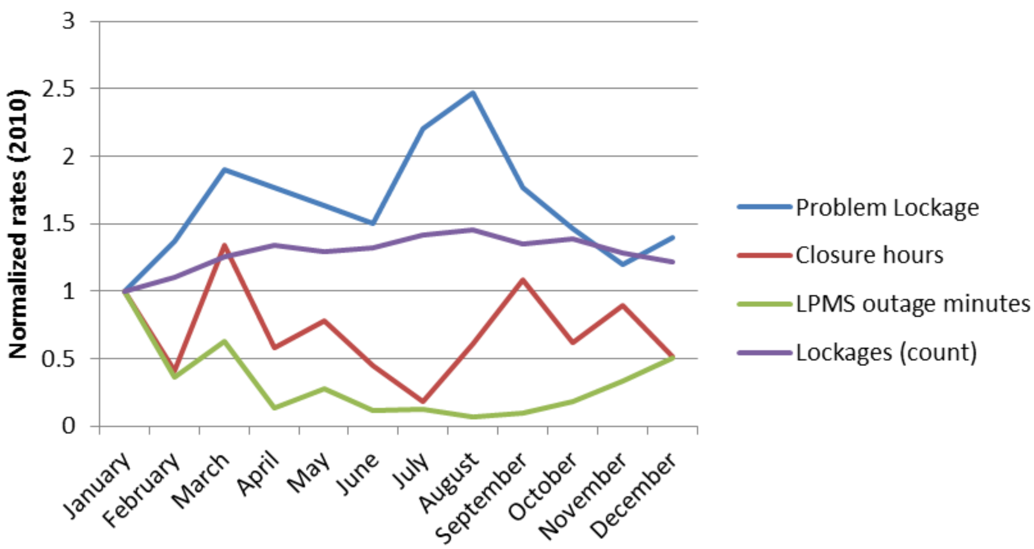
Analysis of consecutive lockages by individual vessels (i.e., trip legs) revealed some issues with the LPMS data quality. Approximately 590 (0.7%) of the legs were incongruous (apparent skippage of locks or incorrect directions between locks). As an example, Table 21 is a sequence of lockages for the "M/V Garyville" on August 19th and 20th. The first lockage shows the Garyville moving upriver through OH4. Logically, the next possible lockages could be either OH3 (continuing upriver), or OH4 (reversing direction and heading downriver). The next recorded lockage, however, is OH72, which is 3 locks below OH4. The third recorded lockage in this sequence is similarly illogical, as it indicates a jump from OH72 back up to above OH4. Email requests for clarification of these types of gas from the LPMS staff were not fruitful – it appears, but cannot be confirmed, that the second lockage was miscoded in some way (e.g., vessel identification, date/time stamp, lock number). Eliminating the second lockage, the remaining lockages fall in a logical pattern.

Table 21. Example lockage data issue for the M/V Garyville, August 19-20, 2010

Lock No.	River Name	Lock Name	Vessel Name	VesselNo	Direction	Num Processed	Arrival Date	SOL Date	End of Lockage
04	Ohio River	New Cumberland	M/V Garyville	1189925	U	1	8/19/2010 5:23:00 PM	8/19/2010 5:23:00 PM	8/19/2010 6:19:00 PM
72	Ohio River	Willow Island	M/V Garyville	1189925	D	4	8/20/2010 12:08:00 AM	8/20/2010 12:08:00 AM	8/20/2010 12:51:00 AM
04	Ohio River	New Cumberland	M/V Garyville	1189925	D	4	8/20/2010 1:52:00 AM	8/20/2010 1:52:00 AM	8/20/2010 3:00:00 AM
05	Ohio River	Pike Island	M/V Garyville	1189925	D	4	8/20/2010 7:30:00 AM	8/20/2010 7:30:00 AM	8/20/2010 8:26:00 AM
71	Ohio River	Hannibal	M/V Garyville	1189925	D	4	8/20/2010 4:04:00 PM	8/20/2010 4:23:00 PM	8/20/2010 5:23:00 PM
Source: USACE [76]									

These incongruous lockages can be partially explained by limited correspondence to gaps in the LPMS dataset that may be associated with downtime in the LPMS. Overall, across the study area, lockages occurred every 4.9 minutes in 2010 (standard deviation 5.6 minutes), as determined by sorting the lockages by their start-of-lockage time stamp and calculating the number of minutes to the next lockage. Gaps of more than 30 minutes when no lockages were recorded at any of the 32 study area locks were flagged as periods when the LPMS may have been offline; there were 563 such gaps ranging from 60 to 135 minutes (see Appendix 13) over the course of 2010. LPMS is routinely offline (monthly) for scheduled updates, etc. The standard operating practice during these periods is that lockages are to be recorded by hand, and entered into the system once it is back online. It is possible that these lockages appear to be incongruous due to missing lockages that were not entered after the system was back online, although this is difficult to ascertain without a log of system outages.

The data do allow for a time series comparison of factors that might influence the lockage dataset. Figure 9 tracks the monthly frequency of the incongruous lockages, the hours of lock closures, the minutes of LPMS gaps, and the total number of lockages, all normalized to January 2010 rates. The closure rates and incongruous lockage frequencies show similar patterns, indicating a potential causality. Note that the incongruous lockage peaks lead the closure curves slightly, as would be expected if the incongruity is caused by unrecorded lockages associated with sorting out closure backups. These conjectures require further examination of actual operating practices to determine the true cause of the incongruities. Where the incongruity impacted the analyses, these legs were omitted.



Source: derived from USACE [76]

Figure 9. Potential correlations between incongruous lockage sequences and closures, outages and lockages in the Pittsburgh and Huntington LPMS dataset for 2010

Prior theories regarding these types of data incongruities have been suggested (e.g., miscoding vessel identification and timestamps), although these were postulated for the Operations and Maintenance of Navigation Information (OMNI) system (not presently used in the Pittsburgh District) [80]. Examination of the current prevalence of incongruous lockages (e.g., using more recent data and the full non-public LPMS dataset) would reveal whether there is a need to improve data entry procedures. While the overall number of incongruous lockages is low at less than 1%, future potential funding innovations may be based on a per lockage basis, at which time accuracy in recording lockages would become more critical.

2. Using EIA data to assess coal shipments

The EIA Survey 923 (EIA-923) collects monthly and annual data from U.S. powerplants, including data about the fuel receipts by utility [50]. The survey is required by all powerplants and combined heat and powerplants that “1) have a total generator nameplate capacity (sum for generators at a single site) of 1 megawatt (MW) or greater; and 2) where the generator(s), or the facility in which the generator(s) resides, is connected to the local or regional electric power grid and has the ability to draw power from the grid or deliver power to the grid” [68]. Data include limited information about fuel type, contract length, quantities, mine and mine owner, and primary and secondary modes of transportation used to move the fuel to the utility. The 2010 dataset included 59,000 fuel receipt records. From these data, downloaded for 2010, an origin/destination table was developed linking barged transactions between 211 mines and 94 powerplants, giving barged and total tonnage shipped from the mines to each utility. The study area covered 24 powerplants and 73 mines, plus 64 additional mines that ship into the study area (e.g., Powder River Basin (PRB) coal mines). Data were also downloaded for 2009-2013.

A number of the secondary transportation responses were noted as duplicates of the primary transportation modes (e.g., RV RV). Email communication with the EIA staff identified on the survey website indicated that this was a data anomaly for 2010, and that the duplicate codes should be ignored. Several EIA-923 respondents were difficult to place geographically and were omitted from the analyses (e.g., Keysone Fuels, LLC, Conemaugh Fuels LLC). In addition, some powerplants did not identify specific mines as their fuel sources, but instead identified regional sources (e.g., “Multiple WV mines – Kanawha”) – these also were not included in the analyses.

The EIA-923 is designed to collect information from powerplants. Coal shipped to other industrial users, such as metallurgical coking facilities, or for export, is not covered by this survey. While the EIA collects data on industrial coal uses [81], these data are presented in aggregated form that are not useful for regional analyses such as those presented in this dissertation [56].

In general, the LPMS and EIA datasets were stable, fairly free of anomalies, and amenable to robust manipulation and analysis.

C. Vessel trips characterization

Information regarding a vessel’s trip across multiple locks can be derived from the LPMS dataset by examining sequences of lockages. Each entry in the dataset represents a single lockage, which can be assessed as a trip node for which the location and direction of movement of a specific vessel is given. A "vessel trip" represents a one-way movement, which may include one or multiple nodes. To capture the vessel trips that encompassed the 86,362 lockages in 2010, a logic and coding scheme was developed to describe the first and last lock in a vessel's trip. It was then possible to characterize typical trip lengths associated with different vessels or stretches of river.

Criteria were developed to account for cut (or "double") lockages and for differentiating between consecutive trips in the same direction with changing numbers of barges. For example, a towboat that locked down the Monongahela through Charleroi (MN24), Elizabeth (MN23), Braddock (MN22), and continued down the Ohio through Emsworth (OH1) before reversing direction and locking through Braddock again was assigned the trip MN24_OH1. If, however, the towboat pushed three barges through Charleroi and Elizabeth, but then pushed nine through Braddock and Emsworth, two trips were coded, MN24_MN23 and MN22_OH1, reflecting the differences in loads. Coding vessel trips in this way creates a more detailed view of barge operations and traffic.

The coding protocols resulted in the identification of a clustering of the 86,362 individual lockages into 30,599 vessel trips. Each vessel trip was characterized in terms of the total number of barges processed (based on the first lockage in the trip), the tonnage associated with those barges (based on the average barge load at the first lock in the trip). Illogical trip legs were flagged, as discussed previously. The trip lengths were tallied, as well as the cumulative ton-mileage per trip. Transit times were calculated, including delays between arrival at the lock and the actual lockage start time, lockage time, and transit times between locks. Horsepower and age of the locking vessels were drawn in from the USACE vessel dataset.

There are several important limitations to this approach. First, the LPMS dataset gives no information about the transfer of barges from vessel to vessel as a flotilla is moved from its initial loading dock to its ultimate offloading dock. Thus it gives a partial picture of the movement of commodities. Second, the LPMS dataset provides no information about movements within a navigation pool – harbor and helper vessels that assist at specific docks may never or rarely need to lock. Third, the LPMS gives no information about shipment transfers to other modes of transport. These limitations also apply to the aggregated WCUS which does not support high resolution trip analysis [82].

The trip coding can be summarized in an origin/destination (O/D) matrix, using the beginning and ending nodes as approximations for the actual trips. In reality, the towboats pick up and deliver barges at specific docks and landings along the river, data which are not captured in the LPMS dataset (but available to USACE in the proprietary VORs) [21]. Portions of the vessel trips that extend beyond the first and last lock were not considered in this analysis.

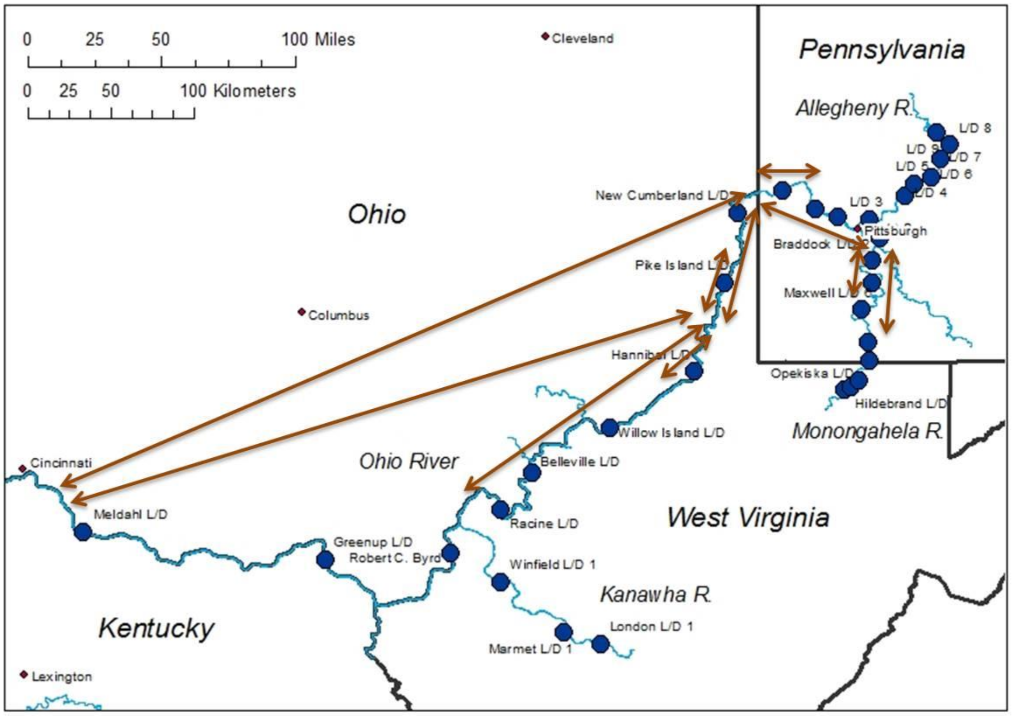
Combined with a mileage O/D matrix and lock-specific ton/barge rates derived from USACE's lock statistics [83], the trips can be characterized and ranked by prevalence (count), tonnage, and ton-mile. The high tonnage trips represent critical commodity movements, trips that are particularly critical to the region's economy. High ton-mile trip rankings correlate with higher fuel consumption and emissions which can be used to prioritize fleet optimization and modernization. High count trips provide a measure of regional traffic intensity. Trips that extend beyond the study area (i.e., below Meldahl (OH25) cannot be fully characterized here. A regional ranking of those trips that originate or end within the Pittsburgh District is provided in Table 22. One trip is ranked highly in all three criteria: OH22_OH71, covering 111 miles of the Ohio River across the Racine, Belleville, Willow Island, and Hannibal locks. This is an important corridor for movement of coal from the Kanawha River mines in West Virginia to the numerous coal-fired powerplants on the middle Ohio. Optimizing river travel in this region, in terms of both vessel and infrastructure investments, will benefit river users and the surrounding communities.

Table 22. Top ten ranked trips terminating within Pittsburgh District, by tonnage, count, and ton-miles, 2010

Trip	Tons (million)	% of total tons	Trip	Count	% of total count	Trip	Ton-mile (million)	% of total ton-miles
OH22_OH71	9.89	10.0%	OH3_OH3	1,167	10.0%	OH25_OH71*	2,019	23.2%
OH4_OH5	7.83	7.9%	MN23_MN25	1,142	9.8%	OH25_OH4*	1,291	14.8%
OH25_OH71*	5.49	5.5%	MN23_MN24	985	8.4%	*OH22_OH71*	1,210	13.9%
OH3_OH3	3.56	3.6%	AG44_AG45	974	8.3%	OH24_OH71	635	7.3%
MN23_MN25	3.32	3.3%	OH4_OH5	793	6.8%	OH22_OH4	496	5.7%
OH5_OH5	3.22	3.2%	MN24_MN24	785	6.7%	OH26_OH71	389	4.5%
MN22_OH3	3.17	3.2%	OH5_OH5	713	6.1%	OH25_OH5*	373	4.3%
OH25_OH4*	2.84	2.9%	OH1_OH1	684	5.8%	OH25_OH72*	373	4.3%
OH71_OH71	2.80	2.8%	*OH22_OH71*	636	5.4%	OH26_OH4	363	4.2%
MN23_MN24	2.51	2.5%	MN23_MN23	569	4.9%	MN22_OH25*	356	4.1%
TOTAL (all trips)	180.5			30,585			18,300	

Italicized trips are in the top ten ranking of all three criteria
Asterisks (*) indicate trips that may be truncated and may extend below OH25, the lowermost lock in the study area.
Source: derived from USACE [76]

Figure 10 shows the top ten tonnage trips with terminal lockages within the Pittsburgh District, illustrating an important aspect of river movements. Five of the top ten trips terminate between Pike Island (OH5) and Hannibal (OH71); multiple mines (e.g., Powhatan 4 and 7, Benwood, McElroy), other industrial docks, several fleeting areas, as well as three powerplants (Burger, Kammer, and Mitchell) are located on this stretch of river [41]. Four of the top ten trips terminate between New Cumberland (OH4) and Montgomery (OH3) where the locks transition from the larger mid-Ohio locks to the smaller upper Ohio locks. Three of the top ten trips terminate between Braddock (MN22) and Elizabeth (MN23) where the locks again constrict. Numerous powerplants and a major metallurgical coke facility are located along these three river stretches. However, they are also common staging or fleeting areas where tows are reconfigured to allow for efficient lockage and commodity delivery [84]. Thus a tow of WV coal loaded below Morgantown on the Monongahela may be reconfigured and handled by several towboats as it moves toward Ohio River powerplants. The full movement of commodity shipments (i.e., commodity trips) thus cannot be seen in the LPMS or VOR datasets when the shipments involve multiple vessel trips and stagings.



Source: derived from USACE [76]

Figure 10. Top 10 Tonnage Trips within Pittsburgh District, 2010.

Fleeting and staging operations are not visible in the LPMS dataset, yet clearly are an important part of commodity movements on the inland waterways. The constriction of the waterways at older and/or smaller locks requires that large tows either be broken into smaller flotillas or subjected to repeated cut lockages to traverse these facilities. Capital projects to remove these constrictions, such as the “Lower Mon Project” (LMP) to replace three antiquated locks with two modern facilities [5], will allow for longer vessel trips and reduced dependence on flotilla breaking.

The LPMS dataset is also limited to those portions of the inland waterways with USACE locks, which does not include the heavily used lower Mississippi. Further, the resolution of the LPMS trip analysis is expected to be less as the distance between locks increases with proximity to the lower Mississippi. In other words, the accuracy of the vessel trip lengths (and subsequent calculation of ton-miles) derived from the LPMS dataset is lessened without actual loading and unloading dock information, particularly in those regions where the locks are hundreds of miles apart.

Understanding the activity level associated with fleeting and staging operations can be developed from automatic identification systems (AIS) [85] [86] [87] [88]. The coverage of the AIS has a primary focus on coastal ports, and does not extend to the entire waterways. The combination of AIS and LPMS data, when available, could provide a more complete picture of the utilization (and value) of the waterways.

D. Commodity trips characterization

Based on data from USACE (and local knowledge), there are several categories of major commodity trips in the study area. Coal for thermoelectric power production (thermal coal) moves from local and distant mines to local and distant coal-fired utilities, accounting for three quarters of all barged commodities in the ports of Pittsburgh and Huntington. Metallurgical coal moves from local and distant mines to local (primarily) and distant metallurgical coking facilities. Raw (such as lime and limestone) and finished materials move to and from local mills and manufacturing plants. These materials account for the large majority of the commodity movements, but other materials are also often barged, including aggregate, mulch, salvaged metals and equipment, road salt, coal combustion residuals, and liquid fuels.

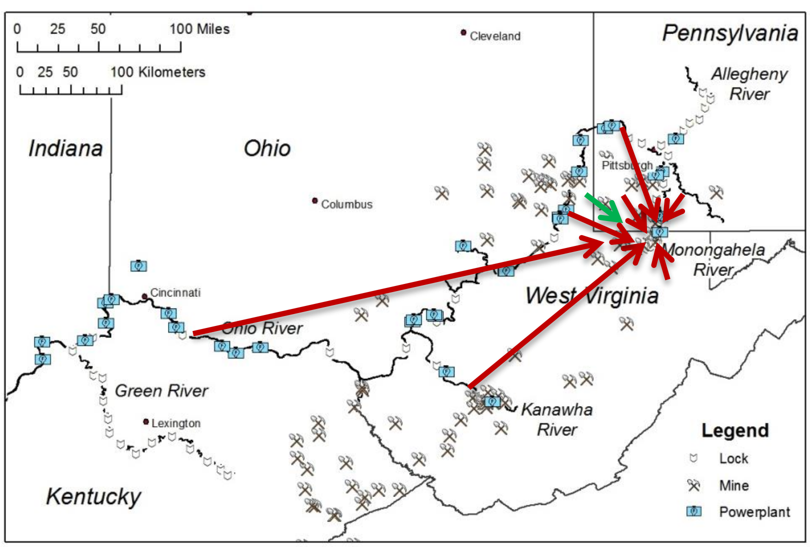
USACE’s LPMS data are based on vessel movements across locks rather than commodity shipments from seller to buyer; USACE’s VOR data can be used to reflect vessel trips between docks or staging areas, a more accurate depiction of vessel trip length. The EIA-923, however, provides good information on fuel shipments such as coal shipments from mines to powerplants, representing more complete commodity trips [50]. (Note that while this analysis focusses on barge trips on the inland waterways, the EIA-923 provides information on all modes of transportation, including rail, truck, tramway, conveyer and pipeline, etc.)

The EIA-923 was used to create a model of thermal coal movements in the study area. The model development methodology is described further in section II.D. Each barged commodity trip was coded using the same nomenclature as for the LPMS data. For example, the Fort Martin power station is located at mile 92 on the Monongahela River, between MN28 and MN29. In 2010, Fort Martin purchased 164,000 tons of coal from the Powhatan No. 6 Mine. The Powhatan mine uses a company-owned transloading facility on the Ohio at Mile 111, below Pike Island (OH5) [89]. This transit accordingly was coded as "OH5_MN28." Note that better trip O/D data can be assigned to the EIA transits based on dock milepoints than is possible for the LPMS trips (without the benefit of the confidential VOR).

An analysis was then conducted to see how well the LPMS trip model correlates with the EIA-based model by comparing how the two models characterize trips ending above the Point Marion lock (MN28). This lock was selected as a terminal for this analysis because there is very little commercial traffic above this lock, other than deliveries to Fort Martin, allowing for isolation of a subset of both vessel and commodity trips (see Table 20). A similar validation process could have been done at the upriver end of other tributaries (e.g., the Allegheny or Kanawha Rivers) where commercial traffic ends, and the complications of through-traffic are avoided. Given the fairly high level of shipments to Fort Martin, this region was expected to serve well for model validation and dataset comparisons.

Overall in 2010, Fort Martin took delivery of 2.7 million tons of coal, virtually all via barge (small amounts were delivered by truck from local strip mines). Half of the delivered coal was barged from WV mines, a quarter from PA mines, and almost 20% from Powder River Basin (PRB) mines. The weighted average barged commodity trip length for coal deliveries to Fort Martin was 325 miles in 2010.

The EIA data show that the average commodity trip length for Fort Martin shortened dramatically over the subsequent three years (320 miles in 2011, 175 miles in 2010, 120 miles in 2013) as Fort Martin has brought a flue gas desulfurization (FGD) unit online and shifted from low sulfur PRB coal to higher sulfur local coal [70]. Figure 11 depicts the commodity trips to Fort Martin reported in the EIA-923.



Source: derived from EIA [50]

Figure 11. Commodity (Coal) Shipments to Fort Martin Power Plant in 2010.

Table 23 summarizes the comparison of the LPMS vessel trip model and the EIA commodity trip model. USACE lockage data reveals 10 unique vessel trips that terminated with a final lockage at Point Marion (MN28), representing an overall delivery of 2.1 million tons of commodities to the region above MN28. Table 24 lists the docks above MN28 and their purpose, as extracted from USACE's dock dataset [41], showing the limited number of receiving docks and solitary powerplant on this portion of the uppermost river.

The EIA-923 commodity trips include 9 unique commodity (i.e., coal) trips to Fort Martin, totaling 2.7 million tons of coal. Note that the observed USACE vessel trips do not match the EIA commodity trips exactly because USACE vessel trips represent the final leg pushed by the last towboat, whereas the EIA commodity trips cover the entire river distance from mine dock to powerplant dock. Also, the EIA trips include 0.9 million tons that are loaded above Point Marion from the Prime No. 1 and Crawdad No. 1 mines (at Milepoint 94.8) and do not require lockage to reach Fort Martin – this tonnage is not visible in the USACE vessel trips.

Adding the 0.9 million tons of non-locked shipments to USACE total locked tonnage of 2.1 million tons gives 3.1 million tons of commodities shipped into the vicinity of Fort Martin. The 0.35 million ton difference between this adjusted USACE tonnage and the EIA tonnage represents the non-coal commodities shipped, expected to be predominantly lime or limestone needed by Fort Martin for its FGD unit. Lime requirements for FGD systems are on the order of 1 ton for each ten tons of coal, or about 0.21 million tons of lime in 2010 for Fort Martin [90]. The remaining difference of 0.14 million tons of unspecified commodities in USACE lockage model is minor, has the proper sign, and is expected to be fuels and aggregates shipped to the BTS and Vance River docks (see Table 24).

Table 23. Comparison of Vessel and Commodity Trips toward Fort Martin, Maidsville, WV, 2010

	USACE Vessel Trip Count	USACE Lockage Trips, All Commodities Tons	EIA-923 Commodity Trips, Coal only Tons
MN22_MN28	63	281,000	-
MN23_MN28	149	576,000	-
MN24_MN28	33	140,000	-
MN25_MN28	130	646,000	638,000
MN26_MN28	161	345,000	287,000
MN28_MN28	8	14,400	22,100
OH1_MN28	7	14,400	-
OH2_MN28	14	64,200	899
OH3_MN28	18	47,600	-
OH4_MN28	-	-	10,800
OH5_MN28	2	2,160	164,000
KA2_MN28	-	-	33,100
OH25_MN28	-	-	623,000
Subtotal (trips with lockages)	585	2,130,000	1,780,000
>MN28 (lockage not required)		976,000 (assumed)	976,000
Total delivered		3,110,000	2,750,000
Sources: derived from USACE [76] and EIA [50]			

Table 24. Docks and Locks on the Upper Monongahela River

NAME	MILE	PURPOSE	COMMODITIES
Point Marion Lock & Dam	90.8		
Allegheny Energy Supply, Fort Martin Power Station Dock	92	Receipt of coal for plant consumption.	Coal, Lignite & Coal Coke | Sand, Gravel, Stone, Rock, Limestone, Soil, Dredged Material | Building Cement & Concrete; Lime; Glass | Primary Non-Ferrous Metal Products; Fabricated Metal Prods. | All Manufactured Equipment, Machinery and Products
Mepco, West Vanvoorhis Dock	94.8	Shipment of coal.	Coal, Lignite & Coal Coke
Rosedale Dock	96.1	Mooring	Coal, Lignite & Coal Coke
Patriot Rail & River Terminal	96.3	Shipment of coal.	Coal, Lignite & Coal Coke
Consol Energy, Humphrey No. 7 Maidsville Dock	96.8	Mooring barges for fleeting.	Coal, Lignite & Coal Coke
BTS/Guttman Oil Co., Star City Dock	97.8	Receipt of fuel oil and kerosene.	Gasoline, Jet Fuel, Kerosene | Distillate, Residual & Other Fuel Oils; Lube Oil & Greases
Vance River Terminal, Westover Dock	99.8	Receipt of miscellaneous dry-bulk materials including sand and gravel; shipment of coal.	Coal, Lignite & Coal Coke | Crude Materials, Inedible Except Fuels | Sand, Gravel, Stone, Rock, Limestone, Soil, Dredged Material
Greer Industries, Morgantown Dock	100.3	Shipment of crushed limestone.	Sand, Gravel, Stone, Rock, Limestone, Soil, Dredged Material
Morgantown Lock & Dam	102		
Greer's Industries, Deckers Creek Morgantown Dock	102.9	Shipment of crushed limestone.	Sand, Gravel, Stone, Rock, Limestone, Soil, Dredged Material
Morgantown Industrial Park, Wharves 1 And 2	103		Sand, Gravel, Stone, Rock, Limestone, Soil, Dredged Material
Hildebrand Lock & Dam	108		
Opekiska Lock & Dam	115.4		
Marion Docks, Hoult Dock	124.6	Receipt of magnetite; and shipment of coal.	Coal, Lignite & Coal Coke | Iron Ore and Iron & Steel Waste & Scrap
Source: USACE [41]			

The EIA model provides the tools needed to track the entire trip length between mine and powerplant, regardless of how many different vessels take part in the transit. This capability differs from the trips derived from the LPMS data and from USACE'S proprietary VOR which are limited to characterization of trips taken by individual vessels. The example given above for Fort Martin and the Point Marion lock could be expanded to reflect all barged coal transits.

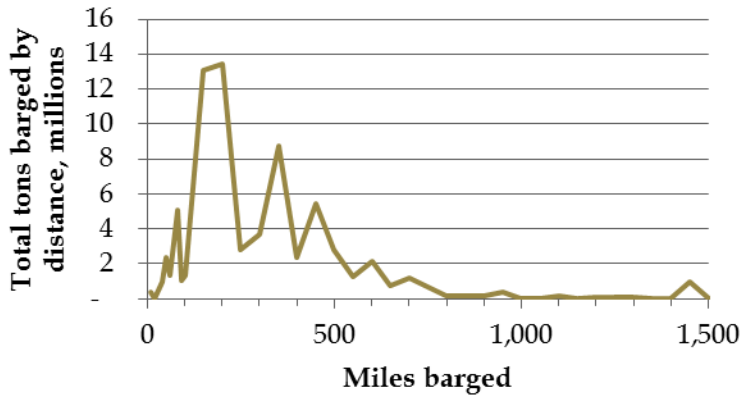
E. Trip length and shipping rate characterizations

Shipping rates have many components, including distance traveled, tonnage moved, loading and transloading [91]. The EIA-923 survey contains valuable data for shipments of fuel to powerplants. The following discussion continues to focus on the study area, but could be expanded to examine other regions.

A typical measure of shipping rates is expressed in $/ton-mile, which allows for comparisons across modes. The EIA-923 allows for the calculation of cost, tonnage, and trip lengths, which can be combined to give $/ton-mile.

Within the study area, the average commodity trip length in 2010 was 256 miles (see Figure 12), based on 2,200 transactions (see Appendix 15 for the powerplants and shipments included in this set, by mine state). The majority of trips are less than 500 miles, with the longer trips representing PRB shipments transloaded from rail to barge on the upper Mississippi.

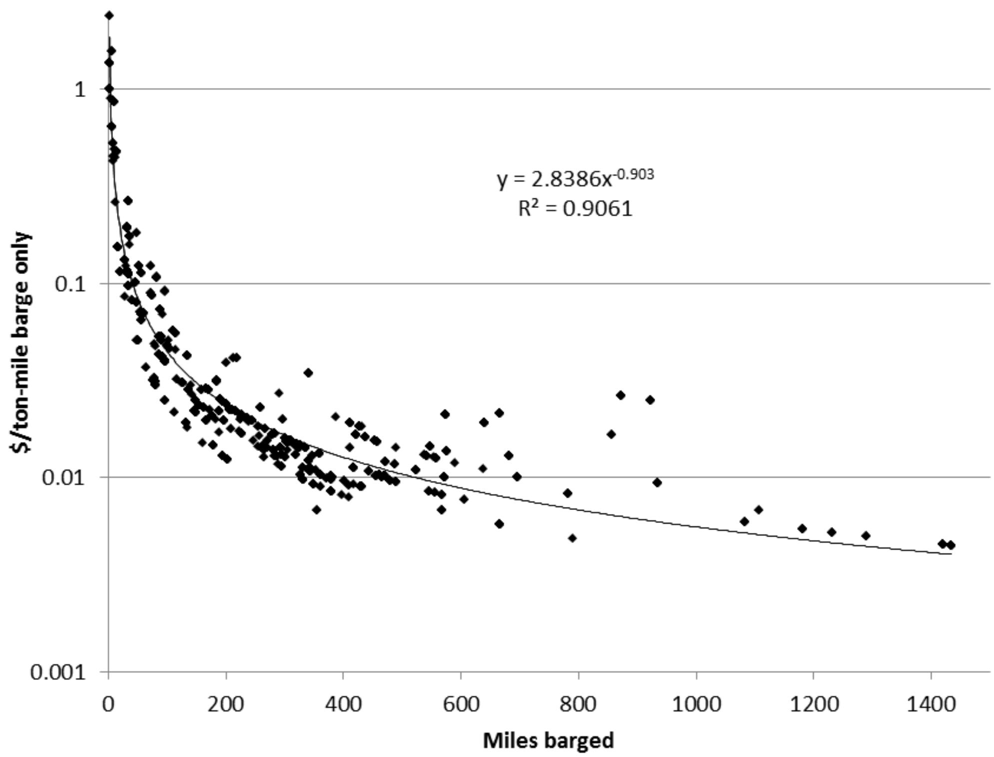
As discussed above, the accuracy of the commodity trip length analysis is dependent on establishing appropriate coordinates for dock locations for the mines that transload from rail or truck; mines and powerplants with dedicated docks are well identified in USACE's dock datasets [41]. Appendix 16 provides a distribution of the 1,400 barged transactions for which mileage has not been calculated, 880 of which are outside of the upper Ohio River Basin (i.e., Pennsylvania/ Ohio/West Virginia). In addition, 520 of these 1,400 uncharacterized transactions have unspecified coal mine identifications, complicating their mileage determinations (many of these problematic transactions are associated with Kanawha mines which are frequently lumped together). Further work could differentiate shipments to southern powerplants (Alabama, Florida, in particular) from West Virginia, Kentucky, and Illinois mines, as well as shipments on different segments of the Ohio and Mississippi Rivers.



Source: derived from EIA [50]

Figure 12. Length of coal shipments to upper Ohio River basin powerplants, 2010.

The EIA-923 includes data on the delivered cost of the powerplants' fuel (included in the public dataset), as well as the commodity cost of that fuel (not released in the public dataset). For coal, EIA calculated the shipping rate ($/ton) from these two data elements, and released it in aggregated form for barge, rail, and truck. EIA notes that their aggregated data represents better coverage than the Surface Transportation Board (STB) Carload Waybill Survey as it represents a full survey rather than a sample [71]. Shipping rates were extracted from the EIA aggregations and applied to each shipment within the study area. For example, EIA reported a barge shipping rate of $8.97/ton in 2010 for shipments from Pennsylvania mines to West Virginia powerplants. This rate was then associated with the matching coal transactions in the EIA-923 dataset. The shipping rate ($/ton-mile) was then calculated for each shipment. A regression analysis shows the expected clear power relationship between the shipping rate (2010$) and the distance traveled (Figure 13, note the logarithmic vertical axis).



Source: derived from EIA [50], [71]

Figure 13. 2010 Barge shipping rates to powerplants in USACE Pittsburgh and Huntington Districts.

At the average trip length for the study area of 256 miles, the regression gives a shipping rate of $0.019/ton-mile for 2010 shipments. EPA uses a shipping rate of $0.0115/ton-mile ($2012) for the upper Ohio in its regulatory impact analysis of nonroad diesel engine regulations [64], and thus underestimates shipping costs for the trips within the study area by 44% (after adjusting to 2010$). At a trip length of 446 miles, the EPA rate gives the same shipping cost as the regression model shown here. Note that the USDOT Research and Innovation Technology Administration (RITA) reported $0.0183/barged ton-mile ($2011) for 2004, the last year that RITA updated barge shipping costs [92]. After adjusted to $2010, the RITA rate is comparable to $0.017/barged ton-mile which overestimates shipping costs by over 20% at the average shipping distance within the study area. A similar analysis was conducted for the Illinois waterway, with a presentation of a regression for barge shipment costs for aggregate [21]. The Illinois waterway results do not correlate well with the results presented in this dissertation, probably due to regional and commodity differences. A study recently released by Kruse et al provides shipping rates derived from survey results for three regions (the Gulf Intracoastal Waterways-East, the Arkansas River, and the Red River) [93]. Extension of this methodology to these regions would provide additional validation.

F. Conclusions

A methodology was presented for extracting vessel trip information from the LPMS, and complementary commodity trip information for coal from the EIA-923. The vessel trip method allows for the assessment of frequency, ton-miles, and tonnage for trips made within the inland waterways. Ranking of these criteria can be used for prioritization of optimization projects, as well as for assessing usage patterns. Individual vessel trips, however, are often only a component of longer commodity trips. The EIA-923 survey provides a valuable tool for understanding the commodity trips for fuels delivered to powerplants. In this study, EIA-923 data for coal barged to powerplants within the study area were examined and compared to corresponding vessel trips. Good conformance between the datasets is demonstrated.

These findings are valuable because they highlight the difference between vessel trips and commodity trips. Each transfer of tows between vessels represents a change in activity level, with implications for cost, efficiency (time and fuel), and run-of-the-river congestion at staging areas. Transfers in the upper inland waterways are related to infrastructure constrictions in the waterways. Transitions between larger and small locks correlate with high levels of transfers. Cost models of commodity trips must consider these transfers between vessels.

The EIA-923 provides valuable information about shipping rates and commodity trip lengths. Barge rates within the study area follow a power curve strongly dependent on trip length. National shipping rates generally overestimate barge shipping costs for coal in the upper Ohio River Basin.

Future analyses could extend the vessel and commodity trip analyses to other regions of interest within the inland waterways. Some uncertainty is inserted into the LPMS analysis by the methodology to identify cut lockages – incorporation of cut lockage designations by USACE into the public dataset would not reveal proprietary data, but would add accuracy to analyses such as those presented in this section (as well as section IV). The EIA analysis could be extended to rail or truck, with respect to both the commodity trip analysis and the shipping rates. As Automatic Identification System (AIS) coverage extends to the upper waterways, additional information about activity levels within navigation pools can be added to the understanding of what it takes to move commodities from origin to destination. Section V describes an approach to using the vessel trip methodology as part of an air emission model to examine vessel impacts on local air monitors.

IV. Alternative Methods to Assess Inland Waterways Efficiency[4]

A. Introduction

Research Goal 2: Assess current and potential new efficiency metrics for the inland waterways

The inland rivers of the United States are heavily used components of the nation's freight network, connecting the interior of the continent with the Gulf of Mexico, Great Lakes and Pacific Northwest. These freight corridors are well suited to the shipment of bulk and containerized commodities internally and to export markets. Regional differences in the role of the inland waterways exist, reflecting differences in regional economic drivers. Grains shipments are predominant on the upper Mississippi River, while coal is the major commodity shipped within the upper Ohio River basin [1]. Regional differences can also be observed in the infrastructure required to maintain efficient commercial navigation. USACE is charged with maintaining the navigability of the inland waterways, including the operation of an extensive series of locks and dams needed to provide navigation pools in the upper reaches of the waterways. The purpose of this analysis was to assess the efficiency and remaining capacity limitations of the upper reaches of the inland waterways, with a particular focus on the upper Ohio River basin.

The motivation for this work was to extend the existing toolset used to assess the inland waterway infrastructure. USACE reports extensive statistics describing the tonnage and commodities handled by the system, including tallies of delays and closures at its 191 locks. USACE also conducts detailed infrastructure analyses in support of investment decision making [84]. Extensive national analyses have recently been done by industry groups as part of recent successful efforts to encourage the U.S. Congress to pass the Water Resources Reform and Development Act of 2014 [32], legislation needed to authorize updated funding strategies for the

[4] Submitted for consideration. Gwen Shepherd DiPietro, Chris T. Hendrickson, H. Scott Matthews. "Alternative Methods to Assess Inland Waterways Efficiency." Transportation Research Record. August 2014.

inland waterways infrastructure [7] [94]. The analyses described here provide useful additional characterizations of the ways the rivers are used and constrained.

Using USACE's operational data for calendar year 2010, analyses have been conducted to examine underlying usage patterns and to predict improvements in efficiency (Objective 2.2). These analyses were then used as the basis for a scenario analysis that models the barged regional movement of coal between a mine and powerplant (Objective 2.3). The scenario analysis shows the time savings that may be accrued by the eventual completion of a long under-funded infrastructure rehabilitation project [5]. This section presents the following analyses, as illustrated in Figure 14:

- Characterize lock efficiency (Objective 2.2)
    - Characterization of the locks and their capacity
    - Time profiles associated with using the locks (delays, time required to lock, closures)
    - Usage patterns
- Estimation of shipping time savings from completion of a long delayed construction project to modernize the lower stretch of the Monongahela River (Objective 2.3).

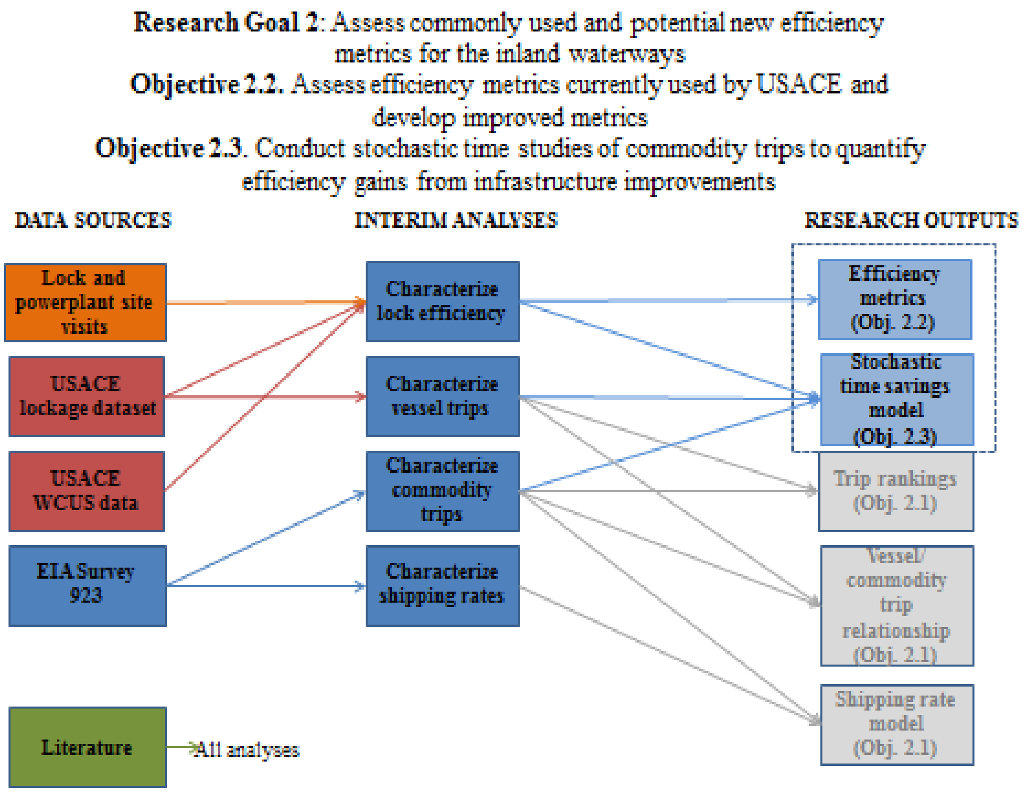


Figure 14. Research Goal 2, Objectives 2.2 and 2.3 Flow Diagram

B. Background

The study area for this research includes 129 navigable miles of the Monongahela River, which runs north from West Virginia into Pittsburgh, 72 navigable miles of the Allegheny River, flowing from the northeast into Pittsburgh, and the upper 440 miles of the Ohio River, running from the confluence of the Monongahela and Allegheny Rivers in Pittsburgh toward Cincinnati. The USACE's Pittsburgh and Huntington Districts operate 32 locks and dams across this region [83]. Without engineering controls, the region's rivers would not naturally support year round navigation. The region's first full lock and dam structures were built prior to the Civil War; the extent of navigable waters expanded rapidly through the early 1900s to support the heavy industrialization of the Pittsburgh region [28]. The waterway infrastructure has been expanded, redesigned, and rebuilt, lock by lock, continuously since that time. On the Monongahela alone, six facilities have been built, served their useful life, and subsequently been completely removed – either replaced in more advantageous locations, or eliminated by the use of improved dam technologies which allowed for fewer lift steps [28].

USACE continues to improve and update the region's river infrastructure. The first phase of the "Lower Mon Project" (LMP), replacement of the Braddock dam, was completed in 2004. The second phase, to replace the narrow 1936 locks at Charleroi with 84'x720' twin chambers, was originally scheduled to be completed in 2004 but has been long delayed due to funding limitations. When the first new chamber at Charleroi is completed, the narrow 1907 locks and dam at Elizabeth will be removed.

Nationally in 2012, the inland waterways system transported 2,307 million tons of commodities, of which 885 million tons were domestic. The Port of Pittsburgh is the 21st busiest port in the Nation, handling 35.1 million tons in 2012; the neighboring Huntington Port handled 52.9 million tons [1].

Efficiency of the existing infrastructure has been assessed in a number of ways for the purpose of supporting investment decisions, and to identify operational opportunities for time savings [95] [96] [2].

Using Lockage Data to Assess River Infrastructure Utilization

The analyses presented here are drawn primarily from USACE's Lock Performance Monitoring System (LPMS) and Waterborne Commerce of the United States (WCUS) data, described previously in section II. NDC provided a subset of the raw LPMS 2010 data for the Pittsburgh and Huntington Districts [76], including lock and vessel identification, number of barges processed, and times of arrival-, start- and end-of-lockage. Data did not include chamber identification (main or auxiliary), whether the barges were loaded, commodities, or type of lockage (single, double, fly, cutback, etc.). The dataset, at over 106,000 records and covering a full year of operations across 32 locks, provides a valuable opportunity for close examination of lock efficiency.

C. Lock characterization

Objective 2.2: Assess efficiency metrics currently used by USACE and develop improved metrics

Moving downriver, the locks increase in size, are separated by increasingly longer distances, and handle progressively greater tonnage (see Table 25). Most of the heavily used locks have both a main chamber (which handles the majority of the commercial tows) and a smaller auxiliary chamber (which handles more of the recreational vessels and serves as a backup in case of main chamber closure or congestion). The Charleroi auxiliary chamber has been closed since 2004 to allow for construction of new larger locks. None of the Allegheny River locks nor the Monongahela River locks above Maxwell have auxiliary chambers.

All of the main chambers below Elizabeth are 110 feet wide, whereas the Elizabeth and Charleroi locks (and all of the Allegheny River locks) are only 56 feet wide. Chamber length also varies; the Allegheny locks are only 360 feet long, while all of the Ohio River main chambers below Montgomery are 1,200 feet long. These fixed dimensions dictate the number and size of the barges that can be processed in a single lockage.

The barges typically used in the study area are open dry cargo barges. The industry standard for this type of barge is known as a "jumbo" barge (35'x195-200'). There are, however, smaller barges used regionally, particularly on the Allegheny and on the constricted portions of the Monongahela. "Standard" (26'x175') and "stumbo" (26'x195') barges can be locked in double-wide tows through these smaller locks. USACE's Ohio River Navigation Investment Model (ORNIM) assumes standard, stumbo, and jumbo barge capacities of 1,069, 1,121, and 1,669 tons, respectively [84]. Actual tonnage is a function of loading depth. National analyses of the value of the inland waterways make the general assumption that the typical barge is a 1,750 tons jumbo [7] which overstates the efficiency of operations in the constrained upper waterways where smaller barges (as well as smaller flotillas) are still used.

Table 25 gives the maximum number of standard and jumbo barges the main chambers at each lock can process with a single cut. The large locks below Montgomery can process 18 jumbo barges per lockage (three abreast, six deep), while the Charleroi lock can only process 3 single-file jumbo barges at a time.

Smaller barges continue in use on the upper rivers. Local carriers maintain stumbo inventories to accommodate the restricted width of local locks [97]. Barge registration data show that the average barge capacity in the Pittsburgh District is 1,200 tons with 60% of the barges having widths of 26-27 feet; the downriver Huntington District-based barge fleet average 1,670 tons with only 16% of the fleet having widths of 27 feet [41].

Table 25. Lock Capacities in the USACE Pittsburgh and Huntington Districts, 2010

Lock and Lock ID	2010 Commodity Tonnage	Miles from Pittsburgh confluence	Main Chamber								Auxiliary Chamber						Max #	
			Width			Length					Width			Length				
			56’ (17m)	84’ (26m)	110’ (34m)	360’ (110m)	600’ (183m)	720’ (245m)	800’ (272m)	1200’ (266m)	56’ (17m)	84’ (26m)	110’ 34m)	360’ (110m)	600’ (183m)	720’ (219m)	Standard	Jumbo
Emsworth-OH1	15.3	6.2			x		x				x			x				
Dashields-OH2	16.4	13.3			x		x				x			x			12	9
Montgomery-OH3	18.2	31.7			x		x				x			x				
New Cumberland-OH4	26.3	54.4			x					x			x		x			
Pike Island-OH5	30.0	84.2			x					x			x		x			
Hannibal-OH71	42.3	126.4			x					x			x		x			
Willow Island-OH72	41.8	162			x					x			x		x		24	18
Belleville-OH21	44.6	204			x					x			x		x			
Racine-OH22	45.6	237			x					x			x		x			
R.C. Byrd-OH26	50.4	279			x					x			x		x			
Greenup-OH24	56.4	341			x					x			x		x			
Meldahl-OH25	57.7	436			x					x			x		x			
Braddock-MN22	14.8	11.2			x			x			x			x			16	9
Elizabeth-MN23*	11.3	23	x					x			x			x			6	3
Charleroi-MN24**	11.2	41.5	x					x										
Maxwell-MN25	10.2	61.2		x				x				x				x		
Grays Landing-MN27	4.6	82		x				x									12	6
Point Marion-MN28	4.5	90.8		x				x										
Morgantown-MN29	0.24	102		x			x										9	6
Allegheny L&D2-AG42	1.22	6.7	x			x												
CW Bill Young-AG43	1.21	14.5	x			x												
Allegheny L&D4/AG44	0.99	24.2	x			x											4	1
Allegheny L&D5-AG45	0.82	30.4	x			x												
Allegheny-AG46	0.01	36.3	x			x												
Allegheny-AG47	0.01	45.7	x			x												
Winfield-KA1	19.9	297			x				x		x			x			16	12
Marmet-KA2	14.6	334			x				x		x			x				
London-KA3	3.5	349	x			x					x			x			4	1

OH - Ohio River; MN - Monongahela River; AG - Allegheny River; KA - Kanawha River
Locks without commercial lockages in 2010 are not shown: Hildebrand (MN29), Opekiska (MN30), AG48 and AG49.
*Scheduled to be removed upon completion of new river chamber at Charleroi
**Construction underway to replace with twin 84x720’ chambers
Source: derived from USACE [44]

The limitations that lock dimensions impose on commodity flow can also be seen by examining the typical tonnage per loaded barge at each lock, calculated from USACE's lock statistics [83]. Allegheny River barges have an average loaded barge tonnage of only 800-1,200 tons/barge, allowing the smaller locks to be used most efficiently. The first three (and most heavily used) locks on the Monongahela typically see barges averaging 1,300-1,400 tons per barge, with smaller barges used upriver (1,100 tons/barge). Still larger barges are used on the Ohio, with the average tonnage/barge at a lock being directly related to the larger lock chamber configuration and proximity to the Mississippi. This differentiation in barge size and tonnage is important for the accurate calculation of ton-miles and operating costs.

USACE does not track barge sizes in the LPMS or the VOR. The LPMS does, however, record how many barges are processed per lockage, providing an additional indicator that smaller barges are still used. On the upper Monongahela, the LPMS shows that many tows exceed the maximum jumbo capacity, indicating that the tows consist of smaller barges. For example, Grays Landing-MN27 can handle 12 standard or 6 jumbo barges. In 2010, 371 of the 1,265 MN27 lockages had tows of more than 6 barges. Similarly sized Maxwell and Point Marion processed 651 and 365 tows larger than 6 barges in 2010. The Pittsburgh District has a number of even smaller barges registered and in use (42 barges at 26’x135’ and 59 barges at 26’x148’).

The national analysis assumption of a barge capacity of 1,750 tons overstates efficiency for tows in the upriver regions [7]. Similarly, the general assumption of a tow consisting of 15 jumbo barges is not feasible within the study area, as the locks are too small for this size. Although the LPMS dataset does not denote whether a lockage is part of a cut operation, cuts can be deduced from reported timestamps and number of barges processed during subsequent lockages. The total number of barges processed in the cut operations can be calculated to estimate the run-of-the-river flotilla size. None of the flotillas processed via cut lockages above Braddock-MN22 had 15 barges in 2010. This flotilla limitation is also determined by the constriction of the river itself as it narrows toward its headwaters. Navigation also is limited by the available clearance under the Monongahela's many bridges – the larger towboats typically used for the larger tows are too tall to work this stretch of the inland waterways (average vessel height at Charleroi, 28 feet; Meldahl, 39 feet).

D. Time requirements for lock passage

> **Objective 2.2**: Assess efficiency metrics currently used by USACE and develop improved metrics

The time required for a vessel to complete a shipment on the inland waterways includes time to pick up a tow, underway movement on open water, approaching locks and entering any queues (i.e., delay), passage through the locks, and delivery of tows to fleeting areas or final destinations [84]. The following analyses explore underlying patterns of note for delays, lockage time, and lock closures.

1. Wait time calculation

USACE reports general statistics about the amount of time **vessels** and **tows** spend waiting to enter a lock chamber, i.e., "delay" by lock chamber [98]. USACE defines "delay" as a "wait time greater than zero minutes" between the arrival point and start of lockage. USACE's statistics for **vessels** include all locking vessels, including both commercial and recreational vessels. Delays associated with recreational lockages are not reported separately in USACE's annual reports. Recreational boaters often lock in groups of vessels. Commercial vessels are given precedence over boaters [57]. Both factors impact the delay statistics that include recreational vessels. USACE's statistics for **tows** only includes those commercial lockages with barges. Given that there are thousands of recreational lockages, as well as thousands of commercial lockages without tows, the lockage dataset was examined with a focus on delays to commercial vessels (regardless of whether they accompanied tows).

As a first step, the dataset was queried to ensure that the statistics reported by USACE could be replicated from the raw data. This effort was only partially successful. The analysis of the raw data shows excellent conformance for the number of lockages, the breakdown between commercial and recreational lockages, tons processed, and the number of barges processed. The full match for these variables indicates that the raw data is representative of the dataset used to generate USACE's statistics. It was not possible, however, to replicate the number of tows (i.e., commercial lockages with barges), the frequency of tow delays, the average length of delays, or the total number of hours delayed. Assuming there is not a calculation error imbedded in the raw data analysis given here, the USACE statistics perhaps warrant further explanation in their derivation. Table 26 provides an example comparison between the USACE's statistics and the calculated raw data statistics for the Charleroi and Emsworth locks. The differences in the breakdowns between commercial, recreational and other types of lockages are small and reflect unimportant differences in categorization of vessels. More significantly, the USACE reported 5,654 **tows** at Charleroi (those commercial vessels locking with barges) to be comparable to the 5,660 reported commercial lockages overall – implying incorrectly that all commercial lockages involve barges. The raw data, however, shows that only 4,501 of Charleroi's commercial lockages involved barges and thus met the USACE's definition of **tows**. The USACE statistics show a 37% delay rate for Charleroi tows, while the raw data analysis shows that 41% of Charleroi's tows are delayed. The variances between the official statistics and those calculated from the raw data are different for Emsworth. The number of Emsworth **tows** is similar for both USACE and raw data analyses, however, the raw data show more delayed tows at Emsworth than the USACE statistics (reversing the pattern seen at Charleroi). The delays calculated for Emsworth from the raw data are significantly higher than those reported by USACE.

Table 26. Comparison of lock statistics from USACE and raw data for Charleroi and Emsworth

Lock statistics	Charleroi/MN24		Emsworth/OH1	
	USACE	Calculated from Raw Data	USACE (sum of main and aux chambers)	Calculated from Raw Data
Lockages, total (count)	5,825	5,825	6,348	6,347
Commercial	5,461	5,459	4,873	4,866
Recreational	353	353	1,368	1,369
Other	11	13	107	112
Barges (count)	15,817	15,806	18,811	18,743
Tons	11,166	11,158	15,326	15,271
Tows (with barges) (count)	5,654	4,501	3,929	3,954
Delayed tows (with barges, >0 minute wait) (count)	2,107	1,862	1,150	1,951
Average delay of ALL tows (hours)	0.28	0.27	1.18-main 2.15-aux	4.83
Average delay of delayed tows (hours)	0.60	0.64	2.74-main 2.39-aux	9.79
Total delay (hours)	1,306	1,194	5,757	19,102
Sources: USACE [44], [76]				

Email exchanges with the NDC staff who supplied the raw data regarding these discrepancies did not provide clarity. Consideration of cut lockages (i.e., counting only delays associated with the first pass through a lock during a cut lockage) was explored as a potential (but ultimately unsatisfactory) explanation for the differences in reported and calculated statistics. It is also possible that USACE's method is applied differently during periods of lock closure, which may explain the significant difference in delay times at Emsworth between the USACE and raw data statistics – Emsworth's main chamber was closed for most of May 2010 for major repairs, resulting in major delays (16,864 hours total from the raw data) as the tows were processed through Emsworth's small auxiliary chamber. To the extent that delay statistics are used to assess lock efficiency (e.g., time series to assess patterns of delays), resolution of this underlying question of a reproducible method for calculation of those delay statistics is needed.

The question of an appropriate delay calculation methodology should include consideration of cut lockages, as these multi-pass lockages contribute directly to the transit times. Three sequences of lockages, extracted from the raw dataset, are presented below (see Table 27), showing three different multi-pass sequences for a large 12-barge tow transiting small locks. The first sequence shows the Mary Rose passing upriver through the three uppermost Ohio locks on June 6th, breaking her tow of 12 barges in two at each lock. The arrival timestamps for the two lockages at each lock are identical (e.g., 8:34am for the two cuts at OH3, 16:30pm at OH2, and 20:23pm at OH1). The start-of-lock (SOL) timestamps for the cuts at each lock differ, reflecting the first and second passes through each lock (e.g., 9:17am and 10:28am at OH3). The calculation of delays should clarify how the apparent and real delays are handled. Upon arriving at OH3, the Mary Rose was delayed by 43 minutes before beginning her first cut. Using the assigned arrival time, the second pass through OH3 was delayed 114 minutes, which includes the same 43 delay minutes tallied for the first pass, as well as additional time needed to turn around the lock and perhaps clear a downbound vessel. Should the 43 minute delay be counted twice? Should the arrival date stamp be the same for both passes? USACE's methodology should (but does not) describe how it handles this type of lockage.

The second sequence of lockages shows the Mary Rose again locking upriver through OH3, OH2 and OH1 pushing 12 barges in October of 2010. On this transit, however, she appears to be using both lock chambers concurrently – the main chamber processing the 12 barges and the Mary Rose using the auxiliary chamber. The arrival times differ (e.g., 6:46am and 7:53am at

OH3). For each set of lockages, the barges passing through the main chamber experience a delay between arrival and SOL (26, 34 and 89 minutes, respectively at OH3, OH2, and OH1), while the towboat does not. It is unclear whether the delay experienced by the barges would be tallied in USACE's statistics, since the towboat locks separately – does this qualify as a **tow** since only the barges are being delayed?

The third set of lockages shows the Tom Hoffman clearing 12 barges across the Elizabeth and Charleroi locks. This maneuver requires three passes per lock. During the first pass, the Tom Hoffman takes 6 barges upriver. The Tom Hoffman locks down river alone on the second pass. After picking up the remaining 6 barges, the Tom Hoffman and 6 barges make the third pass. At Elizabeth, the third pass was delayed 47 minutes, and at Charleroi, the first pass was delayed 15 minutes. Both delayed passes met the **tow** definition. While there are not apparent issues associated with the calculation of delays for this sequence of lockages by the Tom Hoffman, the differences in lockage methods, application of timestamps, and possible delays at different points in the cut maneuvers point out the need for clear methodologies for delay calculations. Note that the impact of the uncertainty about USACE's delay methodology is of particular interest for the upper reaches of the inland waterways where the smaller locks frequently require cut lockages.

Table 27. Sample cut lockage extracts from raw LPMS dataset

River lock	Vessel name	Vessel #	Direction	# processed	Arrival date	SOL date	End of lockage	Wait to lock (min)
OH3	Mary Rose	675220	U	6	06/06/2010 08:34	06/06/2010 09:17	06/06/2010 10:27	43
OH3	Mary Rose	675220	U	6	06/06/2010 08:34	06/06/2010 10:28	06/06/2010 11:33	114
OH2	Mary Rose	675220	U	6	06/06/2010 16:30	06/06/2010 16:30	06/06/2010 17:51	0
OH2	Mary Rose	675220	U	6	06/06/2010 16:30	06/06/2010 18:01	06/06/2010 19:00	91
OH1	Mary Rose	675220	U	6	06/06/2010 20:23	06/06/2010 20:23	06/06/2010 21:46	0
OH1	Mary Rose	675220	U	6	06/06/2010 20:23	06/06/2010 21:59	06/06/2010 23:18	96
OH3	Mary Rose	675220	U	12	10/07/2010 06:46	10/07/2010 07:12	10/07/2010 08:50	26
OH3	Mary Rose	675220	U		10/07/2010 07:53	10/07/2010 07:53	10/07/2010 08:28	0
OH2	Mary Rose	675220	U	12	10/07/2010 15:20	10/07/2010 15:54	10/07/2010 17:03	34
OH2	Mary Rose	675220	U		10/07/2010 16:27	10/07/2010 16:27	10/07/2010 16:47	0
OH1	Mary Rose	675220	U	12	10/07/2010 18:35	10/07/2010 20:04	10/07/2010 21:33	89
OH1	Mary Rose	675220	U		10/07/2010 20:39	10/07/2010 20:39	10/07/2010 20:51	0
MN23	M/V Tom Hoffman	922485	U	6	09/22/2010 16:59	09/22/2010 16:59	09/22/2010 17:44	0
MN23	M/V Tom Hoffman	922485	D		09/22/2010 18:10	09/22/2010 18:10	09/22/2010 18:33	0
MN23	M/V Tom Hoffman	922485	U	6	09/22/2010 19:50	09/22/2010 20:37	09/22/2010 21:26	47
MN24	M/V Tom Hoffman	922485	U	6	09/23/2010 02:45	09/23/2010 03:00	09/23/2010 04:01	15
MN24	M/V Tom Hoffman	922485	D		09/23/2010 05:33	09/23/2010 05:33	09/23/2010 05:55	0
MN24	M/V Tom Hoffman	922485	U	6	09/23/2010 06:18	09/23/2010 06:18	09/23/2010 07:06	0
Source: USACE [76]								

2. Causes of delays

Delays can be caused by many factors, including planned or unplanned closure of a chamber for repairs or maintenance, weather, and river traffic. Infrastructure requires maintenance that temporarily can reduce usage or create delays. The significance of a delay is proportionate to the length of that delay. Encountering a full lock chamber can be considered comparable to a red light on the roadways – a routine and inescapable part of transiting a given region. In contrast, increasingly frequent delays caused by failing aged equipment are more problematic for waterway users.

Figure 15 illustrates these factors for the locks in the study area, disaggregating the commercial lockages with no delays, short delays (less than the average time to lock), and longer delays associated with planned and unplanned closures. The majority of lockages experience no or short delays. Focusing on the Emsworth lock, in 2010, 22% of the 6,348 lockages were recreational vessels. The main chamber was closed for most of May for major announced repairs [99]. During the closure, tows that could not be re-scheduled were shuttled through the auxiliary chamber and were subject to significant delays. Overall, the average delay for all commercial vessels was 4.1 hours, although 55% of the lockages experienced no delay at all. Focusing on the delayed lockages, the average wait time was 9.2 hours. This value is heavily influenced by the delays caused by the May closure – eliminating the 370 May lockages from the subset of lockages that were delayed reduces the average delay to 1.6 hours. Thus USACE’s method for reporting delays could be further broken down to reflect extended delays associated with planned and major closures separately from delays associated with unplanned closures, as well as insignificant delays that are comparable to traffic control delays on roads.

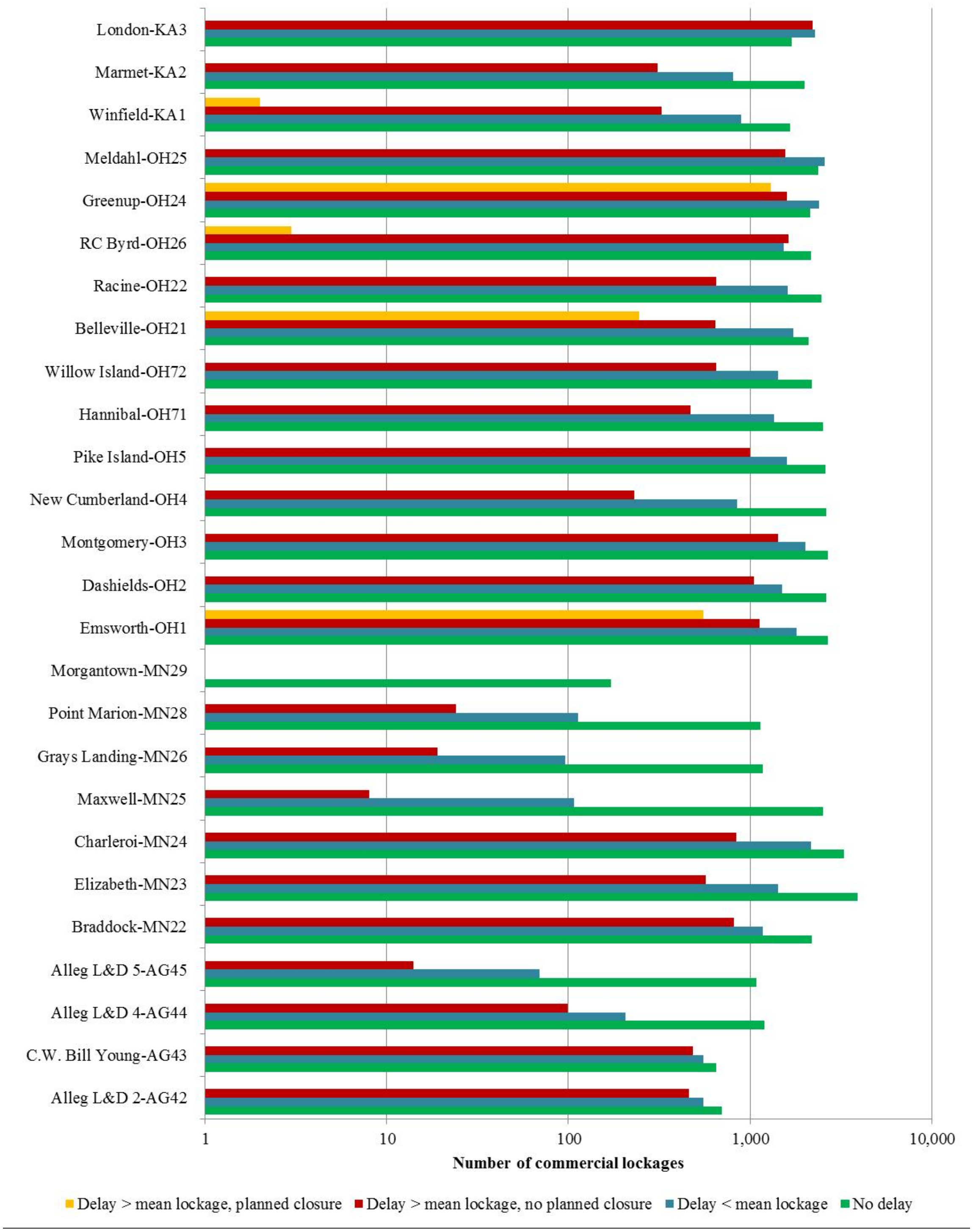


Figure 15. Delays at locks in USACE Pittsburgh and Huntington Districts in 2010 [76].

3. Variability in delay calculations

Delay time calculations are dependent on two variables – the reported arrival and start-of-lock times. The start-of-lock time is defined fairly narrowly as the point in time when the tow or vessel crosses the sill of the lock. The arrival time, however, is set when the approaching vessel radios the lock to formally announce its arrival. This timestamp is not determined at a specific physical location, and thus can vary. The range and significance of this variability does not appear to have been examined in the literature, but certainly impacts the calculation of delay times. For example, if a vessel radios while still underway to secure a favorable queue position, the resultant delay time will be longer than if the vessel calls upon arrival at a designated location.

4. Vessel versus "tow"

As noted above, USACE reports its delay statistics for **vessels** (of any type) and for **tows** (i.e., vessels pushing one or more barges). The vessel statistics combine commercial and recreational lockages, while the tow statistics ignore those commercial vessels who transit the locks without barges. As shown above with the three cut lockage examples, towboats with barge tows will traverse locks separately from their barges as part of efficient lock maneuvers, while encountering delays that might not be tallied in USACE's statistics, or perhaps being double counted, depending on the type of lockage. Overall across the study area, about 10% of commercial lockages involve towboats without barges, with this rate being somewhat higher on the Monongahela, Allegheny and upper Ohio, and lower on the Ohio below Montgomery/OH3. These vessels are delayed about 29% of the time, the same rate that **tows** are delayed. Although these delays are not (apparently) included in the USACE statistics, they accounted for almost 5,000 hours of delay in the study area in 2010. Including these values in the USACE tally of delay hours would increase the total delay statistics by 5% (using the statistics calculated from the raw data).

These alternative ways of describing the likelihood and magnitude of delays that a vessel might encounter are potential tools to prioritize major maintenance projects at locks with exceptionally high rates of extended unplanned delays (e.g., OH3, OH26, OH24, OH25, KA3). First, however, USACE should establish and explain a clear methodology for its calculation of delay statistics.

5. Lockage time

Lockage duration is determined by the physical capacity of the locks (especially which chamber is being used), the number and configuration of barges processed, lock conditions, river conditions, as well as the efficiency of the lock operators to process the vessels and the towboat crew to navigate the lock [95] [21]. Figure 16 shows key statistics associated with lockage (minimum, maximum, median and the bounds of the upper and lower quartiles, as well as the 95^{th} percentile). Note the logarithmic y-axis. The middle quartiles are fairly tightly bound around the medians, while the maximums can be significantly greater than the 95^{th} percentiles. These long lockage times are sometimes associated with lock closures (i.e., OH5, OH24, OH25, OH72).

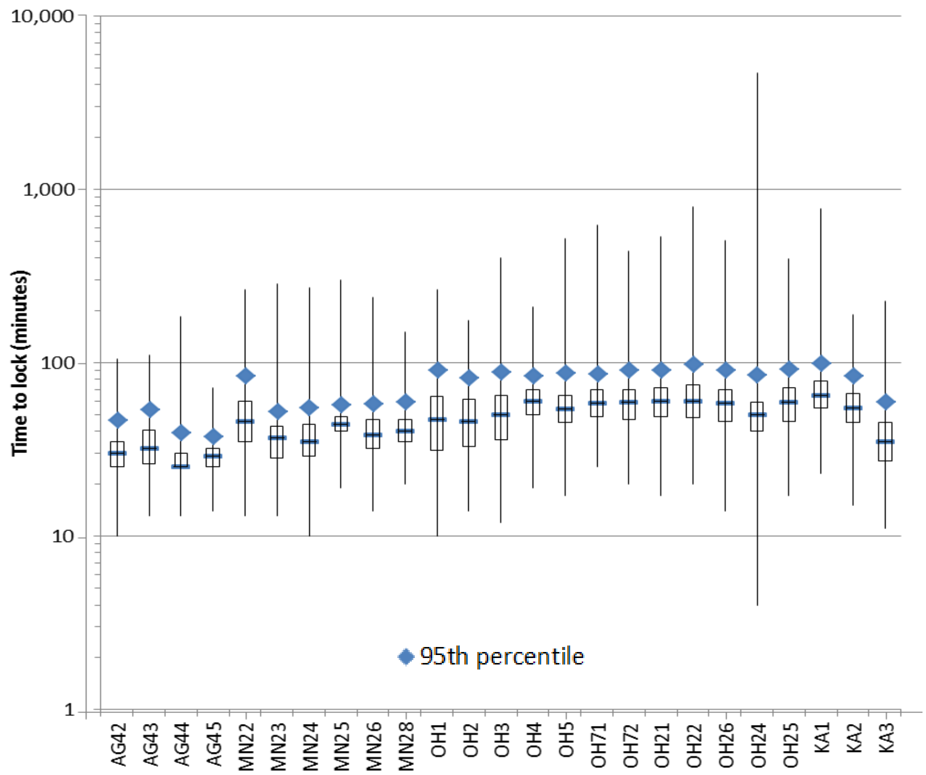


Figure 16. Distribution of lockage times by locks in the USACE Pittsburgh and Huntington Districts, 2010 [76].

Longer lockage times are required for larger tows; Figure 17 shows the average lockage times for some of the study area's locks, differentiating by tow size. Similarly sized locks show similar lockage times (e.g., times for Emsworth and Montgomery track together). Lockages with no barges generally take less than half the time of lockages processing full tows.

Note, however, that the public dataset used for this analysis does not identify whether the main or auxiliary chamber was used for a particular lockage. Similarly the dataset does not describe whether the barges are loaded, and whether the lockage is a fly, turnback, or exchange lockage impacting the readiness of the lock to receive an incoming vessel [95]. A more nuanced analysis of USACE's restricted dataset would provide clearer insights between the factors impacting lockage time.

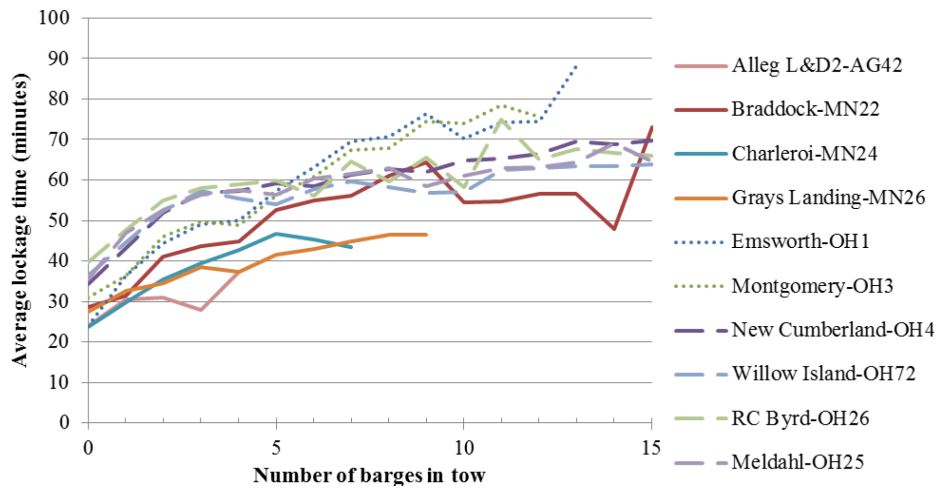


Figure 17. Average lockage times by lock and size of tow, selected locks in the USACE Pittsburgh and Huntington Districts, 2010 [76].

6. Closure frequency

Closure frequency is an important marker of the efficiency of the inland waterways. ASCE examined patterns of closure over time in the Pittsburgh District, as reported USACE's LPMS, showing that "the number of closures varies from year to year and lock to lock," perhaps reflecting the need for, conduct of, and completion of major rehabilitation projects [96].

Locks can be closed for a variety of reasons. USACE provided a dataset of all 2010 closures in the study area, including 1,075 unscheduled closures totaling 12,100 hours (see Table 28). Over 20% of the unscheduled closures were weather or river condition related. A similar number of unscheduled closures were due to lock hardware or equipment malfunction. Over 56% of unscheduled closure time was due to maintaining or repairing lock or lock hardware. The 20 scheduled closures totaled almost 3,300 hours. About 7% of tows in the study area encountered a lock closure (arriving at a lock while one chamber was closed). The availability of a second chamber at many of the locks minimizes the extent of the delay due to closure. Planned closures averaged 163 hours, while unplanned closures averaged 10 hours.

Table 28. USACE Pittsburgh and Huntington Lock Closures in 2010 (hours)

	Chamber	Weather and river conditions	Vessel issues	Lock issues-scheduled	Lock issues-unscheduled	Other	Total
Total (all locks)		3,861	436	3,249	7,629	154	15,330
AG42	main	0	1	407	-	-	409
AG43	main	1	2	-	-	-	3
AG44	main	43	53	-	146	-	242
AG45	main	188	-	-	-	-	188
AG46	main	25	-	-	-	-	25
AG47	main	32	-	-	-	-	32
AG48	main	120	-	-	-	-	120
AG49	main	-	-	-	2	-	2
Braddock	main	8	2	-	28	4	43
	auxiliary	10	-	-	728	-	738
Elizabeth	main	104	1	-	46	-	151
	auxiliary	104	-	-	57	-	161
Charleroi	main	12	4	-	13	4	32
Maxwell	main	4	-	-	123	-	128
	auxiliary	15	1	-	14	-	30
Grays Landing	main	26	3	-	2	13	43
Emsworth	main	19	0	531	5	25	579
	auxiliary	372	1	-	56	29	458
Dashield	main	47	4	-	32	3	85
	auxiliary	58	-	-	19	-	77
Montgomery	main	33	9	-	29	3	74
	auxiliary	188	-	-	77	-	265
New Cumberland	main	2	1	-	11	2	16
	auxiliary	-	-	-	7	-	7
Pike Island	main	15	1	-	906	-	921
	auxiliary	5	3	-	31	11	50
Hannibal	main	18	1	-	6	-	26
	auxiliary	-	1	-	459	-	459
Willow Island	main	17	0	-	3	3	23
	auxiliary	176	-	-	1,689	-	1,865
Belleville	main	94	5	188	85	-	371
	auxiliary	12	3	720	1,507	-	2,242
Racine	main	106	5	-	18	3	132
	auxiliary	762	-	-	231	-	992
RC Byrd	main	35	9	11	29	1	85
	auxiliary	19	5	-	3	2	30
Greenup	main	80	22	1,376	304	5	1,787
	auxiliary	682	280	11	246	28	1,247
Meldahl	main	4	6	2	185	4	201
	auxiliary	251	-	-	470	4	724
Winfield	main	163	13	3	43	12	235
Marmet	main	7	-	-	14	-	21
London	main	5	0	-	6	-	11

Source: USACE [76]

E. Use patterns

> **Objective 2.2**: Assess efficiency metrics currently used by USACE and develop improved metrics

Efficiency is related to the types of usage that infrastructure is subjected to. Thus the efficiency of any given facility will appear to be different from other facilities if they do not process the same type and volumes of users.

1. Number of lockages

Together, Elizabeth and Charleroi handled 22% of the Pittsburgh District's lockages in 2010, and over 55% of the lockages on the Monongahela [83]. The tonnage at these two locks, however, was similar to the tonnage handled by the larger Braddock lock. This disparity is due to the need for multiple cut lockages through the constricted Elizabeth and Charleroi locks. The lockage count at Braddock, accordingly, was lower because of the larger size of the Braddock lock chambers where cut lockages are not required as frequently as at the smaller, older locks upriver. Lockage counts are an appropriate measure of operational activity.

2. Lock users

The locks are used heavily by recreational boaters, particularly on the Allegheny River and through Emsworth (see Figure 18). In 2010, there were over 19,000 recreational lockages in the study area. These users do not pay any direct or fuel surcharges related to their lock usage, although various schemes have been considered for charging for this service [2] [94]. Unmeasured by these statistics are the recreational users who stay within their navigation pools without locking, including crew teams, kayakers, fishing boats, water skiers, etc. These users take great enjoyment from the rivers, but pose navigational challenges to the commercial users during the boating season.

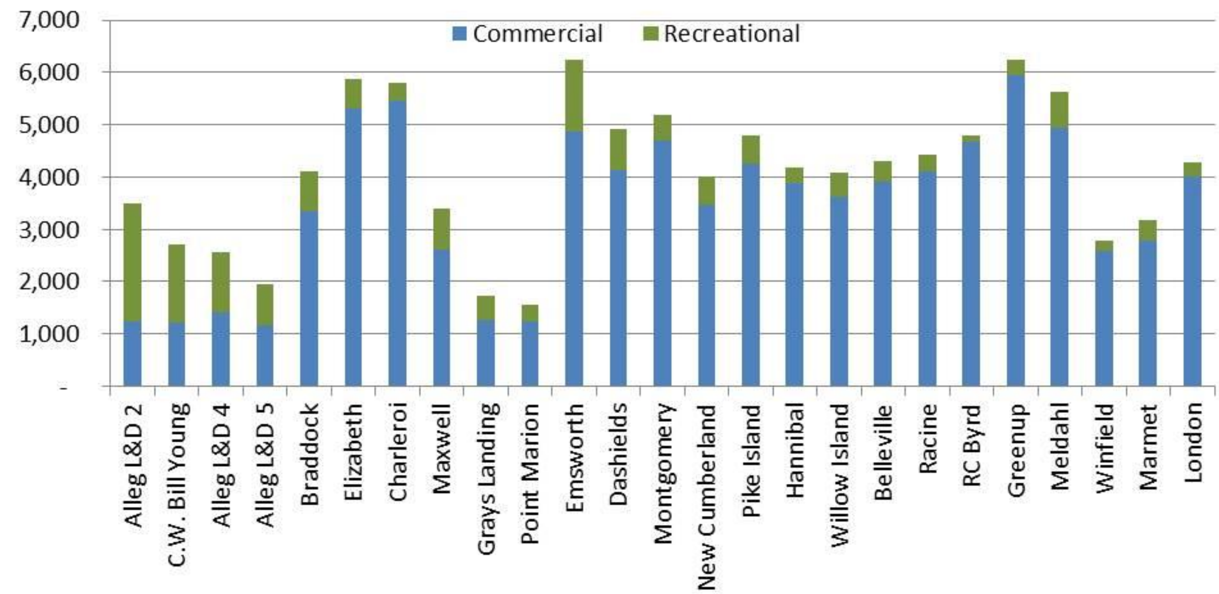


Figure 18. Recreational and commercial lockages by lock, USACE Pittsburgh and Huntington Districts, 2010 [44].

Figure 19 illustrates the seasonal patterns for the locks on the Allegheny and the Monongahela closest to the Pittsburgh confluence, showing the expected peak of recreational lockages over the summer months, as well as the monthly average delays at these two locks. Delays peak do not track particularly well with seasonal peaks. The peak delay months do, however, correlate with significant closures at AG42 and MN22 in September and August, respectively. Seasonality effects differ across geographic regions (e.g., the Upper Mississippi River system is closed during the winter [95]).

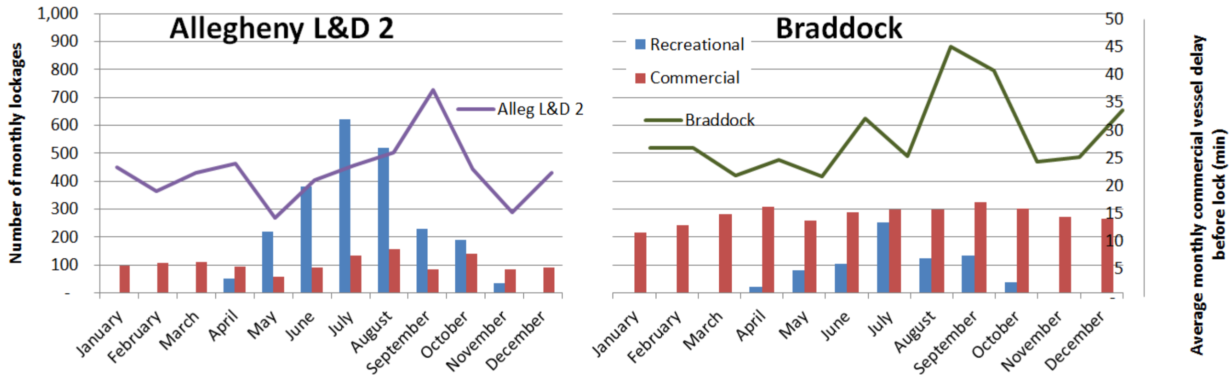


Figure 19. Monthly commercial delays at Braddock-MN22 and Allegheny L&D 2-AG42, 2010 [76].

F. Shipping time components

The LPMS dataset allows for examination of the components of trips and how they contribute to delays, as well as to project changes in efficiency as the inland waterways changes. A stochastic model was built to examine the variability associated with a typical trip made in the study area. Four scenarios were compared, varying the flotilla composition (15 jumbo barges vs. 6 jumbo and 9 standard) and the status of the Lower Mon Project (LMP) (not completed vs. completed).

> **Objective 2.3**: Conduct stochastic time studies of commodity trips to quantify efficiency gains from infrastructure improvements

The modeled trip is a coal shipment from the Powhatan No. 6 mine (loading at Ohio mile 110) to the Fort Martin powerplant (Monongahela mile 92). The Energy Information Administration's Survey 923 (EIA-923) for 2010 shows that 164,000 tons of coal was barged from this mine to Fort Martin [50]. The transit requires lockage through 11 locks, starting below Pike Island-OH5 and ending above Point Marion-MN28. Upon completion of the LMP, the locks and dam at Elizabeth-MN23 will be eliminated and the remaining small lock at Charleroi-MN24 replaced with larger twin locks, allowing for faster movement across the lower Monongahela River. The modeled travel time generally includes the following stochastic components:

$$\begin{aligned} &Total\ travel\ time\ (hours) \\ &\qquad = Time\ underway\ (hours) + (probability\ of\ delay) * (Delay, hours) \\ &\qquad + Lockage\ time\ (hours) + Reconfiguration\ (hours) \end{aligned}$$

Distributions were extracted from the LPMS dataset for time underway (i.e., travel time between locks), probability of encountering delay at each lock using USACE's definition of delay (greater than zero minutes), the length of delays encountered, and the time to lock at each lock. The Palisades DecisionTools Suite was used to build the stochastic model [100]. The @Risk component of this software allows for distribution fitting to raw datasets. Each of the four modeled parameters were fitted to distributions that best matched the available data for each lock. For example, the time underway between Pike Island and New Cumberland was fit as a Loglogistic(6.2352, 5.2061) distribution, the likelihood of delay at New Cumberland as Bernouli(0.26), the delay time at New Cumberland as Gamma(2.1363,0.35853), and the lockage time as Weibull(4.5502,1.1442). All distribution fitting assumed a lower bound of zero, preventing incongruous negative results. No upper bounds were set. The datasets used for distribution fitting reflected all of the lockages that occurred in 2010. For most of the locks, there were over a thousand lockages from which to draw the distributions, creating a representative depiction of conditions in 2010. The distributions are discussed below and the complete set provided in Appendix 14.

1. Time underway

Time underway is a function primarily of the distance between locks. Other factors influencing time underway include direction (against or with the current), weather and related river conditions (flood, low water, ice, fog), vessel power, tow size, tow load. The upriver trip legs were used to create the distributions for time underway. River and weather conditions were not included in the model, but could be considered in a more advanced model that accounted for seasonal conditions and delays. Similarly, tow size could have been considered, although reducing the size of the datasets used to generate the distributions may reduce the representativeness of those distributions. The nonpublic version of the LPMS dataset also differentiates between loaded and empty barges, a variable that may impact time underway.

Transit times also can be extended due to holidays and operating practices. In general, a vessel will take several hours to move between AG42 and AG43. The data show that some extended transit times are associated with holidays (i.e., Labor Day) and overnight transits of short haul vessels where the towboats may be docked overnight. Similarly, the datasets, public and private, are not able to differentiate between true transits across two locks and situations where a vessel is working between those two locks over a period of time, and happens to eventually cross the upstream lock. Inclusion of these extended transits causes the travel time distributions to be somewhat overstated. A future enhancement of this type of analysis could extract transit times only for those vessels with longer haul patterns, eliminating (or assessing separately) those vessels that operate in a restricted area.

2. Probability of delay

For each lock, the arrival timestamp was compared to the start-of-lockage (SOL) timestamp. Identical arrivals and SOLs were counted as "no delay"; in keeping with the USACE definition, all lockages with any delay of start of lockage were considered to be delayed, regardless of length or position within a sequence of cut lockages. This parameter was assumed to be a Bernoulli function for each lock.

3. Length of delay

Using the same calculated length of delay as discussed above, all "no delay" values were set aside. The length of delay distributions thus were based only on delayed lockages. Table 29 shows the correlation between typical delays (taken from the modeled distributions for the upriver trips) and the closures experienced at each lock. Emsworth was closed for most of May for scheduled maintenance, and thus shows the highest average delay. Unscheduled closure for maintenance was required at Pike Island in October and November and Braddock in August, also coinciding with higher average delay rates at these locks.

Table 29. Modeled delays and 2010 closures

Lock/ID	Average delay, when delayed (hours)	Closures (hours)
Pike Island/OH5	2.3	971
New Cumberland/OH4	0.8	22
Montgomery/OH3	1.8	339
Dashields/OH2	1.3	162
Emsworth/OH1	3.2	1,037
Braddock/MN22	1.3	781
Elizabeth/MN23	0.6	312
Charleroi/MN24	0.6	32
Maxwell/MN25	0.4	157
Grays Landing/MN26	0.5	43
Point Marion/MN28	0.0	-
Source: derived from USACE [76]		

4. Lockage time

Lockage times were calculated as the difference between SOL and end-of-lockage (EOL) for each lockage. As discussed previously, the raw dataset does not differentiate between passages through main and auxiliary chambers, although it is the sum of all lockages through all chambers (focusing on commercial lockages). The smaller auxiliary locks can be processed faster simply due to the smaller volume of water that needs to be filled or emptied. Thus time analyses that are dependent on the use or avoidance of the smaller chambers would need to rely on the nonpublic LPMS dataset that includes a designation of chambers used.

As described previously in section IV.D, the time required to lock is a function of the size of the tow being processed. The model does not account for tow size, other than to explore two optimized tow sizes. Figure 20 provides a profile of some of the modeled locks, showing the frequency of different tow sizes at any given lock. Note the prevalence of peaks at multiples of 3, a common tow width at the lower locks, and a common length at the upper locks. See also Table 20 for a profile of lock capacities.

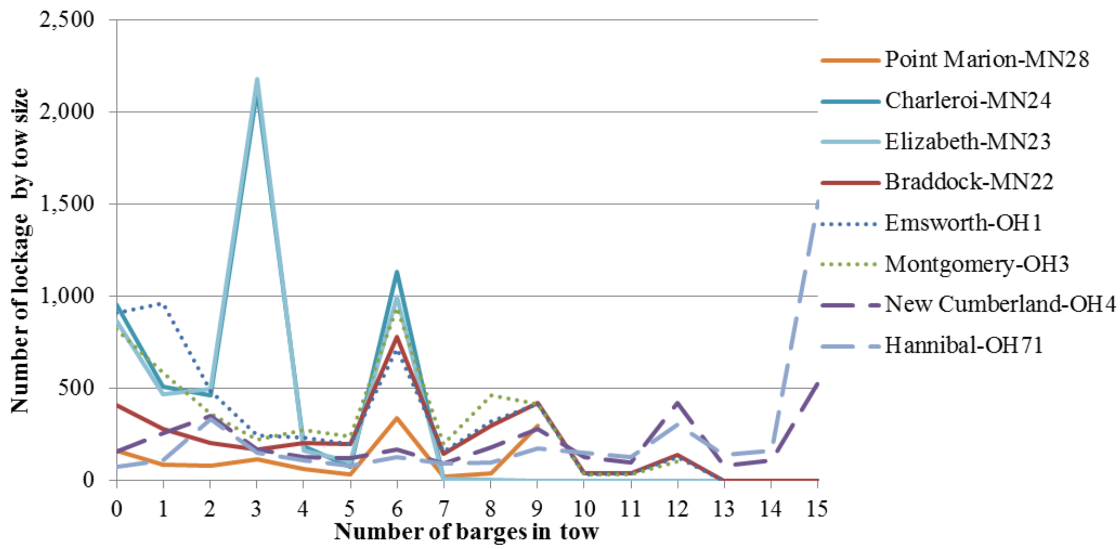


Figure 20. Profile of tow sizes by lock, selected USACE Pittsburgh and Huntington District locks, 2010 [76]

Table 30 provides a comparison of the modeled lockage times (generated without consideration of tow size) with the average upriver lockage times for typical tow sizes calculated from the raw LPMS data. The modeled lockage times tend to underestimate the lockage times required for the modeled tow sizes. Future modeling could include this consideration, however, for the purposes of this analysis, the impact on the results is minimal, as the underestimation is only 3-23 minutes per lockage.

Table 30. Average upriver lockage time (minutes) by tow size, selected locks

Lock Name-ID	Average modeled lockage time	Number of barges per tow					
		0	3	6	9	12	15
Point Marion-MN28	41	30	40	45	47		
Grays Landing-MN26	40	27	38	43	47		
Maxwell-MN25	44	32	43	46	48		
Charleroi-MN24	38	24	39	45			
Elizabeth-MN23	38	21	40	44			
Braddock-MN22	45	29	44	55	64	57	73
Emsworth-OH1	53	24	49	63	76	74	
Dashields-OH2	47	27	46	55	66	64	
Montgomery-OH3	52	31	50	60	74	76	
New Cumberland-OH4	63	34	57	58	62	66	70
Pike Island-OH5	61	35	52	62	65	58	64
Hannibal-OH71	64	39	55	59	60	61	64
Highlighted times reflect assumed size of jumbo tows modeled. Source: derived from USACE [76]							

Direction of lockage has been identified as a potential factor in lockage time studies [95]. Lockage times at Braddock (MN22) were assessed to explore this concept. The average time to lock for vessels moving upriver was 50.4 minutes (standard deviation of 21.7 minutes), while the average downriver lockage was slightly faster at 49.1 minutes (standard deviation of 19.7 minutes). This difference of less than 2 minutes was judged to be insignificant over the course of vessel trips that take hundreds of hours.

5. Reconfigurations

The LPMS dataset and the literature do not shed light on the time required for reconfigurations – a uniform 4 hours was assumed for each reconfiguration. Actual time requirements will vary based on factors such as mooring and river conditions, tow configurations (before and after), barge types, and crew capabilities.

6. Modeled tow sizes and scenarios

The size of the modeled tow was set at 15 barges, the most common tow size at Pike Island. The number of reconfigurations and cut lockages for a 15 barge tow across the modeled transit is a function of the sizes of the locks and the barge sizes. Table 25 previously showed the maximum number of standard and jumbo barges that fit within the locks of interest. The tows were modeled in two ways – as all jumbo barges, and as a mix of standard and jumbo tow that reflects the regional use of smaller barges that fit more efficiently in the constricted locks. A tow of 15 jumbo barges is approximately 22,100 tons, while the modeled mix (6 jumbo, 9 standard) is about 17,200 tons.

A trip analysis of the LPMS dataset showed that only 2 vessels made the full transit between Pike Island-OH5 and Point Marion-MN28 in 2010. Given that the EIA-923 showed that 164,000 tons of coal was barged across this transit, it can be assumed that multiple vessels can be assumed to have been used in sequence to deliver the bulk of these coal shipments to Fort Martin. Transitions between vessels and tow reconfigurations were modeled where lock sizes change (e.g., between OH4 and OH3 and between MN22 and MN23).

Table 31 summarizes the modeled scenarios. The key difference between the before/after LMP for the jumbo tows is the elimination of two vessel trips (Vessels 4 and 5) and lockage at Elizabeth. For the mixed tow, the completion of the LMP allows for the elimination of cut lockages at Charleroi and lockage at Elizabeth.

Table 31. Stochastic model scenarios

	Lower Mon Project Not Completed	Lower Mon Project Completed
Jumbo Scenario	Vessel 1 (15 jumbo barges) travels from the mine through New Cumberland (OH5_OH4), dropping the tow for reconfiguration	Vessel 1 (with 15 jumbo barges) travels from mine through New Cumberland (OH5_OH4), dropping the tow reconfiguration
	Vessel 2 (3x3 barges) and Vessel 3 (2x3 barges) transit three smaller upper Ohio locks and first lock on the Monongahela (OH3_MN22). Vessel 2 then drops its tow for reconfiguration	Vessel 2 (3x3 barges) and Vessel 3 (2x3 barges) transit to the powerplant (OH3_MN28). Double lockages required for Vessel 2 at each lock above Braddock (MN22)
	Vessel 3 (2x3 barges), Vessel 4 (2x3 barges), and Vessel 5 (1x3 barges) delivers to powerplant (MN23_MN28). Double lockages required at Elizabeth and Charleroi for Vessels 3 and 4.	
Mixed Jumbo/ Standard Scenario	Vessel 1 (with 15 barges, 6 jumbo, 9 standard) transits from mine through New Cumberland (OH5_OH4), then drops tow for reconfiguration	Vessel 1 (with 15 barges, 6 jumbo, 9 standard) transits from mine through New Cumberland (OH5_OH4), then drops tow for reconfiguration
	Vessel 2 (3x3 standard barges) and Vessel 3 (2x3 jumbo barges) deliver to powerplant (OH3_MN28). Double lockages required at Elizabeth and Charleroi.	Vessel 2 (3x3 standard barges) and Vessel 3 (2x3 jumbo barges) deliver to powerplant (OH3_MN28). No double lockages required.

7. Stochastic model results

Objective 2.3: Conduct stochastic time studies of commodity trips to quantify efficiency gains from infrastructure improvements

Figure 21 presents the modeling results for overall travel times with and without the LMP. The base case for the jumbo tow scenario shows that 90% of the overall travel times are expected to range between 126 and 182 hours, while the completion of the LMP will allow for travel times between 100 and 152 hours, an average time savings of 17%. The modelling results for the mixed flotilla of standard and jumbo barges show a minimal savings of time due to the completion of the LMP – a mixed flotilla is more closely sized to the smaller upriver locks, and requires fewer reconfigurations and vessels to move the full 15 barges from mine to powerplant. The base case for the mixed flotilla predicts that 90% of the travel times fall between 99 and 151 hours, while the post LMP case predicts travel times between 96 and 147 hours.

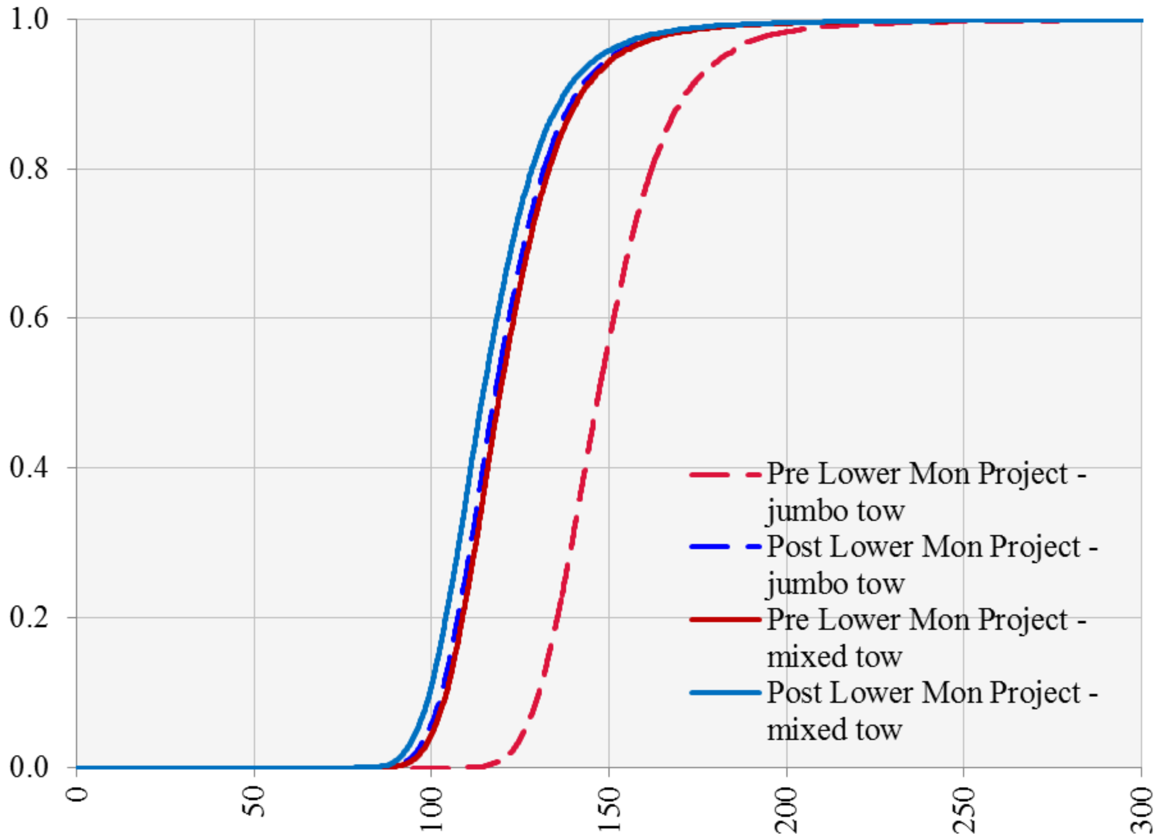


Figure 21. Time savings from completion of Lower Mon Project for 15-barge regional transit.

Figure 22 illustrates the contributions to the overall time profile of the modeled transit. The most significant component of this transit is the underway travel time (75%). The greatest savings from the completion of the LMP will be in travel time due to trip consolidation and the ability to minimize reconfigurations – a reduction of 18% for tows of jumbo barges. These savings may be somewhat understated because the velocity across the current constricted area (MN23_MN24) may be greater upon completion of the project and the resultant increase in the length of open water between Braddock-MN22 and Charleroi-MN24. For the mixed tows, the only savings predicted would be from reduced lockage times (eliminating Elizabeth and faster passage through Charleroi).

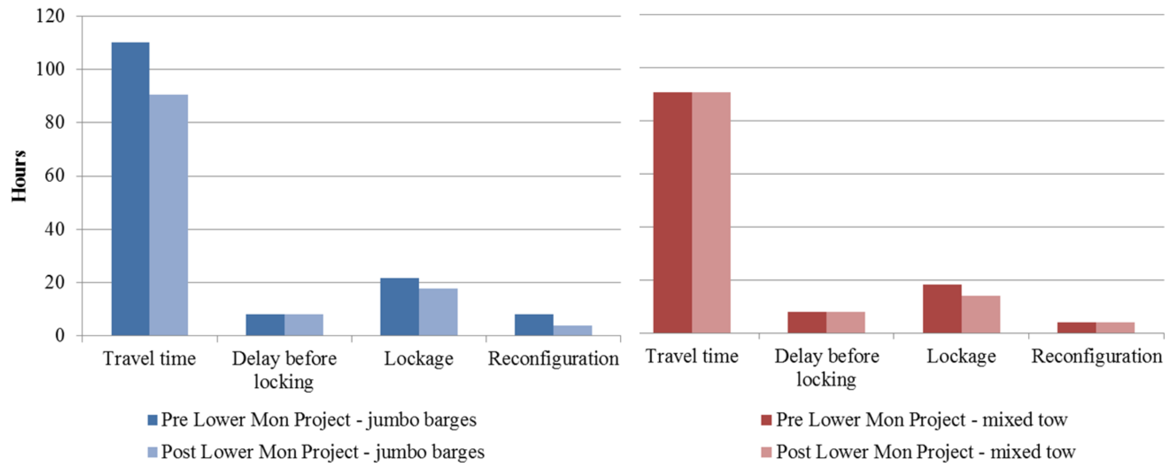


Figure 22. Travel time component comparison.

To ship the entire 164,000 tons of coal from mine to powerplant, multiple trips are required. Given an initial 15 jumbo barge tow would carry 22,100 tons, 7-8 shipments would be needed. In total, considering the time for all 5 vessels in the jumbo scenario, an average of 1,100 hours of operating time would be needed in the "pre-LMP" case. For a mixed jumbo/standard tow which carries 17,200 tons, 9-10 full transits would be needed. The total operating time for the mixed tow scenario is slightly higher, at 1,150 hours in the pre-LMP scenario. The insignificant annual operating time difference between the use of jumbo and mixed tows to accomplish the overall coal shipment may be a partial explanation for why the regional industry continues to use the smaller size barges that have been phased out downriver.

Upon completion of the LMP, however, the annual total operating time for the two flotilla scenarios shows a significant time advantage for the jumbo tow (900 hours) over the mixed flotilla (1,100 hours). These time savings would be amplified by consideration of similar time savings for the return trips (empty barges to mine).

Thus, scaled to the full 2010 shipment of coal between one mine and powerplant, time savings of 8.3 days of towboat operating time may be accrued as a result of completion of the LMP and subsequently shifting to a more efficient jumbo barge flotilla. In 2004, USACE conducted a survey of vessel operators and calculated operating costs for different sizes of towboats and barges operating on the Mississippi River system [101]. After adjusting these costs to a 2010 basis and accounting for low sulfur diesel fuel costs [102], and assuming typical vessel powers at the loading and reconfiguration areas, the annual shipping cost for the modeled coal shipment was estimated. It was not possible to confirm the applicability of these decade-old costs to vessels operating at the upper reaches of the inland waterways. The rates were assumed to be useful for the screening analysis described below.

Operating costs for the jumbo flotilla are estimated to drop from $317,000/year to $295,000/year; the mixed flotilla costs are estimated to drop from $370,000 to $359,000. Note the cost efficiency associated with the increased tonnage that can be moved in the jumbo barges. The annual shipping savings to one powerplant for shipment of 164,000 tons of coal is on the order of $12,000-22,000/year, depending on flotilla composition ($0.07-0.13/ton). (EIA reports 2010 barge shipping rates from Ohio to West Virginia of $2.52/ton and Ohio to Pennsylvania of $4.18/ton [71].) These savings will be extended to all users of this component of the inland waterways. As determined in section II.D, 7 million tons of thermal coal crossed the LMP in 2010. The total savings in coal shipments across the region thus can be estimated at $0.5-0.9 million. (A more complete analysis of these savings would account for the actual trip lengths of all of the 7 million tons, rather than the simple scaling analysis given here.)

The demonstrated methodology can be applied to a wide range of scenarios of interest, including different tow configurations, stages in the transit, vessel size, etc. USACE recently conducted an extensive feasibility analysis of the three elderly locks on the upper Ohio River, exploring options for their replacement or rehabilitation. The methodology could readily be applied to the alternatives under consideration [84], providing an additional tool for alternative assessment where the predicted time and cost savings can be incorporated directly into USACE's benefit cost analyses.

G. Conclusions

Commercial passage across the upper Ohio River basin requires navigation through the numerous locks that provide steps between navigation pools. These locks differ in their size, requiring vessel operators to optimize the type and configuration of barges used within the region, and causing the regional profile to differ from fleet and flotilla profiles generated at a national level or for other regions. Consideration of these differences, as demonstrated in this dissertation, allows for more accurate analysis of usage patterns, with implications for efficiency considerations of time and fuel consumption. The demonstrated continued use of smaller barges to optimize passage through the bottlenecks within this region is an important consideration that should be incorporated into future efficiency analyses of the upper waterways; removal of bottlenecks such as the three upper locks on the Ohio River will allow for more efficient fleeting and commodity movements. Similarly, this dissertation demonstrates that bottleneck removal at Elizabeth and Charleroi will allow for passage of larger flotillas and the subsequent elimination of vessel trips.

The stochastic model developed as part of this research allows for the comparison of time requirements with different flotilla configurations and with different infrastructure configurations. Completion of the Lower Mon Project will clearly reduce the time required, and thus the cost and fuel, to move commodities across the region. The consideration of usage patterns imbedded in the stochastic time studies model allows for the quantification of time savings. The screening analysis of the operating costs, with further validation for current and regional costs, can be used as a direct input to benefit cost analyses of infrastructure investment alternatives.

V. Contribution of Commercial River Traffic to Air Pollution in the Pittsburgh Region

A. Introduction

> **Research Goal 3**: Quantify and assess air emissions from regional commercial river traffic

Air pollution from coastal ports is well studied in the literature, with extensive inventories that attribute emission loadings to different types of vessel activities [103] [104]. Inland ports such as the Port of Pittsburgh are configured differently, dispersed over several hundred miles of river banks, with fewer or no terminals used for container transloading [105] [106], posing different challenges when assessing air emission impacts. In addition, the constrictions of the upper waterways dictate the types of vessels that can be deployed on them, with implications for the accurate characterization of air pollution contributions from river traffic.

There were two primary objectives for this research: to develop a methodology for calculating emission loadings (Objective 3.1), and to develop a methodology to assess the impact of vessel emissions on regional air monitors (Objective 3.2) – see Figure 23 for an overview of this research area. This section first characterizes southwest Pennsylvania's air quality issues, focusing on those criteria pollutants for which the region has not yet reached Clean Air Act (CAA) attainment status. Based on the USACE Navigation Data Center (NDC) data, as well as a number of other public sources, a profile of the regional fleet is presented. Using the trip analysis methodology described previously, an estimate of air emission loadings from commercial river traffic in 2010 is generated and compared with nationally generated loadings (Objective 3.1). The focus in this analysis is on PM2.5 emissions, as this pollutant continues to present regional risk (discussed further in the following section). Finally, a screening model is presented which compares towboat stack emissions to air quality monitors in the Clairton and Elizabeth region where the area's most persistent PM2.5 issues remain (Objective 3.2).

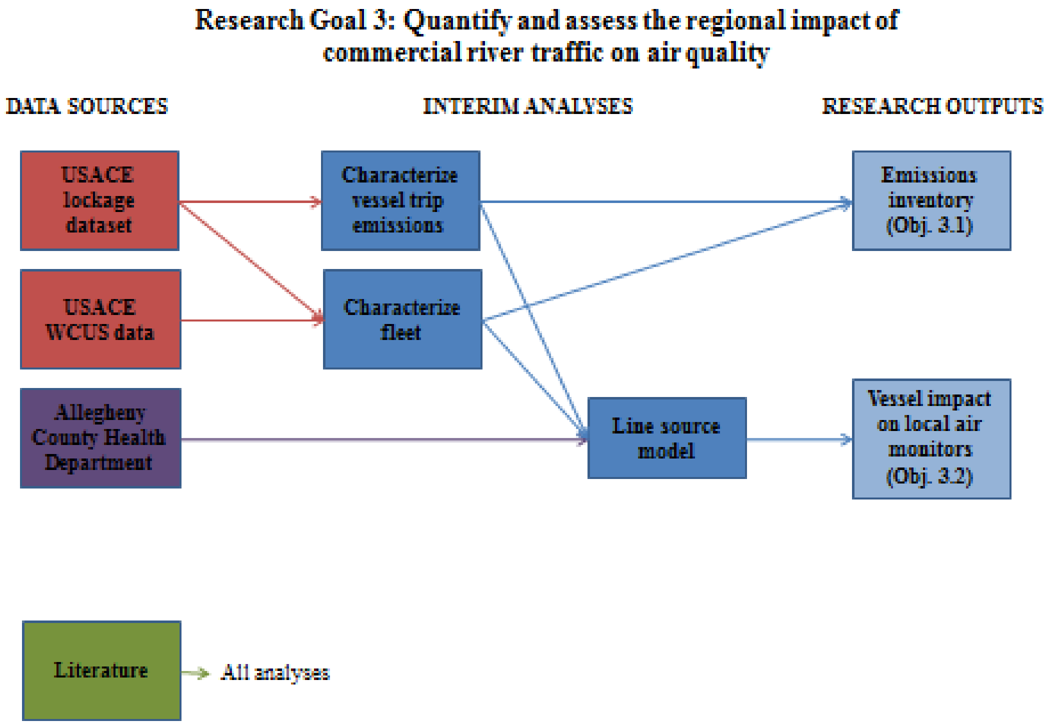


Figure 23. Research Goal 3 Flow Diagram

B. Regional Air Quality

Air quality in Pittsburgh has improved dramatically over the past 100 years as the region has embraced the need to control and reduce air pollution. The decline of the region's industrial base has also had the secondary effect of reducing emissions. However, as of 2013, the region remains in nonattainment with CAA standards for ozone (8-hour), PM2.5 (annual and 24-hour), and SO_2 (1-hour) [107]. Attainment for each standard is based on different geographical boundaries, depending on the extent of the pollution patterns. Ozone attainment is set at a seven county level, the Pittsburgh-Beaver Valley (PBV) area (centered on Allegheny County). PM2.5 attainment is designated at the PBV area, with a separate five-municipality area carved out from the PBV area with its own attainment status (Liberty-Clairton). SO_2 attainment compliance is set at the Allegheny County level.

The Liberty-Clairton region in southeastern Allegheny County is designated as a discrete nonattainment area because of the specific air quality challenge posed by this region. Particulate (and other pollutant) emissions in this area are driven by emissions from the US Steel Clairton Works, the largest metallurgical coking plant in the United States. The Clairton facility produces 4.7 million tons of coke annually [55]. Table 32 summarized this facility's reported particulate and SO2 emissions from 2000 to 2011 [108]. US Steel has installed new coke batteries and other process enhancements to address its emissions, and is under a consent order to reduce emissions [109]. ACHD states that the increase in 2011 was due to two major stack tests of the new coke batteries. 2012 results were downloaded from the PA DEP eFACTS website, showing little to no particulate improvement over 2010 and 2011 and a worsening of SO_2 emissions [110]. A recent Post-Gazette article [111] described on-going problems with the new coke batteries and air pollution control devices.

Table 32. Particulate emissions (tons) reported by US Steel Clairton, 2000-2012 [108]

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
PM2.5	331	311	319	328	306	302	295	249	253	153	345	346	324
PM10	708	688	741	752	712	701	678	418	441	259	370	514	502
SO2	1040	1221	1356	1572	1654	1717	1631	1740	1501	3450	1350	1467	1742

The US Steel Clairton facility is located on the Monongahela River between the Elizabeth and Braddock locks at mile 19, a stretch of river with significant barge traffic. Particulate emissions from diesel engines such as those used in towboats are also of concern, and are subject to a variety of national and local initiatives such as US EPA's National Clean Diesel Campaign (including a sector focus on Ports and Marine emissions) [112] and ACHD's diesel projects [113]. Given this particular challenge, the remainder of this section focuses on PM2.5 levels. Figure 24 depicts the downward trend in PM2.5 emission levels and loadings across the region.

US Steel's Clairton facility accounts for about 30% of the total load from point sources of PM2.5. The Cheswick powerplant is the largest powerplant within Allegheny County, and is located on the Allegheny River. Cheswick released 288 tons of PM10, 177 tons of PM2.5, and 9,290 tons of SO_2 in 2011, representing another major air pollution point source within the county. Note that the other major local powerplants discussed in this dissertation (Fort Martin, Hatfield's Ferry, Mitchell, Elrama, and Bruce Mansfield) are outside of the Allegheny County borders and are not included in the ACHD inventory. The powerplants to the southwest and west of the county, however, contribute directly to the monitored air quality within the county [114].

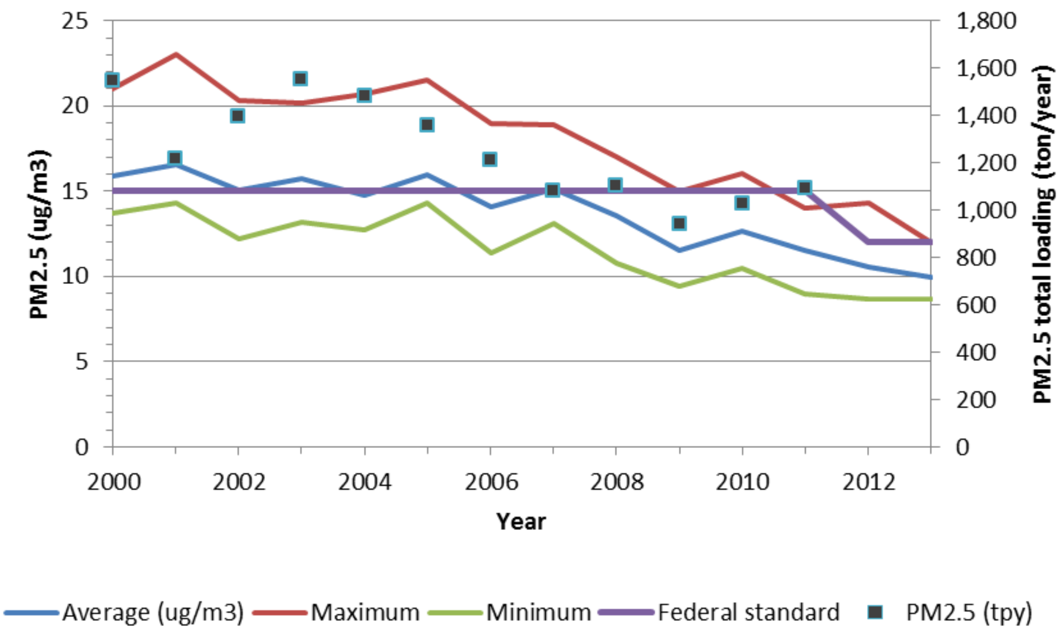


Figure 24. Average PM2.5 levels and loading in Pittsburgh, 2000-2013 [107]

C. Fleet Characterization

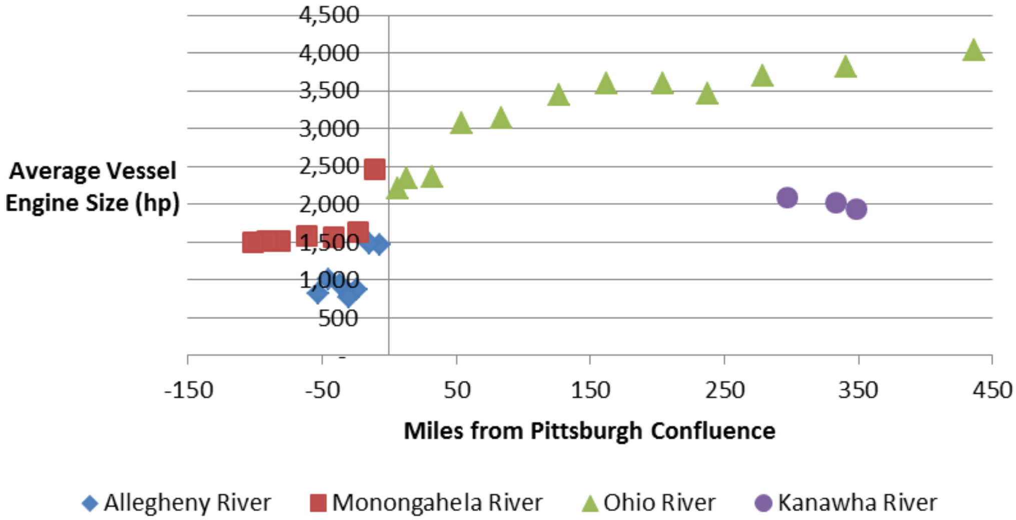
Consideration of regional variation extends to the fleet of vessels that operate from region to region. The Monongahela, Allegheny and Kanawha Rivers are tributaries of the Ohio River. The rivers and lock sizes both constrict as the river traffic moves upstream (see Table 1. Lock dimensions, Pittsburgh District. The restrictions include height clearances under bridges, and maneuverability around increasingly narrow bends in the river courses. As a result, the larger towboats and larger tows cannot traverse the upper rivers, and the tows are re-configured and pushed by smaller towboats above Braddock, as discussed in Section III.

Using Navigation Data Center (NDC) data characterizing registered vessels [73], the U.S. Coast Guard's vessel database [115], towboat websites [116], and the Inland River Record [117], profiles of the fleets commonly working in different regions can be developed. Each of the locking vessels in the raw LPMS dataset were assigned codes classifying them as either towboats (listed in "towboat10"), government vessels (Corps or Coast Guard), tour boats, or recreational vessels. Vessels that did not readily fall into any of these categories (based on their categorization in the NDC vessel dataset, "towboat10") were researched further. One towboat, the Sam S, had an incorrect vessel number in the dataset; this was corrected to match the number listed in the vessel database. Eleven additional vessels were not listed in the NDC vessel dataset, but were listed in the U.S. Coast Guard's vessel database (accessed through NOAA) [115]; entries were added to the towboat file for these vessels for the vessel type (towing, government, recreational), year built, and owner. Additional information about vessel engine size and year of most recent repowering or rebuild were added from the Inland River Record [117] and the Towboat Gallery [116].

Across the study area, there were 476 commercial vessels operating in 2010, 19 government-owned vessels (USACE, USCG, local), a dozen tour boats, and many thousands of recreational vessels (which are not identified uniquely in the LPMS dataset). The weighted average towboat in the study area has a power rating of 2,650 hp, was built (or rebuilt) in 1973, locked 1,200 barges during 180 lockages, and locked through 7 locks. There is considerable variability in these statistics across the region, as illustrated in Table 33 and Figure 25, illustrating the impact of constrictions of the rivers and river infrastructure on river utilization. At Charleroi, the average vessel power rating is 1,000 hp lower than the study area-wide average. Vessels continue to increase in size with their proximity to the Mississippi.

Table 33. Fleet characterization by lock, USACE Pittsburgh and Huntington Districts, 2010

	Lock Name and ID	# of Unique Commercial Vessels	Average HP	Average age	Average height (ft)	Average # of barges per lockage
Allegheny	Alleg L&D 2-AG42	48	1,469	1971	30.8	2
	C.W. Bill Young-AG43	43	1,488	1971	30.8	2
	Alleg L&D 4-AG44	27	876	1973	29.2	1
	Alleg L&D 5-AG45	20	763	1973	28.7	1
	Alleg L&D 6-AG46	7	942	1973	25.0	1
	Alleg L&D 7-AG47	6	1,007	1969	25.4	1
	Alleg L&D 8-AG48	3	820	1966	30.4	1
	Alleg L&D 9-AG49	-				
Monongahela	Braddock-MN22	96	2,455	1970	32.8	6
	Elizabeth-MN23	79	1,633	1970	31.3	3
	Charleroi-MN24	64	1,568	1970	28.0	4
	Maxwell-MN25	41	1,585	1970	31.4	5
	Grays Landing-MN26	30	1,516	1969	30.9	6
	Point Marion-MN28	30	1,519	1970	30.8	6
	Morgantown-MN29	11	1,490	1961	30.2	4
	Hildebrand-MN30	-				
	Opekiska-MN31	-				
Ohio	Emsworth-OH1	111	2,202	1969	30.8	5
	Dashields-OH2	115	2,346	1968	32.3	6
	Montgomery-OH3	135	2,353	1970	31.8	5
	New Cumberland-OH4	192	3,077	1973	35.7	9
	Pike Island-OH5	194	3,146	1974	36.4	8
	Hannibal-OH71	203	3,440	1980	37.2	11
	Willow Island-OH72	202	3,591	1981	37.3	11
	Belleville-OH21	233	3,590	1981	37.7	11
	Racine-OH22	239	3,464	1981	37.3	11
	RC Byrd-OH26	279	3,697	1979	38.4	9
	Greenup-OH24	310	3,813	1981	39.5	9
	Meldahl-OH25	296	4,035	1981	39.0	10
Kanawha	Winfield-KA1	54	2,093	1964	33.0	8
	Marmet-KA2	44	2,022	1964	32.6	7
	London-KA3	23	1,945	1961	32.2	2
Study area		476	2,650	1973		
Sources: derived from USACE [44] [75] [76]						



Sources: derived from USACE [44] [75] [76]

Figure 25. Change in vessel power ratings across USACE Pittsburgh and Huntington Districts, 2010.

The fleet characterization data is imperfect. As noted above, a number of vessels were missing from the NDC vessel dataset, despite their inclusion in the LPMS dataset and their visibility in USCG databases and other public sources. The age of the vessels, updated to reflect "rebuilds" is not consistent with industry experts who indicated in conversation that vessel engines are rebuilt or repowered fairly frequently (e.g., every 5 years), reflective of the heavy duty that they operate under and the fuel savings to be gained from routine engine maintenance. The "rebuild" parameter is intended to capture those "vessel modification or significant improvement that extends the working life of the vessel" [63]. Routine reporting of repowering dates by the vessel operators would give a more complete picture of the status of the region's towboats and reduced impact of these engines as they are updated and move into a higher level of emission compliance. As will be discussed further below, those analyses that depend on characterization of engine age may overstate emissions somewhat.

D. Emission inventories

> **Objective 3.1**: Develop a methodology for calculating emission loading

Emission inventories are useful prioritization tools, quantifying and ranking pollutant sources. Emissions inventories can be built up from regional data, or imputed from nationally aggregated or modeled data. No regional inventory exists for southwest Pennsylvania that captures emissions from river traffic.

1. Existing inventories

The Allegheny County Health Department (ACHD) requires permitted point source emitters to report their emissions on an annual level. The most recent inventory was released for 2011 [108]. The County does not track or model mobile sources such as towboats. The Pennsylvania Department of Environmental Protection (PA DEP) develops a state-wide point source inventory (most recently for 2012) that covers 65 of the state's 67 counties (Allegheny County and Philadelphia County inventories are reported directly to USEPA and are not included in the state's inventory). PA DEP's inventory also only focuses on point sources, with no inventory of mobile sources [118].

The US EPA prepares the National Emissions Inventory (NEI) on a triennial basis (most recently for 2011) [119, 120]. The NEI can be assessed at the county level and reflects a variety of point and non-point sources, including marine vessels. Where possible, the NEI is based on local data; in lieu of local data, the national inventory is generated from emission factors and industry profiles, and allocated regionally. For Pennsylvania, the 2011 marine non-point source allocations were allocated from national estimates (as well as all other non-point sources) using GIS polygons. (Ten 10 states submitted commercial marine emissions data for the 2011 NEI: California, Delaware, Illinois, Maryland, New Hampshire, New Jersey, Oregon, South Carolina, Texas, and Washington). The 2011 NEI website shows an estimated 14.3 tons of PM2.5 from "port emissions" (associated with vessel maneuvering), and 23.6 tons from "underway emissions" (associated with cruising) for Allegheny County [121]; overall county PM2.5 emissions exceeded 6,100 tons. State-wide, NEI estimates an estimated 36.3 tons of PM2.5 from "port emissions" and 88.1 tons from "underway emissions" from diesel-fueled vessels, and an equivalent amount from residual-fueled vessels in Pennsylvania. For context, commercial marine emissions are 0.1% of state-wide PM2.5 emissions which totaled over 110,000 tons. The NEI documentation discusses the issues they encountered with their allocation methodology [120]. It could not be confirmed from a review of the documentation whether the NEI methodology considered underway delays common in the upper inland waterways associated with the locks.

The Pittsburgh Climate Initiative conducts a regional greenhouse gas emission inventory every five years – the authors recommend that the methodology be expanded to incorporate emissions from diesel combustion in boats and locomotives [122].

In 1999, US EPA released a methodology for the characterization of commercial marine activity for Great Lake and inland river ports [123]. Case studies were provided for Cincinnati and St. Louis inland ports. Much of the data used in this methodology was taken from USACE's WCUS, representing aggregated data for ports and waterways. The methodology used in this dissertation uses the more specific data provided in the raw LPMS data, allowing for greater control over the analysis parameters.

Corbett and Fischbeck developed an emissions inventory for waterborne commerce vessels, using fuel consumption rates and fuel-based emission factors for different classes and duties of vessels [124], estimating that total particulate emissions on the inland rivers was 6,400 metric tons in 1997. The analysis provides regional breakdowns for NOx emissions, which show that 24% of NOx emission from the inland rivers was associated with the Ohio River states. Assuming this ratio holds for PM, PM emissions from the Ohio River states would be on the order of 1,500 metric tons. The study area for this dissertation covers the Ohio River states upriver from Cincinnati, about half of the length of the Ohio (plus tributaries). Thus for comparison purposes, the Corbett and Fischbeck analysis would be expected to generate emission estimates of less than half of 1,500 metric tons, or less than 700 metric tons corresponding roughly to the study area emissions. This estimate also is based on outdated emission factors and fuel properties (especially sulfur concentrations) that do not reflect reductions in emission profiles in response to evolving regulatory controls. Further, commercial river traffic in 1997 in the Port of Pittsburgh was approximately 50% higher than levels in 2010 [6].

US EPA released a 2002 report regarding the development of inventories for commercial marine emissions [125] that provides a good overview of the then available emission factors and their application. In 2008, US EPA issued a regulatory impact analysis for the marine and locomotive emission final rulemaking which also contained a national inventory of emissions from the commercial marine industry [126] using emission factors based on engine power, displacement, and service duty; the RIA predicted baseline (50-state) emissions PM10 levels of 10,304 tons and PM2.5 levels of 9,995 tons in 2010 for C1 vessels.

The significance of regional emissions from river traffic cannot be assessed with confidence from these inventories without regional data input. In keeping with the analyses conducted throughout this dissertation, a regional analysis was conducted using the LPMS dataset and vessel trip methodology to predict PM2.5 inventories (a bottom up analysis) within the region for comparison with the NEI and Corbett-Fischbeck values predicted from national assumptions (top down analyses).

2. Calculation of regional PM2.5 emission inventory from LPMS dataset

Emission loadings were calculated from the USACE lockage dataset on a trip-leg basis. The lockage dataset was sorted by vessel and start-of-lockage timestamps. This allowed for the identification of the "next" lock and the calculation of time and distance for each lockage as part of a 2-lock trip. Emissions for each trip leg were calculated, and then summed across the study area.

Note that certain lockages were omitted from this analysis due to methodology limitations, including cut lockages (10,500 records) and lockages coded as the last lockage in a vessel trip (28,700 records). Overall, these omitted records account for half of the total commercial lockages and cause the tally to be underestimated. These records will be incorporated into the inventory analysis submitted for publication, but could not be evaluated for inclusion in this dissertation analysis. The cut lockages should have a minor impact on the overall inventory because they will be comprised only of lockage and delay (if any) activity. The "last lockage" records are problematic because the transit time between the "last lockage" in a vessel trip and the first lockage in the vessel's next trip may not be reflective of underway travel time. The gap between vessel trips can encompass a variety of activities, including fleeting, maintenance, port activities, and moored time. Further work is needed to include these lockages appropriately in the inventory methodology.

Trip leg emissions were calculated using EPA's NONROAD2008 method. The NONROAD2008 model represents the US EPA's most recent work on commercial marine vessel emissions, building on the inventory work listed above [127]. Using the methodology used by USEPA in its NONROAD2008 model (including emission factors and service assumptions), PM2.5 emissions were calculated in general as:

$$PM2.5\ Emissions\ (ton)$$
$$= Vessel\ power\ rating\ (hp) * Load\ factor\ (unitless)$$
$$* Engine\ activity\ (hours) * Emission\ factor\ \left(\frac{g}{hp-hr}\right) * \frac{lb}{454\ g} * \frac{ton}{2000\ lb}$$

Emissions were separately calculated for lockage, delay, and travel times, and summed for each trip leg. The activity level for each trip was derived from the LPMS time stamps, including the lockage, delay, and travel times. The load factors for travel time, as used in the NONROAD model, was assumed to be 0.79 for vessels greater than or equal to 750 hp and 0.45 for vessels rated at less than 750 hp. The load factors for delay and lockages were assumed to be 0.45, in keeping with the minimal movement required during maintaining position during delays and lockage.

Emission factors were assigned based on vessel age, using factors and age brackets associated with the marine diesel rulemakings and associated Tiers [120]. Older engines have significantly higher emission factors, reflecting the stricter regulatory controls placed on for newer vessels.

Table 34 summarizes the distributions of vessels observed in the dataset, as well as some potential data quality issues. Given the range of emission factors, the accuracy of the vessel age classification has a direct impact on the accuracy of the inventory. The age of the vessel was based on either the rebuild age or the original build year reported in the NDC vessel database (if a rebuild had not been recorded). These values are self-reported by vessel operators. These ages are expected to overstate the functional age of the engines; trade data indicates that many vessels have been rebuilt without these updates being incorporated into the NDC dataset. The analysis presented here includes age and/or power rating updates from the literature for 71 of the 472 vessels in the study area.

Table 34. Study area vessel age (updated) and emission factor distribution

Year of last rebuild when available or initial build	Count	Percent	PM10 Emission Factor (g/hp-hr)
<2004, Tier 0 or Base	399	85%	0.402
2004-2006, Tier 1	22	5%	0.1934
>=2007, Tier 2	51	11%	0.1316
Total	472		

Vessels with a reported age older than 2004 were assumed to be Tier 0 vessels, and were assigned a PM10 emission factor of 0.402 g/hp-hr. Vessels with ages between 2004 and 2006 were assumed to be Tier 1 vessels, with an emission factor of 0.1934 g/hp-hr. Vessels with ages of 2007 or more recent were assumed to be Tier 2 vessels, with an emission factor of 0.1316 g/hp-hr. The PM10 emission factors were converted to PM2.5 using NONROAD's factor of 0.97 (based on an analysis of size distribution data for unspecified diesel engines) [126]. The cumulative emissions for each vessel were then summed. Note that emissions from auxiliary engines were not included in this analysis.

Overall, across all the vessels that locked in the study area, the total estimated emissions of PM2.5 are 360 tons (not including emissions from the omitted records discussed above). Tonnage associated with Allegheny County is estimated at 23 tons, calculated by limiting the summation to trip legs that include a lock located within the County (Dashields, Emsworth, Braddock, Elizabeth, and the first three locks on the Allegheny River).

An uncertainty associated with this value is the assignment of appropriate emission factors as a function of the reported the age of the vessel or year of the last rebuild – actual emissions may be lower if more accurate data were available. The sensitivity of the results to this uncertainty can be evaluated by applying the emission rate for the Tier 2 engines (2007 or more recent) to all vessels, generating a total of 119 tons of PM2.5. Thus if all of the region's towboats had been rebuilt or repowered in the past seven years, emissions would have been cut by about 200 tons/year. Including emission factors for Tier 3 and Tier 4, as applicable, and setting a more recent study year (later than 2010) would further improve the accuracy of the emission inventory.

In addition, there are additional emissions associated with auxiliary engines, as well as river activities that do not involve transits across locks. Nevertheless, this inventory provides a useful benchmark for underway emissions, as well as a regional methodology that uses regional data and accounts for delays associated with navigating the region's locks.

3. Comparison with other inventories

To generate a number from the NEI that can be compared with the 360 tons derived from the LPMS dataset, the county-level NEI emissions were extracted and summed for all of the counties that bound or intersect the rivers in the Pittsburgh and Huntington Districts (see Appendix 11). For these 40 counties with river frontage in Pennsylvania, West Virginia, Ohio, and Kentucky, there were 142 tons of emissions predicted for "underway" activity, geographically comparable to the activity measured in the LPMS trip analysis, accounting for 43% of the LPMS-based inventory. (An additional 31 tons was projected for "port" activity, which is not visible in the LPMS dataset.) The agreement between these inventories is reasonable given that the LPMS inventory is derived from "the bottom up" and the NEI inventory uses a "top down" approach. As discussed above, the LPMS inventory may overstate emissions due to the questions about the accuracy of the vessel age parameter, and the NEI inventory may underestimate emissions associated with passage across the region's locks.

The LPMS-based inventory, using 2010 data, is reasonably in agreement with the 1997 inventory generated by Corbett and Fischbeck, based on the scaling described above to focus the PM emission on the upper Ohio River system and taking into consideration the expected overstatement of emission factors used in the Corbett-Fischbeck analysis.

For perspective, the 23 tons of PM2.5 predicted from towboat transits across Allegheny County in 2010 is an order of magnitude lower than the PM2.5 emissions from the US Steel Clairton cokeworks. Hatfield's Ferry reported 1,298 tons of PM2.5 emissions in 2010 [110], almost 4 times greater than US Steel Clairton's emissions.

E. Significance of navigation emissions at specific air monitors

A screening analysis was conducted to assess the contributions of towboat emissions to air quality in the Liberty-Clairton non-attainment zone. A simple Gaussian plume line source model was used to predict air concentrations at various distances from the Monongahela River shipping lane, including the distance to the ACHD's Liberty monitoring station. Key inputs to the model include PM2.5 emissions from the towboat traffic, assumed stack height, wind direction, precipitation, and distance. Calculations were made on an hourly basis, and compared to hourly monitoring data at Liberty for 2010.

> **Objective 3.2**: Develop a methodology to assess the impact of vessel emissions on regional air monitors

The concentration downwind of a line source (such as a road or straight stretch of river) can be modeled by the following equation [128]:

$$C(x, y, z) = \frac{s}{\sqrt{2\pi} u \sigma_y \sigma_z} \left\{ \exp\left[\frac{-(z-h)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+h)^2}{2\sigma_z^2}\right] \right\} \times \int_{\xi_1}^{\xi_2} \left(\frac{1}{\sqrt{2\pi}}\right) \exp\left(\frac{-\xi^2}{2}\right) d\xi$$

- s, emission rate per length (g/km-s)
- u, wind speed (m/s)
- σ_y and σ_z, as calculated using the Pasquill Stability Classes and coefficients for the Pasquill-Gillford expressions for σ_y and σ_z
    - σ_y and σ_z vary with the strength of the daytime solar radiation.
    - The average monthly wind speeds in Pittsburgh neatly falls within the 3-5 mps windspeed in the Pasquill Stability Classes, giving
        - Strong solar radiation: Stability Class B
        - Moderate solar radiation: Class B-C
        - Slight solar radiation: Class C
    - σ_y = ax^b (m)
    - σ_z = cx^d+f (m)
        - a, b, c, d, and f are the coefficients for the Pasquill-Gifford expressions for σ_y and σ_z
- z, stack height
- h, exposure height
- $\xi_1 = y_1/\sigma_y$, where y_1 is the distance from the exposure point (y_0) to the upper endpoint
- $\xi_2 = y_2/\sigma_y$, where y_2 is the distance from the exposure point (y_0) to the lower endpoint.

The model accounts for dispersion in three dimensions, and assumes a simple, flat topography with no reflection. The topography in the Monongahela River valley, however, is quite hilly and convoluted. The results thus are designed to provide screening level analysis of vessel emission dispersion rather than an exact model of a complex topography.

Towboat emissions were estimated by apportioning the reported monthly tonnage at Elizabeth by daily tug count, calculating a daily ton-mile value, applying a PM emission factor of 0.01164 g PM/ton-mile [7], and converted to the emission rate per length, s, g/km-s. This emission rate was used for hourly calculation of air concentrations (ug/m3) at the monitoring site and compared to actual hourly monitoring results. The daily averages were then assessed in terms of changes in compliance with the federal standards. Air stability classes were assigned by time of day. [Note that at the time this analysis was done, the PM emission factor from the Kruse study was used. The emission methodology used above in section V.D.2 could be modified to generate a region-specific emission factor, and provide a more finely tuned model.]

The Liberty monitoring station is positioned to observe emissions from the Clairton coker, one mile to the SSW. Examination of hourly meteorological data over 2010 from the Allegheny County Regional Airport meteorological station shows that the prevailing wind is from the SSW, SW, and WSW 41% of the time. Towboats operating in this area thus would also contribute to air quality measurements at Liberty. However, these contributions continue at other wind headings as the vessels move up and down the river (which bends around the west side of the Liberty bluff). Four different segments of river were thus modeled, depending on the wind direction each hour, with different distances to the monitoring station. No impact was assumed when the wind originated from easterly positions and would be blowing emissions away from the monitoring station. The four river zones were treated as if they were straight and perpendicular to the wind direction. Distances were set for each zone as the measured distance from the center of each zone to the Liberty monitoring station; measurements were estimated by hand on a Mapquest image printout [62]. Figure 26 shows the modeled region, including the ACHD monitoring sites (red triangles). The wind rose gives the number of hourly observations for each of the 16 wind directions over 2010, showing a strong prevalence from the southwest. The US Steel Clairton facility covers most of Zone 3. The Monongahela River runs to the north from Elizabeth to Braddock (neither visible in this Figure), and is joined by the Youghiogheny River at Zone 1.

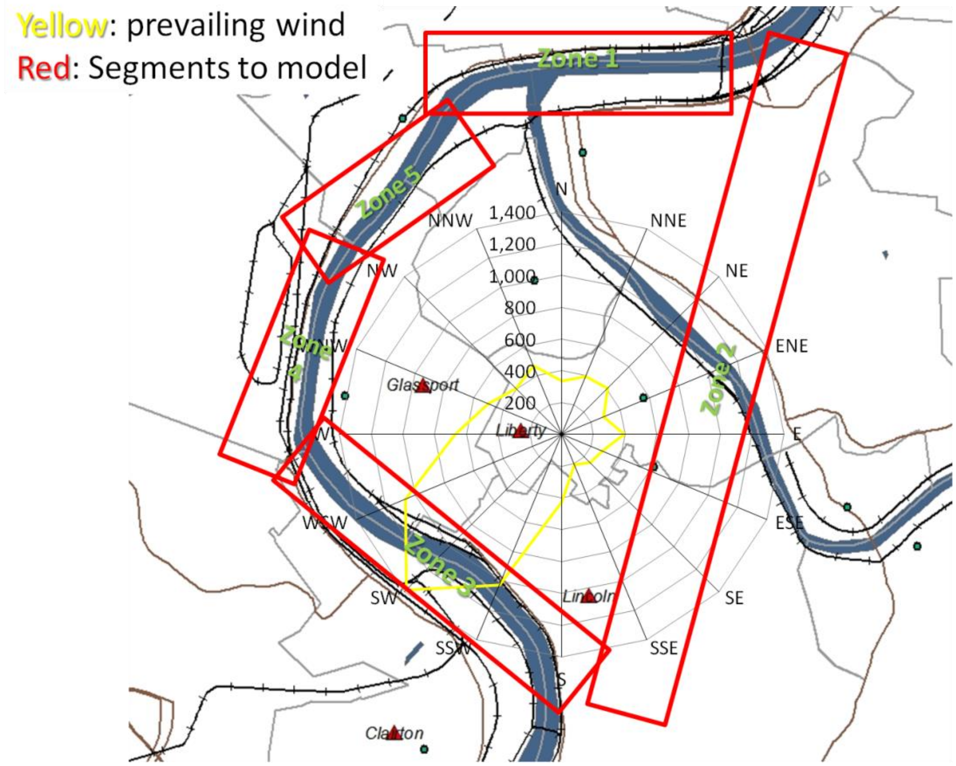


Figure 26. Line source model zones, Liberty, PA.

The analysis was repeated for the Glassport monitor. Modeling results for Glassport focus on change in concentrations with distance from the river centerline.

The Liberty monitoring station, located on the roof of the South Allegheny High School [129], has the highest recorded levels of PM2.5 in the region. The monitoring station is labeled "A" in Figure 27; the US Steel Clairton facility [55] is approximately 3 km downwind (the industrial zone at the southern edge of the figure). Particulate levels vary widely and predictably over the course of the day, with seasonal differences as well (see Figure 28). Emissions are routinely higher at night (perhaps reflective of favorable overnight electricity rates) and in the summer. The daily pattern of highs and lows are unique to this station; the pattern is reversed at all other monitoring stations in the county.

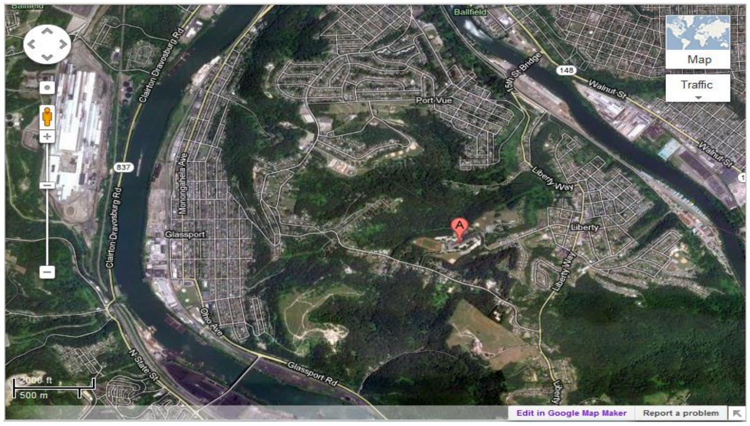


Figure 27. Modeled region: Clairton and the Liberty air monitor

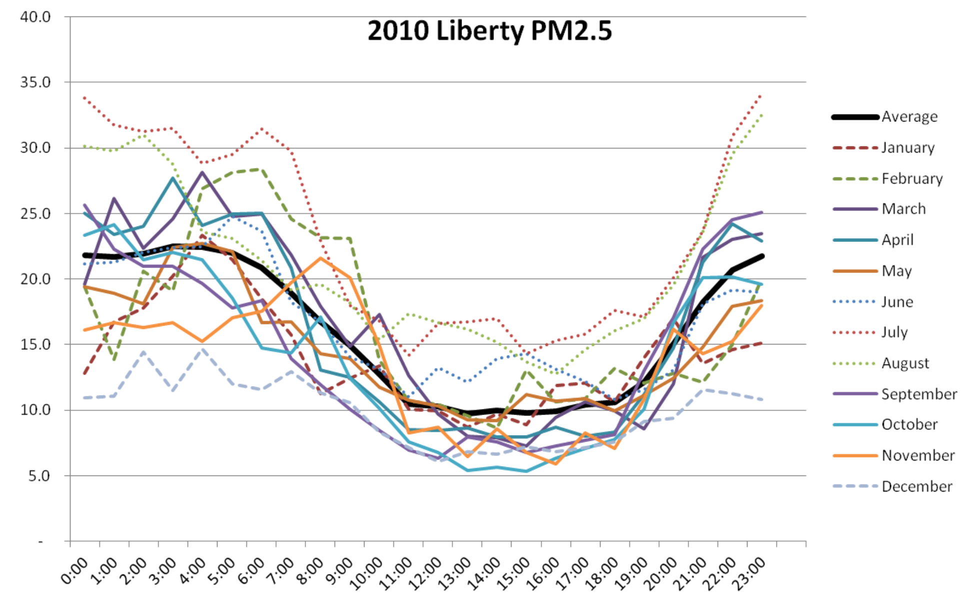
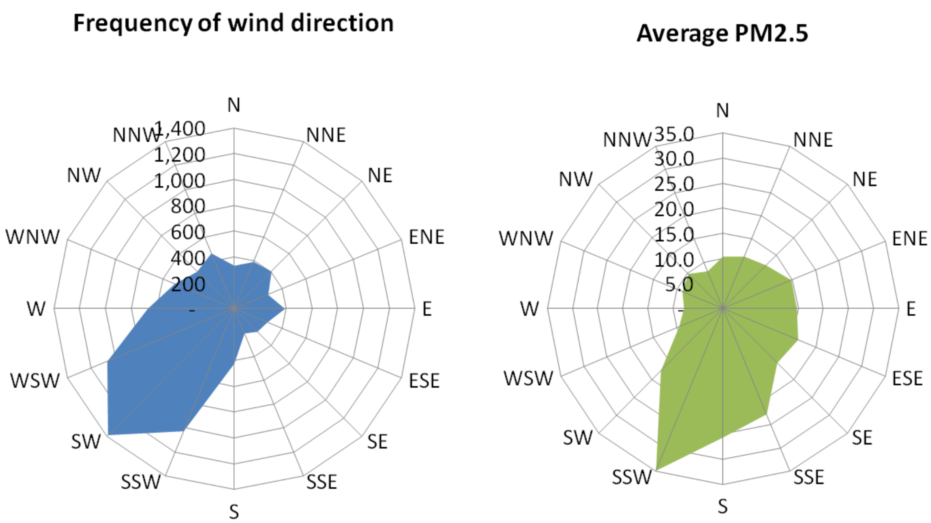


Figure 28. Hourly PM2.5 levels at Liberty, PA monitoring station, 2010 [130]

Meteorological data and air monitoring data were analyzed to illustrate the influence of the Clairton cokeworks on the monitoring station. Hourly wind observations at the nearby regional airport for 2010 were tallied to create a wind rose for the region. The hourly PM2.5 levels were paired with their corresponding hourly wind observation, and average PM2.5 levels were calculated for each wind position. The two resultant graphics, centered on the Liberty Monitor, depict the strong relationship between elevated air pollution levels and the prevailing wind coming from the vicinity of the coker (Figure 29).



Source: derived from ACHD [130]

Figure 29. Wind rose and directional average PM2.5 at Liberty Monitor

The model results show that barge traffic appears to have very little impact on the Liberty monitoring site or compliance (Table 35). Emissions from the modeled vessels would need to increase by a factor of 1,000,000 to increase PM2.5 at the Liberty monitoring station by 0.5 ug/m3. The maximum modeled plume concentration at the Liberty monitor is 0.0004% of that hour's measured concentration (27 ug/m3). Putting these results into context, the Clairton Coke Works emitted 153 tons of PM2.5 in 2009, equivalent to 4.4 g/sec. The modeled towboat emissions in the vicinity of Liberty average 0.002 g/sec (0.04% of Clairton).

Table 35. Air model results for vessel emissions

	Modeled concentration at monitor from vessel emissions (ug/m^3)	Actual PM2.5 at Liberty monitor (ug/m^3)	% of monitor	Actual Daily Average (ug/m^3)	EPA Standard (ug/m^3)
Max	1.19E-05	252.00	0.00045%	70.95	
Mean	5.42E-07	16.12	0.00001%	16.14	15 (12.5 now?)
98th	3.09E-06	71.00	0.00005%	48.36	35

The higher results coincide with conditions classified as "high stability" during which air column mixing is minimal.

The topography of the region is highly complex, resulting in changeable weather conditions, as well as a propensity toward inversions that trap pollutants within the river valley. The flat terrain assumption of the Gaussian plume model therefore cannot give accurate predictions of true contributions. The results are simply an indicator of the magnitude of the vessel emissions and plume concentrations. The model results above assume that the concentration at the monitor is comparable to the concentration in the plume at the elevation of the monitor. If the plume moves in a more laminar flow up the hillside to the monitor, a lower position in the plume would be a more appropriate result. Figure 30 shows the effect of the assumed monitor height on the model results. At no elevation above the stack, the average concentration at the monitor would only be 4E-5 ug/m3. Thus even under these worst case modeling assumptions, the impact of vessel emissions is negligible at the Liberty monitor.

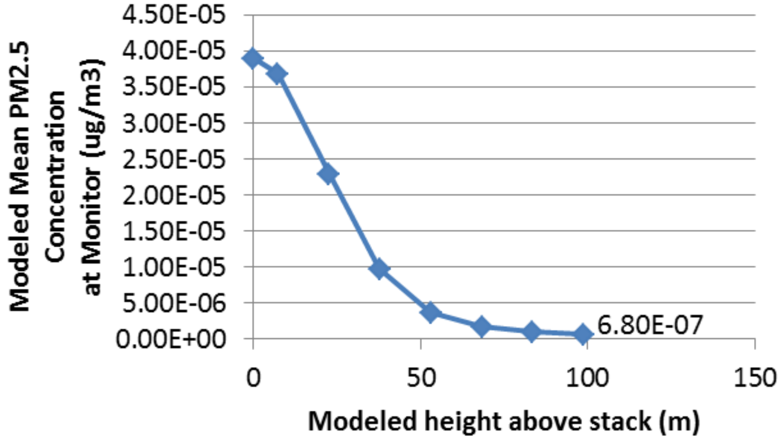


Figure 30. Liberty: Impact of monitor elevation on modeled air concentrations.

The modeling effort was repeated for the nearby Glassport monitor, which is closer to the river, lower in elevation, and in a residential neighborhood. The Glassport monitor only monitors PM10 levels **[129]**. Given the higher population density in the vicinity of the Glassport monitor, the model results are shown differently, providing a crude representation of ground level concentrations as a function of distance from the river centerline. Figure 31 shows the modeling results in terms of distance to the monitor; the left axis gives PM concentrations and the right axis shows the ground level elevation at each modeled distance. As expected, modeled air concentrations drop quickly as the length of the plume increases (as measured in meters from the river centerline), and as the elevation increases. At 100 meters from the river centerline, approximating the river shoreline, the maximum modeled concentration is only 0.002 ug/m3. These results remain negligible in comparison to measured results at the monitor and the EPA standards.

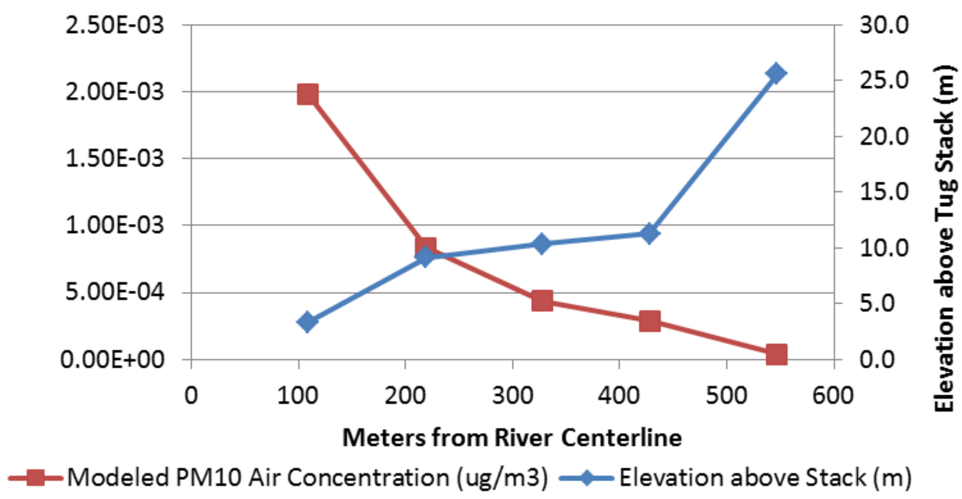


Figure 31. Modeled PM10 from towboat emissions at Glassport

F. Conclusions

The analyses presented in this section continue this dissertation's assessment of regional data, differentiating it from top down analyses that overlook regional specificities. A brief review is provided of the air quality issues in the region that continue to be of concern, with ongoing nonattainment for particulates, ozone and SO_2. A characterization of the regional fleet is provided, demonstrating the specialization of vessels in the upper reaches of the inland waterways.

A review of emission inventories is provided, including the available regional inventories that focus primarily on point source emissions and do not include emissions from river traffic. A number of national inventories of emissions from waterway activities are assessed for their relevance to regional analyses. Generally the national inventories are generated from "top down" assumptions.

The LPMS dataset and trip analysis were used to generate a regional emission inventory for vessels that haul barges across the region. The inventory accounts for vessel activity levels, vessel engine profiles, and assignment of appropriate emission factors. The methodology was demonstrated for PM2.5, a critical pollutant of concern to the region, estimating that underway emissions were about 360 tons in 2010 across the Pittsburgh and Huntington Districts.

The PM2.5 inventory of 360 tons for the study area is in reasonable conformance with both the NEI and Corbett-Fischbeck inventory methods when their results are adjusted to reflect the study area and 2010 river traffic levels.

PM2.5 emissions from underway towboat activity in the study area are comparable to the annual point source emissions of PM2.5 from the US Steel Clairton coking facility. Across Allegheny County, total PM2.5 loadings from point sources are about 600 times higher than the underway towboat emissions across Allegheny County.

The method can easily be extended to other pollutants associated with diesel combustion, and could be modified to reflect other geographic boundaries. Specifically, the methodology could readily be extended to fuel consumption rates and greenhouse gases for inclusion in the regional GHG inventory. In addition, the methodology allows for the calculation of emissions/ton-mile, a commonly used metric for comparison with other modes of transportation [7].

VI. Dissertation Conclusions and Recommendations for Future Work

A. Conclusions

This dissertation has examined the operation of the inland waterways, with a particular focus on the specific challenges present in the upper Ohio River basin. Three goals drove the research: assessing the impact of an extended loss of commercial river navigation due to catastrophic infrastructure failure; assessing current and potential new efficiency metrics for inland waterways freight movement, both in terms of vessel movements and the infrastructure itself; and quantifying and assessing air emissions from regional commercial river traffic. Useful new methodologies were developed and demonstrated in each of the research areas. Innovative applications of valuable data sources not previously used for inland waterways analyses were demonstrated to provide valuable insights into the efficiency of the inland waterways for commodity shipments.

Broad national analyses of the benefits and risks associated with the inland waterways do not address the challenges, usage patterns, and constraints specific to the upper reaches of the waterways. Consideration of these more localized constraints and operating practices allows for a more finely tuned decisionmaking framework, whether applied to major infrastructure investment decisions, optimization of operational practices, or identification of impactful opportunities related to pollution abatement and overall regional sustainability.

The inland waterways are an important component of the national freight network, carrying over 2.2 billion tons of commodities in 2012. Barge shipment is particularly well suited for high volume, low value, time insensitive commodities, such as coal, aggregate, grains, liquid fuels. Unlike rail and truck shipments, the waterways are geographically constrained to those portions of the country with navigable rivers. Fortunately the concentrated regions of industrial and agricultural development are often co-located with these waterbodies.

Navigation in the upper reaches of the inland waterways requires a series of locks and dams to create sufficient river depth to allow for sustained river traffic. Each lock(s) and dam facility represents a significant capital investment and engineering accomplishment to exert effective control over major waterways. These projects are designed to last for many decades, and through careful rehabilitation, many have lasted well beyond their design lives. There is a limit, however, at which fundamental components of these systems require replacement.

The inland waterways stakeholders have recently completed a successful effort to bring the U.S. Congress' attention the need for sustained and appropriate funding for this infrastructure. Passage of the WRRDA eliminates a number of impediments to timely and sufficient infrastructure investments to allow for the continued efficient use of waterborne commerce as part of the Nation's broader freight network. The actual improvement in the flow of funding to these capital investment projects will depend on a variety of additional steps, foremost being appropriation bills that follow through on WRRDA intent and promulgation of the funding mechanism reforms that will improve and rebalance public-private sector cost-sharing.

The underlying concern, as reflected in **Research Goal 1**, remains – what would happen if the investments and additional reforms are not made in a timely manner? Specifically, what would be the impact of a catastrophic failure of an outdated navigation facility as a result of a continued inefficient funding process? The risk is not zero. The locks and dams at Elizabeth and Charleroi on the lower Monongahela River are well beyond their design

> **Research Goal 1**: Assess the impact of an extended loss of navigation due to catastrophic infrastructure failure

lives, have known major structural issues, and have been slated for removal and replacement for decades. The issues associated with the three uppermost locks and dams on the Ohio are similar, with initiation of replacement unlikely to occur for at least another decade. Conversation with USACE engineers and review of Corps documents indicates that the risk of dam failure at Elizabeth cannot be ignored, and the cascading impact of such a failure could include the collapse of the fragile Charleroi lock walls.

Prior national analyses have examined the value of the waterways by using simplifying assumptions such as the wholesale closure of entire rivers and the shifting of all river freight to rail or truck. These analyses show dramatic national impacts. They do not generally attempt, however, to measure regional impacts or to acknowledge regional differences. The work summarized in section II of this dissertation represents alternative tools for the quantification of those regional impacts, and for the identification of more feasible scenarios for assessment in the face of a regional infrastructure failure.

Within the upper Ohio River basin, waterways traffic is dominated by the movement of coal from mines to coal-fired utilities, most of these transactions occurring within the region. While there is some exchangeability among these transactions, the mines and powerplants have been located and designed to make use of the advantages of the inland waterways. Some of these entities rely entirely on the rivers for the shipment of coal, with no flexibility to shift to other transport modes. Others rely partially on rail and truck, but could not operate at full capacity without access to waterway shipments. Methods were described to assess the presence of these operational constraints and resiliency, including assessment of mine-powerplant relationships described in the EIA-923 survey, patterns of coal shipments from individual mines and to specific powerplants, potential for plant closure based on historical production patterns.

A methodology was also presented to examine the regional nature of a catastrophic loss of navigation at a particular position on the waterways. Rather than assuming an entire river has been taken out of commission, the more reasonable assumption was explored that a limited stretch of navigation would be unavailable as a result of failure of antiquated infrastructure. The specific shipments between powerplants and mines that traverse the Elizabeth/Charleroi transit were identified and assessed, in terms of quantity and significance to the shipping mines and the receiving powerplants. In 2010, 7.0 million tons of coal shipments would have been displaced by this failure scenario. The impact to the two powerplants directly within the failure zone clearly would be dramatic, both in terms of coal shipments, but also water intakes needed to operate the plants. Facilities above the failure zone would also be significantly impacted due to their isolation within a much smaller post-failure market. The ability of these facilities to continue operation would depend on the ability of the regional market to shift to heavier uses of regional partners. Below the failure zone, the mines and powerplants have access to a much larger market and thus were assessed to be less vulnerable to operational issues caused by the failure scenario assessed.

The regional mines and powerplants operate within competitive markets. To the extent that they cannot adapt to a constrained waterway, the possibility that they would close must be considered, as well as the resultant ripple effects through the regional economy. In general, the broader national analyses do not account for entities that cease to exist in response to severe regional constraints. Similarly, the catastrophic loss of navigation is expected to include direct losses of stranded or grounded towboats and barges, costs not generally considered in national analyses. Only considering facility closures and ignoring all other costs associated with adapting to loss of navigation through Elizabeth and Charleroi, the displaced revenues are estimated to range between $0.6 and 1.7 trillion for a year-long closure.

An important innovation deployed in the modeling scenario described in this dissertation is the demonstrated use of powerplant survey data not previously described in the literature related to waterways analyses. The EIA-923 survey represents a high value data source spanning multiple years with excellent industry coverage. This dissertation demonstrated the usefulness of this data source as a means to identify real shipments of a critical and high volume commodity, characterizing potentially vulnerable shipments and the resiliency of the mines and powerplants to a specific river segment outage. Further, this data source provides extensive information about shipping costs for barging, rail, and truck; this dissertation provides an initial exploration of the usefulness of these data. Future work can further quantify regional differences in shipping costs within and between shipping modes, allowing for more accurate understanding of costs and mode choices in the upper inland waterways. (In contrast, this dissertation shows the significant limitations of the FAF to accurately depict shipping at a regional level, particularly with respect to barge shipments.)

Research Goal 2 focused on identifying appropriate and useful measures of efficiency for the inland waterways are used in the upper Ohio River system. There were three major components to the analyses addressing this goal. First, the LPMS dataset was used to characterize the vessel trips that are commonly made across the region. A methodology was developed that ranks these vessel trips in terms of their frequency, tonnage, and ton-miles. Frequency rankings can be used as a measure of regional traffic intensity. Tonnage rankings are directly related to economic value, as these trips move the highest volume of commodities. Ton-mileage rankings may be of use for the

Research Goal 2: Assess current and potential new efficiency metrics for the inland waterways prioritization of vessel improvements, as high ton-mileage is related directly to high emission loadings. One specific vessel trip ranked highly for all three parameters, the 111-mile trip on the Ohio River across the Racine, Belleville, Willow Island and Hannibal locks. This corridor is used heavily to move Kanawha coal to Ohio powerplants.

Tow operators must reconfigure their tows multiple times when crossing the study area. A method was developed to compare the vessel trips that can be extracted from the public LPMS dataset with the longer commodity (i.e., coal) trips visible in the EIA-923 datasets. The conflation of these datasets allowed for the development of an improved understanding of vessel and commodity trip lengths, the need for and frequency of tow reconfiguration, with the accompanying implications for efficiency gain opportunities as the river constrictions are removed with the completion of projects such as the Lower Mon Project. Using the LPMS and EIA-923 together highlights the gap in the regional understanding of vessel movements, as neither dataset covers the harbor or staging activities of the line haul vessels as they reconfigure their tows, and the harbor vessels that operate in these staging areas. As AIS coverage eventually provides more complete coverage of the upper inland waterways, these gaps should disappear, allowing for a more complete understanding of inland vessel operating practices and requirements. (A valuable side analysis related to trip length was the calculation of a shipping cost function.)

The second set of analyses addressing **Research Goal 2** examined the characteristics of the existing infrastructure and the various statistics that have been or could be used to assess vessel movement across the region. The upper Ohio River basin infrastructure poses unique challenges to navigation in that the locks are not of uniform size, and the rivers themselves constrict. Tows below Montgomery are generally comprised of 15 jumbo barges which can pass through the locks below Montgomery in single passes. The locks at Elizabeth and Charleroi are particularly small, and were sized to handle the “standard” barges that were typical at the time these locks were built. At best, these locks can only handle 3 jumbo barges at a time. As a result, the smaller locks run at proportionately higher lockage rates, with more required cut lockages. Each additional lockage represents additional operational wear and tear on the lock mechanisms, which is expected to contribute to the high rate of closures at these locks.

National analyses of the inland waterways generally assume that the common barge unit for dry bulk commodities such as coal is the “jumbo” barge. In the upper reaches of the inland waterways, however, analysis of the locking statistics demonstrates the prevalent use of smaller “standard” and “stumbo” barges, sizes that are well suited to the smaller upriver locks and the river constrictions.

Examination of USACE’s routinely reported statistics revealed questions and opportunities. The statistics related to lockage delays are important efficiency metrics, yet it was not possible to replicate USACE’s results, with significant differences in total hours of delay and average length of delays – these differences were not consistent across locks, ruling out straightforward calculation errors (on either my part or USACE’s), and instead pointing toward unstated methodological assumptions. Treatment of delays associated with cut lockages, in particular, could be handled with greater clarity by USACE.

Delay was examined for potential correlation with a variety of factors. Only extended lock closures showed matching trends. Other potential factors such as increased numbers of recreational lockages or seasonal patterns were not significant. Future work could quantify the degree of correlation between these types of factors. Alternative statistics were explored which may provide USACE with more descriptive tools for characterizing whether or not vessels will be delayed and the significance of those delays.

The third component of the analyses addressing **Research Goal 2** used the understanding gained from the first two components to support the development of a stochastic modeling tool that can be used to predict time savings across different operating conditions. The model considers underway transit, delay, lockage and reconfiguration times. Two particular variations were assessed – changes in transit times for a typical commodity trip across the region before and after completion of the Lower Mon Project, as well as differences in efficiency associated with different tow configurations (jumbo versus mixed barge size tows). These analyses quantify the savings associated with the removal of river bottlenecks. For a single 15-barge jumbo tow, the completion of the LMP will reduce transit times by 17%. For a single 15-barge mixed tow scenario, however, there is very little time savings associated with the LMP due to the continued presence of smaller upriver locks. Extending the analysis to consider an annual commodity shipment across this transit (i.e., one year of coal shipments from the Powhatan mine to the Fort Martin powerplant), the larger tonnage carried by the jumbo tow evens out the difference between the advantage of the mixed tow over the jumbo tow in the baseline scenario – both tow configurations would require about 1,100 hours of operating time to move one year's coal shipments between Powhatan and Fort Martin. Upon completion of the LMP, the efficiency of and the time savings for the jumbo tows becomes evident, with a 300 hour annual advantage over the mixed tow.

A screening analysis of the cost savings associated with the modeled operating hour reductions was based on USACE's 2004 Mississippi River vessel operating cost survey. While it was not possible to assess the validity of these decade-old cost data for the upper Ohio River basin vessels, the screening analysis indicates that LMP completion could save the modeled powerplant $12,000-22,000/year in shipping costs. These savings, if extended to the 7 million tons of thermal coal shipments across the LMP (as determined in section II.H), may reduce shipping costs across the region by $0.5-1.9 million/year.

This model could readily be extended to other river segments for which streamlining is under consideration (e.g., the Emsworth, Montgomery, Dashields locks).

Research Goal 3: Quantify and assess air emissions from regional commercial river traffic

The third **Research Goal** asked how much commercial river traffic contributes to air pollution in the Pittsburgh region. This dissertation addressed this goal in two primary ways. First, the LPMS dataset analysis allows for the calculation of pollutant loadings from underway activity within the study area. Across the Pittsburgh and Huntington Districts, the movement of commodities by towboat transits is estimated to cause the release of 360 tons of PM2.5. This widely dispersed loading, spread along the upper Ohio River basin from Cincinnati, OH to Morgantown, WV, is equivalent in size to the emission loading of one regional point source, the US Steel Clairton coking facility and is one fourth the amount of PM2.5 loadings from a regional power plant. Updated reporting of vessel rebuild age, and emission factors for Tier 3 and 4 vessels, as deployed, would result in reductions in the calculated emission loadings.

The second approach to the third research goal was to model air emissions from towboats traversing the Monongahela River in the vicinity of the US Steel coking facility and the Clairton and Liberty ACHD air monitors in order to assess the significance of towboat emissions at these monitors. This screening analysis shows that the towboat emissions are not expected to exert any measurable impact on the air monitors.

In conclusion, this dissertation has examined the efficiency and resiliency of the upper Ohio River basin infrastructure, contrasting findings relevant to this region with assumptions and finding of broader national studies. Valuable new methodologies and data sources have been developed and demonstrated. The unique attributes of this region's infrastructure and usage patterns have been characterized – the shipment of coal, mines and powerplants with heavy and inflexible dependence on barge shipments, and the constrictions of the waterway infrastructure. Acknowledging these attributes allows for a more accurate assessment of risks due to infrastructure failure and opportunities for efficiency gains.

B. Future Work

The new methodologies demonstrated in this dissertation have promising applications in numerous areas. The consideration of facility closures is a significant gap in current resiliency analyses, and in benefit cost analyses used by USACE to assess infrastructure investment alternatives. The methodologies presented in Section II related to the identification of facilities that may close in response to extended loss of navigation can be applied to other regions and failure scenarios.

The demonstrated applicability of the EIA-923 survey to the assessment of the coal-to-utility network has many future applications. Methodologies developed for this dissertation use the EIA-923 to assess transportation mode alternative availability, supply chain flexibility, and shipping costs as a function of distance. Future work should extend the shipping cost analyses to other regions and to rail and truck shipments. Changes in shipping practices can be evaluated over time from the EIA-923, understanding historical patterns and predicting future shifts as the electricity generation industry continues to evolve. In combination with USACE's lockage dataset and the methodologies to identify and link vessel and commodity trips, the relative efficiencies of important commodity shipping routes can be assessed (particularly for coal).

The results of the vessel trip methodology showed the importance of specific river segments as common staging areas for tow reconfigurations. Future work is needed to understand vessel activities in these regions, including the use of Automatic Identification System vessel data to characterize intralock activity.

The stochastic time savings model has numerous future applications, including the assessment of potential efficiency gains with alternative infrastructure enhancement projects such as the proposed Upper Ohio lock replacements at Emsworth, Montgomery and Dashields. Alternatively, the model could be used to assess waterway performance over time, using distributions for additional years. A valuable extension of this work would be the validation of the cost savings component of the methodology to update or determine the applicability of USACE's 2004 Mississippi River vessel operating cost survey to the upper waterways.

The methodology used to calculate a PM2.5 emission loading for commercial river traffic across the Pittsburgh and Huntington Districts can be used to inventory greenhouse gases and other pollutants associated with diesel marine engines. The methodology could be modified to reflect particular stretches of river, such as those specific to the City of Pittsburgh, or riverlines within Pennsylvania.

VII. Glossary

Acronym	Definition
ACHD	Allegheny County Health Department
AIS	Automatic Identification System
BTS	Bureau of Transportation Statistics
CAA	Clean Air Act
CEIWR	Corps of Engineers Institute for Water Resources
CFS	Commodity Flow Survey
CPI	Consumer Price Index
CSA	Combined Statistical Area
CTDM	Combined Travel Demand Model
DSAC	Dam Safety Action Classification System
EOL	End of Lockage
FAF	Freight Analysis Framework
FGD	Flue Gas Desulfurization
FOB	Freight on Board
EIA	Energy Information Administration
GIS	Geographic Information System
L&D, L/D	Lock and dam
LMP	Lower Mon Project
LPMS	Lock Monitoring Performance System
MSHA	Mine Safety and Health Administration
M/V	Marine Vessel
MWhr	Megawatt hour
NDC	Navigation Data Center
NETS	Navigation Economic Technologies Program
NOAA	National Oceanic and Atmospheric Administration
NRC	National Resources Council
O/D	Origin/destination
OMNI	Operations and Maintenance of Navigation Information
ORNIM	Ohio River Navigation Investment Model
ORS	Ohio River System
PBV	Pittsburgh-Beaver Valley
PM10	Particulate Matter, 10 microns
PM2.5	Particulate Matter, 2.5 microns
PRB	Powder River Basin
RITA	Research and Innovation Technology Administration
SO2	Sulfur dioxide
SOL	Start of Lockage
STB	Surface Transportation Board
USACE	U.S. Army Corps of Engineers
USDOE	U.S. Department of Energy
USDOT	U.S. Department of Transportation

Acronym	**Definition**
USEPA	U.S. Environmental Protection Agency
VOR	Vessel Operator Reports
WCSC	Waterborne Commerce Statistical Codes
WCUS	Waterborne Commerce in the United States
WRDA	Water Resources and Development Act
WRRDA	Water Resources Reform and Development Act

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APPENDICES

Appendix 1. EIA O/D tonnage barged between PA, OH, WV mines and powerplants, 2010 (tons) [50]

Power plant #	Power plant name	Mine name	Hopedale Mine	Century Mine	Powhatan No. 6 Mine	Orange Strip	Oxford Loading Dock	Oxford Mining #2	Oxford Contract Auger # 2- No. 11	Oxford Contract Auger # 1- No. 4	Oxford Beagle Club	Oxford Jockey Hollow	Yellowbush Mine
		State	OH	OH	OH	OH	OH	OH	OH	OH	OH	OH	OH
			3300968	3301070	3301159	3301925	3302937	3304213	3304522	3304524	3304584	3304585	3304595
2828	Cardinal	OH	0	0	851513	0	0	0	0	0	0	0	0
2830	Walter C Beckjord	OH	0	0	0	0	0	0	0	0	0	0	0
2832	Miami Fort	OH	0	0	1120952	0	0	0	0	3283	1624	0	0
2850	J M Stuart	OH	0	0	0	0	0	0	0	0	0	0	0
2864	R E Burger	OH	0	0	0	0	0	0	0	0	0	0	0
2866	W H Sammis	OH	0	0	0	0	17088	0	0	0	0	0	0
2872	Muskingum River	OH	0	0	0	0	0	0	0	0	0	0	0
2876	Kyger Creek	OH	0	249343	1041288	0	0	0	0	0	0	0	0
2917	Hamilton	OH	0	0	38297	0	0	0	0	0	0	0	0
3098	Elrama Power Plant	PA	0	0	0	0	0	0	0	0	0	0	0
3149	PPL Montour	PA	0	0	0	0	0	0	0	0	0	0	0
3179	Hatfields Ferry Power Station	PA	0	0	539065	0	0	0	0	0	0	0	112606
3181	Mitchell Power Station	PA	0	0	1117	0	0	0	0	0	0	0	7103
3935	John E Amos	WV	0	0	2421775	0	0	0	0	0	0	0	0
3936	Kanawha River	WV	0	0	0	0	0	0	0	0	0	0	0
3938	Philip Sporn	WV	0	0	0	0	0	0	0	0	0	0	0
3943	Fort Martin Power Station	WV	0	0	163968	0	0	0	0	0	0	0	0
3946	Willow Island	WV	0	0	0	0	0	0	0	0	0	0	0
3947	Kammer	WV	0	0	0	0	0	0	0	0	0	0	0
3948	Mitchell	WV	0	0	0	0	0	0	0	0	0	0	0
6004	Pleasants Power Station	WV	0	0	2261330	0	0	0	0	0	0	0	237585
6019	W H Zimmer	OH	0	0	1584408	0	0	0	0	6457	425340	0	0
6031	Killen Station	OH	0	0	0	0	0	0	0	0	0	0	0
6094	Bruce Mansfield	PA	0	0	0	0	238320	420946	226603	0	0	0	0
6264	Mountaineer	WV	0	0	1367300	0	0	0	0	0	0	125924	350471
7286	Richard Gorsuch	OH	0	0	0	18788	0	0	0	0	0	0	0
8102	General James M Gavin	OH	13043	0	1759410	0	0	0	0	0	0	0	0
8226	Cheswick Power Plant	PA	0	0	0	0	0	0	0	0	0	0	0
10676	AES Beaver Valley Partners Be	PA	0	0	0	0	0	0	0	0	0	0	0
50130	G F Weaton Power Station	PA	0	0	0	0	0	0	0	0	0	0	0
50491	PPG Natrium Plant	WV	0	0	0	0	112104	0	0	0	0	0	0

			North Barnesville	Tusky Prep	Mine 84	Cumberland Mine	Emerald Mine No 1	Bailey Mine	Fayette Co Strips	Gameland SE	Neiswonger Mines	Washington County Strips	Robinson Run No 95
		State	OH	OH	PA	PA	PA	PA	PA	PA	PA	PA	WV
			3304606	3304609	3600958	3605018	3605466	3607230	3607973	3608802	3609226	3609597	4601318
2828	Cardinal	OH	0	0	0	0	0	0	0	0	0	0	0
2830	Walter C Beckjord	OH	0	0	0	0	0	0	0	0	0	0	0
2832	Miami Fort	OH	0	0	0	561026	0	0	0	0	0	0	0
2850	J M Stuart	OH	0	0	0	96031	0	0	0	0	0	0	0
2864	R E Burger	OH	0	0	0	79950	0	0	0	5248	0	0	0
2866	W H Sammis	OH	0	0	0	294038	0	0	0	1723	0	0	0
2872	Muskingum River	OH	0	0	0	0	0	0	0	0	0	0	0
2876	Kyger Creek	OH	0	0	0	0	0	0	0	0	0	0	0
2917	Hamilton	OH	0	0	0	0	0	0	0	0	0	0	0
3098	Elrama Power Plant	PA	0	0	12725	94883	0	105568	0	0	0	0	0
3149	PPL Montour	PA	0	0	0	0	0	0	0	0	0	0	0
3179	Hatfields Ferry Power Station	PA	0	0	0	1292679	0	0	72567	0	0	99439	0
3181	Mitchell Power Station	PA	0	0	0	131887	0	0	0	0	11584	53195	0
3935	John E Amos	WV	0	0	0	0	0	0	0	0	0	0	0
3936	Kanawha River	WV	0	0	0	0	0	0	0	0	0	0	0
3938	Philip Sporn	WV	0	0	0	0	0	0	0	0	0	0	0
3943	Fort Martin Power Station	WV	0	0	0	47344	221559	346094	22126	0	0	20168	0
3946	Willow Island	WV	0	0	0	0	0	24816	0	0	0	0	0
3947	Kammer	WV	0	0	0	0	0	0	0	0	0	0	0
3948	Mitchell	WV	0	0	0	0	0	0	0	0	0	0	0
6004	Pleasants Power Station	WV	0	162970	0	0	0	0	0	0	0	0	0
6019	W H Zimmer	OH	0	0	0	137441	0	0	0	0	0	0	0
6031	Killen Station	OH	0	0	0	236837	0	0	0	0	0	0	0
6094	Bruce Mansfield	PA	0	0	0	51296	0	10434	0	79607	0	0	21223
6264	Mountaineer	WV	0	0	0	0	0	0	0	0	0	0	0
7286	Richard Gorsuch	OH	0	0	0	0	0	0	0	0	0	0	0
8102	General James M Gavin	OH	239212	0	0	0	0	0	0	0	0	0	0
8226	Cheswick Power Plant	PA	0	0	0	0	0	491560	0	0	0	0	0
10676	AES Beaver Valley Partners Be	PA	0	0	0	256032	0	0	0	0	0	0	0
50130	G F Weaton Power Station	PA	0	0	0	0	0	0	0	0	0	0	0
50491	PPG Natrium Plant	WV	0	0	0	0	0	0	0	0	0	0	0

			Loveridge #22	Shoemaker Mine	McElroy Mine	Federal No 2	Winifrede Dock	Prime No. 1 Mine	Crown Hill Dock	American Eagle Mine	Coalburg Dock	Crawdad No 1 Mine	River Point Dock
			WV	WV	WV	WV	WV	WV	WV	WV	WV	WV	WV
		State	4601433	4601436	4601437	4601456	4603090	4604387	4605382	4605437	4605472	4605589	4606694
2828	Cardinal	OH	0	0	0	0	0	0	0	0	0	0	0
2830	Walter C Beckjord	OH	0	8312	677840	0	0	0	38363	0	0	0	0
2832	Miami Fort	OH	0	6587	88949	0	0	0	0	0	0	0	0
2850	J M Stuart	OH	0	0	0	0	225429	0	0	0	0	0	0
2864	R E Burger	OH	0	0	10532	0	0	0	0	0	0	0	0
2866	W H Sammis	OH	0	0	388693	0	0	0	0	0	225618	0	0
2872	Muskingum River	OH	62384	34771	216041	0	0	0	0	0	0	0	0
2876	Kyger Creek	OH	0	0	0	0	0	0	0	0	0	0	0
2917	Hamilton	OH	0	0	0	0	0	0	0	0	0	0	0
3098	Elrama Power Plant	PA	0	0	0	0	0	0	0	0	0	0	0
3149	PPL Montour	PA	0	0	0	0	0	0	0	0	0	0	0
3179	Hatfields Ferry Power Station	PA	0	0	0	107165	0	488802	0	0	0	488802	0
3181	Mitchell Power Station	PA	0	0	0	610	0	3709	0	0	0	3709	0
3935	John E Amos	WV	0	0	0	0	0	0	0	0	0	0	0
3936	Kanawha River	WV	0	0	0	0	0	0	0	0	0	0	0
3938	Philip Sporn	WV	0	0	0	0	0	0	0	0	0	0	0
3943	Fort Martin Power Station	WV	0	10793	0	50198	0	486417	0	0	0	486417	0
3946	Willow Island	WV	0	0	0	0	0	0	0	0	0	0	0
3947	Kammer	WV	0	0	0	0	0	0	0	0	0	0	0
3948	Mitchell	WV	0	4848	7645	0	0	0	0	0	0	0	0
6004	Pleasants Power Station	WV	0	16901	0	0	0	0	0	0	0	0	0
6019	W H Zimmer	OH	0	235981	88769	0	0	0	0	0	0	0	0
6031	Killen Station	OH	0	0	0	0	0	0	0	0	0	0	0
6094	Bruce Mansfield	PA	0	11403	4689640	0	0	0	0	0	0	0	0
6264	Mountaineer	WV	0	0	0	101926	0	0	0	0	0	0	0
7286	Richard Gorsuch	OH	0	0	0	0	0	0	0	0	0	0	0
8102	General James M Gavin	OH		2131967	2014410	0	0	0	0	0	0	0	0
8226	Cheswick Power Plant	PA	0	199988	0	0	0	0	0	58333	0	0	0
10676	AES Beaver Valley Partners Be	PA	0	0	237761	0	0	0	0	0	0	0	0
50130	G F Weaton Power Station	PA	0	0	0	0	0	0	0	0	0	0	0
50491	PPG Natrium Plant	WV	0	0	0	0	0	0	0	0	13509	0	6397

			Cheylan Dock	Patriot Mining Company Inc	Quincy Dock	Kiah Creek Preparation Plant	Big Mountain No 16	Birch River Mine	Mammoth Coal Co. Surface Mine	Fourmile Fork	Crooked Run Surface Mine	Tunnel Ridge Mine	Quincy Manufactured Home Park
			WV	WV	WV	WV	WV	WV	WV	WV	WV	WV	WV
		State	4606956	4607654	4607736	4607809	4607908	4607945	4608110	4608596	4608675	4608864	4608869
2828	Cardinal	OH	0	0	0	0	0	0	0	0	0	0	0
2830	Walter C Beckjord	OH	0	0	0	0	0	0	0	0	0	0	0
2832	Miami Fort	OH	0	0	0	0	0	0	0	0	0	0	0
2850	J M Stuart	OH	0	0	0	0	0	0	0	0	0	0	0
2864	R E Burger	OH	0	0	0	0	0	0	0	0	0	0	0
2866	W H Sammis	OH	0	0	258286	0	0	0	0	0	0	0	0
2872	Muskingum River	OH	0	0	0	0	0	0	0	0	0	0	0
2876	Kyger Creek	OH	0	0	0	0	0	0	0	0	0	0	0
2917	Hamilton	OH	0	0	0	0	0	0	0	45469	0	0	0
3098	Elrama Power Plant	PA	0	0	0	0	0	0	0	0	0	0	0
3149	PPL Montour	PA	0	0	0	0	0	0	0	0	0	0	0
3179	Hatfields Ferry Power Station	PA	0	0	0	0	0	0	0	0	0	8748	0
3181	Mitchell Power Station	PA	0	0	0	0	0	0	0	0	0	9362	0
3935	John E Amos	WV	0	0	0	3299	0	0	301688	0	0	0	0
3936	Kanawha River	WV	0	0	0	0	0	0	154296	0	0	0	0
3938	Philip Sporn	WV	0	0	0	0	0	0	530513	0	0	0	0
3943	Fort Martin Power Station	WV	0	3052	0	0	0	239501	0	0	0	0	33133
3946	Willow Island	WV	0	0	0	0	0	6317	0	0	0	0	0
3947	Kammer	WV	0	0	0	0	0	0	0	0	0	0	0
3948	Mitchell	WV	0	0	0	0	0	0	60692	48983	91610	0	49211
6004	Pleasants Power Station	WV	0	0	0	0	0	0	0	0	0	0	0
6019	W H Zimmer	OH	0	0	0	0	0	0	0	0	0	0	0
6031	Killen Station	OH	0	0	0	0	0	0	0	0	0	0	0
6094	Bruce Mansfield	PA	0	0	0	0	0	0	0	0	0	0	0
6264	Mountaineer	WV	0	0	0	0	0	0	201518	0	0	0	0
7286	Richard Gorsuch	OH	0	0	127347	0	19992	0	0	0	0	0	0
8102	General James M Gavin	OH	0	0	0	0	0	0	0	0	0	0	0
8226	Cheswick Power Plant	PA	0	0	0	0	0	0	0	0	0	0	0
10676	AES Beaver Valley Partners Be	PA	0	0	0	0	0	0	0	0	0	0	0
50130	G F Weaton Power Station	PA	0	0	0	0	0	0	0	0	0	0	0
50491	PPG Natrium Plant	WV	47498	0	0	0	0	0	0	0	0	0	0

			S11 Keystone Surface Mine	Marmet Dock	Republic Energy	Mammoth #2 Gas	Coalburg No. 2 Mine	Total tons by river
			WV	WV	WV	WV	WV	
		State	4608906	4608961	4609054	4609108	4609231	
2828	Cardinal	OH	0	0	0	0	0	854682
2830	Walter C Beckjord	OH	0	242827	0	0	0	1084841
2832	Miami Fort	OH	0	0	0	0	0	3537792
2850	J M Stuart	OH	0	0	0	0	0	3577310
2864	R E Burger	OH	0	0	0	0	0	95730
2866	W H Sammis	OH	0	11190	0	0	0	1424026
2872	Muskingum River	OH	0	0	0	0	0	313196
2876	Kyger Creek	OH	0	0	0	0	0	2883732
2917	Hamilton	OH	0	0	0	0	0	83766
3098	Elrama Power Plant	PA	0	0	0	0	0	213176
3149	PPL Montour	PA	0	0	0	0	0	90029
3179	Hatfields Ferry Power Station	PA	0	0	0	0	0	3954943
3181	Mitchell Power Station	PA	0	0	0	0	0	402828
3935	John E Amos	WV	0	0	544965	0	0	3356396
3936	Kanawha River	WV	24610	0	37582	4214	0	220702
3938	Philip Sporn	WV	33376	0	0	16363	35301	686971
3943	Fort Martin Power Station	WV	0	0	0	0	0	2754601
3946	Willow Island	WV	0	0	0	0	0	104519
3947	Kammer	WV	0	0	0	0	0	150441
3948	Mitchell	WV	0	0	0	0	0	262989
6004	Pleasants Power Station	WV	0	0	0	0	0	3465990
6019	W H Zimmer	OH	0	0	0	0	0	3856177
6031	Killen Station	OH	0	0	0	0	0	1617979
6094	Bruce Mansfield	PA	0	0	0	0	0	5845189
6264	Mountaineer	WV	38747	0	14580	17624	41934	2339727
7286	Richard Gorsuch	OH	0	0	0	0	0	354872
8102	General James M Gavin	OH		0	0	0	0	6379584
8226	Cheswick Power Plant	PA	0	0	0	0	0	749881
10676	AES Beaver Valley Partners Be	PA	0	0	0	0	0	493793
50130	G F Weaton Power Station	PA	0	0	0	0	0	370424
50491	PPG Natrium Plant	WV	0	168661	0	0	0	348169

Appendix 2. Barging mine profiles, 2010 [50] [52]

Coal Mine MSHA ID	Coal Mine State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	% tallied	Mine status	Latitude	Longitude	River	River Mile
503836	CO	Foidel Creek Mine	5,440,924	284,110	30%	Active	40.3528	-107.07	NA	
1100726	IL	Shay #1 Mine	399,795	250,995	1%	Active	39.2058	-89.863	Ohio	941
1102408	IL	Gateway Mine	2,551,693	551,955	14%	Active	38.1583	-89.625	Mississippi	98.5
1102752	IL	The American Coal Company New Era Mine	4,430,148	3,657,140	51%	Active	37.8333	-88.583	Ohio	947
1103054	IL	Willow Lake Portal	4,956,958	4,956,958	83%	Non-Producing	37.7583	-88.383	Ohio	943.2
1103058	IL	Pattiki	3,417,785	2,471,930	72%	Active	38.075	-88.1	Ohio	827
1103141	IL	Mach #1 Mine	4,806,334	2,850,478	50%	Active	37.8389	-88.831	Ohio	827
1103143	IL	Prairie Eagle	771,470	548,507	86%	Active	38.0806	-89.591	Mississippi	105
1202010	IN	Air Quality #1 Mine	608,448	306,475	100%	Non-Producing	38.625	-87.447	Ohio	784
1202189	IN	Air Quality South Wash Plant	429,384	66,955	101%	Non-Producing	38.6167	-87.341	Ohio	784
1202207	IN	Somerville	2,641,068	1,700,688	94%	Active	38.3778	-87.346	Ohio	784
1202441	IN	Wild Boar Mine	12,515	12,515	112%	Active	38.1783	-87.28	Ohio	747
1502057	KY	Advantage #1	38,005	38,005	100%	Temporarily Idled	37.2075	-82.835	Big Sandy	7
1502709	KY	Highland 9 Mine	2,789,946	2,789,946	75%	Active	37.7406	-87.769	Ohio	870
1503178	KY	River View Facilities	634,607	634,607	61%	Active	37.76	-87.947	Ohio	843
1510358	KY	Arch Coal Terminal Inc	134,211	134,211	17%	Active	38.3297	-82.58	Ohio	317
1510789	KY	Colona Synfuel	40,316	40,316	96%	Non-Producing	38.1689	-82.647	Big Sandy	7
1512914	KY	Sapphire Prep Plant	929,316	36,668	100%	Non-Producing	37.2036	-82.822	Big Sandy	7
1516734	KY	Clintwood Elkhorn II	197,555	32,425	101%	Active	37.4283	-82.243	Ohio	315
1516749	KY	Kentucky Coal Terminal	54,194	54,194	100%	Active	38.3181	-82.573	Big Sandy	7.8
1517044	KY	Vision #9	675,177	575,543	20%	Non-Producing	37.575	-87.542	Green	43
1517232	KY	Richland No 9	54,241	54,241	100%	Active	37.2875	-87.594	Green	40
1517278	KY	Red Bud Dock North	48,567	48,567	100%	Active	38.3133	-82.573	Big Sandy	7.8
1517403	KY	Pleasant View Washer Plant	7,075	7,075	101%	Abandoned	37.2936	-87.596	Green	40
1517587	KY	Freedom	1,417,781	1,345,038	34%	Abandoned and Sealed	37.7289	-87.416	Ohio	785
1518040	KY	No. 6	53,350	15,726	102%	Active	37.4283	-82.429	Ohio	316
1518335	KY	Dodge Hill Mine #1	853,580	853,580	44%	Active	37.5547	-88.022	Ohio	870
1518542	KY	South	223,586	223,586	101%	Active	37.3061	-82.576	Ohio	843
1518547	KY	Onton #9	1,209,467	1,097,535	29%	Active	37.5822	-87.479	Green	45.6
1518568	KY	No 2 Mine	273,964	3,169	100%	Abandoned	37.4575	-82.663	Big Sandy	7

Coal Mine MSHA ID	Coal Mine State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	% tallied	Mine status	Latitude	Longitude	River	River Mile
1518622	KY	Back in Black	7,991	7,991	101%	Abandoned	37.1803	-87.114	Green	85.9
1518639	KY	Calvert City Terminal LLC	273,421	273,421	100%	Active	37.0019	-88.38	Ohio	933
1518826	KY	Elk Creek Mine	721,390	495,149	99%	Active	37.355	-87.439	Green	85.9
1519088	KY	Surface #3	103,586	103,586	98%	Abandoned	37.9142	-82.963	Big Sandy	7.6
1519365	KY	Schoate Preparation Plant	1,040,536	77,130	99%	Active	37.2547	-87.123	Green	85
1519374	KY	River View Mine	3,696,419	3,696,419	24%	Active	37.7431	-87.888	Ohio	843
2401457	MT	Spring Creek Coal Company	12,916,230	1,808,933	0.16%	Active	45.3583	-106.75	Ohio	23
2401950	MT	Bull Mountains Mine No 1	1,613,438	105,510	91%	Active	46.4508	-108.71	Ohio	23
3300968	OH	Hopedale Mine	838,475	13,043	101%	Active	40.3472	-80.919	Ohio	69
3301070	OH	Century Mine	260,081	249,343	100%	Active	39.59	-81.01	Ohio	110.6
3301159	OH	Powhatan No. 6 Mine	14,173,355	13,150,423	64%	Active	39.9147	-80.983	Ohio	110.6
3301358	OH	Sands Hill Strip	492,692	368,173	7%	Active	39.1167	-82.402	Ohio	256
3301925	OH	Orange Strip	546,327	401,679	5%	Active	39.6503	-81.468	Ohio	189
3302937	OH	Oxford Loading Dock	367,512	367,512	70%	Active	40.0189	-80.74	Ohio	92.8
3304213	OH	Oxford Mining #2	754,947	420,946	100%	Non-Producing	40.0667	-81.867	Ohio	93
3304522	OH	Oxford Contract Auger # 2-No. 11	226,603	226,603	100%	Abandoned	40.1681	-80.951	Ohio	92.8
3304524	OH	Oxford Contract Auger # 1-No. 4	9,740	9,740	102%	Abandoned	40.1853	-80.753	Ohio	81
3304584	OH	Oxford Beagle Club	426,964	426,964	100%	Abandoned	40.1447	-80.909	Ohio	92
3304585	OH	Oxford Jockey Hollow	150,255	125,924	100%	Temporarily Idled	40.2181	-81.096	Ohio	165
3304595	OH	Yellowbush Mine	707,765	707,765	67%	Direct	38.9593	-81.896857	Ohio	240.5
3304606	OH	North Barnesville	1,008,666	819,064	100%	Abandoned	39.9878	-81.178	Ohio	92
3600958	PA	Mine 84	12,725	12,725	#####	Direct	40.1383	-80.183	Mon	58
3605018	PA	Cumberland Mine	5,313,087	5,191,021	100%	Active	39.7997	-79.971	Mon	81.5
3605466	PA	Emerald Mine No 1	4,223,891	221,559	100%	Active	39.8753	-80.124	Mon	58
3607230	PA	Bailey Mine	16,199,193	1,004,362	100%	Active	39.9694	-80.421	Mon	58
3607973	PA	Fayette Co Strips	129,178	94,693	100%	Active	40.07	-79.43	Mon	86.3
3608802	PA	Gameland S E	114,995	86,578	100%	Abandoned	40.3822	-80.404	Ohio	66
3609226	PA	Neiswonger Mines	60,887	11,584	100%	Active	40.1736	-80.092	Mon	42.8
3609597	PA	Washington County Strips	172,802	172,802	100%	Active	40.1464	-80	Mon	42.8
4405971	VA	Stoker	173,800	75,719	23%	Active	36.9389	-82.646	Ohio	315
4601318	WV	Robinson Run No 95	5,140,771	21,223	100%	Active	39.4028	-80.363	Mon	100

Coal Mine MSHA ID	Coal Mine State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	% tallied	Mine status	Latitude	Longitude	River	River Mile
4601368	WV	Fanco	2,309,564	33,424	101%	Active	37.7781	-81.817	Ohio	308
4601433	WV	Loveridge #22	3,500,909	251,910	100%	Active	39.6083	-80.291	Mon	58
4601436	WV	Shoemaker Mine	3,821,248	3,821,248	69%	Active	40.2017	-80.733	Ohio	80.9
4601437	WV	McElroy Mine	10,211,137	8,420,280	92%	Active	39.4844	-80.485	Ohio	110.4
4601456	WV	Federal No 2	3,644,537	515,454	100%	Active	39.6678	-80.253	Mon	58
4603090	WV	Winifrede Dock	225,429	225,429	100%	Temporarily Idled	38.2108	-81.521	Kanawha	69
4604387	WV	Prime No. 1 Mine	1,026,057	978,928	100%	Active	39.7047	-80.008	Mon	94.8
4605437	WV	American Eagle Mine	58,333	58,333	100%	Active	38.1642	-81.474	Kanawha	73.15
4605472	WV	Coalburg Dock	239,127	239,127	94%	Active	38.2028	-81.469	Kanawha	73.15
4605544	WV	Sawmill Run Preparation Plant	716,013	80,435	100%	Non-Producing	38.9036	-80.224	Mon	105
4605589	WV	Crawdad No 1 Mine	1,031,517	978,928	100%	Active	39.7078	-79.996	Mon	94.8
4607555	WV	Patriot Rail & River Terminal	406,939	15,898	101%	Abandoned	39.63	-79.975	Mon	96
4607654	WV	Patriot Mining Company Inc	94,773	3,052	103%	Abandoned	39.6056	-80.086	Mon	96.3
4607736	WV	Quincy Dock	393,740	393,740	100%	Active	38.1997	-81.501	Kanawha	73.15
4607809	WV	Kiah Creek Preparation Plant	644,619	465,446	21%	Active	38.0244	-82.284	Ohio	308
4607908	WV	Big Mountain No 16	580,304	19,992	100%	Non-Producing	38.0069	-81.64	Kanawha	73.2
4607945	WV	Birch River Mine	2,415,662	550,221	100%	Non-Producing	38.4178	-80.584	Mon	63
4607946	WV	Cyrus Dock	90,807	90,807	61%	Active	38.3028	-82.571	Big Sandy	8
4608110	WV	Mammoth Coal Co. Surface Mine	1,248,707	1,248,707	64%	Active	38.2092	-81.306	Kanawha	73
4608596	WV	Fourmile Fork	94,452	94,452	52%	Active	38.625	-81.218	Ohio	308
4608675	WV	Crooked Run Surface Mine	461,278	91,610	100%	Active	38.3917	-80.733	Ohio	308
4608864	WV	Tunnel Ridge Mine	59,630	18,110	101%	Active	40.1247	-80.589	Ohio	82.2
4608869	WV	Quincy Manufactured Home Park	82,344	82,344	100%	Active	38.2164	-81.504	Kanawha	73
4608906	WV	S11 Keystone Surface Mine	96,733	96,733	75%	Active	38.2489	-81.596	Kanawha	31
4608961	WV	Marmet Dock	476,632	476,632	10%	Active	38.1997	-81.501	Kanawha	73.15
4609054	WV	Republic Energy	597,127	597,127	2%	Active	37.9761	-81.347	Kanawha	71.7
4609071	WV	Airport Strip	47,419	47,419	0%	Abandoned	40.4514	-80.485	Ohio	74
4609107	WV	Campbells Creek No 7 Mine	197,471	197,471	92%	Abandoned and Sealed	38.2983	-81.46	Kanawha	31
4609108	WV	Mammoth #2 Gas	38,201	38,201	89%	Non-Producing	38.2683	-81.372	Kanawha	70
4609231	WV	Coalburg No. 2 Mine	112,272	112,272	82%	Abandoned and Sealed	38.1583	-81.586	Kanawha	69
4800977	WY	Black Thunder	101,222,051	7,827,616	10%	Active	42.6936	-105.27	Mississippi	361

Coal Mine MSHA ID	Coal Mine State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	% tallied	Mine status	Latitude	Longitude	River	River Mile
4801337	WY	Antelope Coal Mine	33,129,444	3,337,715	54%	Active	43.5	-105.17	Mississippi	361
4801353	WY	North Antelope Rochelle Mine	98,718,235	8,640,739	38%	Active	43.7183	-105.19	Mississippi	361
NA			27,007,523	12,036,878					unknown	

Appendix 3. Power plant profiles and modeled impacts

Plant No	Name	State	River	Mile No	# of Barging Mines Used in 2010	# of Mines Not Feasible	Non-feasible Tons	% of barged	% of total	Tonnage	RV	RR	TR	Pl	Other
MORGANTOWN L/D 29				102											
3943	Fort Martin Power Station	WV	Mon	92	18	8	831,725	30%	30%	2,784,283	2,754,601	-	29,682	-	-
POINT MARION L/D 28				91											
GRAYS LANDING L/D 26				82											
3179	Hatfield's Ferry Power Station	PA	Mon	79	14	8	1,405,489	36%	35%	4,001,198	3,954,943	-	46,255	-	-
MAXWELL L/D 25				61											
CHARLEROI L/D 24				42											
3181	Mitchell Power Station	PA	Mon	30	11	11	402,828	100%	81%	498,836	402,828	-	30,228	52,222	13,558
3098	Elrama Power Plant	PA	Mon	25	3	3	213,176	100%	73%	293,087	200,451	-	92,636	-	-
ELIZABETH L/D 23				24											
BRADDOCK L/D 22				11											
ALLEGHENY L/D 44 (NATRONA)				24											
8226	Cheswick Power Plant	PA	Alleg.	16	3	1	491,560	66%	50%	981,012	749,881	37,733	108,178	-	85,220

Plant No	Name	State	River	Mile No	# of Barging Mines Used in 2010	# of Mines Not Feasible	Non-feasible Tons	% of barged	% of total	Tonnage	RV	RR	TR	Pl	Other
C.W. BILL YOUNG L/D 43				15											
ALLEGHENY L/D 42 (SHARPSBURG)				7											
EMSWORTH L/D 1				7											
DASHIELDS L/D 2				13											
10676	AES Beaver Valley Partners	PA	Ohio	30	2	1	256,032	52%	51%	501,727	493,793	-	7,934	-	-
MONTGOMERY L/D 3				31											
6094	Bruce Mansfield	PA	Ohio	34	10	3	82,953	1%	1%	6,563,622	5,833,355	638,835	91,432	-	-
2866	W H Sammis	OH	Ohio	53	12	1	294,038	21%	7%	4,280,959	1,424,026	2,831,214	25,719	-	-
NEW CUMBERLAND L/D 4				54											
2828	Cardinal	OH	Ohio	77	3	0	-	0%	0%	3,925,317	2,418,000	183,179	1,324,138	-	-
PIKE ISLAND L/D 5				85											
2864	R E Burger	OH	Ohio	102	3	1	79,950	84%	59%	136,298	95,730	37,889	2,679	-	-
3947	Kammer	WV	Ohio	111	4	0	-	0%	0%	700,429	530,905	160,427	9,097	-	-
3948	Mitchell	WV	Ohio	112	7	0	-	0%	0%	4,187,133	655,381	1,796,363	-	-	1,735,389
HANNIBAL L/D 71				126											
6004	Pleasants Power Station	WV	Ohio	160	0	0	-	0%	0%	3,612,554	3,466,188	-	3,014	143,352	-
3946	Willow Island	WV	Ohio	160	5	2	31,133	30%	21%	145,116	104,519	-	-	33,563	7,034
WILLOW ISLAND L/D 72				161											
2872	Muskingum River	OH	Musk.	24	3	1	62,384	20%	2%	2,918,731	313,196	2,373,605	231,930	-	-

Plant No	Name	State	River	Mile No	# of Barging Mines Used in 2010	# of Mines Not Feasible	Non-feasible Tons	% of barged	% of total	Tonnage	RV	RR	TR	Pl	Other
7286	Richard Gorsuch	OH	Ohio	177	4	0	-	0%	0%	564,808	354,872	-	144,648	6,000	59,288
BELLEVILLE L/D OH21				203											
RACINE L/D OH22				237											
3938	Philip Sporn	WV	Ohio	242	6	0	-	0%	0%	1,015,037	1,001,513	-	13,524	-	-
6264	Mountaineer	WV	Ohio	243	13	1	101,926	4%	3%	3,082,320	2,884,726	10,489	21,015	-	166,090
8102	General James M Gavin	OH	Ohio	258	8	0	-	0%	0%	7,836,805	6,419,607	1,417,198	-	-	-
2876	Kyger Creek	OH	Ohio	260	4	0	-	0%	0%	2,904,776	1,290,631	1,603,839	10,306	-	-
3935	John E Amos	WV	Kanawha	39	0	0	-	0%	0%	5,327,790	3,802,000	1,525,790	-	-	-
3936	Kanawha River	WV	Kanawha	79	0	0	-	0%	0%	387,084	383,871	-	3,213	-	-
ROBERT C. BYRD L/D OH26				279											
GREENUP L/D OH24				341											
6031	Killen Station	OH	Ohio	390	6	1	236,837	15%	14%	1,717,977	1,705,591	-	12,386	-	-
6041	H L Spurlock	KY	Ohio	400	0	0	-	0%	0%	4,069,427	4,038,821	10,111	20,495	-	-
2850	J M Stuart	OH	Ohio	405	7	1	96,031	3%	2%	6,036,990	5,961,658	-	75,332	-	-
CAPTAIN ANTHONY MELDAHL L/D OH25				436											
6019	W H Zimmer	OH	Ohio	442	14	1	137,441	4%	3%	3,940,173	3,938,070	-	2,103	-	-
2830	Walter C Beckjord	OH	Ohio	453	0	0	-	0%	0%	1,698,769	1,698,769	-	-	-	-
2832	Miami Fort	OH	Ohio	490	18	1	561,026	16%	16%	3,613,979	3,593,916	-	20,063	-	-
2917	Hamilton	OH	Miami	no barge	0	0	-	0%	0%	140,613	83,766	-	-	56,847	-

Plant No	Name	State	River	Mile No	# of Barging Mines Used in 2010	# of Mines Not Feasible	Non-feasible Tons	% of barged	% of total	Tonnage	RV	RR	TR	Pl	Other
				acces s											
988	Tanners Creek	IN	Ohio	493	5	1	476,487	60%	26%	1,863,628	812,955	1,030,8 40	19,833	-	-
6018	East Bend	KY	Ohio	510	11	2	205,424	11%	11%	1,910,105	1,895,459	-	14,646	-	-
MARKLAND L/D				532											
1356	Ghent	KY	Ohio	536	0	0	-	0%	0%	5,481,934	4,947,566	514,086	20,282	-	-
3406	Johnsonville	TN	Kent.	0	0	0	-	0%	0%	5,200,812	467,538	3,430,2 89	217,61 5	-	1,085,3 70
983	Clifty Creek	IN	Ohio	559	5	2	1,052,608	27%	27%	3,877,235	752,613	3,116,0 76	8,546	-	-
6071	Trimble County	KY	Ohio	560	0	0	-	0%	0%	10,522,38 8	2,227,243	11,253	158,81 4	-	8,125,0 78
1008	R Gallagher	IN	Ohio	605	9	0	-	0%	0%	1,202,226	1,157,305	-	44,921	-	-
MCALPINE L/D															
1364	Mill Creek	KY	Ohio	626	0	0	-	0%	0%	5,274,556	1,517,211	3,416,8 54	-	-	340,491
CANNELTON L/D				721											
3399	Cumberland Power	TN	Cumb.	104	6	1	49,463	1%	1%	5,973,029	5,939,655	-	33,374	-	-

Appendix 4. Terminals on the Monongahela River

Company name	Rivers	Mon Milepost	Site
Josh Steel	Monongahela	10.1 RDB	Braddock
Gulf Materials LLC	Monongahela	10.2 RDB	Braddock
Transtar/Union Railroad	Ohio, Monongahela	12.1 LDB	Duquesne
Kinder Morgan Dravosburg Terminal	Ohio, Monongahela	16.1 LDB	Dravosburg
Three Rivers Marine & Rail Terminals -- Glassport Terminal	Monongahela	19.5 RDB	Glassport
RiverLift Industries	Ohio, Monongahela	23.5 LDB	West Elizabeth
McGrew Welding	Monongahela	38.4 LDB	
Three Rivers Marine & Rail Terminals -- Gibsonton Terminal	Monongahela	43.2 RDB	Gibsonton
Matt Canestrale Contracting, Inc.	Monongahela	63.5 RDB	Luzerne Township Road, LaBelle, PA
Source: [43]			

Appendix 5. Water intakes within the potential failure zone on the Monongahela River

Mon Milepost	Name	Type
16.5	City of McKeesport	Municipal
17-21 (multiple)	U.S. Steel Clairton Works	Industrial
18.5	Riverview Steel	Industrial
23.5	PA American Water Co.	Municipal
23.75	Eastman Chemical Resins	Industrial
25	Elrama Power Plant	Electric Utility
25.2	PA American Water Co.	Municipal
29.5	Mitchell Power Plant	Electric Utility
30.5	Maple Creek Mining	Industrial (coal prep plant)
40, 40.5	Koppers	Industrial
Source: [57]		

Appendix 6. Docks and marinas within potential failure zone on the Monongahela River

Mon Milepost	Name	Type
16	Mon Valley Speedboat Club	Recreational
18.5	C&C Marine Maintenance	Industrial
22	Mon River Towing	Industrial
22.5	Elizabeth Boat Club	Recreational
23.4	PA Fish Commission	State
23	Elizabeth Riverfront Park	Municipal
24.5	HBC Fleeting	Industrial
26.4	Pine Run Outboard Club	Recreational
26.6	Boaterz Extreme	Recreational
27.5	Sloan's Carousel Marina	Recreational
28.5	Matt Canestrale Contracting	Industrial
29	Molnar's Marina	Recreational
30	New Eagle Public Ramp	Municipal
30.7	Beach Club Marina	Recreational
31.8	Monongahela Mariners Boat Club	Recreational
31.9	Monongahela Public Ramp	Municipal
32.2	Monteray Restaurant and Marina	Recreational
32.3	Edsel & Harriett Marina	Recreational
32.6	Johnny's Marine Services	Recreational
33.1	PA Fish Commission	State
34	Forward Township Public Ramp	Municipal
34.2	Barcord's Marina	Recreational
34.5	Matt Canastrale Contracting	Industrial
36.2	Rostaver Township Ramp	Municipal
36.3	Webster Boat Club	Recreational
41.2	Charleroi Public Dock	Municipal
Source: [57]		

Appendix 7. Mine profile and modeled impacts

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasible
503672	CO	West Elk	3,630,926	1,988,560	Active	NA		3	1	-	-	-	0%
503836	CO	Foidel Creek	5,440,924	284,110	Active	NA		4	1	-	-	-	0%
504591	CO	Bowie No 2	1,536,576	717,286	Active	NA		4	1	-	-	-	0%
504674	CO	Elk Creek	1,940,197	900,576	Active	NA		9	1	-	-	-	0%
1100726	IL	Shay #1 Mine	399,795	250,995	Active	Ohio	941	3	1	-	-	-	0%
1102408	IL	Gateway Mine	2,551,693	551,955	Active	Miss.	98.5	5	2	-	-	-	0%
1102752	IL	The American Coal Company New Era Mine	4,430,148	3,657,140	Active	Ohio	947	11	8	-	-	-	0%
1103054	IL	Willow Lake Portal	4,956,958	4,956,958	Non-prod	Ohio	943.2	5	5	-	-	-	0%
1103058	IL	Pattiki	3,417,785	2,471,930	Active	Ohio	827	4	3	-	-	-	0%
1103141	IL	Mach #1 Mine	4,806,334	2,850,478	Active	Ohio	827	10	7	1	16,369	-	0%
1103143	IL	Prairie Eagle	771,470	548,507	Active	Miss.	105	4	2	-	-	-	0%
1202010	IN	Air Quality #1	608,448	306,475	Non-prod.	Ohio	784	1	1	-	-	-	0%
1202189	IN	Air Quality South Wash Plant	429,384	66,955	Non-prod.	Ohio	784	1	1	-	-	-	0%
1202207	IN	Somerville	2,641,068	1,700,688	Active	Ohio	784	5	4	-	-	-	0%
1202215	IN	Gibson Mine	3,079,904	1,083,028	Active	Ohio	747	5	1	-	-	-	0%
1202358	IN	South Augusta	4,805	4,805	Aban.	Ohio	747	1	1	-	-	-	0%
1202410	IN	Log Creek Surface	54,992	54,992	Active	Ohio	747	1	1	-	-	-	0%
1202441	IN	Wild Boar Mine	12,515	12,515	Active	Ohio	747	2	2	-	-	-	0%
1502057	KY	Advantage #1	38,005	38,005	Temp Idled	Big Sandy	7	1	1	-	-	-	0%
1502132	KY	Dotiki Mine	4,567,539	1,047	Active	Ohio	827	4	1	-	-	-	0%
1502709	KY	Highland 9 Mine	2,789,946	2,789,946	Active	Ohio	870	7	6	-	-	-	0%
1503178	KY	River View Facilities	634,607	634,607	Active	Ohio	843	3	2	-	-	-	0%
1510271	KY	#1 Plant	75,624	19,863	Active	Big	7	1	1	-	-	-	0%

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasible
						Sandy							
1510358	KY	Arch Coal Terminal Inc	134,211	134,211	Active	Ohio	317	5	4	-	-	-	0%
1510789	KY	Colona Synfuel	40,316	40,316	Non-prod.	Big Sandy	7	2	2	-	-	-	0%
1512914	KY	Sapphire Prep Plant	929,316	36,668	Non-prod.	Big Sandy	7	2	1	-	-	-	0%
1513936	KY	Frasure Creek Mine No 6	1,437,098	270,991	Active	Big Sandy	7	1	1	-	-	-	0%
1516231	KY	Patriot Surface	1,110,356	1,110,356	Non-prod.	Ohio	726	3	3	-	-	-	0%
1516734	KY	Clintwood Elkhorn II	197,555	32,425	Active	Ohio	315	1	1	-	-	-	0%
1516749	KY	Kentucky Coal Terminal	54,194	54,194	Active	Big Sandy	7.8	1	1	-	-	-	0%
1517044	KY	Vision #9	675,177	575,543	Non-prod.	Green	43	2	1	-	-	-	0%
1517216	KY	Cardinal	5,093,279	323,551	Active	Ohio	827	3	2	-	-	-	0%
1517232	KY	Richland No 9	54,241	54,241	Active	Green	40	1	1	-	-	-	0%
1517278	KY	Red Bud Dock North	48,567	48,567	Active	Big Sandy	7.8	1	1	-	-	-	0%
1517403	KY	Pleasant View Washer Plant	7,075	7,075	Aban.	Green	40	1	1	-	-	-	0%
1517587	KY	Freedom	1,417,781	1,345,038	Aban., sealed	Ohio	785	5	2	-	-	-	0%
1517821	KY	Mill Branch	533,628	8,768	Temp Idled	Big Sandy	7.8	1	1	-	-	-	0%
1518040	KY	No. 6	53,350	15,726	Active	Ohio	316	1	1	-	-	-	0%
1518134	KY	Halls Creek Mine	296,074	296,074	Active	Green	85	2	1	-	-	-	0%
1518335	KY	Dodge Hill Mine #1	853,580	853,580	Active	Ohio	870	7	5	-	-	-	0%
1518418	KY	Joe's Run	843,359	382,837	Active	Ohio	730	3	3	-	-	-	0%
1518542	KY	South	223,586	223,586	Active	Ohio	843	2	2	-	-	-	0%
1518547	KY	Onton #9	1,209,467	1,097,535	Active	Green	45.6	3	1	-	-	-	0%
1518552	KY	Big Run Mine	1,454,749	690,652	Aban.,	Green	76.9	5	4	-	-	-	0%

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasible
					sealed								
1518558	KY	Big Branch	283,714	8,250	Aban.	Big Sandy	7	1	1	-	-	-	0%
1518568	KY	No 2 Mine	273,964	3,169	Aban.	Big Sandy	7	3	1	-	-	-	0%
1518622	KY	Back in Black	7,991	7,991	Aban.	Green	85.9	1	1	-	-	-	0%
1518639	KY	Calvert City Terminal LLC	273,421	273,421	Active	Ohio	933	1	1	-	-	-	0%
1518695	KY	Mine 3	276,487	276,487	Aban.	Green	85.9	1	1	-	-	-	0%
1518728	KY	Mine No 2	387,203	387,203	Aban.	Green	85.9	3	3	-	-	-	0%
1518823	KY	Job #42	161,820	121,854	Active	Big Sandy	7	1	1	-	-	-	0%
1518826	KY	Elk Creek Mine	721,390	495,149	Active	Green	85.9	3	3	-	-	-	0%
1518969	KY	Tarkiln 1	1,648	1,648	Temp Idled	Big Sandy	7	1	1	-	-	-	0%
1519088	KY	Surface #3	103,586	103,586	Aban.	Big Sandy	7.6	3	3	-	-	-	0%
1519109	KY	Bee Tree Surface	3,215	3,215	Aban.	Big Sandy	7	1	1	-	-	-	0%
1519146	KY	Diablo West Surface	70,806	20,845	Active	Big Sandy	7	1	1	-	-	-	0%
1519165	KY	Midway Coal Handling Facility	915,680	441,200	Active	Green	76.7	1	1	-	-	-	0%
1519200	KY	No. 1	185,146	12,120	Active	Big Sandy	7	2	1	-	-	-	0%
1519203	KY	Wolf Pen #1	132,419	132,419	Aban.	Big Sandy	7.8	1	1	-	-	-	0%
1519217	KY	Midway Mine	2,104,939	842,335	Active	Green	76.7	3	3	-	-	-	0%
1519303	KY	K O Mine	18,444	18,444	Aban.	Green	85.9	1	1	-	-	-	0%
1519344	KY	Equality	25,505	25,505	Active	Green	76.7	1	1	-	-	-	0%
1519365	KY	Schoate Prep Plant	1,040,536	77,130	Active	Green	85	3	1	-	-	-	0%
1519368	KY	Mill Creek 1	32,006	32,006	Temp	Big	7	1	1	-	-	-	0%

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasible
					Idled	Sandy							
1519374	KY	River View Mine	3,696,419	3,696,419	Active	Ohio	843	10	10	3	554,548	-	15%
1519437	KY	S-11	51,403	32,772	Aban.	Big Sandy	7	1	1	-	-	-	0%
2401457	MT	Spring Creek Coal Company	12,916,230	1,808,933	Active	Ohio	23	3	2	2	2,826	-	0%
2401950	MT	Bull Mountains Mine No 1	1,613,438	105,510	Active	Ohio	23	3	1	-	-	-	0%
3300789	OH	Bowman Strip	212,417	86,581	Active	Ohio	354	1	1	-	-	-	0%
3300965	OH	Rice #1 (Strip)	622,762	622,762	Active	Ohio	92	1	1	-	-	-	0%
3300968	OH	Hopedale	838,475	13,043	Active	Ohio	69	2	1	-	-	-	0%
3301070	OH	Century Mine	260,081	249,343	Active	Ohio	110.6	1	1	-	-	-	0%
3301159	OH	Powhatan No. 6 Mine	14,173,355	13,150,423	Active	Ohio	110.6	12	12	3	704,150	-	5%
3301358	OH	Sands Hill Strip	492,692	368,173	Active	Ohio	256	3	3	-	-	-	0%
3301925	OH	Orange Strip	546,327	401,679	Active	Ohio	189	2	2	-	-	-	0%
3302937	OH	Oxford Loading Dock	367,512	367,512	Active	Ohio	92.8	3	2	-	-	-	0%
3304213	OH	Oxford Mining #2	754,947	420,946	Non-prod.	Ohio	93	1	1	-	-	-	0%
3304386	OH	Belmont County Strip - Fox Farms	93,669	93,669	Active	Ohio	70	3	3	-	-	-	0%
3304414	OH	Snyder Mine	236,024	43,335	Active	Ohio	70	2	2	-	-	-	0%
3304522	OH	Oxford Contract Auger # 2-No. 11	226,603	226,603	Aban.	Ohio	92.8	1	1	-	-	-	0%
3304524	OH	Oxford Contract Auger # 1-No. 4	9,740	9,740	Aban.	Ohio	81	2	2	-	-	-	0%
3304584	OH	Oxford Beagle Club	426,964	426,964	Aban.	Ohio	92	2	2	-	-	-	0%
3304585	OH	Oxford Jockey Hollow	150,255	125,924	Temp Idled	Ohio	165	1	1	-	-	-	0%
3304595	OH	Yellowbush Mine	707,765	707,765	Direct	Ohio	240.5	4	4	2	119,709	-	17%
3304606	OH	North Barnesville	1,008,666	819,064	Aban.	Ohio	92	3	2	-	-	-	0%

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasible
3304609	OH	Tusky Prep	162,970	162,970	Active	Ohio	80.9	1	1	-	-	-	0%
3600958	PA	Mine 84	12,725	12,725	Direct	Mon	58	1	1	1	12,725	-	100%
3605018	PA	Cumberland Mine	5,313,087	5,191,021	Direct	Mon	81.5	15	15	13	3,276,424	1,292,679	62%
3605466	PA	Emerald Mine No 1	4,223,891	221,559	Active	Mon	58	5	1	-	-	-	0%
3607230	PA	Bailey Mine	16,199,193	1,004,362	Active	Mon	58	8	5	4	632,378	-	4%
3607973	PA	Fayette Co Strips	129,178	94,693	Active	Mon	86.3	2	2	-	-	72,567	0.0%
3608802	PA	Gameland S E	114,995	86,578	Aban.	Ohio	66	4	3	-	-	5,248	0%
3609226	PA	Neiswonger Mines	60,887	11,584	Active	Mon	42.8	1	1	1	11,584	-	19%
3609597	PA	Washington County Strips	172,802	172,802	Active	Mon	42.8	3	3	1	53,195	99,439	31%
4201890	UT	Dugout Canyon Mine	2,827,824	528,465	Active	NA	NA	3	1	-	-	-	0%
4405971	VA	Stoker	173,800	75,719	Active	Ohio	315	2	2	-	-	-	0%
4601318	WV	Robinson Run No 95	5,140,771	21,223	Active	Mon	100	1	1	1	21,223	-	0.4%
4601368	WV	Fanco	2,309,564	33,424	Active	Ohio	308	5	1	-	-	33,424	0%
4601433	WV	Loveridge #22	3,500,909	251,910	Active	Mon	58	3	2	2	251,910	-	7%
4601436	WV	Shoemaker Mine	3,821,248	3,821,248	Active	Ohio	80.9	14	14	1	10,793	-	0%
4601437	WV	McElroy Mine	10,211,137	8,420,280	Active	Ohio	110.4	10	10	-	-	248,293	0%
4601456	WV	Federal No 2	3,644,537	515,454	Active	Mon	58	9	5	3	344,091	107,165	9%
4603090	WV	Winifrede Dock	225,429	225,429	Temp Idled	Kanawha	69	1	1	-	-	-	0%
4604387	WV	Prime No. 1 Mine	1,026,057	978,928	Active	Mon	94.8	3	3	1	3,709	488,802	0.4%
4605382	WV	Crown Hill Dock	38,363	38,363	Active	Kanawha	79	1	1	-	-	-	0%
4605437	WV	American Eagle Mine	58,333	58,333	Active	Kanawha	73.15	1	1	-	-	-	0%
4605472	WV	Coalburg Dock	239,127	239,127	Active	Kanawha	73.15	2	1	-	-	-	0%
4605544	WV	Sawmill Run Preparation Plant	716,013	80,435	Non-prod.	Mon	105	3	0	-	-	-	0.0%

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasible
4605589	WV	Crawdad No 1 Mine	1,031,517	978,928	Active	Mon	94.8	3	3	1	3,709	488,802	0.4%
4607458	WV	Docks Creek, LLC	188,022	79,127	Active	Big Sandy	4	1	1	-	-	-	0%
4607555	WV	Patriot Rail & River Terminal	406,939	15,898	Aban.	Mon	96	1	1	1	15,898	-	4%
4607654	WV	Patriot Mining Company Inc	94,773	3,052	Aban.	Mon	96.3	1	1	-	-	-	0.0%
4607736	WV	Quincy Dock	393,740	393,740	Active	Kanawha	73.15	3	3	-	-	-	0%
4607809	WV	Kiah Creek Preparation Plant	644,619	465,446	Active	Ohio	308	3	2	-	-	97,099	0%
4607908	WV	Big Mountain No 16	580,304	19,992	Non-prod.	Kanawha	73.2	1	1	-	-	-	0%
4607938	WV	Black Castle Mining Co	1,170,008	374,818	Active	Kanawha	73.2	1	1	-	-	-	0%
4607945	WV	Birch River Mine	2,415,662	550,221	Non-prod.	Mon	63	6	2	1	6,317	-	0.3%
4607946	WV	Cyrus Dock	90,807	90,807	Active	Big Sandy	8	1	1	-	-	-	0%
4608110	WV	Mammoth Coal Co. Surface Mine	1,248,707	1,248,707	Active	Kanawha	73	5	5	-	-	-	0%
4608596	WV	Fourmile Fork	94,452	94,452	Active	Ohio	308	2	2	-	-	-	0%
4608675	WV	Crooked Run Surface Mine	461,278	91,610	Active	Ohio	308	1	1	-	-	-	0%
4608864	WV	Tunnel Ridge	59,630	18,110	Active	Ohio	82.2	2	2	2	18,110	-	30%
4608869	WV	Quincy Manufactured Home Park	82,344	82,344	Active	Kanawha	73	2	2	1	33,133	-	40%
4608906	WV	S11 Keystone Surface Mine	96,733	96,733	Active	Kanawha	31	3	3	-	-	-	0%
4608961	WV	Marmet Dock	476,632	476,632	Active	Kanawha	73.15	3	2	-	-	-	0%
4608984	WV	Coal-Mac Inc Holden #22 Surface	224,332	109,041	Active	Big Sandy	7	2	1	-	-	-	0%

Coal Mine MSHA ID	State	Coal Mine Name	Total Mined (tons)	Total Barged (tons)	Mine status	Loading River	River Mile	Power Plants served	Power Plants barged to	Power Plant transits not feasible	Not feasible Tons	River tons to closing pp	% not feasib le
4609037	WV	Airport Strip	9,925	9,925	Aban., sealed	Ohio	82	1	1	-	-	-	0%
4609046	WV	Cardinal Preparation Plant	479,741	115,199	Active	Ohio	309	1	1	-	-	-	0%
4609054	WV	Republic Energy	597,127	597,127	Active	Kanawha	71.7	3	3	-	-	-	0%
4609071	WV	Airport Strip	47,419	47,419	Aban.	Ohio	74	1	1	-	-	-	0%
4609107	WV	Campbells Creek No 7 Mine	197,471	197,471	Aban., sealed	Kanawha	31	2	1	-	-	182,393	0%
4609108	WV	Mammoth #2 Gas	38,201	38,201	Non-prod.	Kanawha	70	3	3	-	-	-	0%
4609174	WV	Spruce No. 1 Mine	143,067	65,161	Active	Ohio	308	2	1	-	-	-	0%
4609231	WV	Coalburg No. 2 Mine	112,272	112,272	Aban., sealed	Kanawha	69	2	2	-	-	-	0%
4800977	WY	Black Thunder	101,222,051	7,827,616	Active	Miss.	361	31	8	2	675,086	27,989	1%
4801337	WY	Antelope Coal Mine	33,129,444	3,337,715	Active	Miss.	361	16	5	2	269,451	39,228	1%
4801353	WY	North Antelope Rochelle Mine	98,718,235	8,640,739	Active	Miss.	361	31	10	2	31,173	6,169	0%

Appendix 8. Plant by plant assessment of failure response alternatives

Power plants on the Monongahela River above the failure zone

Two above-average sized coal-fired power plants are sited well above the failure zone on the Monongahela River: Fort Martin (Mile 92) and Hatfield's Ferry (Mile 79). Both plants depended entirely on barge delivery of coal, and neither plant had rail access. Similarly, truck delivery would not have been feasible. Hatfield's Ferry burned 4 million tons of coal in 2010. Assuming that a highway tractor trailer can handle 25 tons of material, it would require offloading a new truck every three minutes, 24 hrs per day, 365 days per year to deliver this volume of coal. Thus truck delivery is highly infeasible, even if the plants and mines were known to have the requisite truck off-loading and loading equipment, and sufficient excess truck capabilities existed to step into a sudden need.

Consideration was then given to the river loading locations of the mines used by these plants in 2010. Hatfield's Ferry obtained 64% of its coal from mines that load barges above the failure zone of interest, while 70% of Fort Martin's coal came from mines that would also still be able to ship to the plant despite river closure at Charleroi. The remainder of the coal shipments, totaling almost 2.9 million tons, would need to be re-routed around the failure zone or otherwise replaced to allow these plants to operate at 2010 levels.

Fort Martin obtained 17% of its 2010 fuel from Wyoming and Montana. Their percentage of PRB coal dropped to 13% in 2011 and 2% in 2012, coincident with the successful installation and deployment of flue gas scrubbers in 2009 and the expiration of long term contracts with the PRB suppliers. If the failure scenario had occurred in 2010, Fort Martin may have been able to break their purchase agreements (force majeure) and source the replacement coal locally, without needing to match the low sulfur properties of the PRB coal. Hatfield's Ferry's use of PRB coal similarly declined over the same period. (Note that other EIA-923-reported fuel properties -- heat, ash and sulfur content -- were not evaluated in this analysis, but would impact the feasibility of certain source substitutions.)

Both Fort Martin and Hatfield's Ferry purchased significant quantities of coal (350,000 and 900,000 tons, respectively) that was barged from Ohio River mines. These shipments would either need to be re-routed or replaced with local coal in the face of river closure at Elizabeth. Mines with rail access might re-route to a transloading dock above the failure zone. Mines without rail access could only physically reach these power plants by adding transloading to rail below the failure zone, rail past the failure zone, then transloading back to barge for delivery to the plants. Transloading costs and rail switching to short line rails can cost $1.5-2 per ton per transload [66]. The added cost of re-routing this coal ($2-5 million) will make replacement with local coal a more attractive option, presuming sufficient supply exists.

If the plants cannot obtain sufficient coal with the necessary attributes, the plants could close. Hatfield's Ferry, in fact, closed in 2013 due to compliance costs associated with EPA's Mercury and Air Toxics Standards (MATS) regulation and a highly competitive electricity market [70]. Challenges associated with replacement of coal shipments disrupted by dam failure could be sufficient reason to close plants that are otherwise financially marginal.

Power plants within the Monongahela River failure zone

Two relatively small coal-fired power plants were operating in 2010 within the potential failure zone. Mitchell and Elrama are both located between the Elizabeth and Charleroi locks. Neither plant have rail access, and both power plants would have lost their river access completely. Further, both plants rely on once-through cooling water drawn from the Monongahela [131] -

loss of pool would have required plant shutdowns. Both plants probably would have been forced to close if river navigation were lost in 2010. In fact, both plants were marginal operations: Elrama had a capacity factor of 0.11 in 2010, down from 0.26 in 2008, and closed in 2012; Mitchell's capacity factor in 2010 was 0.29 (0.38 in 2008) and was announced as targeted for retirement in October 2013. (Capacity factor time series for all of the power plants of interest is provided in Appendix 12 [131].)

Non-Monongahela River power plants burning coal sourced from Monongahela River loading coal mines

Sixteen coal-fired power plants located below the failure zone drew some portion of their coal from upper Monongahela coal mines in 2010; these shipments would not be feasible after catastrophic infrastructure failure at Elizabeth and Charleroi.

The most significant impacts would occur at three relatively small power plants that relied on Monongahela River mines for more than fifty percent of their coal deliveries: Cheswick, AES Beaver Valley (announced potential conversion to natural gas in 2013 [132]), and R. E. Burger (not operating as of 2012). Beaver Valley and R.E. Burger probably would have shut down in 2010 in response to the loss of a major portion of their coal.

Cheswick's potential response to a river outage is illustrative of the remainder of the down-river power plants. Barge shipments of 500,000 tons of coal from the Bailey mine would have been disrupted, while rail shipments of 110,000 tons of Bailey coal by rail could have continued or perhaps been increased. If the outage occurred in 2012, however, there would have been no direct impact on Cheswick as all of its 2012 coal came from Ohio River loading coal mines. It seems reasonable to assume that Bailey would have shifted displaced barge shipments to rail, as possible, and the down-river mines would have been able to increase shipments to Cheswick in the event of a 2010 river closure.

Monongahela River loading coal mines

Fifteen mines load coal on the Monongahela River, all above the potential failure zone. While these mines would maintain their ability to feed the upper Monongahela power plants, barge transport to all other power plants would be disrupted by outages at Elizabeth and Charleroi; these down-river shipments exceeded 4.6 million tons in 2010. The significance of these disruptions is a function of how much of their overall shipments are disrupted, the capability of the mine to reach power plants by alternative transit routes, and the overall viability of the mine.

Four mines are wholly dependent on the river for transport of their coal output, and thus are most susceptible to impacts from failure at Charleroi and Elizabeth. The largest mine, Cumberland Mine, would have been the most severely impacted mine in the face of river closure. Cumberland produced over 5.3 million tons of coal in 2010. The Cumberland Mine coal is transferred to the Monongahela via a dedicated rail line from the mine to a company-owned barge loading facility. Over 3.2 million tons of this mine's output was barged down the Monongahela through the potential failure zone. The private rail line is not connected to the national rail system -- the mine's primary access to its markets is at its dock and the impact of river closure would be significant to this mine. Mine 84 is a barge-only mine that shipped only to Elrama in 2010, and has since stopped operations. Mine 84 was assumed to close in the modeled scenarios

Potential responses to a river outage by Cumberland could include stepping up shipments to the upper Monongahela power plants, barging to a transloading dock on the upper Monongahela to access the national rail system and customers below the failure zone, or closure (temporary or permanent). It is uncertain whether this mine would remain cost-effective to operate at reduced output for an extended period of time. Increased shipments to Fort Martin and/or Hatfield's Ferry, however, cannot be assumed to be a highly probable outcome as other upper Monongahela River mines also supply these power plants. Many of these competing mines have good access to the national rail system and would be less threatened by a river outage. Closure of Hatfield's Ferry would have further complicated Cumberland's failure response, displacing an additional 1.2 million tons of output.

The Crawdad No. 1 and Prime No. 1 mines also rely predominantly on barge shipments. Coal is trucked from these sister mines to a upper Monongahela dock owned by their parent company; the majority of their output is then barged to Hatfield's Ferry and Fort Martin. These barge transits would not have been directly impacted by downstream river closure. However, the closure of Hatfield's Ferry would have displaced almost half of Prime No. 1 and Crawdad No. 1's 2010 outputs.

Several strip mines truck their output to Monongahela docks, and reach their customers via barge. While a river outage would certainly impact these mines, it is expected that they could truck to other docks below the failure zone.

Four facilities identified in the EIA database have subsequently halted operations [52]. The demonstrated precarious state of these operations indicates that these facilities may have ceased operations sooner in response to river closure at Elizabeth (Sawmill Run, Patriot (mine and terminal), Birch River), although each of these mines had rail access.

Six other mines would have had no or minimal direct impact, with less than 10% of their total 2010 shipments disrupted by closure at Elizabeth. Most of these mines shipped significant volumes of coal by rail, conveyer belt or truck, and thus have demonstrated fallback transport options. These mines are direct competitors of the barge-only mines.

Non-Monongahela coal mines fueling Monongahela River power plants

Eleven mines barge their coal upriver to the Monongahela River power plants, requiring passage through the locks at Elizabeth to reach Elrama and Mitchell, and then through the Charleroi locks to reach Fort Martin and Hatfield's Ferry. Over 2.4 million tons of coal shipments from these mines would have been disrupted by river closure in 2010.

Shipments from four PRB mines probably would have been cancelled given the updated status of the air pollution control equipment at Fort Martin and Hatfield's Ferry and the likelihood of closure at Elrama and Mitchell. The impact to these mines would be minimal, as the disrupted shipments amount to less than 1% of their 2010 outputs.

Two regional mines (Mach No. 1 and Shoemaker) barged less than 1% of their total outputs to the Monongahela power plants. Loss of access to these power plants would have an insignificant impact on these mines.

Three barge-only mines shipped more significant amounts through the potential failure zone (River View, 15% of total outputs; Yellowbush, 17%; and Quincy, 40%). Without rail options, these mines would not be able to shift modes to get around Elizabeth and Charleroi. The tonnage from these mines is significant as well, totaling over 700,000 tons in 2010. Losing access to these power plants would have impacted the profitability of these mines in the short term until they were successful in readily finding replacement customers. Yellowbush's status dropped to "non-producing" in 2011, indicating that a loss of access to an important customer in 2010 might have accelerated closure of these operations. Each of these mines, however, is at least 300 miles downriver from the failure zone, within closer reach of dozens of other power plants on the Ohio River and its tributaries.

Two mines have ready access to rail (Powhatan No. 6 and Tunnel Ridge), and thus could send their coal via rail to a transloading dock above the failure zone, and continue to supply Fort Martin and Hatfield's Ferry. Alternatively they might increase shipments to other non-Monongahela River power plants as the displaced shipments only account for less than 30% of their total shipments.

Appendix 9. Estimated barge transportation rates for coal, state to state

Origin State	Destination State	Nominal dollars per ton (EIA) 2008	2009	2010	Modeling assumptions	O/D Count in 2010 EIA-923	Derived?
AL	AL	$4.31	$4.36	$5.01		252	n
CO	AL	W	-	13.27	same as FL	59	y
CO	FL	$11.08	$12.65	$13.27		10	n
CO	IN	$6.29	W	$6.29	same as 2008	12	y
CO	KY	W	-	-		46	y
CO	MS	-	-	W		13	y
CO	TN	W	-	-		74	y
IL	AL	W	$13.15	$14.28		17	n
IL	FL	$14.68	$10.31	$12.03		84	n
IL	IN	W	W	11.81	same as IA	59	y
IL	KY	$6.43	$7.47	$7.87		125	n
IL	MS	-	-	14.28	same as AL	15	y
IL	MO	-	W	$10.92		71	n
IL	OH	$7.76	$7.26	$7.02		100	n
IL	PA	-	-	14.15	same as WV	3	y
IL	TN	$4.21	$3.54	$3.88	average 2008-9	42	y
IL	WV	W	$14.15	$14.15	same as 2009	12	y
IL	WI	-	-	W		30	y
IN	AL	W	$18.38	$20.54		42	n
IN	FL	W	-	-		1	y
IN	IN	$3.43	W	$2.62		578	n
IN	KY	$4.89	$5.15	$4.45		42	n
IN	OH	W	$4.09	$4.20		41	n
IN	TN	-	-	4.45	same as KY	2	y
KY	AL	$8.37	-	$8.37	same as 2008	43	y
KY	FL	$17.61	$13.90	$13.08		344	n
KY	IN	W	$3.80	$3.36		69	n
KY	KY	$4.69	$4.28	$4.78		1097	n
KY	MS	-	-	$10.56		18	n
KY	MO	-	W	-		12	y
KY	OH	$3.83	$4.20	$3.84		225	n
KY	PA	W	$24.27	$23.04		27	n
KY	TN	W	$3.49	$3.63		120	n
KY	WV	W	$3.02	$8.80		99	n
MT	PA	W	W	5.20	same as WV	5	y
MT	WV	$5.58	$4.82	$5.20	average 2008-9	1	y
MT	WI	W	W	W		10	y
OH	KY	$5.77	$4.85	$4.67		106	n
OH	OH	$4.73	$3.46	$3.24		362	n
OH	PA	$2.93	$3.60	$4.18		133	n
OH	WV	W	$2.69	$2.52		106	n

Origin	Destination	Nominal dollars per ton (EIA)			Modeling	O/D Count	Derived?
PA	FL	-	-	W		9	y
PA	IN	$12.15	W	$12.15	same as 2008	61	y
PA	MS	-	-	W		1	y
PA	OH	$5.59	$5.01	$5.70		140	n
PA	PA	$4.76	$5.92	$6.34		1443	n
PA	TN	W	W	7.51	same as KY	2	y
PA	WV	W	W	$8.97		238	n
PA	WI	-	W	-		12	y
VA	FL	-	W	-		7	y
VA	WV	-	W	W		18	y
WV	AL	-	W	11.24	same as MS	6	y
WV	FL	$14.57	$10.03	$11.88		266	n
WV	IN	W	$9.17	$5.88		65	n
WV	KY	$4.97	$5.02	$4.64		166	n
WV	MS	-	-	$11.24		24	n
WV	OH	$5.31	$3.76	$3.70		403	n
WV	PA	$3.43	$2.35	$2.42		248	n
WV	TN	W	W	4.64	same as KY	47	y
WV	VA	-	-	W		291	y
WV	WV	W	$7.75	$3.84		937	n
WY	AL	-	-	W		129	y
WY	IL	W	$11.42	$12.78		629	n
WY	IN	W	W	-		232	y
National average (used where not otherwise specified or derived)				$6.41		13,557	
Source: [71]							

Appendix 10. Rail premium over barge rates, coal ($/ton)

Origin State	Destination State	2010 Rail premium over barge rates, $/ton
KY	WV	$5.90
OH	PA	$19.2
PA	OH	$5.00
PA	PA	$8.60
PA	WV	$0.90
WV	KY	$2.20
WV	OH	$6.80
WV	PA	$13.6
WV	WV	$4.70

Appendix 11. NEI commercial vessel emission PM2.5 estimates for Pittsburgh and Huntington District counties (tons)

Lock Code	Lock Name	State	County	NEI Marine Diesel	
				Port	Underway
AG44	Lock & Dam 4	PA	Allegheny	14.3	23.6
AG43	Lock & Dam 3	PA			
AG42	Lock & Dam 2	PA			
MN23	Lock & Dam 3	PA			
MN22	Lock & Dam 2	PA			
OH2	Dashields Lock & Dam	PA			
OH1	Emsworth Lock & Dam	PA			
AG49	Lock & Dam 9	PA	Armstrong	NA	1.1
AG47	Lock & Dam 7	PA			
AG48	Lock & Dam 8	PA			
AG46	Lock & Dam 6	PA			
AG45	Lock & Dam 5	PA			
OH3	Montgomery Lock & Dam	PA	Beaver	NA	13.1
		PA	Butler	NA	NA
MN26	Grays Landing Lock & Dam	PA	Fayette	NA	3.6
MN25	Maxwell Lock & Dam	PA			
MN28	Port Marion	PA	Greene	NA	3.0
		PA	Washington	NA	1.8
MN24	Lock & Dam 4	PA	Westmoreland	NA	0.79
		WV	Brooke	NA	2.4
		WV	Cabell	1.7	5.4
		WV	Jackson	NA	2.6
		WV	Marshall	NA	4.8
OH26	Robert C. Byrd	WV	Mason	4.5	12.2
OH22	Racine Locks & Dam	WV			
MN31	Opekiska Lock & Dam	WV	Monongalia	NA	8.2
MN30	Hildebrand Lock & Dam	WV			
MN29	Morgantown Lock & Dam	WV			
OH5	Pike Island Lock & Dam	WV	Ohio	NA	NA
		WV	Pleasants	NA	3.3
		WV	Tyler	NA	1.6
		WV	Wayne	0.93	3.7
		WV	Wetzel	NA	3.2
		WV	Wood	NA	14.2
		OH	Adams	NA	0.29
		OH	Athens	NA	NA
		OH	Belmont	NA	0.13
		OH	Brown	NA	0.55
OH25	Meldahl Lock & Dam	OH	Clermont	NA	0.58

Lock Code	Lock Name	State	County	NEI Marine Diesel	
				Port	Underway
		OH	Columbiana	NA	NA
		OH	Gallia	1.9	1.4
OH4	New Cumberland Lock & Dam	OH	Jefferson	NA	0.87
		OH	Lawrence	2.8	NA
OH21	Belleville Locks & Dam	OH	Meigs	NA	1.5
OH71	Hannibal Locks & Dam	OH	Monroe	NA	2.0
		OH	Scioto	1.5	0.58
OH72	Willow Island Locks & Dam	OH	Washington	NA	1.3
OH24	Greenup Locks & Dam	KY	Greenup	2.1	8.7
			Boyd	1.1	3.4
			Bracken	NA	3.0
			Campbell	NA	2.6
			Lewis	NA	4.4
			Mason	NA	1.5
			Pendelton	NA	0.92
TOTAL				30.8	142.3
Source:	[121]				

Appendix 12. Capacity factor trends for impacted powerplants

Source: U.S. Energy Information Administration, various [50]

Power Plant		Capacity Factors			
EIA Plant ID #	Name	2008	2009	2010	2011
56	Charles R Lowman	0.76	0.64	0.67	0.65
983	Clifty Creek	0.74	0.73	0.69	0.70
988	Tanners Creek	0.49	0.28	0.40	0.41
1008	R Gallagher	0.52	0.35	0.44	0.14
1356	Ghent	0.64	0.58	0.65	0.64
1364	Mill Creek	0.69	0.69	0.69	0.60
1731	Harbor Beach	0.22	0.12	0.16	0.15
1745	Trenton Channel	0.58	0.57	0.50	0.51
2828	Cardinal	0.63	0.65	0.61	0.49
2830	Walter C Beckjord	0.26	0.41	0.35	0.29
2832	Miami Fort	0.59	0.73	0.76	0.63
2850	J M Stuart	0.65	0.71	0.63	0.64
2864	R E Burger	0.30	0.15	1.19	0.00
2866	W H Sammis	0.68	0.41	0.57	0.47
2872	Muskingum River	0.68	0.54	0.50	0.44
2876	Kyger Creek	0.72	0.71	0.71	0.68
2917	Hamilton	0.27	0.16	0.18	0.08
3098	Elrama Power Plant	0.26	0.08	0.12	0.03
3179	Hatfield's Ferry Power Station	0.73	0.60	0.59	0.71
3181	Mitchell Power Station	0.38	0.25	0.29	0.23
3399	Cumberland	0.72	0.70	0.62	0.57
3406	Johnsonville	0.29	0.18	0.48	0.19
3407	Kingston	0.69	0.13	0.19	0.32
3935	John E Amos	0.63	0.49	0.60	0.59
3936	Kanawha River	0.64	0.43	0.30	0.42
3938	Philip Sporn	0.51	0.26	0.25	0.15
3943	Fort Martin Power Station	0.67	0.40	0.63	0.71
3946	Willow Island	0.26	0.04	0.07	0.09
3947	Kammer	0.50	0.28	0.24	0.28
3948	Mitchell	0.74	0.66	0.72	0.64
6004	Pleasants Power Station	0.70	0.48	0.69	0.69
6018	East Bend	0.72	0.73	0.75	0.72
6019	W H Zimmer	0.75	0.58	0.78	0.54
6031	Killen Station	0.58	0.71	0.70	0.64
6041	H L Spurlock	0.62	0.54	0.64	0.64
6071	Trimble County	0.27	0.20	0.80	0.34
6094	Bruce Mansfield	0.77	0.72	0.75	0.75

Power Plant		Capacity Factors			
EIA Plant ID #	Name	2008	2009	2010	2011
6264	Mountaineer	0.86	0.79	0.71	0.82
7286	Richard Gorsuch	0.68	0.46		
8102	General James M Gavin	0.93	0.84	0.83	0.80
8226	Cheswick Power Plant	0.44	0.50	0.32	0.45
10043	Logan Generating Company LP	0.79	0.47	0.50	0.42
10676	AES Beaver Valley Partners	0.65	0.69	0.71	0.68

Appendix 13. LPMS lockage gap analysis

Time Out Start	Time Out End	Gap Length (min)
1/1/2010 10:15:00 AM	1/1/2010 10:50:00 AM	35.0
1/2/2010 4:43:00 AM	1/2/2010 5:14:00 AM	31.0
1/2/2010 6:27:00 AM	1/2/2010 7:00:00 AM	33.0
1/2/2010 11:35:00 AM	1/2/2010 12:07:00 PM	32.0
1/2/2010 12:44:00 PM	1/2/2010 1:22:00 PM	38.0
1/2/2010 1:35:00 PM	1/2/2010 2:11:00 PM	36.0
1/2/2010 6:29:00 PM	1/2/2010 7:00:00 PM	31.0
1/2/2010 7:35:00 PM	1/2/2010 8:30:00 PM	55.0
1/2/2010 10:19:00 PM	1/2/2010 10:55:00 PM	36.0
1/3/2010 12:00:00 PM	1/3/2010 12:30:00 PM	30.0
1/3/2010 9:45:00 PM	1/3/2010 10:15:00 PM	30.0
1/4/2010 1:40:00 AM	1/4/2010 2:10:00 AM	30.0
1/4/2010 4:20:00 AM	1/4/2010 4:55:00 AM	35.0
1/4/2010 7:35:00 AM	1/4/2010 8:05:00 AM	30.0
1/4/2010 3:10:00 PM	1/4/2010 3:40:00 PM	30.0
1/4/2010 6:25:00 PM	1/4/2010 7:11:00 PM	46.0
1/5/2010 2:44:00 AM	1/5/2010 3:20:00 AM	36.0
1/5/2010 3:45:00 AM	1/5/2010 4:20:00 AM	35.0
1/5/2010 6:40:00 AM	1/5/2010 7:20:00 AM	40.0
1/5/2010 9:00:00 AM	1/5/2010 9:38:00 AM	38.0
1/5/2010 3:19:00 PM	1/5/2010 3:50:00 PM	31.0
1/6/2010 5:40:00 AM	1/6/2010 6:11:00 AM	31.0
1/6/2010 3:45:00 PM	1/6/2010 4:22:00 PM	37.0
1/7/2010 1:55:00 AM	1/7/2010 2:31:00 AM	36.0
1/7/2010 3:20:00 PM	1/7/2010 3:59:00 PM	39.0
1/8/2010 4:59:00 AM	1/8/2010 5:30:00 AM	31.0
1/8/2010 12:47:00 PM	1/8/2010 1:25:00 PM	38.0
1/8/2010 3:35:00 PM	1/8/2010 4:06:00 PM	31.0
1/8/2010 7:06:00 PM	1/8/2010 7:41:00 PM	35.0
1/8/2010 11:47:00 PM	1/9/2010 12:18:00 AM	31.0
1/9/2010 2:35:00 AM	1/9/2010 3:09:00 AM	34.0
1/9/2010 9:18:00 AM	1/9/2010 9:55:00 AM	37.0
1/9/2010 1:34:00 PM	1/9/2010 2:06:00 PM	32.0
1/9/2010 11:05:00 PM	1/9/2010 11:43:00 PM	38.0
1/10/2010 2:45:00 AM	1/10/2010 3:34:00 AM	49.0
1/10/2010 5:17:00 AM	1/10/2010 5:50:00 AM	33.0
1/10/2010 11:05:00 AM	1/10/2010 11:44:00 AM	39.0
1/10/2010 2:09:00 PM	1/10/2010 2:46:00 PM	37.0
1/10/2010 6:57:00 PM	1/10/2010 7:35:00 PM	38.0
1/10/2010 8:38:00 PM	1/10/2010 9:26:00 PM	48.0
1/10/2010 9:45:00 PM	1/10/2010 10:16:00 PM	31.0
1/10/2010 10:55:00 PM	1/10/2010 11:30:00 PM	35.0
1/11/2010 1:26:00 AM	1/11/2010 2:10:00 AM	44.0
1/11/2010 3:15:00 AM	1/11/2010 4:00:00 AM	45.0
1/11/2010 5:15:00 AM	1/11/2010 5:45:00 AM	30.0
1/11/2010 9:45:00 AM	1/11/2010 10:20:00 AM	35.0
1/11/2010 8:10:00 PM	1/11/2010 8:51:00 PM	41.0
1/12/2010 2:55:00 AM	1/12/2010 3:30:00 AM	35.0
1/12/2010 12:03:00 PM	1/12/2010 12:47:00 PM	44.0
1/13/2010 8:15:00 AM	1/13/2010 8:45:00 AM	30.0

Time Out Start	Time Out End	Gap Length (min)
1/13/2010 9:20:00 AM	1/13/2010 10:02:00 AM	42.0
1/13/2010 3:48:00 PM	1/13/2010 4:45:00 PM	57.0
1/13/2010 5:26:00 PM	1/13/2010 6:08:00 PM	42.0
1/14/2010 3:10:00 AM	1/14/2010 3:42:00 AM	32.0
1/14/2010 11:32:00 AM	1/14/2010 12:07:00 PM	35.0
1/14/2010 6:13:00 PM	1/14/2010 6:45:00 PM	32.0
1/14/2010 6:45:00 PM	1/14/2010 7:15:00 PM	30.0
1/14/2010 10:00:00 PM	1/14/2010 10:30:00 PM	30.0
1/14/2010 10:55:00 PM	1/14/2010 11:27:00 PM	32.0
1/15/2010 1:25:00 AM	1/15/2010 2:03:00 AM	38.0
1/15/2010 2:33:00 PM	1/15/2010 3:19:00 PM	46.0
1/16/2010 5:35:00 AM	1/16/2010 6:19:00 AM	44.0
1/16/2010 6:43:00 AM	1/16/2010 7:16:00 AM	33.0
1/16/2010 9:30:00 PM	1/16/2010 10:10:00 PM	40.0
1/17/2010 5:50:00 AM	1/17/2010 6:21:00 AM	31.0
1/17/2010 8:44:00 AM	1/17/2010 9:15:00 AM	31.0
1/18/2010 3:23:00 PM	1/18/2010 4:00:00 PM	37.0
1/19/2010 2:47:00 AM	1/19/2010 3:40:00 AM	53.0
1/20/2010 2:27:00 PM	1/20/2010 3:02:00 PM	35.0
1/21/2010 2:30:00 AM	1/21/2010 3:00:00 AM	30.0
1/21/2010 9:15:00 AM	1/21/2010 9:50:00 AM	35.0
1/21/2010 2:03:00 PM	1/21/2010 2:51:00 PM	48.0
1/23/2010 1:25:00 AM	1/23/2010 1:59:00 AM	34.0
1/23/2010 10:35:00 PM	1/23/2010 11:10:00 PM	35.0
1/24/2010 4:31:00 AM	1/24/2010 5:10:00 AM	39.0
1/24/2010 9:50:00 AM	1/24/2010 10:20:00 AM	30.0
1/24/2010 4:41:00 PM	1/24/2010 5:14:00 PM	33.0
1/24/2010 5:45:00 PM	1/24/2010 6:27:00 PM	42.0
1/24/2010 10:50:00 PM	1/24/2010 11:25:00 PM	35.0
1/25/2010 12:59:00 AM	1/25/2010 1:36:00 AM	37.0
1/25/2010 3:25:00 AM	1/25/2010 3:57:00 AM	32.0
1/25/2010 5:04:00 AM	1/25/2010 5:45:00 AM	41.0
1/25/2010 2:46:00 PM	1/25/2010 3:25:00 PM	39.0
1/25/2010 3:45:00 PM	1/25/2010 4:18:00 PM	33.0
1/25/2010 4:45:00 PM	1/25/2010 5:30:00 PM	45.0
1/25/2010 5:32:00 PM	1/25/2010 6:10:00 PM	38.0
1/25/2010 6:42:00 PM	1/25/2010 7:25:00 PM	43.0
1/25/2010 9:40:00 PM	1/25/2010 10:29:00 PM	49.0
1/25/2010 10:29:00 PM	1/25/2010 11:25:00 PM	56.0
1/25/2010 11:48:00 PM	1/26/2010 12:19:00 AM	31.0
1/26/2010 1:00:00 AM	1/26/2010 1:38:00 AM	38.0
1/26/2010 2:20:00 AM	1/26/2010 3:30:00 AM	70.0
1/26/2010 3:30:00 AM	1/26/2010 4:41:00 AM	71.0
1/26/2010 4:41:00 AM	1/26/2010 6:11:00 AM	90.0
1/26/2010 6:21:00 AM	1/26/2010 7:30:00 AM	69.0
1/26/2010 8:35:00 AM	1/26/2010 10:01:00 AM	86.0
1/26/2010 10:01:00 AM	1/26/2010 11:00:00 AM	59.0
1/26/2010 11:30:00 AM	1/26/2010 12:02:00 PM	32.0
1/26/2010 1:38:00 PM	1/26/2010 2:45:00 PM	67.0
1/26/2010 3:00:00 PM	1/26/2010 3:35:00 PM	35.0
1/26/2010 4:00:00 PM	1/26/2010 4:42:00 PM	42.0
1/26/2010 4:56:00 PM	1/26/2010 6:07:00 PM	71.0

Time Out Start	Time Out End	Gap Length (min)
1/26/2010 7:05:00 PM	1/26/2010 7:50:00 PM	45.0
1/26/2010 8:32:00 PM	1/26/2010 9:51:00 PM	79.0
1/26/2010 9:55:00 PM	1/26/2010 11:42:00 PM	107.0
1/27/2010 12:11:00 AM	1/27/2010 1:00:00 AM	49.0
1/27/2010 1:01:00 AM	1/27/2010 2:55:00 AM	114.0
1/27/2010 3:17:00 AM	1/27/2010 3:58:00 AM	41.0
1/27/2010 4:12:00 AM	1/27/2010 5:05:00 AM	53.0
1/27/2010 5:50:00 AM	1/27/2010 7:02:00 AM	72.0
1/27/2010 7:55:00 AM	1/27/2010 8:57:00 AM	62.0
1/27/2010 9:03:00 AM	1/27/2010 9:40:00 AM	37.0
1/27/2010 10:23:00 AM	1/27/2010 10:55:00 AM	32.0
1/27/2010 11:22:00 AM	1/27/2010 12:08:00 PM	46.0
1/27/2010 12:20:00 PM	1/27/2010 1:05:00 PM	45.0
1/27/2010 1:05:00 PM	1/27/2010 1:43:00 PM	38.0
1/27/2010 2:38:00 PM	1/27/2010 3:16:00 PM	38.0
1/27/2010 4:26:00 PM	1/27/2010 5:10:00 PM	44.0
1/27/2010 5:10:00 PM	1/27/2010 5:49:00 PM	39.0
1/28/2010 12:01:00 AM	1/28/2010 12:36:00 AM	35.0
1/28/2010 12:58:00 AM	1/28/2010 1:34:00 AM	36.0
1/28/2010 1:45:00 AM	1/28/2010 2:20:00 AM	35.0
1/28/2010 4:33:00 AM	1/28/2010 5:16:00 AM	43.0
1/28/2010 5:16:00 AM	1/28/2010 5:54:00 AM	38.0
1/28/2010 9:10:00 AM	1/28/2010 9:45:00 AM	35.0
1/28/2010 10:00:00 AM	1/28/2010 10:44:00 AM	44.0
1/28/2010 11:05:00 AM	1/28/2010 11:53:00 AM	48.0
1/28/2010 12:44:00 PM	1/28/2010 1:40:00 PM	56.0
1/28/2010 6:23:00 PM	1/28/2010 7:02:00 PM	39.0
1/29/2010 12:32:00 AM	1/29/2010 1:25:00 AM	53.0
1/29/2010 3:22:00 AM	1/29/2010 4:00:00 AM	38.0
1/29/2010 11:17:00 AM	1/29/2010 11:52:00 AM	35.0
1/30/2010 4:00:00 AM	1/30/2010 4:34:00 AM	34.0
1/30/2010 9:15:00 AM	1/30/2010 9:46:00 AM	31.0
1/30/2010 10:36:00 PM	1/30/2010 11:10:00 PM	34.0
1/31/2010 7:10:00 AM	1/31/2010 7:40:00 AM	30.0
2/1/2010 3:44:00 AM	2/1/2010 4:18:00 AM	34.0
2/1/2010 7:40:00 PM	2/1/2010 8:17:00 PM	37.0
2/2/2010 5:05:00 AM	2/2/2010 5:45:00 AM	40.0
2/2/2010 8:54:00 PM	2/2/2010 9:25:00 PM	31.0
2/3/2010 1:10:00 AM	2/3/2010 1:50:00 AM	40.0
2/5/2010 3:53:00 AM	2/5/2010 4:32:00 AM	39.0
2/5/2010 4:45:00 AM	2/5/2010 5:16:00 AM	31.0
2/5/2010 3:05:00 PM	2/5/2010 3:39:00 PM	34.0
2/6/2010 12:02:00 AM	2/6/2010 12:34:00 AM	32.0
2/6/2010 2:18:00 AM	2/6/2010 2:50:00 AM	32.0
2/6/2010 3:02:00 AM	2/6/2010 3:47:00 AM	45.0
2/6/2010 5:16:00 AM	2/6/2010 5:50:00 AM	34.0
2/6/2010 7:10:00 AM	2/6/2010 7:43:00 AM	33.0
2/6/2010 8:33:00 PM	2/6/2010 9:15:00 PM	42.0
2/7/2010 6:20:00 PM	2/7/2010 6:54:00 PM	34.0
2/8/2010 5:16:00 AM	2/8/2010 5:49:00 AM	33.0
2/8/2010 7:27:00 PM	2/8/2010 8:03:00 PM	36.0
2/8/2010 11:38:00 PM	2/9/2010 12:14:00 AM	36.0

Time Out Start	Time Out End	Gap Length (min)
2/9/2010 3:19:00 AM	2/9/2010 3:50:00 AM	31.0
2/9/2010 7:17:00 AM	2/9/2010 8:00:00 AM	43.0
2/9/2010 10:00:00 AM	2/9/2010 10:35:00 AM	35.0
2/9/2010 3:26:00 PM	2/9/2010 4:05:00 PM	39.0
2/9/2010 6:32:00 PM	2/9/2010 7:04:00 PM	32.0
2/10/2010 6:35:00 AM	2/10/2010 7:05:00 AM	30.0
2/11/2010 4:40:00 AM	2/11/2010 5:10:00 AM	30.0
2/11/2010 5:14:00 AM	2/11/2010 5:46:00 AM	32.0
2/11/2010 12:56:00 PM	2/11/2010 1:41:00 PM	45.0
2/12/2010 12:05:00 AM	2/12/2010 12:40:00 AM	35.0
2/12/2010 9:10:00 AM	2/12/2010 9:40:00 AM	30.0
2/13/2010 5:33:00 AM	2/13/2010 6:04:00 AM	31.0
2/13/2010 2:30:00 PM	2/13/2010 3:00:00 PM	30.0
2/13/2010 10:27:00 PM	2/13/2010 11:00:00 PM	33.0
2/14/2010 2:20:00 AM	2/14/2010 2:50:00 AM	30.0
2/14/2010 5:20:00 AM	2/14/2010 5:50:00 AM	30.0
2/14/2010 6:00:00 AM	2/14/2010 6:30:00 AM	30.0
2/14/2010 11:48:00 AM	2/14/2010 12:19:00 PM	31.0
2/15/2010 10:04:00 PM	2/15/2010 10:36:00 PM	32.0
2/16/2010 4:20:00 AM	2/16/2010 4:50:00 AM	30.0
2/16/2010 5:06:00 AM	2/16/2010 5:38:00 AM	32.0
2/16/2010 1:25:00 PM	2/16/2010 2:06:00 PM	41.0
2/16/2010 7:00:00 PM	2/16/2010 7:32:00 PM	32.0
2/17/2010 3:06:00 AM	2/17/2010 3:41:00 AM	35.0
2/18/2010 2:09:00 AM	2/18/2010 2:40:00 AM	31.0
2/19/2010 2:08:00 AM	2/19/2010 2:41:00 AM	33.0
2/20/2010 8:55:00 AM	2/20/2010 9:30:00 AM	35.0
2/20/2010 10:35:00 AM	2/20/2010 11:06:00 AM	31.0
2/20/2010 2:06:00 PM	2/20/2010 2:42:00 PM	36.0
2/21/2010 3:30:00 AM	2/21/2010 4:06:00 AM	36.0
2/21/2010 5:30:00 AM	2/21/2010 6:05:00 AM	35.0
2/21/2010 7:45:00 PM	2/21/2010 8:15:00 PM	30.0
2/22/2010 5:35:00 PM	2/22/2010 6:15:00 PM	40.0
2/25/2010 6:00:00 AM	2/25/2010 6:31:00 AM	31.0
2/26/2010 3:53:00 AM	2/26/2010 4:25:00 AM	32.0
2/26/2010 10:30:00 AM	2/26/2010 11:00:00 AM	30.0
2/26/2010 9:10:00 PM	2/26/2010 9:43:00 PM	33.0
2/27/2010 4:00:00 AM	2/27/2010 4:30:00 AM	30.0
2/27/2010 9:38:00 PM	2/27/2010 10:09:00 PM	31.0
2/27/2010 11:46:00 PM	2/28/2010 12:20:00 AM	34.0
2/28/2010 1:51:00 AM	2/28/2010 2:25:00 AM	34.0
2/28/2010 9:50:00 PM	2/28/2010 10:20:00 PM	30.0
3/1/2010 3:25:00 AM	3/1/2010 3:59:00 AM	34.0
3/1/2010 1:00:00 PM	3/1/2010 1:30:00 PM	30.0
3/1/2010 11:30:00 PM	3/2/2010 12:06:00 AM	36.0
3/2/2010 11:14:00 PM	3/2/2010 11:46:00 PM	32.0
3/3/2010 11:05:00 AM	3/3/2010 11:35:00 AM	30.0
3/6/2010 4:27:00 PM	3/6/2010 5:00:00 PM	33.0
3/7/2010 2:50:00 PM	3/7/2010 3:25:00 PM	35.0
3/8/2010 1:00:00 AM	3/8/2010 1:31:00 AM	31.0
3/10/2010 9:19:00 PM	3/10/2010 9:52:00 PM	33.0
3/11/2010 8:30:00 PM	3/11/2010 9:00:00 PM	30.0

Time Out Start	Time Out End	Gap Length (min)
3/12/2010 1:24:00 AM	3/12/2010 2:25:00 AM	61.0
3/12/2010 2:44:00 AM	3/12/2010 3:44:00 AM	60.0
3/12/2010 4:15:00 AM	3/12/2010 5:50:00 AM	95.0
3/12/2010 5:50:00 AM	3/12/2010 6:49:00 AM	59.0
3/12/2010 6:49:00 AM	3/12/2010 8:05:00 AM	76.0
3/12/2010 11:10:00 AM	3/12/2010 11:42:00 AM	32.0
3/12/2010 8:54:00 PM	3/12/2010 9:25:00 PM	31.0
3/12/2010 11:45:00 PM	3/13/2010 12:30:00 AM	45.0
3/13/2010 12:45:00 AM	3/13/2010 1:34:00 AM	49.0
3/13/2010 1:55:00 AM	3/13/2010 2:25:00 AM	30.0
3/13/2010 2:27:00 AM	3/13/2010 4:10:00 AM	103.0
3/13/2010 4:35:00 AM	3/13/2010 5:15:00 AM	40.0
3/13/2010 9:20:00 AM	3/13/2010 10:11:00 AM	51.0
3/13/2010 12:41:00 PM	3/13/2010 1:20:00 PM	39.0
3/13/2010 2:56:00 PM	3/13/2010 3:30:00 PM	34.0
3/13/2010 4:36:00 PM	3/13/2010 5:15:00 PM	39.0
3/13/2010 6:50:00 PM	3/13/2010 7:30:00 PM	40.0
3/13/2010 8:40:00 PM	3/13/2010 9:10:00 PM	30.0
3/13/2010 9:19:00 PM	3/13/2010 10:17:00 PM	58.0
3/14/2010 12:12:00 AM	3/14/2010 12:45:00 AM	33.0
3/14/2010 12:45:00 AM	3/14/2010 3:00:00 AM	135.0
3/14/2010 3:22:00 AM	3/14/2010 4:06:00 AM	44.0
3/14/2010 4:06:00 AM	3/14/2010 4:40:00 AM	34.0
3/14/2010 4:40:00 AM	3/14/2010 5:11:00 AM	31.0
3/14/2010 5:12:00 AM	3/14/2010 5:52:00 AM	40.0
3/14/2010 7:35:00 AM	3/14/2010 8:05:00 AM	30.0
3/14/2010 11:25:00 AM	3/14/2010 12:35:00 PM	70.0
3/14/2010 12:50:00 PM	3/14/2010 1:38:00 PM	48.0
3/14/2010 1:47:00 PM	3/14/2010 2:22:00 PM	35.0
3/14/2010 3:30:00 PM	3/14/2010 4:12:00 PM	42.0
3/14/2010 5:36:00 PM	3/14/2010 6:12:00 PM	36.0
3/14/2010 7:18:00 PM	3/14/2010 8:05:00 PM	47.0
3/14/2010 8:35:00 PM	3/14/2010 9:18:00 PM	43.0
3/14/2010 9:18:00 PM	3/14/2010 10:03:00 PM	45.0
3/14/2010 10:03:00 PM	3/14/2010 10:38:00 PM	35.0
3/14/2010 10:38:00 PM	3/14/2010 11:10:00 PM	32.0
3/14/2010 11:10:00 PM	3/15/2010 1:00:00 AM	110.0
3/15/2010 1:04:00 AM	3/15/2010 2:43:00 AM	99.0
3/15/2010 2:51:00 AM	3/15/2010 3:25:00 AM	34.0
3/15/2010 3:31:00 AM	3/15/2010 4:15:00 AM	44.0
3/15/2010 4:20:00 AM	3/15/2010 5:00:00 AM	40.0
3/15/2010 5:00:00 AM	3/15/2010 5:33:00 AM	33.0
3/15/2010 5:57:00 AM	3/15/2010 7:25:00 AM	88.0
3/15/2010 7:30:00 AM	3/15/2010 8:05:00 AM	35.0
3/15/2010 11:40:00 AM	3/15/2010 12:20:00 PM	40.0
3/15/2010 12:55:00 PM	3/15/2010 1:38:00 PM	43.0
3/15/2010 3:00:00 PM	3/15/2010 3:30:00 PM	30.0
3/15/2010 10:18:00 PM	3/15/2010 10:51:00 PM	33.0
3/15/2010 11:45:00 PM	3/16/2010 12:24:00 AM	39.0
3/16/2010 12:44:00 AM	3/16/2010 1:30:00 AM	46.0
3/16/2010 2:30:00 AM	3/16/2010 3:05:00 AM	35.0
3/16/2010 3:05:00 AM	3/16/2010 3:35:00 AM	30.0

Time Out Start	Time Out End	Gap Length (min)
3/16/2010 4:01:00 AM	3/16/2010 4:31:00 AM	30.0
3/16/2010 5:40:00 AM	3/16/2010 6:15:00 AM	35.0
3/16/2010 7:03:00 AM	3/16/2010 7:35:00 AM	32.0
3/16/2010 11:05:00 AM	3/16/2010 11:43:00 AM	38.0
3/16/2010 11:51:00 AM	3/16/2010 12:31:00 PM	40.0
3/16/2010 6:55:00 PM	3/16/2010 7:25:00 PM	30.0
3/17/2010 1:28:00 AM	3/17/2010 2:02:00 AM	34.0
3/17/2010 2:30:00 AM	3/17/2010 3:00:00 AM	30.0
3/17/2010 7:41:00 PM	3/17/2010 8:15:00 PM	34.0
3/19/2010 7:13:00 PM	3/19/2010 7:49:00 PM	36.0
3/19/2010 8:27:00 PM	3/19/2010 9:00:00 PM	33.0
3/20/2010 12:02:00 AM	3/20/2010 12:35:00 AM	33.0
3/20/2010 2:01:00 PM	3/20/2010 2:34:00 PM	33.0
3/21/2010 7:35:00 AM	3/21/2010 8:18:00 AM	43.0
3/24/2010 2:28:00 AM	3/24/2010 2:58:00 AM	30.0
3/24/2010 3:21:00 AM	3/24/2010 3:55:00 AM	34.0
3/24/2010 4:25:00 AM	3/24/2010 4:57:00 AM	32.0
3/24/2010 5:55:00 AM	3/24/2010 6:35:00 AM	40.0
3/27/2010 1:40:00 AM	3/27/2010 2:17:00 AM	37.0
3/28/2010 3:25:00 AM	3/28/2010 3:56:00 AM	31.0
3/29/2010 5:35:00 AM	3/29/2010 6:10:00 AM	35.0
4/2/2010 11:15:00 AM	4/2/2010 11:51:00 AM	36.0
4/3/2010 10:25:00 PM	4/3/2010 11:00:00 PM	35.0
4/4/2010 10:06:00 PM	4/4/2010 10:36:00 PM	30.0
4/5/2010 2:05:00 AM	4/5/2010 2:40:00 AM	35.0
4/6/2010 4:23:00 PM	4/6/2010 5:10:00 PM	47.0
4/7/2010 2:32:00 PM	4/7/2010 3:22:00 PM	50.0
4/8/2010 8:47:00 PM	4/8/2010 9:27:00 PM	40.0
4/9/2010 4:23:00 AM	4/9/2010 4:53:00 AM	30.0
4/10/2010 4:59:00 AM	4/10/2010 5:30:00 AM	31.0
4/12/2010 5:20:00 AM	4/12/2010 6:04:00 AM	44.0
4/13/2010 5:52:00 AM	4/13/2010 6:25:00 AM	33.0
4/15/2010 11:00:00 AM	4/15/2010 11:34:00 AM	34.0
4/18/2010 1:55:00 AM	4/18/2010 2:38:00 AM	43.0
4/20/2010 3:09:00 AM	4/20/2010 3:39:00 AM	30.0
4/21/2010 1:30:00 AM	4/21/2010 2:05:00 AM	35.0
4/21/2010 5:47:00 AM	4/21/2010 6:25:00 AM	38.0
4/21/2010 5:46:00 PM	4/21/2010 6:18:00 PM	32.0
4/22/2010 6:15:00 AM	4/22/2010 6:46:00 AM	31.0
4/23/2010 2:25:00 AM	4/23/2010 2:55:00 AM	30.0
4/26/2010 6:10:00 AM	4/26/2010 6:44:00 AM	34.0
4/30/2010 2:47:00 AM	4/30/2010 3:22:00 AM	35.0
5/2/2010 10:13:00 PM	5/2/2010 10:47:00 PM	34.0
5/3/2010 5:25:00 AM	5/3/2010 6:00:00 AM	35.0
5/3/2010 9:16:00 AM	5/3/2010 9:53:00 AM	37.0
5/4/2010 2:30:00 AM	5/4/2010 3:04:00 AM	34.0
5/4/2010 9:30:00 AM	5/4/2010 10:03:00 AM	33.0
5/5/2010 3:36:00 AM	5/5/2010 4:08:00 AM	32.0
5/5/2010 5:15:00 AM	5/5/2010 5:48:00 AM	33.0
5/5/2010 3:05:00 PM	5/5/2010 3:35:00 PM	30.0
5/6/2010 3:06:00 AM	5/6/2010 3:37:00 AM	31.0
5/6/2010 9:13:00 PM	5/6/2010 9:51:00 PM	38.0

Time Out Start	Time Out End	Gap Length (min)
5/6/2010 9:51:00 PM	5/6/2010 10:21:00 PM	30.0
5/7/2010 1:02:00 AM	5/7/2010 1:40:00 AM	38.0
5/7/2010 10:40:00 AM	5/7/2010 11:10:00 AM	30.0
5/7/2010 9:05:00 PM	5/7/2010 9:35:00 PM	30.0
5/10/2010 5:04:00 AM	5/10/2010 5:45:00 AM	41.0
5/10/2010 6:08:00 AM	5/10/2010 6:40:00 AM	32.0
5/10/2010 7:07:00 AM	5/10/2010 7:37:00 AM	30.0
5/11/2010 1:43:00 PM	5/11/2010 2:17:00 PM	34.0
5/11/2010 6:07:00 PM	5/11/2010 6:40:00 PM	33.0
5/13/2010 3:03:00 AM	5/13/2010 3:33:00 AM	30.0
5/13/2010 3:42:00 PM	5/13/2010 4:15:00 PM	33.0
5/15/2010 2:46:00 AM	5/15/2010 3:25:00 AM	39.0
5/15/2010 11:12:00 PM	5/15/2010 11:45:00 PM	33.0
5/17/2010 2:06:00 AM	5/17/2010 2:38:00 AM	32.0
5/18/2010 3:05:00 AM	5/18/2010 3:40:00 AM	35.0
5/18/2010 5:09:00 AM	5/18/2010 5:42:00 AM	33.0
5/18/2010 6:47:00 AM	5/18/2010 7:33:00 AM	46.0
5/18/2010 11:25:00 PM	5/18/2010 11:55:00 PM	30.0
5/19/2010 8:33:00 PM	5/19/2010 9:04:00 PM	31.0
5/20/2010 1:27:00 AM	5/20/2010 1:57:00 AM	30.0
5/20/2010 2:30:00 AM	5/20/2010 3:00:00 AM	30.0
5/20/2010 4:31:00 AM	5/20/2010 5:05:00 AM	34.0
5/20/2010 5:46:00 AM	5/20/2010 6:18:00 AM	32.0
5/21/2010 12:29:00 AM	5/21/2010 1:04:00 AM	35.0
5/23/2010 12:37:00 AM	5/23/2010 1:19:00 AM	42.0
5/23/2010 1:31:00 AM	5/23/2010 2:18:00 AM	47.0
5/23/2010 3:50:00 AM	5/23/2010 4:35:00 AM	45.0
5/23/2010 4:40:00 AM	5/23/2010 5:45:00 AM	65.0
5/24/2010 7:10:00 AM	5/24/2010 7:40:00 AM	30.0
5/28/2010 12:33:00 AM	5/28/2010 1:08:00 AM	35.0
5/28/2010 7:10:00 AM	5/28/2010 7:48:00 AM	38.0
5/29/2010 2:27:00 AM	5/29/2010 3:00:00 AM	33.0
5/29/2010 4:12:00 AM	5/29/2010 4:45:00 AM	33.0
5/29/2010 6:18:00 AM	5/29/2010 6:50:00 AM	32.0
5/31/2010 9:55:00 PM	5/31/2010 10:27:00 PM	32.0
6/2/2010 1:45:00 AM	6/2/2010 2:15:00 AM	30.0
6/2/2010 6:25:00 AM	6/2/2010 6:56:00 AM	31.0
6/3/2010 6:42:00 AM	6/3/2010 7:15:00 AM	33.0
6/3/2010 3:10:00 PM	6/3/2010 3:41:00 PM	31.0
6/5/2010 12:32:00 AM	6/5/2010 1:24:00 AM	52.0
6/5/2010 2:20:00 AM	6/5/2010 3:00:00 AM	40.0
6/6/2010 5:02:00 AM	6/6/2010 5:33:00 AM	31.0
6/6/2010 11:44:00 PM	6/7/2010 12:34:00 AM	50.0
6/10/2010 4:05:00 PM	6/10/2010 4:40:00 PM	35.0
6/11/2010 3:55:00 AM	6/11/2010 4:28:00 AM	33.0
6/14/2010 4:59:00 AM	6/14/2010 5:30:00 AM	31.0
6/18/2010 5:24:00 AM	6/18/2010 6:13:00 AM	49.0
6/20/2010 1:30:00 AM	6/20/2010 2:00:00 AM	30.0
6/21/2010 4:51:00 AM	6/21/2010 5:24:00 AM	33.0
6/23/2010 12:42:00 AM	6/23/2010 1:12:00 AM	30.0
6/23/2010 3:25:00 AM	6/23/2010 4:00:00 AM	35.0
6/25/2010 6:02:00 AM	6/25/2010 6:33:00 AM	31.0

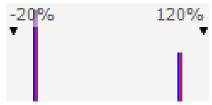
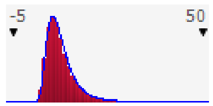
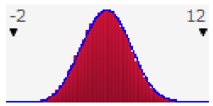
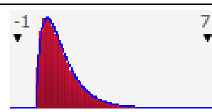
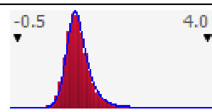
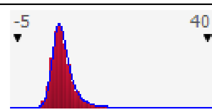
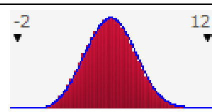
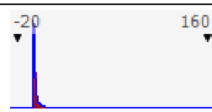
Time Out Start	Time Out End	Gap Length (min)
6/27/2010 1:42:00 AM	6/27/2010 2:15:00 AM	33.0
7/3/2010 1:39:00 AM	7/3/2010 2:13:00 AM	34.0
7/6/2010 6:10:00 AM	7/6/2010 6:45:00 AM	35.0
7/6/2010 9:45:00 PM	7/6/2010 10:15:00 PM	30.0
7/7/2010 5:40:00 AM	7/7/2010 6:17:00 AM	37.0
7/10/2010 2:55:00 AM	7/10/2010 3:37:00 AM	42.0
7/12/2010 1:45:00 AM	7/12/2010 2:15:00 AM	30.0
7/12/2010 9:05:00 AM	7/12/2010 9:42:00 AM	37.0
7/12/2010 1:40:00 PM	7/12/2010 2:10:00 PM	30.0
7/13/2010 6:19:00 AM	7/13/2010 6:56:00 AM	37.0
7/15/2010 2:02:00 AM	7/15/2010 2:33:00 AM	31.0
7/15/2010 5:00:00 AM	7/15/2010 5:46:00 AM	46.0
7/16/2010 1:35:00 AM	7/16/2010 2:06:00 AM	31.0
7/17/2010 3:20:00 AM	7/17/2010 4:00:00 AM	40.0
7/18/2010 11:41:00 PM	7/19/2010 12:16:00 AM	35.0
7/19/2010 10:20:00 PM	7/19/2010 10:50:00 PM	30.0
7/19/2010 11:30:00 PM	7/20/2010 12:01:00 AM	31.0
7/22/2010 4:30:00 AM	7/22/2010 5:03:00 AM	33.0
7/27/2010 3:00:00 AM	7/27/2010 3:30:00 AM	30.0
7/27/2010 5:18:00 AM	7/27/2010 5:57:00 AM	39.0
7/28/2010 4:12:00 AM	7/28/2010 4:45:00 AM	33.0
8/2/2010 5:59:00 AM	8/2/2010 6:32:00 AM	33.0
8/3/2010 9:15:00 PM	8/3/2010 9:45:00 PM	30.0
8/7/2010 4:45:00 AM	8/7/2010 5:17:00 AM	32.0
8/8/2010 4:20:00 AM	8/8/2010 4:50:00 AM	30.0
8/9/2010 3:49:00 AM	8/9/2010 4:26:00 AM	37.0
8/12/2010 4:17:00 AM	8/12/2010 4:53:00 AM	36.0
8/16/2010 3:31:00 AM	8/16/2010 4:05:00 AM	34.0
8/17/2010 8:47:00 AM	8/17/2010 9:20:00 AM	33.0
8/25/2010 12:48:00 AM	8/25/2010 1:18:00 AM	30.0
8/28/2010 4:48:00 AM	8/28/2010 5:21:00 AM	33.0
8/30/2010 5:24:00 AM	8/30/2010 6:00:00 AM	36.0
9/2/2010 5:30:00 AM	9/2/2010 6:00:00 AM	30.0
9/3/2010 2:15:00 AM	9/3/2010 2:49:00 AM	34.0
9/5/2010 1:30:00 AM	9/5/2010 2:15:00 AM	45.0
9/10/2010 3:20:00 AM	9/10/2010 3:53:00 AM	33.0
9/14/2010 3:21:00 AM	9/14/2010 3:55:00 AM	34.0
9/18/2010 4:10:00 AM	9/18/2010 4:48:00 AM	38.0
9/18/2010 5:00:00 AM	9/18/2010 6:36:00 AM	96.0
9/18/2010 7:00:00 AM	9/18/2010 7:40:00 AM	40.0
9/21/2010 4:32:00 AM	9/21/2010 5:12:00 AM	40.0
9/22/2010 5:05:00 AM	9/22/2010 5:35:00 AM	30.0
9/22/2010 3:55:00 PM	9/22/2010 4:25:00 PM	30.0
9/23/2010 7:20:00 AM	9/23/2010 7:55:00 AM	35.0
9/25/2010 4:30:00 AM	9/25/2010 5:00:00 AM	30.0
9/27/2010 3:30:00 AM	9/27/2010 4:07:00 AM	37.0
10/2/2010 4:46:00 AM	10/2/2010 5:25:00 AM	39.0
10/2/2010 5:50:00 AM	10/2/2010 7:23:00 AM	93.0
10/3/2010 11:05:00 PM	10/3/2010 11:40:00 PM	35.0
10/8/2010 12:44:00 AM	10/8/2010 1:17:00 AM	33.0
10/8/2010 3:58:00 AM	10/8/2010 4:31:00 AM	33.0
10/8/2010 4:31:00 AM	10/8/2010 5:05:00 AM	34.0

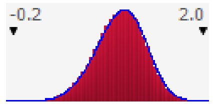
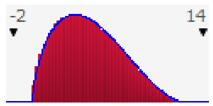
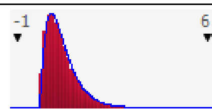
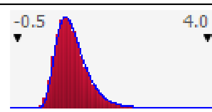
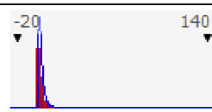
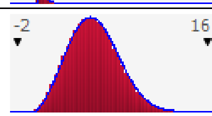
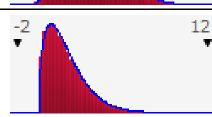
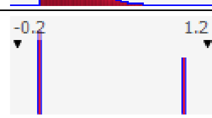
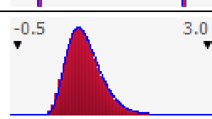
Time Out Start	Time Out End	Gap Length (min)
10/8/2010 5:25:00 AM	10/8/2010 6:30:00 AM	65.0
10/8/2010 7:42:00 AM	10/8/2010 8:13:00 AM	31.0
10/9/2010 9:57:00 PM	10/9/2010 10:27:00 PM	30.0
10/10/2010 3:54:00 AM	10/10/2010 4:25:00 AM	31.0
10/10/2010 4:35:00 AM	10/10/2010 5:16:00 AM	41.0
10/10/2010 11:05:00 PM	10/10/2010 11:45:00 PM	40.0
10/11/2010 11:30:00 PM	10/12/2010 12:03:00 AM	33.0
10/13/2010 5:18:00 AM	10/13/2010 5:51:00 AM	33.0
10/15/2010 3:00:00 AM	10/15/2010 3:32:00 AM	32.0
10/15/2010 4:09:00 AM	10/15/2010 4:55:00 AM	46.0
10/16/2010 1:28:00 AM	10/16/2010 2:15:00 AM	47.0
10/16/2010 4:37:00 AM	10/16/2010 5:10:00 AM	33.0
10/20/2010 7:50:00 AM	10/20/2010 8:25:00 AM	35.0
10/23/2010 1:30:00 AM	10/23/2010 2:06:00 AM	36.0
10/24/2010 4:35:00 AM	10/24/2010 5:06:00 AM	31.0
10/25/2010 1:42:00 AM	10/25/2010 2:13:00 AM	31.0
10/26/2010 5:06:00 PM	10/26/2010 5:38:00 PM	32.0
10/28/2010 9:05:00 AM	10/28/2010 9:40:00 AM	35.0
10/28/2010 4:20:00 PM	10/28/2010 4:50:00 PM	30.0
10/29/2010 6:11:00 PM	10/29/2010 6:51:00 PM	40.0
10/30/2010 7:20:00 AM	10/30/2010 7:50:00 AM	30.0
11/1/2010 3:15:00 AM	11/1/2010 3:48:00 AM	33.0
11/1/2010 7:15:00 AM	11/1/2010 8:02:00 AM	47.0
11/1/2010 8:41:00 AM	11/1/2010 9:27:00 AM	46.0
11/2/2010 3:00:00 AM	11/2/2010 3:32:00 AM	32.0
11/4/2010 1:45:00 AM	11/4/2010 2:25:00 AM	40.0
11/4/2010 2:02:00 PM	11/4/2010 2:35:00 PM	33.0
11/4/2010 10:50:00 PM	11/4/2010 11:28:00 PM	38.0
11/5/2010 4:00:00 AM	11/5/2010 4:32:00 AM	32.0
11/5/2010 7:20:00 AM	11/5/2010 7:56:00 AM	36.0
11/5/2010 3:00:00 PM	11/5/2010 3:34:00 PM	34.0
11/6/2010 3:45:00 AM	11/6/2010 4:15:00 AM	30.0
11/6/2010 5:29:00 AM	11/6/2010 6:10:00 AM	41.0
11/7/2010 2:15:00 AM	11/7/2010 2:54:00 AM	39.0
11/7/2010 4:53:00 AM	11/7/2010 5:34:00 AM	41.0
11/7/2010 5:36:00 AM	11/7/2010 6:09:00 AM	33.0
11/7/2010 7:40:00 PM	11/7/2010 8:11:00 PM	31.0
11/9/2010 6:32:00 AM	11/9/2010 7:37:00 AM	65.0
11/9/2010 7:45:00 AM	11/9/2010 8:25:00 AM	40.0
11/10/2010 12:25:00 AM	11/10/2010 12:56:00 AM	31.0
11/12/2010 5:00:00 AM	11/12/2010 5:35:00 AM	35.0
11/12/2010 6:24:00 AM	11/12/2010 7:00:00 AM	36.0
11/13/2010 12:58:00 PM	11/13/2010 1:30:00 PM	32.0
11/15/2010 3:30:00 AM	11/15/2010 4:02:00 AM	32.0
11/15/2010 4:28:00 AM	11/15/2010 5:33:00 AM	65.0
11/15/2010 5:33:00 AM	11/15/2010 6:30:00 AM	57.0
11/15/2010 7:30:00 AM	11/15/2010 8:00:00 AM	30.0
11/17/2010 4:03:00 AM	11/17/2010 4:48:00 AM	45.0
11/18/2010 12:09:00 AM	11/18/2010 12:40:00 AM	31.0
11/18/2010 5:17:00 AM	11/18/2010 5:53:00 AM	36.0
11/20/2010 12:37:00 AM	11/20/2010 1:10:00 AM	33.0
11/20/2010 5:29:00 AM	11/20/2010 6:05:00 AM	36.0

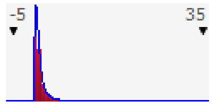
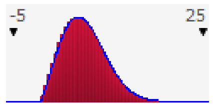
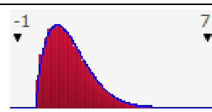
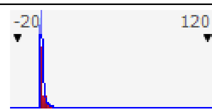
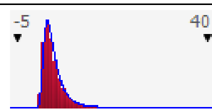
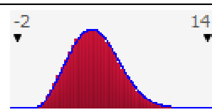
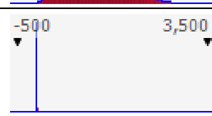
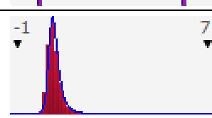
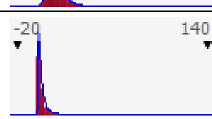
Time Out Start	Time Out End	Gap Length (min)
11/21/2010 4:00:00 AM	11/21/2010 4:40:00 AM	40.0
11/21/2010 4:40:00 AM	11/21/2010 5:14:00 AM	34.0
11/21/2010 5:54:00 AM	11/21/2010 6:26:00 AM	32.0
11/21/2010 6:30:00 AM	11/21/2010 7:03:00 AM	33.0
11/21/2010 7:30:00 AM	11/21/2010 8:03:00 AM	33.0
11/24/2010 11:36:00 PM	11/25/2010 12:08:00 AM	32.0
11/25/2010 4:25:00 AM	11/25/2010 4:56:00 AM	31.0
11/25/2010 6:50:00 PM	11/25/2010 7:20:00 PM	30.0
11/25/2010 8:55:00 PM	11/25/2010 9:33:00 PM	38.0
11/25/2010 10:45:00 PM	11/25/2010 11:15:00 PM	30.0
11/26/2010 4:29:00 PM	11/26/2010 5:00:00 PM	31.0
11/27/2010 7:48:00 AM	11/27/2010 8:23:00 AM	35.0
11/28/2010 7:53:00 AM	11/28/2010 8:25:00 AM	32.0
11/29/2010 1:25:00 AM	11/29/2010 2:00:00 AM	35.0
11/29/2010 3:33:00 AM	11/29/2010 4:12:00 AM	39.0
11/29/2010 5:00:00 AM	11/29/2010 5:33:00 AM	33.0
11/29/2010 10:15:00 AM	11/29/2010 10:46:00 AM	31.0
11/29/2010 9:42:00 PM	11/29/2010 10:21:00 PM	39.0
11/30/2010 6:13:00 AM	11/30/2010 6:45:00 AM	32.0
11/30/2010 2:17:00 PM	11/30/2010 2:55:00 PM	38.0
12/1/2010 12:41:00 AM	12/1/2010 1:15:00 AM	34.0
12/1/2010 7:29:00 AM	12/1/2010 8:00:00 AM	31.0
12/1/2010 9:45:00 AM	12/1/2010 10:15:00 AM	30.0
12/1/2010 4:37:00 PM	12/1/2010 5:12:00 PM	35.0
12/1/2010 5:25:00 PM	12/1/2010 5:55:00 PM	30.0
12/1/2010 10:00:00 PM	12/1/2010 10:40:00 PM	40.0
12/2/2010 12:59:00 AM	12/2/2010 1:30:00 AM	31.0
12/2/2010 2:34:00 AM	12/2/2010 3:36:00 AM	62.0
12/2/2010 4:30:00 AM	12/2/2010 5:44:00 AM	74.0
12/2/2010 7:10:00 AM	12/2/2010 7:40:00 AM	30.0
12/2/2010 9:00:00 AM	12/2/2010 9:37:00 AM	37.0
12/2/2010 9:43:00 AM	12/2/2010 10:15:00 AM	32.0
12/2/2010 10:22:00 AM	12/2/2010 10:55:00 AM	33.0
12/2/2010 11:20:00 AM	12/2/2010 11:50:00 AM	30.0
12/2/2010 12:00:00 PM	12/2/2010 12:30:00 PM	30.0
12/2/2010 12:57:00 PM	12/2/2010 1:47:00 PM	50.0
12/2/2010 6:22:00 PM	12/2/2010 7:01:00 PM	39.0
12/2/2010 7:30:00 PM	12/2/2010 8:14:00 PM	44.0
12/2/2010 11:25:00 PM	12/3/2010 12:01:00 AM	36.0
12/3/2010 1:37:00 AM	12/3/2010 2:19:00 AM	42.0
12/3/2010 3:45:00 AM	12/3/2010 4:20:00 AM	35.0
12/3/2010 4:20:00 AM	12/3/2010 5:06:00 AM	46.0
12/3/2010 5:06:00 AM	12/3/2010 5:44:00 AM	38.0
12/3/2010 6:13:00 AM	12/3/2010 6:45:00 AM	32.0
12/3/2010 10:04:00 AM	12/3/2010 10:35:00 AM	31.0
12/4/2010 1:15:00 AM	12/4/2010 1:46:00 AM	31.0
12/4/2010 11:44:00 AM	12/4/2010 12:15:00 PM	31.0
12/4/2010 7:19:00 PM	12/4/2010 8:01:00 PM	42.0
12/5/2010 11:20:00 PM	12/5/2010 11:50:00 PM	30.0
12/6/2010 8:55:00 PM	12/6/2010 9:35:00 PM	40.0
12/7/2010 12:56:00 AM	12/7/2010 1:28:00 AM	32.0
12/9/2010 4:55:00 PM	12/9/2010 5:28:00 PM	33.0

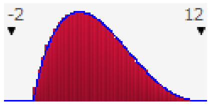
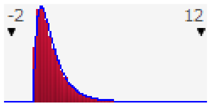
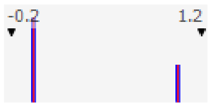
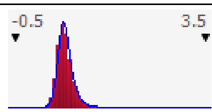
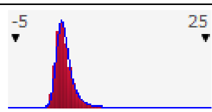
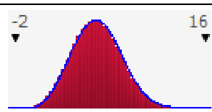
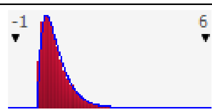
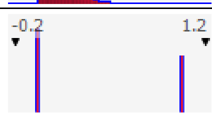
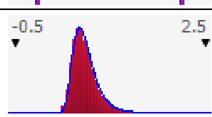
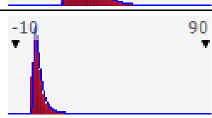
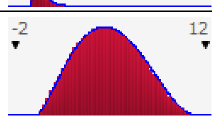
Time Out Start	Time Out End	Gap Length (min)
12/12/2010 4:41:00 AM	12/12/2010 5:12:00 AM	31.0
12/12/2010 4:30:00 PM	12/12/2010 5:05:00 PM	35.0
12/14/2010 8:42:00 AM	12/14/2010 9:20:00 AM	38.0
12/16/2010 11:25:00 AM	12/16/2010 11:55:00 AM	30.0
12/16/2010 9:18:00 PM	12/16/2010 9:54:00 PM	36.0
12/18/2010 1:11:00 AM	12/18/2010 1:44:00 AM	33.0
12/19/2010 1:00:00 AM	12/19/2010 1:47:00 AM	47.0
12/19/2010 1:52:00 AM	12/19/2010 2:27:00 AM	35.0
12/19/2010 11:15:00 AM	12/19/2010 11:52:00 AM	37.0
12/22/2010 3:07:00 AM	12/22/2010 3:38:00 AM	31.0
12/22/2010 12:50:00 PM	12/22/2010 1:23:00 PM	33.0
12/22/2010 2:40:00 PM	12/22/2010 3:45:00 PM	65.0
12/22/2010 5:37:00 PM	12/22/2010 6:10:00 PM	33.0
12/23/2010 12:00:00 AM	12/23/2010 12:46:00 AM	46.0
12/24/2010 6:15:00 AM	12/24/2010 6:47:00 AM	32.0
12/24/2010 6:45:00 PM	12/24/2010 7:30:00 PM	45.0
12/24/2010 10:30:00 PM	12/24/2010 11:11:00 PM	41.0
12/25/2010 1:46:00 AM	12/25/2010 2:19:00 AM	33.0
12/25/2010 3:49:00 AM	12/25/2010 4:26:00 AM	37.0
12/25/2010 5:51:00 AM	12/25/2010 6:25:00 AM	34.0
12/25/2010 10:45:00 AM	12/25/2010 11:25:00 AM	40.0
12/25/2010 2:13:00 PM	12/25/2010 2:48:00 PM	35.0
12/25/2010 4:13:00 PM	12/25/2010 4:49:00 PM	36.0
12/25/2010 4:55:00 PM	12/25/2010 5:35:00 PM	40.0
12/25/2010 6:20:00 PM	12/25/2010 7:00:00 PM	40.0
12/25/2010 8:05:00 PM	12/25/2010 8:46:00 PM	41.0
12/25/2010 11:06:00 PM	12/25/2010 11:41:00 PM	35.0
12/25/2010 11:41:00 PM	12/26/2010 12:12:00 AM	31.0
12/26/2010 2:21:00 AM	12/26/2010 2:55:00 AM	34.0
12/26/2010 4:15:00 AM	12/26/2010 4:53:00 AM	38.0
12/26/2010 5:00:00 AM	12/26/2010 5:50:00 AM	50.0
12/26/2010 6:51:00 AM	12/26/2010 7:30:00 AM	39.0
12/26/2010 2:07:00 PM	12/26/2010 2:39:00 PM	32.0
12/26/2010 5:39:00 PM	12/26/2010 6:22:00 PM	43.0
12/27/2010 2:30:00 AM	12/27/2010 3:00:00 AM	30.0
12/27/2010 6:01:00 AM	12/27/2010 6:32:00 AM	31.0
12/28/2010 8:02:00 AM	12/28/2010 8:40:00 AM	38.0
12/28/2010 12:35:00 PM	12/28/2010 1:05:00 PM	30.0
12/30/2010 1:49:00 AM	12/30/2010 2:20:00 AM	31.0
12/30/2010 3:50:00 AM	12/30/2010 4:36:00 AM	46.0
12/30/2010 8:15:00 PM	12/30/2010 8:45:00 PM	30.0
12/30/2010 10:27:00 PM	12/30/2010 10:58:00 PM	31.0
12/30/2010 11:50:00 PM	12/31/2010 12:21:00 AM	31.0
12/31/2010 4:21:00 AM	12/31/2010 4:55:00 AM	34.0
12/31/2010 2:20:00 PM	12/31/2010 2:55:00 PM	35.0

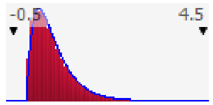
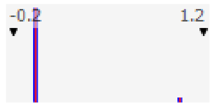
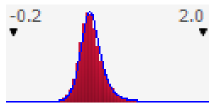
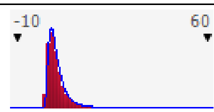
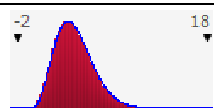
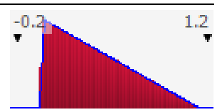
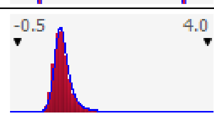
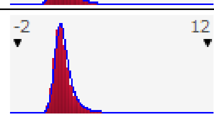
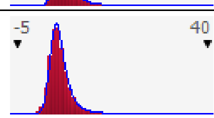
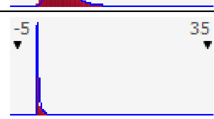
Appendix 14. Stochastic model parameter distributions

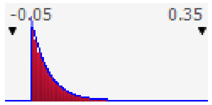
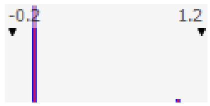
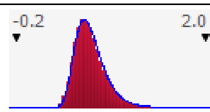
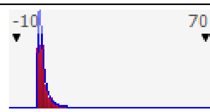
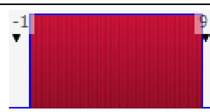
Name	Cell	Graph	Function	Min	Mean	Max	5%	95%
OH71_Delayed? / Distribution	I5		RiskBernoulli(G5)	0%	35%	100%	0%	100%
OH71_Time to next lock in trip (hr)	D9		RiskPearson5(8.4105,71.675,RiskName("OH71_Time to next lock in trip (hr)"))	2.403	9.672	48.568	5.239	16.774
OH71_Speed (MPH)	D10		RiskWeibull(3.3855,5.4979,RiskName("OH71_Speed (MPH)"))	0.361	4.938	10.961	2.286	7.601
OH71_Only delays (hours) all cuts	I7		RiskGamma(1.8311,0.53506,RiskName("OH71_Only delays (hours) all cuts"))	0.001	0.980	6.126	0.155	2.389
OH5_Delayed? / Distribution	T5		RiskBernoulli(R5)	0	0.3946	1	0	1
OH5_lockage time (hr)	O8		RiskLoglogistic(0,0.97707,6.8506,RiskName("OH5_lockag e time (hr)"))	0.208	1.012	3.892	0.636	1.501
OH5_Time to next lock in trip (hr)	O9		RiskLoglogistic(0,6.2352,5.2061,RiskName("OH5_Time to next lock in trip (hr)"))	0.933	6.630	38.738	3.541	10.974
OH5_Speed (MPH)	O10		RiskWeibull(3.3021,5.5162,RiskName("OH5_Speed (MPH)"))	0.228	4.948	11.181	2.243	7.690
OH5_Only delays (hours) All	T7		RiskLognorm(2.3345,3.7369,RiskName("OH5_Only delays (hours) All"))	0.011	2.339	154.191	0.194	7.891
OH4_Delayed? / Distribution	AE5		RiskBernoulli(AC5)	0	0.2608	1	0	1

Name	Cell	Graph	Function	Min	Mean	Max	5%	95%
OH4_lockage time (hr) 2	Z8		RiskWeibull(4.5502,1.1442,RiskName("OH4_lockage time (hr) 2"))	0.133	1.045	1.893	0.595	1.456
OH4_Time to next lock in trip (hr)	Z9		RiskPearson5(2.3733,11.539,RiskName("OH4_Time to next lock in trip (hr)"))	0.736	8.380	389.891	2.161	22.406
OH4_Speed (MPH)	Z10		RiskBetaGeneral(1.7306,2.8458,0,12.071,RiskName("OH4_Speed (MPH)"))	0.015	4.565	11.755	0.922	8.994
OH4_Only delays (hours) ALL	AE7		RiskGamma(2.1363,0.35853,RiskName("OH4_Only delays (hours) ALL"))	0.007	0.766	5.390	0.147	1.779
OH3_Delayed? / Distribution	AP5		RiskBernoulli(AN5)	0	0.505	1	0	1
OH3_lockage time (hr)	AK8		RiskPearson6(8.9205,27.335,2.5801,RiskName("OH3_lockage time (hr)"))	0.143	0.874	3.768	0.414	1.514
OH3_Time to next lock in trip (hr)	AK9		RiskPearson5(4.7867,16.185,RiskName("OH3_Time to next lock in trip (hr)"))	0.808	4.282	132.104	1.827	8.802
OH3_Speed (MPH)	AK10		RiskWeibull(2.6836,6.089,RiskName("OH3_Speed (MPH)"))	0.155	5.414	14.131	2.013	9.164
OH3_Only delays (hours) All	AP7		RiskWeibull(1.3793,2.007,RiskName("OH3_Only delays (hours) All"))	0.001	1.834	10.785	0.233	4.445
OH2_Delayed? / Distribution	BA5		RiskBernoulli(AY5)	0	0.399	1	0	1
OH2_lockage time (hr)	AV8		RiskGamma(7.0467,0.11166,RiskName("OH2_lockage time (hr)"))	0.098	0.787	2.502	0.370	1.329

Name	Cell	Graph	Function	Min	Mean	Max	5%	95%
OH2_Time to next lock in trip (hr)	AV9		RiskPearson5(3.5823,3.8155,RiskName("OH2_Time to next lock in trip (hr)"))	0.232	1.478	34.514	0.533	3.378
OH2_Speed (MPH)	AV10		RiskWeibull(2.1922,7.4441,RiskName("OH2_Speed (MPH)"))	0.087	6.593	20.577	1.919	12.278
OH2_Only delays (hours) All	BA7		RiskWeibull(1.6349,1.5069,RiskName("OH2_Only delays (hours) All"))	0.002	1.349	6.659	0.245	2.948
OH1_Delayed? / Distribution	BL5		RiskBernoulli(BJ5)	0	0.5126	1	0	1
OH1_Only delays (hours)	BG7		RiskLoglogistic(0,1.5313,2.2366,RiskName("OH1_Only delays (hours)"))	0.011	2.177	112.973	0.410	5.707
OH1_Time to next lock in trip (hr)	BG9		RiskPearson5(5.4446,20.232,RiskName("OH1_Time to next lock in trip (hr)"))	1.047	4.551	36.988	2.072	8.981
OH1_Speed (MPH)	BG10		RiskWeibull(2.6735,5.2623,RiskName("OH1_Speed (MPH)"))	0.162	4.678	12.218	1.731	7.932
OH1_Only delays (hours) All	BL7		RiskLoglogistic(0,1.6724,1.7086,RiskName("OH1_Only delays (hours) All"))	0.006	3.429	3225.719	0.298	9.365
MN22_Delayed? / Distribution	BW5		RiskBernoulli(BU5)	0	0.3345	1	0	1
MN22_lockage time (hr)	BR8		RiskLoglogistic(0,0.70262,5.3918,RiskName("MN22_lockage time (hr)"))	0.125	0.744	6.485	0.407	1.213
MN22_Time to next lock in trip (hr)	BR9		RiskPearson5(2.7542,8.103,RiskName("MN22_Time to next lock in trip (hr)"))	0.553	4.613	136.187	1.367	11.669

Name	Cell	Graph	Function	Min	Mean	Max	5%	95%
MN22_Speed (MPH)	BR10		RiskBetaGeneral(1.8985,3.4005,0,11.625,RiskName("MN22_Speed (MPH)"))	0.018	4.165	11.364	0.921	8.165
MN22_Only delays (hours) All	BW7		RiskPearson6(1.8557,16.016,10.374,RiskName("MN22_Only delays (hours) All"))	0.003	1.282	10.749	0.190	3.275
MN23_Delayed? / Distribution	CH5		RiskBernoulli(CF5)	0	0.2997	1	0	1
MN23lockage time (hr) 3	CC8		RiskLoglogistic(0,0.60711,7.3402,RiskName("MN23lockage time (hr) 3"))	0.150	0.626	3.222	0.406	0.907
MN23Time to next lock in trip (hr) 4	CC9		RiskLoglogistic(0,3.1219,4.8098,RiskName("MN23Time to next lock in trip (hr) 4"))	0.460	3.355	23.292	1.692	5.757
MN23_Speed (MPH)	CC10		RiskWeibull(3.0498,6.5788,RiskName("MN23_Speed (MPH)"))	0.298	5.879	14.151	2.484	9.426
MN23_Only delays (hours) All	CH7		RiskGamma(1.8921,0.33545,RiskName("MN23_Only delays (hours) All"))	0.003	0.635	5.080	0.105	1.532
MN24_Delayed? / Distribution	CS5		RiskBernoulli(CQ5)	0	0.4005	1	0	1
MN24_lockage time (hr)	CN8		RiskPearson5(14.598,8.6455,RiskName("MN24_lockage time (hr)"))	0.239	0.636	2.411	0.404	0.968
MN24_Time to next lock in trip (hr)	CN9		RiskPearson5(4.2089,16.716,RiskName("MN24_Time to next lock in trip (hr)"))	0.847	5.210	79.943	2.076	11.225
MN24_Speed (MPH)	CN10		RiskBetaGeneral(2.4447,2.9366,0,10.907,RiskName("MN24_Speed (MPH)"))	0.083	4.955	10.710	1.540	8.595

Name	Cell	Graph	Function	Min	Mean	Max	5%	95%
MN24_Only delays (hours) All	CS7		RiskGamma(1.8518,0.34522,RiskName("MN24_Only delays (hours) All"))	0.001	0.639	4.194	0.103	1.554
MN25_Delayed? / Distribution	DD5		RiskBernoulli(DB5)	0	0.0317	1	0	0
MN25_lockage time (hr)	CY8		RiskLoglogistic(0,0.71983,10.63,RiskName("MN25_lockage time (hr)"))	0.301	0.730	1.801	0.546	0.949
MN25_Time to next lock in trip (hr)	CY9		RiskPearson5(5.3247,25.865,RiskName("MN25_Time to next lock in trip (hr)"))	1.321	5.980	52.975	2.694	11.890
MN25_Speed (MPH)	CY10		RiskBetaGeneral(4.0601,11.937,0,16.868,RiskName("MN25_Speed (MPH)"))	0.290	4.281	12.234	1.674	7.493
MN25_Only delays (hours) All	DD7		RiskTriang(0,0.033333,1.1022,RiskName("MN25_Only delays (hours) All"))	0.001	0.379	1.096	0.044	0.859
MN26_Delayed? / Distribution	DO5		RiskBernoulli(DM5)	0	0.084	1	0	1
MN26_lockage time (hr)	DJ8		RiskLoglogistic(0,0.63476,6.4741,RiskName("MN26_lockage time (hr)"))	0.149	0.660	3.789	0.403	1.000
MN26_Time to next lock in trip (hr)	DJ9		RiskLoglogistic(0,1.5719,5.0001,RiskName("MN26_Time to next lock in trip (hr)"))	0.195	1.680	10.026	0.872	2.832
MN26_Speed (MPH)	DJ10		RiskLoglogistic(0,5.5984,5.0001,RiskName("MN26_Speed (MPH)"))	0.721	5.984	36.382	3.106	10.086
MN26_Only delays (hours) All	DO7		RiskLoglogistic(0,0.36161,2.2178,RiskName("MN26_Only delays (hours) All"))	0.004	0.517	30.370	0.096	1.363

Name	Cell	Graph	Function	Min	Mean	Max	5%	95%
MN28_Only delays (hours) All	DZ7		RiskExpon(0.032583,RiskName("MN28_Only delays (hours) All"))	0.000	0.033	0.304	0.002	0.098
MN28_Delayed? / Distribution	DZ5		RiskBernoulli(DX5)	0	0.0244	1	0	0
'MN28_lockage time (hr)	DU8		RiskPearson5(18.795,12.223,RiskName("'MN28_lockage time (hr)"))	0.300	0.687	1.916	0.462	0.995
MN28_Time to next lock in trip (hr)	DU9		RiskPearson5(3.3918,7.9993,RiskName("MN28_Time to next lock in trip (hr)"))	0.460	3.343	68.584	1.163	7.806
MN28_Speed (MPH)	DU10		RiskUniform(0,8.61,RiskName("MN28_Speed (MPH)"))	0.000	4.305	8.609	0.430	8.179

Appendix 15. Distribution of fuel transactions by state shipped by barge with mileage and cost data (count)

Plant #	Plant Name	Plant State	Total count	Mine location (transaction counts)								
				PA	WV	OH	KY	IL	WY	IN	VA	MT
3098	Elrama Power Plant	PA	18	18	-	-	-	-	-	-	-	-
3179	FirstEnergy Hatfields Ferry Power	PA	125	37	45	18	9	-	15	-	-	1
3181	FirstEnergy Mitchell Power Station	PA	50	27	5	5	10	3	-	-	-	-
6094	FirstEnergy Bruce Mansfield	PA	62	21	15	25	-	-	-	-	-	1
8226	Cheswick Power Plant	PA	19	10	9	-	-	-	-	-	-	-
10676	AES Beaver Valley Partners	PA	24	12	12	-	-	-	-	-	-	-
3935	John E Amos	WV	84	-	55	12	3	-	-	-	14	-
3936	Kanawha River	WV	27	-	27	-	-	-	-	-	-	-
3938	Philip Sporn	WV	45	-	41	-	4	-	-	-	-	-
3943	FirstEnergy Fort Martin Power	WV	122	33	55	11	10	-	12	-	-	1
6264	Mountaineer	WV	72	-	34	29	5	-	-	-	4	-
3946	FirstEnergy Willow Island	WV	8	4	1	-	-	-	3	-	-	-
3947	Kammer	WV	2	-	-	-	2	-	-	-	-	-
3948	Mitchell	WV	34	-	34	-	-	-	-	-	-	-
6004	FirstEnergy Pleasants Power	WV	64	-	1	40	11	12	-	-	-	-
7286	Richard Gorsuch	OH	30	-	9	1	20	-	-	-	-	-
8102	General James M Gavin	OH	62	-	24	32	6	-	-	-	-	-
6019	W H Zimmer	OH	129	13	20	49	27	1	-	19	-	-
6031	Killen Station	OH	45	8	-	-	-	37	-	-	-	-
2828	Cardinal	OH	13	-	-	12	1	-	-	-	-	-
2830	Walter C Beckjord	OH	49	-	33	-	15	1	-	-	-	-
2832	Miami Fort	OH	145	26	10	27	41	23	-	18	-	-
2850	J M Stuart	OH	44	4	2	-	-	38	-	-	-	-
2864	FirstEnergy R E Burger	OH	8	7	1	-	-	-	-	-	-	-
2866	FirstEnergy W H Sammis	OH	48	17	23	4	3	-	1	-	-	-
2872	Muskingum River	OH	10	-	10	-	-	-	-	-	-	-
2876	Kyger Creek	OH	22	-	-	22	-	-	-	-	-	-
983	Clifty Creek	IN	17	17	-	-	-	-	-	-	-	-
988	Tanners Creek	IN	43	24	19	-	-	-	-	-	-	-
1008	R Gallagher	IN	41	-	5	-	15	10	-	11	-	-
1356	Ghent	KY	204	-	19	17	137	31	-	-	-	-

Plant #	Plant Name	Plant State	Total count	Mine location (transaction counts)								
				PA	WV	OH	KY	IL	WY	IN	VA	MT
1364	Mill Creek	KY	68	-	4	3	54	2	-	5	-	-
6018	East Bend	KY	76	-	8	22	33	13	-	-	-	-
6041	H L Spurlock	KY	202	-	66	43	58	28	-	7	-	-
6071	Trimble County	KY	120	-	11	21	83	1	2	2	-	-
3399	Cumberland	TN	52	2	-	-	27	23	-	-	-	-
3406	Johnsonville	TN	17	-	1	-	-	16	-	-	-	-
	TOTAL		2,201	280	599	393	574	239	33	62	18	3

Appendix 16. Barging powerplants transactions without mileage assigned (count)

Plant #	Plant Name	Plant State	Total count	Transactions without calculated mileage											
				PA	WV	OH	AL	CO	IL	IN	KY	MT	UT	WY	CL
3149	PPL Montour	PA	7	-	-	-	-	-	-	-	7	-	-	-	-
8846	Conemaugh Fuels LLC	PA	14	13	-	1	-	-	-	-	-	-	-	-	-
8845	Keystone Fuels LLC	PA	8	8	-	-	-	-	-	-	-	-	-	-	-
50491	PPG Natrium Plant	WV	36	-	24	12	-	-	-	-	-	-	-	-	-
8848	Ceredo	WV	1	1	-	-	-	-	-	-	-	-	-	-	-
3935	John E Amos	WV	54	-	35	-	-	-	-	-	10	-	-	-	9
3936	Kanawha River	WV	18	-	16	-	-	-	-	-	-	-	-	-	2
3938	Philip Sporn	WV	37	-	21	-	-	-	-	-	12	-	-	-	4
3947	Kammer	WV	12	-	-	-	-	-	-	-	9	-	-	2	1
3948	Mitchell	WV	43	-	25	-	-	-	-	-	16	-	-	-	2
6264	Mountaineer	WV	43	-	42	-	-	-	-	-	-	-	-	-	1
2917	Hamilton	OH	24	-	12	12	-	-	-	-	-	-	-	-	-
2828	Cardinal	OH	57	-	44	-	-	-	-	-	10	-	-	2	1
2830	Walter C Beckjord	OH	89	-	25	-	-	-	-	-	64	-	-	-	-
2832	Miami Fort	OH	4	-	2	1	-	-	-	-	1	-	-	-	-
2850	J M Stuart	OH	60	-	27	-	-	-	-	-	33	-	-	-	-
6019	W H Zimmer	OH	9	-	3	-	-	-	-	4	2	-	-	-	-
6031	Killen Station	OH	4	2	-	-	-	-	-	-	2	-	-	-	-
3407	Kingston	TN	1	-	-	-	-	-	-	1	-	-	-	-	-
3403	Gallatin	TN	20	-	-	-	-	-	-	-	-	-	-	20	-
892	Hennepin Power Station	IL	11	-	-	-	-	-	-	-	-	-	-	11	-
897	Vermilion	IL	1	-	-	-	-	-	-	-	-	-	-	1	-
898	Wood River	IL	1	-	-	-	-	-	-	-	-	-	-	1	-
6705	Warrick	IN	25	-	-	-	-	-	-	1	24	-	-	-	-
6166	Rockport	IN	57	-	29	-	-	-	-	-	28	-	-	-	-
988	Tanners Creek	IN	4	-	2	-	-	-	-	-	2	-	-	-	-
6639	R D Green	KY	41	-	-	-	-	-	11	-	30	-	-	-	-
6823	D B Wilson	KY	16	-	-	-	-	-	3	-	13	-	-	-	-
1381	Kenneth C Coleman	KY	48	-	-	-	-	-	13	-	35	-	-	-	-

Plant #	Plant Name	Plant State	Total count	Transactions without calculated mileage											
				PA	WV	OH	AL	CO	IL	IN	KY	MT	UT	WY	CL
1378	Paradise	KY	30	-	-	-	-	-	10	-	20	-	-	-	-
10	Greene County	AL	34	-	-	-	27	-	-	7	-	-	-	-	-
26	E C Gaston	AL	4	-	-	-	4	-	-	-	-	-	-	-	-
8	Gorgas	AL	103	-	-	-	92	-	-	11	-	-	-	-	-
3	Barry	AL	46	-	-	-	7	-	-	-	-	-	-	-	39
56	Charles R Lowman	AL	40	-	-	-	-	-	17	23	-	-	-	-	-
47	Colbert	AL	4	-	4	-	-	-	-	-	-	-	-	-	-
6002	James H Miller Jr	AL	5	-	-	-	-	-	-	-	-	-	-	5	-
594	Indian River Generating Station	DE	7	-	2	-	-	1	-	-	4	-	-	-	-
8816	Davant Transfer	FL	66	-	-	-	-	1	49	-	16	-	-	-	-
8827	IMT Transfer	FL	88	-	41	-	-	2	21	-	24	-	-	-	-
8829	US United Bulk Terminal	FL	73	1	34	-	-	6	13	-	19	-	-	-	-
641	Crist	FL	32	-	24	-	-	1	1	-	-	-	2	-	4
628	Crystal River	FL	9	-	2	-	-	-	-	-	7	-	-	-	-
643	Lansing Smith	FL	18	-	18	-	-	-	-	-	-	-	-	-	-
7242	Polk	FL	2	-	-	-	-	-	-	-	-	-	-	-	2
1047	Lansing	IA	3	-	-	-	-	-	-	-	-	-	-	3	-
1048	Milton L Kapp	IA	7	-	-	-	-	-	-	-	-	-	-	7	-
1733	Monroe	MI	1	-	-	-	-	-	-	-	-	-	-	1	-
2107	Sioux	MO	16	-	-	-	-	-	16	-	-	-	-	-	-
6073	Victor J Daniel Jr	MS	4	-	-	-	-	2	-	-	-	-	-	2	-
8851	Associated Terminals	MS	31	1	16	-	-	-	5	-	9	-	-	-	-
2049	Jack Watson	MS	1	-	1	-	-	-	-	-	-	-	-	-	-
10071	Portsmouth Genco LLC	VA	12	-	12	-	-	-	-	-	-	-	-	-	-
4140	Alma	WI	12	-	-	-	-	-	12	-	-	-	-	-	-
4054	Nelson Dewey	WI	5	-	-	-	-	-	-	-	-	5	-	-	-
4271	John P Madgett	WI	1	-	-	-	-	-	-	-	-	-	-	1	-
	Total		1,399	26	461	26	130	13	171	47	397	5	2	56	65

Appendix 17. Partial list of significant assumptions

Obj.	Assumptions	Validity concerns
1.1 Failure scenario	1. The emergency repairs at the DASC 1 Elizabeth Dam are nearing the end of their expected "lifespan" and may fail, resulting in a catastrophic loss of the Elizabeth pool	• Aging infrastructure is more susceptible to failure as time goes by. • Ongoing inspections might catch signs of imminent failure, allowing for additional emergency repairs – failure might never occur. Impact limited to cost of additional emergency repairs. • Failure might not be catastrophic – river closure might be 1-2 months. Facility closures unlikely due to ability to "live" off stockpiles for several months
	2. Loss of the Elizabeth pool could cause cascading failure of the upstream lock walls at Charleroi	• Scenario described by USACE engineers as their personal nightmare. • Walls might hold. River closure might be 1-2 months. Facility closures unlikely due to ability to "live" off stockpiles for several months
	3. The Charleroi and Braddock Dams would hold	• Braddock Dam is new. Charleroi Dam has been repaired recently • Dam(s) fail. River closure is even longer. More facilities either close or invest in alternative transportation infrastructure.
	4. The upper Charleroi lock gates could be closed, preserving the Charleroi pool	• Gates are not closed, Charleroi pool is compromised. Repairs are more complicated and take longer. More vessels at risk of being stranded. Lost vessel costs underestimated.
	5. Restoration of navigation would be take longer than other lock failures (e.g., gates), taking an assumed 12 months to (1) clear failed dam and lock walls, (2) clear navigation channels of stranded vessels and debris, (3) contract and construct replacement lock walls, (4) restore Charleroi lock functionality	• USACE can clear wreckage and restore navigation more quickly. Facilities avoid closure by using stockpiles or reducing operations

Obj.	Assumptions	Validity concerns
1.2 Identify at-risk shipments	6. Docks identified in USACE survey are still used 7. Satellite images provide valid information about dock usage 8. Velocity Suites can be used cautiously to identify dock locations	• If actual docks are elsewhere, estimation of at-risk shipments may over- or underestimate impacts
	9. Thermal coal shipments are the most important at-risk commodities	• Metallurgical coal and lime shipments are also important. Accounting for their disruption would increase costs
	10. Shipments to several regional facilities were not included in the model because their location could not be determined (Conemaugh Fuels, Keystone Fuels) 11. Combined shipments from multiple mines were not included	• At-risk shipments may be underestimated depending on docks for these facilities
1.3 Failure response alternatives	12. Facilities may close if they do not have alternate transport modes in place 13. Establishing new rail access is expensive, time consuming, and subject to sufficient land availability	• Facilities might have non-obvious options (buried but accessible rail spurs?). Avoid closure, but incur cost of spur rehab and higher shipping costs
	14. Facilities may close if they are marginal operations, as demonstrated by their actual recent closure	• Facilities might not actually be marginal (under construction for expansion?). Alternate higher shipping costs
	15. Switching from barge to truck delivery is not logistically feasible for large powerplants	• Combination of reduced operation and use of stockpile, increased truck delivery. Shipping costs higher
	16. Powerplants and mines switch linkages easily	• Coal quality requirements not easily met from spot market. Prices on spot market sky rocket. Increased pressure to close
	17. Force majure can be used to break coal supply contracts in the face of infrastructure failure	• Coal contracts NOT breakable. Increased costs and pressure to close
	18. Powerplants hold up to (but not more than) 90 days of coal stockpile, providing some buffer, in the short term aftermath of an extended river outage	• Closure avoided for 3 months. Lost revenue reduced by 25%
	19. Powerplants within the failure zone will close	• The combination of loss of their coal supply and cooling water and their

Obj.	Assumptions	Validity concerns
		already marginal status with reduced operations support this assumption
	20. Low capacity factors, dropping production rates, or closure since 2010 are good proxies for facility closure in response to river outage	• Continued operation in a constrained supply network could occur, at increased cost.
	21. The EIA-923 can be used to deduce mode availability at specific facilities in 2010, and over time	• No known issues with data quality. Well established, annual survey with almost full industry coverage.
	22. Observed maximum truck/day deliveries are a proxy for an upper limit of logistical feasibility	• Truck logistics are also a function of distance and road quality, which were not considered.