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Estimating economic and resilience consequences of potential navigation infrastructure failures: A case study of the Monongahela River

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ABSTRACT

The paper examines the potential effects of failure of heavily used, outdated locks and dams on the Monongahela River in southwestern Pennsylvania. Catastrophic failure would result in lengthy outage of barge traffic. The displaced volume of coal shipments from mines to power plants is estimated using Energy Information Administration survey data. The resilience of the impacted facilities, the viability of their shipping alternatives, and their ability to re-organize into new markets is assessed. Lost revenues are 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 are estimated at $0.56-1.7 billion.

1. Introduction

The motivation for this study is the concern about the reliability of the inland waterway infrastructure. This infrastructure, managed by the U.S. Army Corps of Engineers (USACE), allows for the shipment of 2.3 billion tons of commodities in 2010 (USACE, various). More narrowly, this study is motivated by the extended delay in the completion of a major USACE project to replace the antiquated components of the three lower Monongahela lock and dam facilities with two modern facilities. Replacement of the first dam at Braddock is complete, while work on the third lock at Charleroi (and subsequent removal of the second lock and dam at Elizabeth) is delayed due to Federal funding constraints. These funding constraints are felt throughout the U.S. inland waterways (NRC, 2012). In the interim, river transportation is reliant on the ability of USACE to keep the Elizabeth and Charleroi facilities functioning. Catastrophic failure of the highly compromised Elizabeth dam would likely cascade into loss of the fragile river lock wall at the Charleroi lock, resulting in a complete and prolonged loss of navigation on this stretch of the Monongahela. The risks of this specific failure scenario exist at various other aged components of the Nation's inland waterways system.

The purpose of this paper is to examine the potential impacts associated with extended loss of navigation due to catastrophic failure of aging infrastructure on the Monongahela River in southwestern Pennsylvania. The analysis focuses on coal shipments from mines to power plants; coal shipments account for three quarters of the commodity tonnage shipped on the region's rivers. An assessment is provided of 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 GIS tools and national databases, making general assumptions

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about the impact of river failure on commodity movements (Kruse et al., 2007, amended 2009; USACE, 2011b). This analysis looks 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 power plants to adjust to a long-term system constraint.

The contributions of this paper 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 power plant 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 2 reviews key prior studies and concepts relevant to this work. Section 3 provides a description of the river infrastructure in the study area and the commodities that are shipped through the region. Section 4 identifies at-risk coal shipments that were barged through the potential failure zone in 2010. Section 5 characterizes the impacts on the mines and power plants that relied on barge shipment of coal in 2010, and attempts to predict likely responses to an unexpected and prolonged closure of a portion of the Monongahela River. Section 6 explores the likelihood that new markets could successfully emerge above and below the failure zone, allowing the impacted facilities to remain operational. Section 7 quantifies the financial impacts to the mines, power plants, and barge shipping operations due to displacement of their coal shipments. Analysis conclusions are presented in Section 8. Additional data and supporting analyses are available in a Supplementary materialdocument.

2. Prior studies and key concepts

Extensive work precedes this analysis developing increasingly sophisticated approaches to modeling the transport of commodities with differing levels of focus on economic theory (Chulkov, 2012), traffic flow modeling, queuing modeling, agent-based modeling (Reis, 2014), and optimization. These analyses differ in terms of whether they assess normal, unperturbed conditions, short-term disruptions (Jenelius et al., 2006; MacKenzie et al., 2012; Wang et al., 2006; Pant et al., 2011), or long-term catastrophic disruptions (Tsang et al., 2002). Some assess broad commodity flows using input/output models (Ham et al., 2005; MacKenzie et al., 2012; Pant et al., 2011), while others focus more narrowly on specific commodities of importance to a specific region (Kruse et al., 2011). 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 (Bray et al., 2004). Second, national security concerns have increasingly driven more sophisticated failure and resiliency analyses – both in assessing 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 (Department of Homeland Security, 2009; Baroud et al., 2014; Folga et al., 2009; Campo et al., 2012). Third, the transportation sector accounts for 32 percent of U.S. greenhouse gas emissions (U.S. Environmental Protection Agency, 2014), 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 (Reis, 2014).

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. to be "an emergent property of what an engineering system does, rather than a static property the system has" (Park et al., 2013). In the context of the commodity distribution system that supplies coal to power plants, 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 power plants), and more broadly the integrated energy system. Park et al. goes 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. We will demonstrate 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). We will also explore 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). We explore 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.

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 discusses accessibility as a key component in road network vulnerability analysis, and the concept is useful in this waterway network as well (Jenelius et al., 2006). Geurs and van Wee explore different accessibility measures for land-use and transportation strategies, as well as the inaccuracies that can arise in analyses with incomplete