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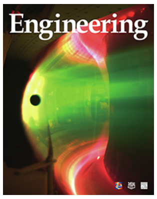

Views & Comments

Toward Systemic Thinking in Managing Environmental Risks

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1. Introduction

The world today is strongly interconnected. Numerous interdependent and complex networks have been formed between environmental, economic, and social systems, through which people, resources, materials, goods, and information are exchanged at unprecedented speeds [1]. At the same time, however, such networks are profoundly changing the global risk landscape and making the whole system more vulnerable [2]. In particular, there is a growing concern about cascading and systemic risks. In such cases, a localized initial damaging event (e.g., the coronavirus disease 2019 (COVID-19) pandemic) can spread rapidly and globally, resulting in disruptive influences and countless societal costs [3]. To control and reduce systemic risks, concerted research efforts and integrated approaches are urgently required.

In the *Global Risks Report 2021* released by the World Economy Forum (WEF), environmental risk is ranked first among the most likely and impactful risks [4]. Environmental risk mitigation, as one of the key targets of the United Nations (UN) Sustainable Development Goals, is now an important policy agenda and collective endeavor all over the world [5]. Human and environmental systems nowadays are "tele-coupled" as never before, as interactions such as trade can be driven by distant social demand, while influencing regional sustainability and causing environmental inequality and injustice [6,7]. Extreme ecological events can also destroy adaptive feedback mechanisms and lead to a breakdown of the entire economic and social system. Thus, it is fundamental to take a holistic and systemic view of environmental risk in order to uncover spillover consequences, as well as the vulnerable and blind spots hidden in these complex systems. Thus far, most of the efforts and progress that have been made in understanding systemic risks lie within the financial system; recently, however, scholars have begun to pay attention to possible systemic risks embedded within environmental problems [8]. Furthermore, while existing systemic risk frameworks are focused on the role of global environmental issues such as climate change, they fail to integrate cross-scale risks or resolve the processes of local and regional feedbacks across different systems [9].

In this opinion paper, we formulate the concept and analytic frameworks of systemic environmental risk and elaborate how environmental risks transfer within and across different systems and multiscale networks. We introduce water risks in the Yangtze River Basin (YRB), China, as a case to illustrate how to understand and manage systemic risks in a region with complex economic and environmental interactions. From the perspective of system engineering, we specify strategies that should be taken in order to cope with the challenges posed by ecological risks; we also highlight research frontiers of interest to scholars from a wide range of disciplines.

2. Complex systems and systemic environmental risks

Systemic risks are generally viewed as an emergent feature of complex systems. A complex system can be represented by a network in which the nodes characterize numerous components and the edges characterize the interactions of these components [9]. Many interdependencies in environmental, economic, and social domains can be described as complex systems, including biological systems, climate systems, traffic systems, financial systems, the Internet, and social networks [10]. Systemic risks can thus be understood as the risks of potential interdependent failures within strongly interconnected networks.

In view of the poor understanding of environmental risks and their potential consequences in complex systems and networks, we introduce here the concept of systemic environmental risks as a complementary framework to facilitate the analysis of human–environment system interactions. We define systemic environmental risks as those arising from or related to human activities that can interact with human systems by transferring through complex ecological, economic, and social networks. Unlike other systemic risks that transfer only within a single system, systemic environmental risks couple networks in both human and natural systems and can leave very long cross-system "risk footprints." In other words, environmental risks trigger instability in human systems along certain directions and can be further affected in turn by human systems' responses through feedback loops. Fig. 1 conceptually depicts the pathways through which systemic environmental risks interact with human systems. Most risks (e.g., toxic pollutants) originate from anthropogenic activities, and are particularly driven by sophisticated economic networks (e.g., industrial supply chains). Within the environmental system, risks transfer along food chains and through pollutant transformations, and exhibit various patterns of evolution. Accumulated

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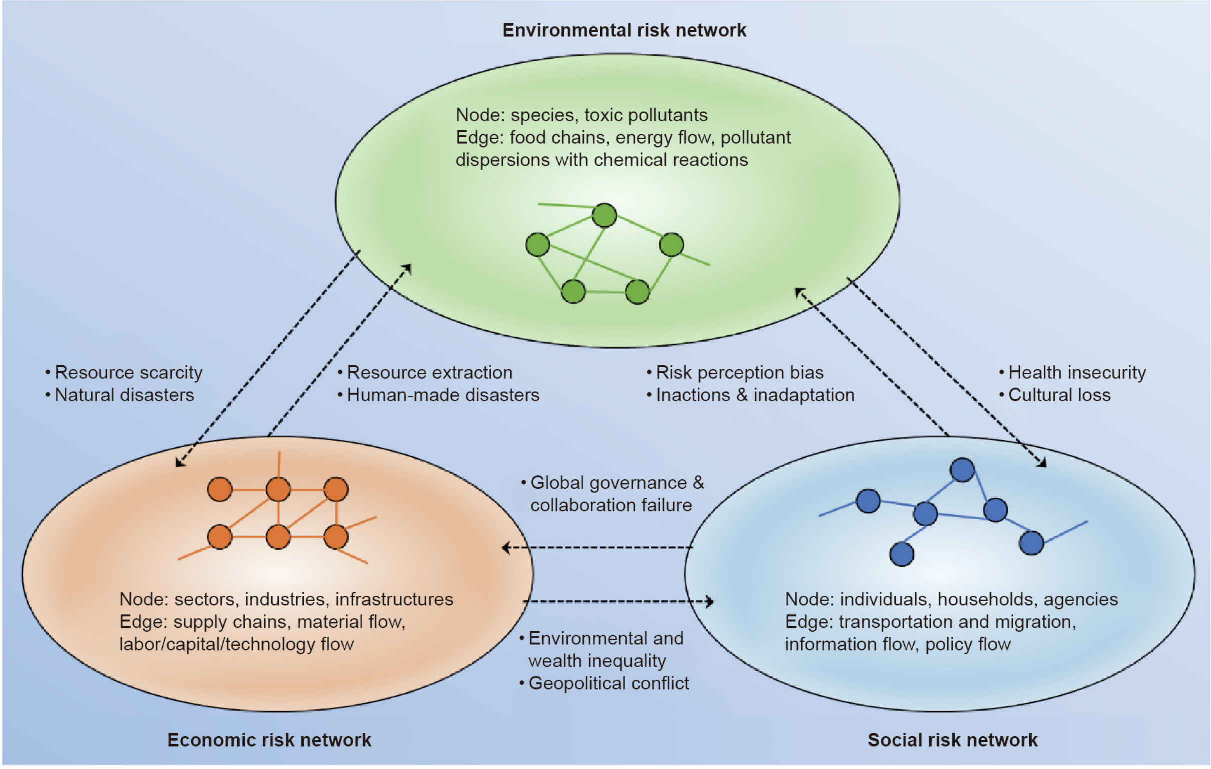

Fig. 1. Conceptual diagram of systemic environmental risk.

environmental risks then increase the scarcity of resources such as freshwater and energy, which challenges the operation of economic systems. In the meantime, individual exposure to environmental risks causes public health issues and undermines social stability. Even worse, wealth and social capital are disproportionately accumulated in the real world, and a few powerful nodes in human systems (e.g., a few countries and companies) are far more dominant in driving the network. This process will accelerate ecological and wealth inequality and collaboration failures, which will in turn exacerbate the systemic environmental risks. In the end, single system mitigation and adaptation cannot address systemic risks due to the strong lock-in effects embedded in cross-system interactions.

The concept of systemic environmental risk contains three distinguishing characteristics that make this issue difficult to manage without systemic thinking.

2.1. Interactions across different spatiotemporal scales

Systemic environmental risks occur at the local (e.g., chemical leakage), regional (e.g., land degradation, air pollution), and global scales (e.g., climate change). The spatial scale of environmental risks depends on the size of the human systems that the environment system is interacting with [11]. In addition, environmental risk evolution follows different speeds and thus has variant temporal scales. We classify systemic environmental risks into three categories, as follows: ① risks that happen in short time horizons as sudden accidents, such as explosions at a chemical plant or forest wildfires; ② risks that accumulate continuously and break out as serious events, most commonly including algal bloom and brown field; and ③ risks that pose long-term chronic threats to human systems and may induce systemic shifts, such as climate change. Human–environment interactions across dynamic spatiotemporal scales increase the difficulties of risk detection and governance.

2.2. Nonlinear mechanisms underlying risk interconnections

Systemic environmental risks follow nonlinear cause-and-effect relationships and therefore cannot be simply understood as the sum of all parts [12]. Interactions between different environment-related risks may have synergetic and spillover effects and exhibit complex phenomena. Self-organization and negative feedback effects enable a complex system to be resilient to limited disturbances; however, when accumulated nonlinear interactions reach certain tipping points, they create systemic and irreversible shifts and induce domino-like cascade consequences [13]. For example, frequent natural disasters may occur in marginalized poor regions where the risks of economic and resource disparity are already profound. Under such conditions, environmental risks may accelerate the collapse of economic networks. Because of these nonlinear relationships, it is difficult to predict risks based on individual components alone, and tipping points usually emerge unexpectedly.

2.3. Irrational human perceptions and decision-making

Humans play a central role in producing, taking, and mitigating risks. However, attempts to manage strongly coupled environmental risks can be interfered with irrational human perceptions and behaviors. First and foremost, public risk judgements are often constrained by limited perception ability. For example, humans are more wary of tangible risks that can be directly seen, such as local air pollutants, but underestimate the risks of long-term global-scale issues, such as climate change [14]. In terms of decision-making in human systems, some “win–win” collective behaviors can be destabilized by issues such as the free-riding problem (i.e., a failure that occurs when those who benefit from public goods do not pay for them) and the prisoner’s dilemma game (i.e., a failure that occurs when people rationalize their lack of contribution to public good and do not cooperate), which may finally result in the failure of global environmental risk governance.

3. Understanding systemic environmental risks: A case in the Yangtze River Basin

In this section, we introduce the water risk management in the YRB, China, as an example to illustrate the importance of understanding systemic environmental risks. The Yangtze River is the world's third longest river and has created a wide range of natural ecosystems. At the same time, the YRB is the heartland of economic and social activities in China, generating almost half of the country's gross domestic product (GDP) and feeding one-third of its total population. Unprecedented industrial expansion and urbanization have produced severe risk of water pollution; moreover, in the face of climate change, the region is also at risk of more frequent extreme weather events, such as floods.

Fig. 2 briefly illustrates the water-related ecological risks and their coupling with human economic and social systems in the YRB. Heavy water uses and wastewater discharge from agricultural and industrial sectors are the major sources of environmental pressure from the economic system. It is estimated that more than 60% of China's lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) pollution is discharged into the water body of the Yangtze River every year [15]. As the economy grows and urbanization processes proceed, the demand for water and pollution discharge will likely rise.

There are multiple seldom-investigated pathways through which environmental risks drive and amplify networked risks in economic systems. For example:

(1) Water pollution, intensive water use, and abnormal precipitation patterns caused by climate change increase the risk of water scarcity. Water scarcity risks will induce potential economic output losses in water-using sectors through a set of nonlinear economic networks, such as global supply chains, upstream and downstream trade networks, food–water–energy nexuses, and so forth [16,17].

(2) Climate change and increasing extreme weather risks damage public infrastructures and private properties, causing direct economic losses and destroying upstream supply chains. These environmental risks often occur at the local level, aggregate at the regional level, and exhibit heterogeneity across sectors and regions due to these areas' different resilience capacities [18].

Meanwhile, there are poorly understood water risks in the YRB that are associated with social behaviors and inequality:

(1) Water pollution and water disasters are related to many acute or chronic health risks, including digestive cancers and epidemic diseases [19]. Disproportionate public health resources may exacerbate regional inequalities and create numerous overlooked risk hotspots.

(2) Water risk is also an important driver of wealth disparity and migration. The imbalanced economic impacts of water risks increase the wealth gap and direct more social capital and labor resources to urban areas and developed coastal regions.

Potential risks of governance failure are worth watching for when managing water risks. The YRB stretches over 19 provinces and municipalities. Local governments play a leading role in managing environmental risks, but their decision-making is based on tradeoffs among economic and environmental targets. Moreover, because the governance and ecological system boundaries are always misaligned, the risk of cooperation breakdowns between local governments is high [20]. Taken together, these factors may lead to governance failure, amplify the impacts of water risks on sustainable economic growth and social stability, and gradually result in the formation of a closed loop, making it more difficult to address these issues.

4. Dealing with systemic environmental risks

Controlling systemic environmental risks requires systemic strategies. State-of-the-art risk management has a number of shortcomings that result in a failure to address risk interconnections across human–environment systems:

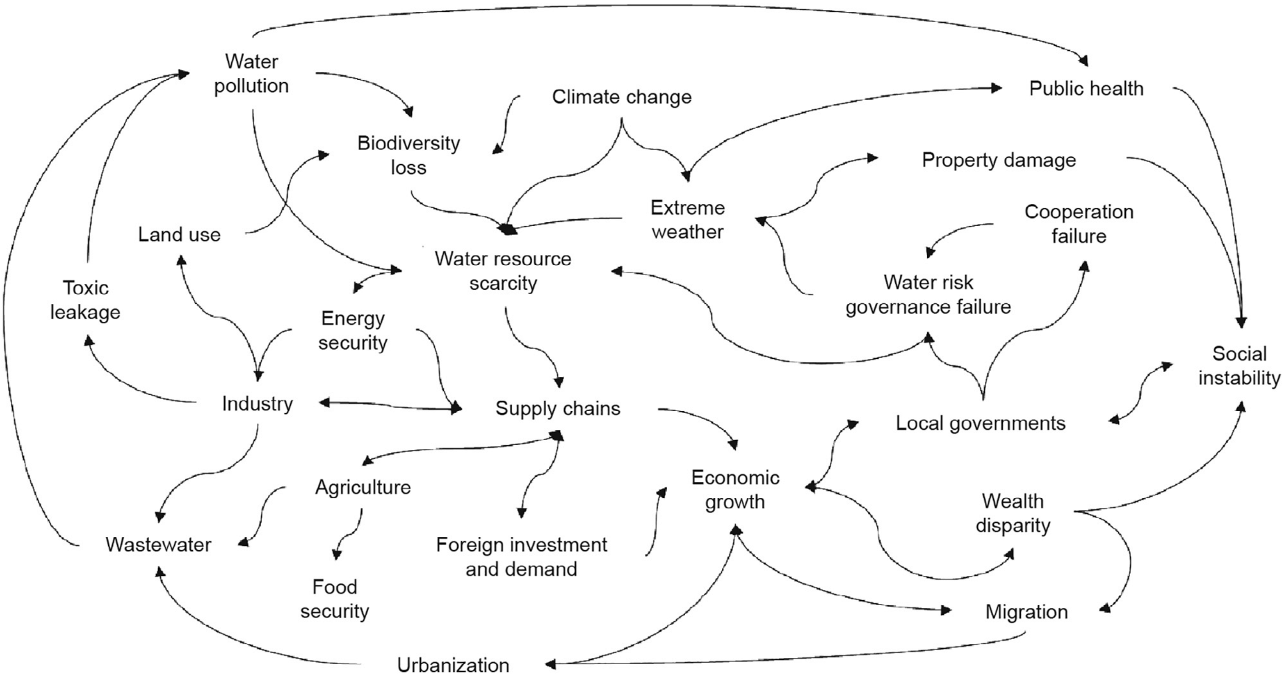

Fig. 2. Diagram of systemic environmental risks in the Yangtze River Basin.

(1) **Lack of attention to the social, political, and economic factors that drive environmental risks.** For example, the current environmental health risk analysis paradigm mainly relies on a four-step process that includes hazard identification, dose–response assessment, exposure assessment, and risk characterizations. Most efforts to eliminate risks are exerted to prevent the risk from spreading among environmental media and to reduce human exposure. The original imbalanced structure of the social and economic networks that drive environmental risk transfers and shape the landscape of inequality is seldom investigated.

(2) **Failure to integrate feedback loops into risk modeling.** Typical fault tree and event tree analysis is a top–down technique used to identify risky nodes and assess failure probabilities. These methods cannot handle risks in feedback loops. For example, human activities alter the climate and are in turn influenced by climatic warming, which may further amplify anthropogenic contributions to climate change [21].

(3) **Underestimation of the likelihood of rare extreme events and human-system surprising behaviors.** Mainstream economics are based on the equilibrium paradigm and assume that the system will make optimal decisions and evolve toward a stable state. The probability of the occurrence of rare events is not sufficiently analyzed. The most typical example of an insufficiently analyzed risk is the Natural Hazards Triggering Technological Disasters ("Natech") risk [22], which is exemplified by the Fukushima nuclear accident in 2011 and the subsequent social nuclear panic.

Below, we recommend a series of approaches that tackle environmental risks as a systemic problem.

4.1. Shift toward systemic environmental risk assessment and whole-process management

Given the abovementioned gaps, instead of focusing on an analysis of single environmental risk factors, there is an urgent need to carry out cross-system risk assessment and shift toward whole-process management. First and foremost, the current linear environmental risk chain analysis paradigm should be transformed into a paradigm based on circular feedback loop analysis. Social and economic networks should be added to the framework, and their roles as the drivers and amplifiers of environmental risks should be investigated simultaneously with the environmental risks themselves. In addition to modeling cumulative environmental risk evolutions before they reach their tipping points, it is important to simulate risk network shifts when rare "black swan" events (i.e., unexpected events with major repercussions) occur and design corresponding emergency plans.

4.2. Establish priorities for systemic environmental risks and identify urgent management needs

Given the broad spectrum of systemic environmental risks and the limited management resources, a meaningful practice is to establish a priority list for management and identify the key nodes that should be regulated in advance. Related nodes include high-risk processing chains, resource-intensive sectors, and powerful social agents. Building a priority list must involve a large set of quantitative data, and a ranking criteria should be developed based on likelihood and impacts. Qualitative data such as experts' opinions is also helpful in this process and may sometimes be more insightful than the massive amounts of quantitative data collected from different systems. For example, the annual Global Risks Perception Survey conducted by the WEF is based on consultation with a panel of 650 experts from broad communities [4]. Moreover, since environmental risk priorities and goals will change with socioeconomic development, and as there are an increasing number of emerging risks, such a ranking exercise should be conducted periodically and dynamically in order to detect new challenges.

4.3. Promote resilience by integrating engineering projects, marketing tools, and civic engagement

Resilience determines how vulnerable the coupling human–environment networks are to systemic environmental risks. There are several principles that should be obeyed in order to promote systemic resilience. For example, backup systems should be designed to increase error tolerance and decentralize network couplings, so that risks are widely dispersed and diluted. In practice, promoting resilience against systemic environmental risks should involve toolkits from different systems. Engineering projects such as ecosystem restoration and risk inspections in industrial parks are the most direct measures to mitigate environmental risks and increase risk adaptability. Green financial tools such as liability insurance from the economic system are useful to keep the economy resilient when faced with disruptive environmental risks. Last but not least, integrating multilateral institutions and civil society is critical for early risk detection to compare the tradeoffs required by different stakeholders.

Preventing and defusing major risks has been set up as one of the most important national-level strategies in China in order to ensure social security and sustainable development. The government has also initiated plans to achieve carbon neutrality by 2060 and boost a new green economy. To ensure ecological safety and upgrade the economy in a networked era, it is crucial for decision-makers to evaluate and control environmental risks in a systemic way and realize the necessity of joint efforts from multiple systems. Successful practices and experience in managing systemic environmental risks will also inform global efforts and coordination for tackling large-scale ecological crises.

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