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New model examines the effects of toxicants on organism populations in polluted rivers

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When designing environmental policies to limit the damage of river pollution, it is paramount to assess the specific risks that particular pollutants pose to different species. However, rigorously testing the effects of toxicants—like insecticides, plastic debris, pathogens, and chemicals—on entire groups of organisms without severely damaging their whole ecosystems is simply not feasible. Mathematical modeling can provide a flexible way to assess toxicants' impact on river populations without endangering the environment.

In a paper that published today in the *SIAM Journal on Applied Mathematics*, Peng Zhou (Shanghai Normal University) and Qihua Huang (Southwest University, Chongqing) develop a model that describes the interactions between a population and a toxicant in an advective environment—a setting in which a fluid tends to transport material in one direction, like a river. Such a model can help scientists study how the way in which a pollutant moves through a river affects the well-being and distribution of the river's inhabitants.

Much of the previous experimental research on the ecological risks of toxicants has been performed on individual organisms in controlled laboratory conditions over a fairly short-term basis. The design of environmental management strategies, however, requires an understanding of toxicants' impact on the health of entire exposed natural populations in the long term. Fortunately, there is an intermediary. "Mathematical models play a crucial role in translating individual responses to population-level impacts," Huang said.

The existing models that describe the way in which toxicants affect population dynamics generally ignore many of the properties of water bodies. But in doing so, they are missing a big piece of the puzzle. "In reality, numerous hydrological and physical characteristics of water bodies can have a substantial impact on the concentration and distribution of a toxicant," Huang said. "[For example], once a toxicant is released into a river, several dispersal mechanisms—such as diffusion and transport—are present that may aid in the spread of the toxicant."

Similarly, the models that mathematicians often use to portray the transport of pollutants through a river also do not include all of the necessary components for this study. These are reaction-advection-diffusion equation models, whose solutions can show how pollutants distribute and vary under different influences like changes in the rate of water flow. While such models enable researchers to predict the evolution of toxicant concentrations and assess their impact on the environment, they do not consider toxicant influence on the dynamics of affected populations. Zhou and Huang thus expanded upon this type of model, adding new elements that allowed them to explore the interaction between a toxicant and a population in a polluted river.

The authors' model consists of two reaction-diffusion-advection equations—one that governs the population's dispersal and growth under the toxicant's influence, and another that describes the processes that the toxicant experiences. "As far as we know, our model represents the first effort to model the population-toxicant interactions in an advective environment by using reaction-diffusion-advection equations," Zhou said. "This new model could potentially open a [novel] line of research."

The model allows Zhou and Huang to tweak different factors and investigate the resulting changes to the ecosystem. They tried altering the river's flow speed and the advection rate—i.e., the rate at which the toxicant or organisms are carried downstream—and observing these parameters' influence on the population persistence and distribution of both the population and toxicant. These theoretical results can provide insights that could help inform ecological policies when taken in concert with other information.

One scenario that the researchers studied involved a toxicant that had a much slower advection rate than the population and thus was not washed away as easily. The model showed that intuitively, the population density decreases with increasing water flow because more individuals are carried downstream and out of the river area in question. However, the concentration of the toxicant increases with the increasing flow speed because it can resist the downstream current and the organisms are often swept away before they can uptake it.

In the opposite case, the toxicant has a faster advection rate and is therefore much more sensitive to water flow speed than the population. Increasing the water flow then reduces the toxicant concentration by sweeping the pollutants away. For a medium flow speed, the highest population density occurs downstream because the water flow plays a trade-off role; it transports more toxicants away but also carries more individuals downstream.

This demonstrates that a higher sensitivity of a pollutant to water flow is generally more advantageous to population persistence. "In the absence of toxicants, it is generally known that the higher the flow speed, the more individuals will be washed out of the river," Zhou said. "However, our findings suggest that for a given toxicant level, population abundance may increase as flow rate increases."

By providing this model with the parameters for certain species and pollutants, one may be able to determine criteria regarding the water quality that is necessary to maintain aquatic life. This outcome could ultimately aid in the development of policy guidelines surrounding the target species and toxicants. "The findings here offer the basis for effective decision-making tools for water and environment managers," Huang said. Managers could connect the results from the model with other factors, such as what may happen to the pollutant after it washes downstream.

Further extensions to Zhou and Huang's new model could make it even more applicable to real river ecosystems—for example, by allowing the flow velocity and release of toxicants to vary over time, or accounting for the different ways in which separate species may respond to the same pollutant. This mathematical model's capability to find the population -level effects of toxicants might play a critical part in the accurate assessment of pollutants' risk to rivers and their inhabitants.

More information: Peng Zhou et al, A Spatiotemporal Model for the Effects of Toxicants on Populations in a Polluted River, *SIAM Journal on Applied Mathematics* (2022). DOI: 10.1137/21M1405629

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