26th International Congress on Modelling and Simulation, Adelaide, SA, Australia, 30 Nov–4 Dec 2025
mssanz.org.au/modsim2025

An integrated PMP-ABM model of adaptive enforcement and behavioral spillover

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Abstract: Coupling economic optimization and behavioral models is critical to understanding how agents (farmers) respond to water scarcity, policy enforcement, and social dynamics and nonlinear changes. This study presents a novel hybrid framework that couples Positive Mathematical Programming (PMP) with Agent-Based Modeling (ABM) to simulate illegal water use decisions under uncertainty, peer influence, and evolving enforcement pressure. While the PMP model ensures economic realism by calibrating profit-maximizing land and water allocation based on observed data, the ABM layer introduces bounded rationality, non-compliance behaviors, dynamic risk perception, peer imitation, and learning mechanisms.

The core innovation of this approach lies in its dynamic coupling: economic shocks, such as profit loss due to reduced water allocations, trigger behavioral responses in the ABM layer, where agents decide whether to engage in water theft. These decisions are shaped by their perceived risk of detection, which evolves over time as agents learn from personal detection experiences and from their peers' outcomes. The risk perception updates follow a reinforcement learning rule that includes memory decay, enabling agents to 'forget' past enforcement if not recently reinforced. Social contagion also plays a role: higher theft among peers may reduce deterrence, while higher detection may increase it.

Uncertainty is explicitly modeled in two key dimensions. First, water availability is subject to stochastic reductions each simulation year, representing droughts, climatic shocks, or policy constraints. Second, enforcement uncertainty is introduced through probabilistic detection events for agents who steal water, simulating the limitations of real-world monitoring. These combined uncertainties create a rich feedback environment where rational planning and adaptive behavior interact.

The simulation replicates multiple years of decision-making across heterogeneous agents with varying land and crop profiles. Results show that in the early years, low enforcement and high opportunity can lead to an increase in theft. However, as target detections accumulate and the perceived risk of detection spreads through the agent population, non-compliance rates tend to decrease when the probability of detection is high. Conversely, non-compliance may persist or even increase when the probability of detection remains very low. Land use and profit trajectories differ markedly between scenarios with and without behavioral coupling, demonstrating the importance of integrating human dynamics into socio-ecological models. This PMP–ABM hybrid framework offers a tool for policy analysis. It allows researchers and decision-makers to explore how enforcement design, detection probability, and behavioral feedback affect long-term compliance. It also highlights how water governance must consider both economic incentives and evolving human responses to uncertainty and enforcement. The approach has broad applicability to other contexts of natural resource management where rule-breaking, peer effects, and adaptive behavior are present.

Keywords: *Model coupling, Water theft, Agent-based modeling, Positive mathematical programming, Adaptive enforcement*