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Social dilemmas and poor water quality in private water systems

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Abstract. Private water supply systems consisting of a domestic well and septic system are used throughout the world where households lack access to public water supply and sewers. In residential areas with high housing density, septic contamination of private wells is common and associated with multiple health concerns. This situation can give rise to social dilemmas, where individual costs dis-incentivize homeowners from investing in enhanced septic systems that would reduce well contamination and bring communal benefits. We combine a stylized game-theoretical model with a probabilistic groundwater model to characterize how economic and hydrogeological conditions interact to produce misaligned incentives conducive to social dilemmas. The occurrence of social dilemmas depends on the relative costs of well contamination versus the cost of installing an enhanced septic treatment system, and the relative probabilities of cross-contamination versus self-contamination. The game reveals three three types of social dilemmas that occur in such systems, with each calling for distinct policy solutions. We demonstrate how the model can be applied to existing systems using a case study of St Joseph County, Indiana, where high nitrate contamination rates have raised public health concerns. This analysis represents a step towards identifying alternative policy solutions for a problem that has remained difficult to address for decades.

1 Introduction

Groundwater plays a critical role in supporting social and ecological systems throughout the world (Gleeson and Richter, 2018). Groundwater provides over 50% of urban water supply (Zektser and Everett, 2004) and 40% of water for irrigation (Siebert et al., 2010). Protecting the groundwater commons has become increasingly important and challenging as aquifers deplete and become contaminated (Gleeson et al., 2020; Hartmann et al., 2021). Indeed, contamination has become prevalent in groundwater systems throughout the world (Charalambous, 2020). In many cases, regulatory frameworks struggle to provide effective preventative measures and the challenge of groundwater protection transforms into a problem of groundwater remediation (Nieto et al., 2005; Hou et al., 2018). Fundamental to the challenge of groundwater protection is the issue of environmental externalities, where the polluter gains some benefit from inadequate (or faulty) treatment prior to water being discharged or leaked to the subsurface (Hellegers et al., 2001). Although this problem arises in a variety of industrial and agricultural settings, groundwater systems that supply residential communities can also be compromised by inadequate private water systems (Withers et al., 2014).

Private water systems consisting of a domestic well and septic system are common throughout the world in areas without piped supply and sewers. In the United States, approximately 13% of the population relies on water supply from a private

domestic well (Dieter et al., 2018, also see Fig. 1) and 25% of households discharge wastewater through a septic system (US EPA, 2005a). Although the installation of septic systems is generally governed by a combination of guidelines from state and local governments (Thomassey and Dutcher, 2017), over half of septic systems were installed at least 30 years ago and up to 20% are malfunctioning with potentially more underperforming (US EPA, 2005a). Domestic wells are unregulated and the responsibility for maintaining water quality is left to each individual household (Bowen et al., 2019). Private water systems are at a relatively high risk of contamination from a variety of sources, and water quality in private systems often fails to match water quality in highly-regulated public water supply systems (Focazio et al., 2006; DeSimone et al., 2009). Surveys indicate that 2-14% of private wells are contaminated with nitrates (Hoppe et al., 2011), but this can rise considerably higher in locations with high housing density (Yates, 1985; Bremer and Harter, 2012).

Septic tanks represent one of the major threats to water quality in domestic wells and the high concentration of contaminants in septic leachate creates a variety health concerns (US EPA, 2005b; Katz et al., 2011). Septic contamination has been associated with endemic diarrheal illness in Wisconsin (Borchardt et al., 2003), viral discharge and transport exceeding typical well-drainfield setback distances (DeBorde et al., 1998), and multiple disease outbreaks in the United States and Canada (Craun et al., 1994; Beller et al., 1997). In addition to pathogens, septic systems also discharge high levels of nitrates, which can cause acute health problems in infants (Knobeloch et al., 2000), and other emerging contaminants such as PFAS, flame retardants, and endocrine disruptors (Schaider et al., 2016), which also present long-term exposure risks (Bergman et al., 2013).

The issue of septic contamination has been widely recognized for at least half a century (Yates, 1985). While technological solutions (e.g., reverse osmosis) are available to treat water from contaminated wells, due to high costs such systems are often
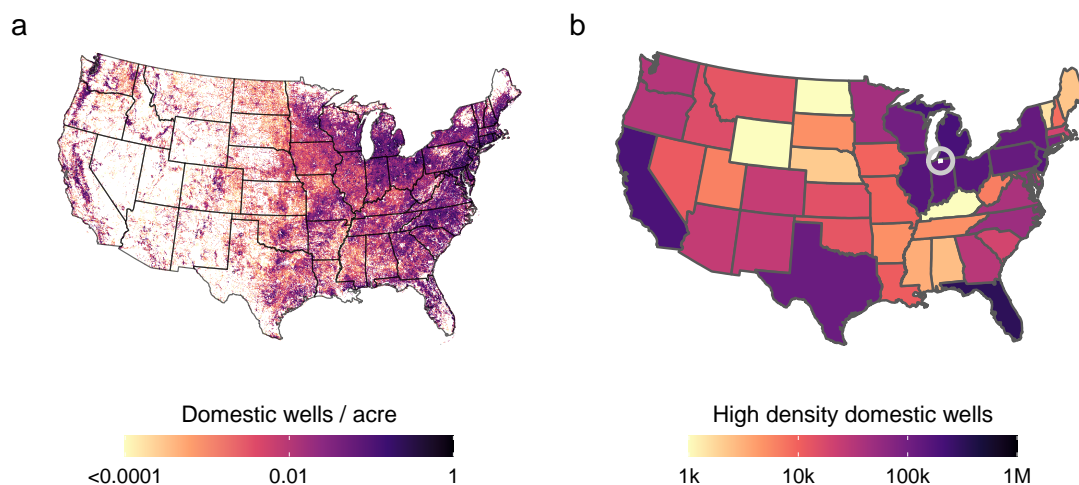

Figure 1. Concentration of households with domestic wells in the contiguous United States. (a) Gridded (1 km) density of wells. (b) Total number of high density wells by state, defined as wells (in 1 km pixels) where the average density is at least 1 per acre. Data are from Johnson et al. (2019). The location of the case study (Sect. 4) is marked inside the gray circle.

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45 limited to wealthier households and only implemented at select points of consumption (e.g., kitchen sinks), leaving potential
contamination pathways open through other water points. Furthermore, a well contaminated with nitrate pollution can reduce
the value of a home by up to 6% (Guignet et al., 2016). Additional options exist to remove contaminants at the source. For
instance, traditional septic systems are designed to mitigate the effect of pathogens, and advanced septic systems can remove
nitrates from septic leachate (Washington State Department of Health, 2005). However, the uncertainty of groundwater flow,
50 combined with the lay knowledge of most homeowners, means that residents often have little clarity about the source of
contamination of their own well. Given that contamination could originate from a neighboring well, homeowners may lack
incentives to maintain or upgrade their septic system even if doing so would decrease pollution risk for all residents. This
discrepancy means that the best choice for each individual household may be in conflict with the best choice for the community
as a whole. Such scenarios are known as social dilemmas because the solution that maximizes the welfare of the community
55 does not correspond to outcomes that arise from individual community members acting rationally and independently (Kollock,
1998).

The management challenge pertaining to private water systems has focused primarily on understanding the water quality,
public health, and technical aspects of these systems. These analyses are directly related to questions of the severity of the
problem and the extent to which such systems should be regulated. Here, we re-frame the problem from the perspective of
60 household utility, with the goal of identifying when households may benefit from policy instruments to support solutions
that maximize collective welfare. To address this challenges, we develop a game theoretic model to understand how social
dilemmas might arise in private water systems. Framing pollution and treatment behavior through game theory has been done
in a variety of case studies (Madani, 2010). However, most game theoretic models of water quality focus predominantly on
surface water quality (Šauer et al., 2003; Schreider et al., 2007; Estalaki et al., 2015) and we are unaware of any studies that
65 apply game theory to water quality in private water systems with a domestic well and septic field. In order to frame the problem
in quantitative terms, we consider the net utility, including the costs and benefits of water protection (as identified by Raucher,
1983; Crocker et al., 1991), and the perceived economic value of clean groundwater (Caudill and Hoehn, 1992; Brouwer and
Neverre, 2020; Charalambous, 2020).

We proceed to develop theory regarding social dilemmas in communities with predominantly private water systems. We be-
70 gin by focusing on two-household scenarios to capture different social dilemmas that could occur in such simple configurations
(Sect. 2) and how player preferences depend on the cost of septic treatment as well as the cost of contaminated well water.
We then build on this framework to understand how social dilemmas arise in N-player games with varying housing density
(Sect. 3). In order to evaluate the potential for social dilemmas in a real-world scenario, we apply the model to a case study
in St. Joseph County, Indiana (Sect. 4) where nitrate contamination in private water systems has been an ongoing concern for
75 the county health department. Finally, we review the different types of social dilemmas that may occur in such private water
systems, along with a discussion of barriers and policy opportunities to support effective management strategies (Sect. 5).

2 Two-household contamination games

2.1 Expected utility and payout matrices

We first consider a two-player static game with complete information, wherein the payout structure of both players is common
80 knowledge. Each player chooses whether to upgrade their septic to an enhanced system with contaminant removal (E) at some
cost, or to keep a basic septic system (B) at no cost. The cost of upgrading, C_σ, represents the difference between the enhanced
septic system and the cost for a conventional system (e.g., as mandated by local regulations). If a player's well becomes
contaminated, that player also incurs a cost, C_x. The expected utility of an individual household i is therefore

$$\mathbb{E}[U_i] = -\sigma_i C_\sigma - p_i C_x, \tag{1}$$

85 where $\sigma_i \in \{0,1\}$ represents the choice of each household to maintain a basic septic system (0) or upgrade to an enhanced
system (1). The probability p_i describes the likelihood of contamination of player i's well, which depends on the septic system
decisions made by *both* players (σ_i and σ_j) and on the groundwater flow direction. Lastly, the cost of contamination, C_x,
can either represent the individual cost of household water treatment to improve household water quality (which represents
a lower bound on the cost, Yadav and Wall, 1998), or the cost of using contaminated water and associated consequences
90 (Raucher, 1983). Note that no player would benefit from upgrading their system if doing so was more expensive the cost of
contamination. To avoid this trivial outcome, we consider only situations with C_x larger than C_σ. We evaluate this requirement
and explore associated costs of nitrate contamination in greater detail in Sect. 4.

Because Eq. (1) depends on binary decisions taken by two interacting players, its outcomes can be represented as a 2×2
matrix. The rows and columns of the matrix represent the decision by players 1 and 2, respectively, on whether or not to
95 upgrade. Each cell of the matrix is populated by a pair of normalized payouts representing the expected utility of each player
for each combination of decisions. Payouts from Eq. (1) are normalized so that the summed total payout across players for
each cell ranges between 0 and 2. Two types of matrix cells are particularly noteworthy:

- The Nash Equilibrium (NE) represents each player's best (i.e., utility maximizing) response to the other player's own
utility-maximizing decision.

100 - The Social Optimum (SO) represent the combination of decision that maximizes the summed expected utility of both
players.

Whether or not the NE and SO decision outcomes overlap depends on the ratio of costs (i.e., the "cost ratio", C_x/C_σ) and the
groundwater configuration between households. We define a social dilemma as a situation where the SO outcome is different
from at least one NE outcome. We proceed to enumerate the different configurations of NE and SO in the 2×2 games that
105 emerge from Eq. (1) for symmetric cases (Sect. 2.2), and in the situation where the two players face different and uncertain
costs (Sect. 2.3). In both situations, we identify and characterize emerging social dilemmas.

2.2 Symmetric two-player games

If both players face identical costs (C_x and C_σ) and contamination by (and of) each player is symmetric, four different game configurations emerge depending on the spatial configuration of the two players (Fig. 2). If neither player contaminates their

110 own well or that of the other player, neither player wishes to upgrade to an enhanced septic system and the Nash Equilibrium is identical to the Social Optimum (Fig. 2a). When both players contaminate only their own wells, they are both incentivized to upgrade their septic system and the Nash Equilibrium and Social Optimum solutions are again identical (Fig. 2b).

A social dilemma only occurs when each player's decision affects water quality in the other player's well. In the case where both players only contaminate the other player's well without contaminating their own well (Fig. 2c), the best response for

115 each player would be *not* to upgrade, regardless of the decision of the other player. While neither player has anything to gain from paying to upgrade their own septic, both players would benefit if the other player upgrades. This leads to a classic Prisoner's dilemma (see Kollock, 1998) where neither player upgrades, despite the fact that a situation where both players upgrading would improve their utility and is the social optimal outcome. The final situation, where players contaminate both their own and the other players' well (Fig. 2d) gives rise to a second Nash Equilibrium where both players upgrade. In this

120 case, upgrading is the best response for each player when the other player also decides to upgrade. However, *not* upgrading will be the best response for each player if the other player decides not to upgrade. By upgrading in the latter case, the player would pay the full cost of upgrading while still being contaminated by the other player's septic system. Under these conditions, the benefits of upgrading are contingent on the other player doing the same (Fig. 2d). This scenario is known as a Stag-hunt game, where players face conflict between individual safety and social cooperation (Kollock, 1998). In the canonical Stag-Hunt

125 game, two hunters independently decide whether to hunt a stag or a hare. A hare can be hunted by an individual hunter, while an individual player deciding to hunt a stag will fail. The much more valuable stag can only be successfully hunted if both hunters decide to hunt it. The game has two Nash Equilibria, where either both players hunt the stag or both players hunt the hare. The second Nash Equilibrium (which, here, corresponds to a situation where neither household updates their septic) is *not* a Social Optimum and therefore creates a social dilemma.

130 2.3 Uncertainty and asymmetry in groundwater behavior

In addition to these symmetric games with complete information, households may have uncertainty with respect to groundwater behavior. We consider five different configurations of households (Fig. 3, I-V) and allow groundwater to flow west, east, or north, with corresponding probability $P(West)$, $P(East)$, and $P(North)$. Allowing flow towards the south would produce identical game structures as flow towards the north, and we exclude this unnecessary possibility. The expected util-

135 ity can be calculated as the weighted average utility from the end-member scenarios. For instance, consider scenario II in Fig. 3. If $P(West) = 0.4$, $P(East) = 0$, $P(North) = 0.6$, and neither player upgrades their septic system, the expected utility for each player would be $0.4C_x$. Considering all combinations of household configurations and flow probabilities (i.e., with $P(North), P(West), P(East) \in \{0, 0.2, 0.6, 0.6, 0.8, 1\}$), this approach generates three types of social dilemmas (Fig. 3, right): the aforementioned Prisoner's Dilemma (PD) and Stag-Hunt game (SH), and an additional situation that we refer to as
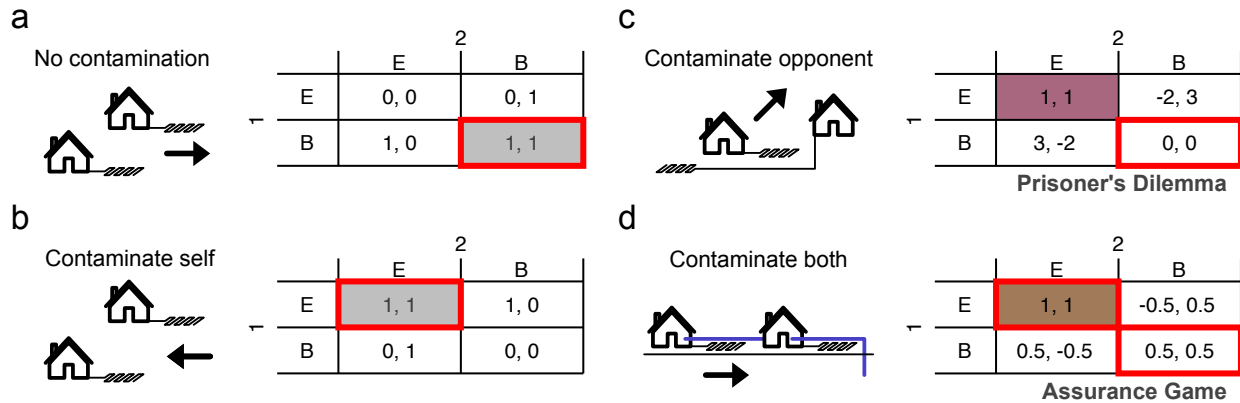
Figure 2. Payouts and social dilemmas in symmetric games. In each scenario, the choice to keep a basic septic system results in (a) no contamination, (b) self-contamination, (c) contamination of the other player, and (d) contamination of both players. Payouts represent the situation where $C_x = 1.5C_\sigma$. Utility is normalized so that the social optimal scenario produces an average payout of 1, and the joint worst scenario produces an average payout of 0. Arrows indicate direction of groundwater flow. For scenarios (a) and (b) the Nash equilibrium (red outline) and social optimal (gray shading) are equivalent. A social dilemma arises for scenarios (c) and (d), as there exists a difference between (at least one) Nash equilibrium and the social optimum (red for Prisoner's dilemma and orange for Stag-Hunt).

an Asymmetric Dilemma (AD). In the latter dilemma, the social optimum differs from the Nash equilibrium which exhibits asymmetric payouts favoring one player over the other.

To better understand how asymmetric dilemmas arise, consider configuration I as an example, where $P(West) = 0.2$, $P(East) = 0.8$, and $P(North) = 0$ (i.e., marked by the $+$, $\circ$, and $\times$ in Fig. 3, I). If neither player upgrades, the player on the left faces low *expected* cost of contamination due to the low probability of flow to the west, whereas the player on the right faces a high expected cost of contamination due high probability of flow to the east. This creates an asymmetric dilemma where the left household chooses not to upgrade in the Nash equilibrium, but would need to upgrade to reduce costs for the other player and achieve the Social Optimum. Multiple types of Asymmetric Dilemmas exist. In AD-i, one player upgrades in the Nash equilibrium because they have a high risk of self-contamination. However the social optimum requires that the second player upgrade because both have a modest risk of contamination from this player. In this situation the Nash equilibrium is (E, B) or (B, E) and the social optimum is (E, E). In AD-ii, neither player faces a high risk of self-contamination, but one player faces a high risk of contamination from the other player. The Nash is (B, B) and the social optimal is (E, B) or (B, E). Similarly in AD-iii, neither player has a high risk of self-contamination. However, the combined risk of contamination from either player means that both players must upgrade to achieve the Social Optimum. In this situation, the Nash is (B, B), and the social optimum is (E, E).

Generally, there tends to be greater likelihood of a social dilemma if the relative risk of contamination is high. This can arise if the cost of contamination is high compared to the cost of upgrading (i.e. $C_x >> C_\sigma$, Fig. 3, right) or if the probability of contaminating the other player is high compared to the probability of self-contamination. Conversely, a high probability of
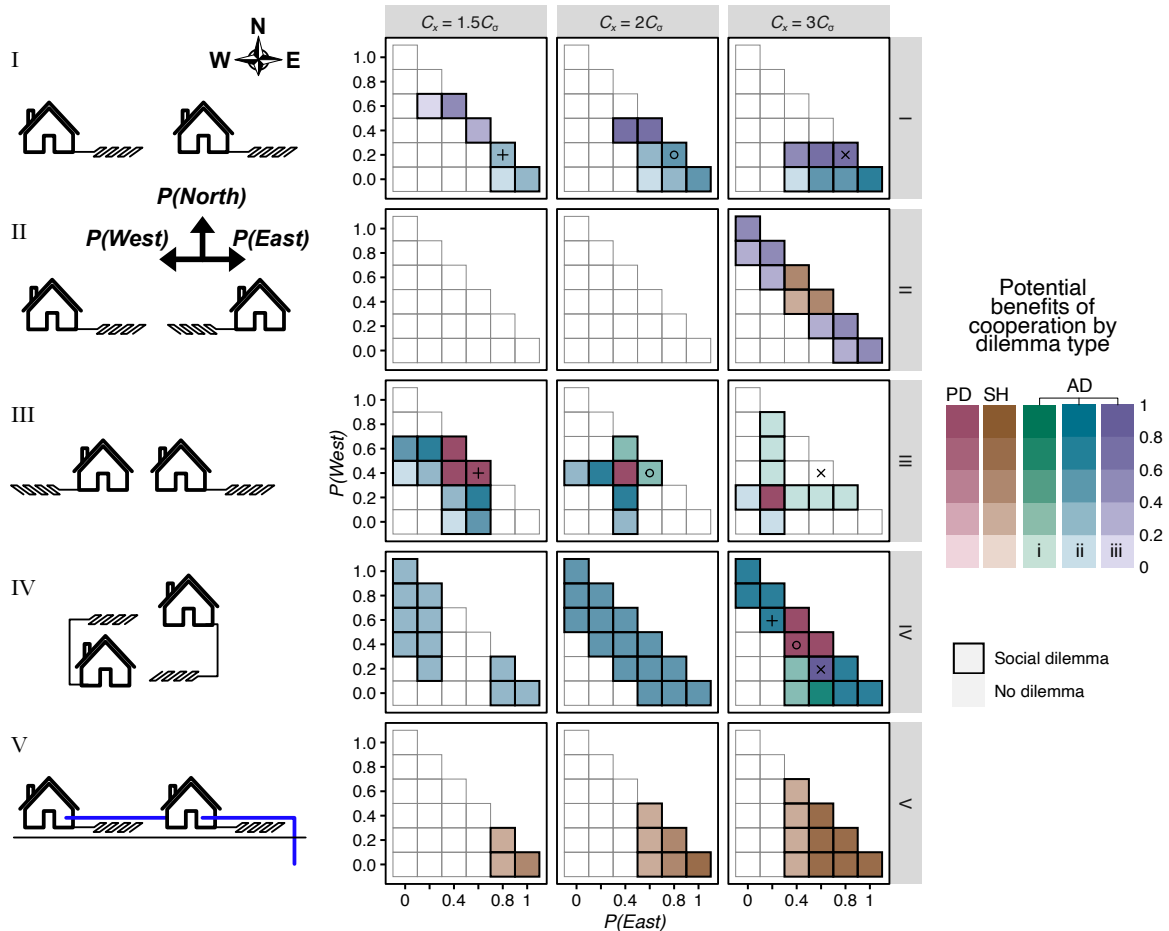
Figure 3. Social dilemmas under various household configurations and various cost ratios. (left) Household configurations I-V, with uncertainty about the mean direction of groundwater flow. (right) Social dilemma types Prisoner's Dilemma (PD), Stag-Hunt game (SH), and Asymmetric Dilemma (AD) along with the potential benefits of cooperation, given as the difference in normalized payouts between the social optimal and the (least desirable) Nash equilibrium, averaged for both players. The main axes represent the probability of flow towards the west and east, respectively, with the remainder being the probability of flow towards the north (i.e., $P(North) = 1 - P(West) - P(East)$).

self-contamination circumvents social dilemmas by incentivizing the contaminating household to upgrade, as seen in scenario I ($P(West) \rightarrow 1$) and III ($P(West) \rightarrow 1$ or $P(East) \rightarrow 1$).

Changing costs (either C_x or C_σ) lead to transitions across different types of social dilemmas, indicated by the symbols +, ∘, × in Fig. 3, with payouts shown in Fig. 4. For instance in configuration I, the social dilemma changes from AD-ii with $C_x = 2C_\sigma$ (∘) to AD-iii with $C_x = 3C_\sigma$ (×) (Fig. 4a). Conversely, in configuration III, the social dilemma changes from a Prisoner's Dilemma with $C_x = 1.5C_\sigma$ (+) to AD-i with $C_x = 2C_\sigma$ (∘) to no dilemma with $C_x = 3C_\sigma$ (×) (Fig. 4b).
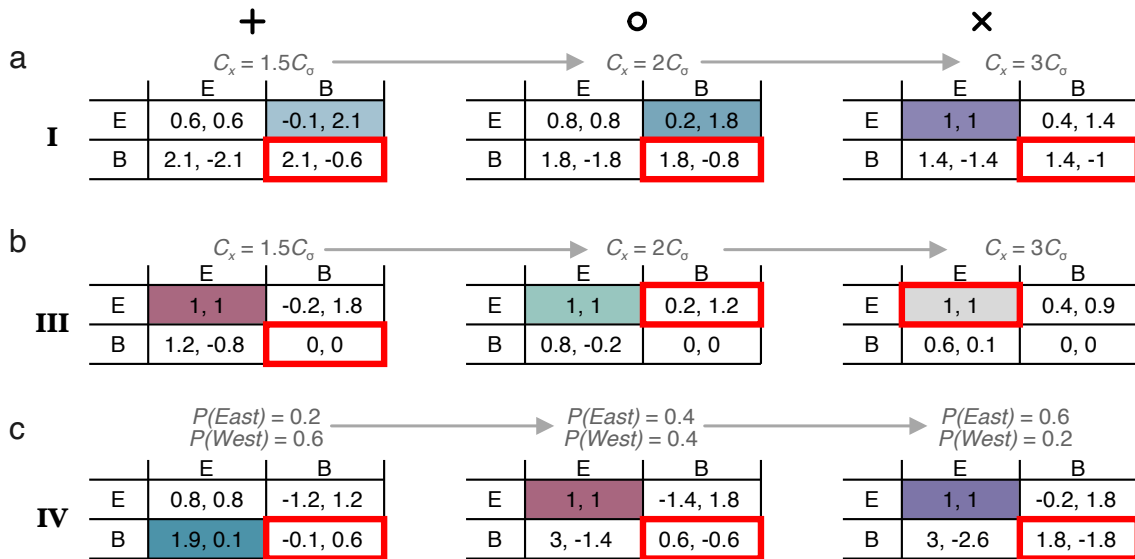
Figure 4. Transitions among social dilemmas by changing the cost ratio and the probability of groundwater flow direction. Each scenario corresponds to the configuration (I, III, IV) and parameters (+, ○, ×) presented in Fig. 3. (a) Household configuration I with $P(West) = 0.2$, $P(East) = 0.8$, and multiple cost ratios including $C_x = 1.5C_\sigma$ (AD-ii), $C_x = 2C_\sigma$ (AD-ii), and $C_x = 3C_\sigma$ (AD-iii). (b) Household configuration III with $P(West) = 0.4$, $P(East) = 0.6$, and cost ratios including $C_x = 1.5C_\sigma$ (Prisoner's Dilemma), $C_x = 2C_\sigma$ (AD-i), and $C_x = 3C_\sigma$ (no dilemma). (c) Household configuration IV with $P(West) = 0.2$, $C_x = 3C_\sigma$, and multiple probabilities flow direction including $P(East) = 0.2$, $P(West) = 0.6$ (AD-ii), $P(East) = 0.4$, $P(West) = 0.4$ (Prisoner's Dilemma), and $P(East) = 0.6$, $P(West) = 0.2$ (AD-iii).

Changes in the uncertainty associated with groundwater behavior can also lead to transitions across different types of social dilemmas. In particular, in configuration IV with $C_x = 3C_\sigma$, the social dilemma changes from AD-ii with $P(East) = 0.2$ (+) to PD with $P(East) = 0.4$ (○) to AD-iii with $P(East) = 0.6$ (×) (Fig. 4c). These dynamics have practical implications because each type of dilemma (PD, SH, and AD) is associated with a distinct set of appropriate policy responses, as discussed in Sect. 5.

3 A general N-player game and groundwater model

3.1 Social dilemmas in the symmetric game

The two-by-two games described above demonstrate the variety of social dilemmas that can exist within groundwater contamination games. We now translate the game to an N-player system in which each player faces the same decision (σ_i) and costs (C_x and C_σ) as above, while also generating a more plausible representation of groundwater behavior and probabilities of contamination.

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175   Consider the binary random variable X_i to denote the event that player i has their well contaminated. In this version of the game, the associated probability $p_i = P(X_i)$ is the union of probabilities that the well is contaminated by any septic system j:

$$p_i = \bigcup_j p_{ij} \,. \tag{2}$$

    We write the probability of well i being contaminated by septic tank j as $p_{ij} = P(X_{ij} \,|\, \sigma_j, d_{ij}, G)$, where d_{ij} is the distance between the domestic well and septic system, and G represents the set of hydrogeological parameters that determine groundwa-

180 ter flow. The probability p_{ij} therefore encapsulates the groundwater hydrology between i and j and the decision by j whether or not to upgrade their septic system. This probability associated with each of the N players can therefore be determined by a groundwater model (Sect. 3.2).

    We begin by considering the key economic trade-off that is encapsulated by the decision (and associated risks) of whether or not to upgrade a septic system. Utility within the game can be considered from the perspective of the individual household

185 (whether or not they should upgrade) and the perspective of the community (whether or not everyone should upgrade). Because the game is fully symmetric, we focus on the utility of an individual player given by Eq. (1), which also representative of the mean utility for households in the community. The reduction in probability of contamination for player i if everyone upgrades is given as $\Delta p_i = p_i(\sigma_j = 0) - p_i(\sigma_j = 1) \,\forall\, j$. All players would be better off with everyone upgrading if $\Delta p_i C_x / C_\sigma - 1$ is positive. In contrast, the reduction in the probability of contamination of player i if he is the only one to upgrade is $\Delta p_{ii} =$

190 $p_i(\sigma_i = 0, \sigma_j = 0) - p_i(\sigma_i = 1, \sigma_j = 0) \,\forall\, j \neq i$. An individual player wishes to upgrade their septic system if $\Delta p_{ii} C_x / C_\sigma - 1$ is positive. Furthermore, a social dilemma occurs when

$$\Delta p_{ii} C_x - C_\sigma < 0 < \Delta p_i C_x - C_\sigma \,. \tag{3}$$

In other words, all players would benefit from upgrading (right hand side), but any individual player will endure a decrease in utility if they are the only one to upgrade (left hand side). The occurrence of a social dilemma can be understood by plotting

195 these quantities against each other (Fig. 5). In particular, high Δp_i and $C_x/C\sigma$ increase the benefits of cooperation (everyone upgrades) because the consequences of not upgrading are steep (high probability, and associated costs, of contamination). Conversely, low Δp_{ii} and $C_x/C\sigma$ increase the maximum loss of upgrading individually (i.e., the expected decrease in utility when no one else upgrades), because individual benefits of upgrading are small. Both the cost ratio C_x/C_σ and probability ratio $\Delta p_{ii}/\Delta p_i$ play an important role in determining whether or not a social dilemma occurs, and characterizing social dilemmas

200 requires understanding both properties together (Fig. 5c).

    Cooperation is more likely to emerge when the maximum loss of upgrading (which occurs if a player is the only individual to upgrade) is low relative to the benefits of cooperation. This situation is represented by the ○ in Fig. 5c, which could occur when the cost of contamination is relatively high ($C_x >> C_\sigma$) and there is a reasonable chance of self contamination ($\Delta p_{ii}/\Delta p_i \to 1$) but not enough to convince an individual to upgrade without collective action (i.e., not in quadrant I). Conversely, cooperation is

205 likely more difficult when the maximum loss of upgrading is high in comparison to the benefits of cooperation. This situation is represented by the × in Fig. 5c, and would occur when the cost ratio (C_x/C_σ) is just over 1 and the probability of self contamination is negligible ($\Delta p_{ii} \to 0$).
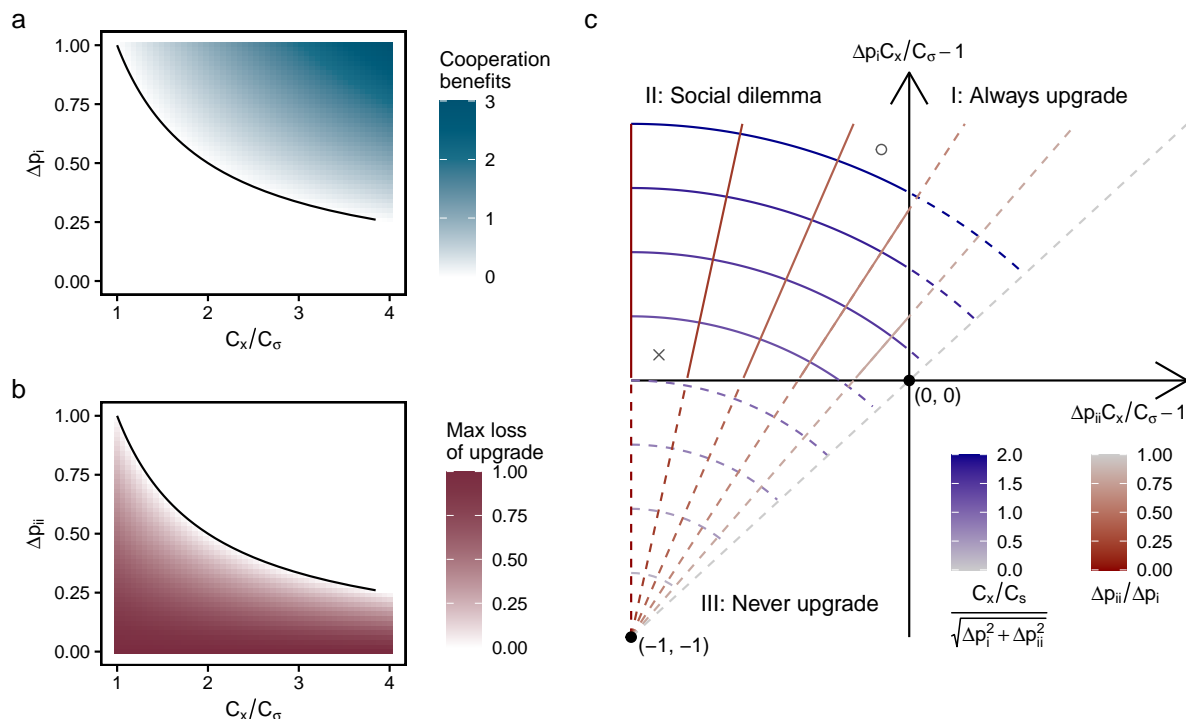
Figure 5. Social dilemmas as a result of individual and collective upgrades. (a) Benefits of cooperation, given as $\Delta p_i C_x / C_\sigma - 1$. (b) The maximum loss of upgrading, given as the expected decrease in utility for a single house to upgrade in the absence of cooperation ($1 - \Delta p_{ii} C_x / C_\sigma$). (c) Benefits of cooperation versus the (inverse) maximum loss of upgrading, with a social dilemma occurring in quadrant II. Blue contours indicate constant cost ratios (C_x / C_s), with higher cost ratios increasing the benefits of upgrading. Red contours indicate the ratio of $\Delta p_{ii} / \Delta p_i$, with lower values meaning that players get little benefit from upgrading their own septic tank relative to all other players upgrading.

3.2 Groundwater model

Groundwater behavior determines the probability that any well i could be contaminated by leachate from a septic field j, p_{ij}.

210 These probabilities and their unions, as required by Eq. (3), could be determined via any groundwater model appropriate for the circumstances. Horn and Harter (2009) used a MODFLOW model with a fine-scale grid to demonstrate that domestic wells capture groundwater primarily from a region that approximates a cylinder extending outwards from the screened portion of the well. Bremer and Harter (2012) extended this concept by assuming constant recharge and uniform lateral groundwater flow, such that the probability of domestic well contamination could be determined purely from the configuration of septic tanks and

215 domestic wells along with uncertainty on the mean direction of flow.

Based on these considerations, we incorporate uncertainty in the vertical direction of flow, allowing the calculation of p_{ij} using neighborhood layouts and simple aquifer geometries. The resulting model can be calibrated such that overall probability

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of contamination reflects actual contamination rates. In the model, the probability of contamination p_{ij} is equivalent to the probability that a particle from septic system j intersects well source area i (Fig. 6). The model encapsulates uncertainty in

220   the mean horizontal direction of flow (θ, Fig. 6a) as well as uncertainty in the flow trajectory within the vertical plane (u_z/u_r, Fig. 6b), given that the particle may pass over or underneath the well (Horn and Harter, 2009).
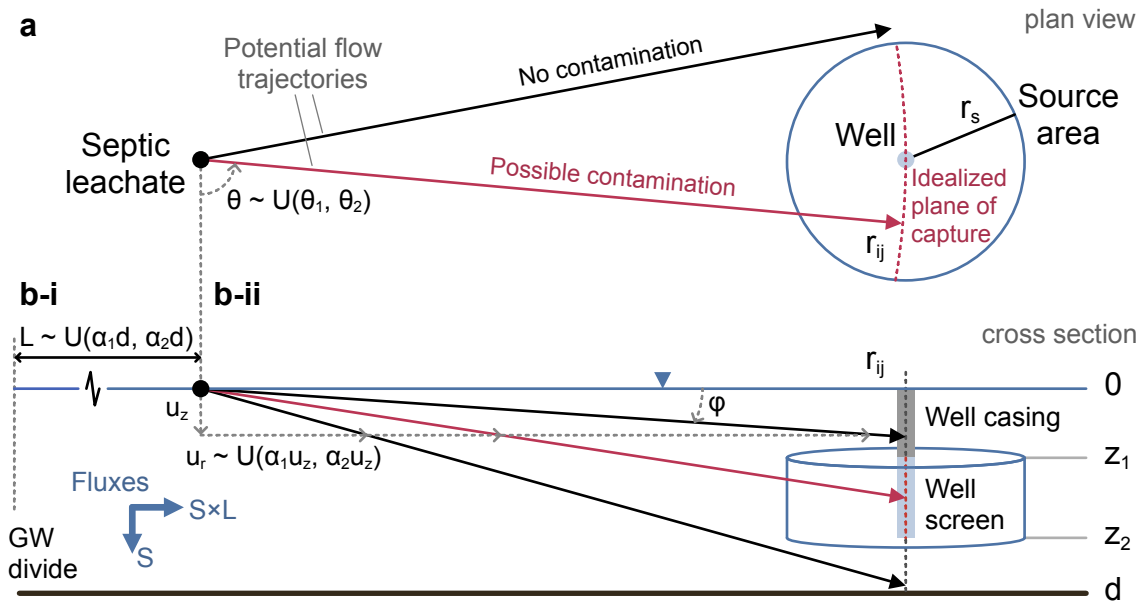

Figure 6. Groundwater model to determine the probability of contamination of well i from septic system j. (a) Plan view of the septic field, domestic well, and possible flow trajectories. The mean direction of flow is unknown and follows a uniform distribution with $\theta \sim U(0, 2\pi)$. (b-i) Vertical and horizontal groundwater fluxes are determined by seepage, S, and the distance to the groundwater divide, approximated by $L \sim U(0, L_{max})$. (b-ii) The well is cased to a depth z_1 and screened from z_1 to z_2, with the possibility that contaminants can pass over or under the well. Velocities are determined from the fluxes such that $u_z = f(S)$ and $u_r = f(S \times L)$. It follows that u_z is fixed while u_r contains uncertainty represented by a uniform distribution. The well is contaminated if the flow path intersects the idealized plane of capture (red dashed line), representing the source area of the well, in both the horizontal and vertical planes. See text for details.

     Flow velocities in the θ-z plane are determined by the vertical and horizontal velocities, u_z and u_r, which are, in turn, determined by the vertical and horizontal fluxes. We assume steady state behavior, such that the vertical flux is given by average annual seepage to the water table, S. All water is assumed to eventually flow toward a linear sink (e.g., a gaining

225   stream), so that the horizontal flux can be estimated as the rate of seepage multiplied by the uphill contributing area. When considering a unit width of the aquifer, this rate is given by $S \times L$, where L is the distance to the groundwater divide.

     For parsimony and in the absence of additional information, we assume that uncertainty in the mean direction of groundwater flow can be represented by a uniform distribution, $\theta \sim U(\theta_1, \theta_2)$. Uncertainty in the θ-z trajectory of flow is determined by uncertainty in the distance to the groundwater divide, also parameterized as as uniform distribution, $L \sim U(L_1, L_2)$. Wells are

230   cased from the ground surface to depth z_1 and screened from z_1 to z_2. Flow paths to the well occur only from groundwater

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within the range of depth of the screened portion of the well, $[z_1, z_2]$. The assumption of uniform uncertainty in flow direction has been applied in similar systems (Bremer and Harter, 2012), and the possibility that contamination can pass over or underneath a well has been demonstrated using MODFLOW (Horn and Harter, 2009). The groundwater model was implemented in an R package (Penny, 2021) that allows the calculation of both p_{ij} and p_i. As information is gained and the most critical

235   components identified, more complex representations can readily be added, but starting with a parsimonious representation and set of models has significant benefits with any probabilistic risk assessment (Bolster et al., 2009; de Barros et al., 2011).

4   Case study

4.1   Study site: St. Joseph County, Indiana

In order to evaluate the potential for social dilemmas to emerge in real-world scenarios, we apply the N-player game described

240   above to community nitrate contamination in St. Joseph County in northwestern Indiana, United States (see Fig. 1b). The county is home to 271,000 residents, with approximately half (152,000) living in the cities of South Bend and Mishawaka (U.S. Census Bureau, 2019). Outside the city boundaries, the most common water supply and treatment are domestic wells and septic systems, respectively, that abstract from and discharge to the St. Joseph Aquifer (Bayless and Arihood, 1996). We obtained data on nitrate levels in domestic wells from the St. Joseph County Health Department (https://www.sjcindiana.com/

245   302/Health-Department), which maintains publicly available records of nitrate tests recorded when new wells are installed or when houses are sold. The data confirm that in higher-density residential areas of the county, nitrate contamination is common, particularly in Centre Township and Granger Census Designated Place (CDP). For instance, 7% and 5% of household tests, in Centre Township and Granger, respectively, exhibited nitrate concentrations over the Environmental Protection Agency (EPA) Maximum Contaminant Level (MCL) of 10 ppm. Moreover, 43% and 30% of household tests in each of the two areas

250   exhibited nitrate concentrations over 5 ppm. To address this problem, the city has been working towards extending sewer lines into Granger, but sewer connections are optional and residents must pay a fee for the connection (St. Joseph County, 2011). New developments may be more likely to be connected to piped water and sewers (Sheckler, 2021), but the issue in existing homes remains. As yet, there is no clear solution to the problem. To explore the possibility of social dilemmas and potential policy solutions, we generate parameter estimates for the contamination game described above, and calibrate the model to

255   observed prevalence of contamination in Centre Township and Granger CDP.

4.2   Model parameterization and calibration

Both the economic portion of the model and the groundwater portion must be parameterized. For the economic portion, a complete cost of contamination is difficult to obtain. The health consequences of nitrate contamination are most acute for infants who may develop methaemoglobinaemia (Knobeloch et al., 2000), whereas the long-term consequences of exposure

260   for children and adults are potentially concerning but unclear (Ward et al., 2018). We therefore focused on the perceived cost of contamination, using existing empirical studies that associate the effect of contamination with a reduction in the price of

houses. In particular, Guignet et al. (2016) used a hedonic analysis of nitrate well tests and real estate transactions in Lake County, Florida to determine that the typical reduction in home value was 2-6% for those homes with nitrate contamination over the EPA MCL. We consider this loss in home value to be a plausible estimate of the cost of contamination.

265   The cost of upgrading the septic system to reduce or prevent nitrate contamination has been documented for EPA approved systems. We consider the Aquapoint, Inc., Bioclere^{TM} 16/12 system, with a typical price range of \$6000-8000 USD and Bio-Microbics, Inc., RetroFAST®0.375 System, with a price range of \$4000-5500 USD (Washington State Department of Health, 2005; US EPA, 2007).

For the groundwater model, we assumed that the mean direction of flow can be parameterized by a uniform distribution

270   spanning West to South (in Granger) and Northwest to Northeast (in Centre), roughly approximating the most common directions of flow in the St. Joseph Aquifer towards the St. Joseph River (Bayless and Arihood, 1996). Indiana regulations require that wells are installed at a depth of at least 25 ft (7.6 m) (Indiana State Department of Health, 2021), and the depth to the groundwater table is typically 5-15 ft (Bayless and Arihood, 1996). Given that wells reduce the water level locally, we assume a groundwater depth at the upper end of this range (15 ft, 4.6 m). We further assume that wells were screened down to the bot-

275   tom of this aquifer layer (70 ft, 21.3 m) (Bayless and Arihood, 1996). We approximate the distance to the groundwater divide as a uniform distribution characterized by the average width of the aquifer divided by the average height, giving an approximate ratio of 10-to-1 (Bayless and Arihood, 1996). Although these parameters are representative of the groundwater scenario, the uncertainty embedded in these estimates underscores the importance of calibrating the model to observed contamination probabilities.

280   We use the radius of well capture (r_s) as the only calibration parameter. This value represents the maximum lateral distance from the well that the center of a septic plume could pass through to generate contamination within the well. Therefore, the value could potentially change for different regions of the aquifer and different thresholds of contamination. We calibrate the model in both Centre Township and Granger CDP for contamination thresholds of 5 ppm and 10 ppm (Fig. 7a).

In general, with a 10 ppm threshold, the probability of contamination is low (see figure 7a). With a 5 ppm threshold, the

285   likelihood is much higher, and there is a clearer relationship between contamination rates and housing density. The issue of social dilemmas depends on assumptions of the system. We specify four scenarios, representing different assumptions on the costs and likelihood of contamination. In all cases the cost of contamination is a fraction of the home value:

– i. Centre 5 ppm calibration, \$4000 to upgrade septic, C_x equals 5% of home value.

– ii. Centre 10 ppm, \$4000 to upgrade septic, C_x equals 5% of home value.

290   – iii. Granger 5 ppm, \$8000 to upgrade septic, C_x equals 4% of home value.

– iv. Granger 10 ppm, \$8000 to upgrade septic, C_x equals 4% of home value.

We calibrated r_s for each scenario using observed data, allowing us to determine Δp_i and Δp_{ii} based on housing density. We used three values housing density to evaluate the model: 1, 2, and 3 households per acre. We further calculated the cost of
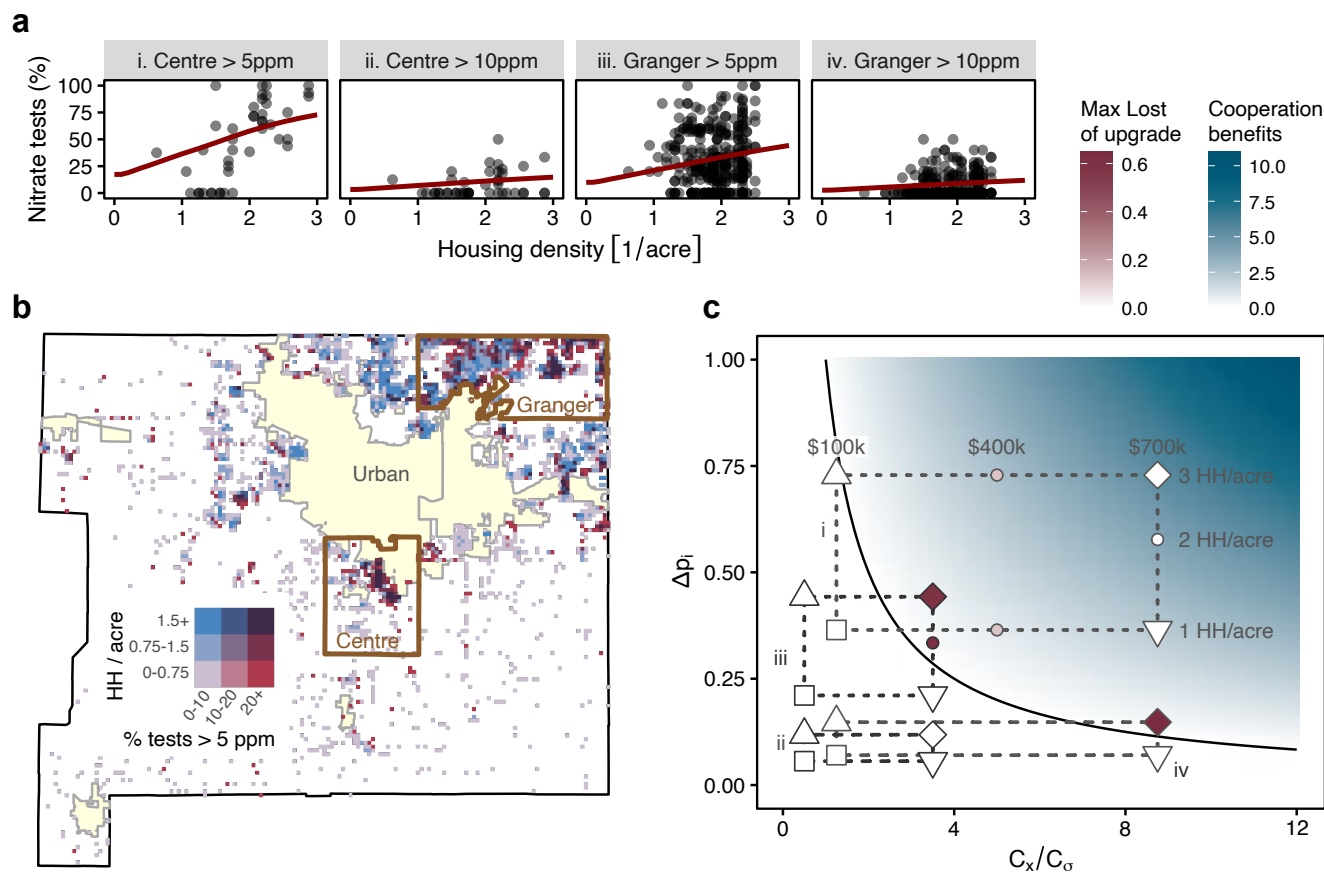
Figure 7. St. Joseph Case study. (a) Percent of nitrates tests exceeding a given threshold versus the housing density for Centre Township and Granger CDP. (b) Map of St. Joseph County, with colors indicating the housing density and percent of nitrates tests exceeding 5 ppm. (c) Social dilemmas based on housing price and housing density (shown), and costs of contamination and septic upgrades (not shown, see text). Cooperation benefits, $\Delta p_i C_x/C_\sigma - 1$, are shown as background shading (in blue) and the maximum loss of upgrading, $1 - \Delta p_{ii} C_x/C_\sigma$, is shown as the fill color of example points (in red). Note that both are defined the same as in Fig. 5.

contamination for multiple values of home prices: \$100k, 400k, and 700k. These can be mapped to the space Δp_i vs C_x/C_σ
295 (Fig. 7c).

4.3 Social dilemmas

With a 10 ppm threshold, it is generally unlikely, except for more expensive houses (see Fig. 7c for ranges), that a social dilemma will occur under the assumptions in scenarios ii and iv. With a 5 ppm threshold and assumptions as shown, it is much more likely that a social dilemma would occur. In fact, in some cases everyone chooses to upgrade (no social dilemma). This
300 represents an extreme case with a large-enough region of well capture and co-located wells and septic systems. If the direction of groundwater flow were known, the septic would likely be placed downstream from the well such that Δp_{ii} would be reduced
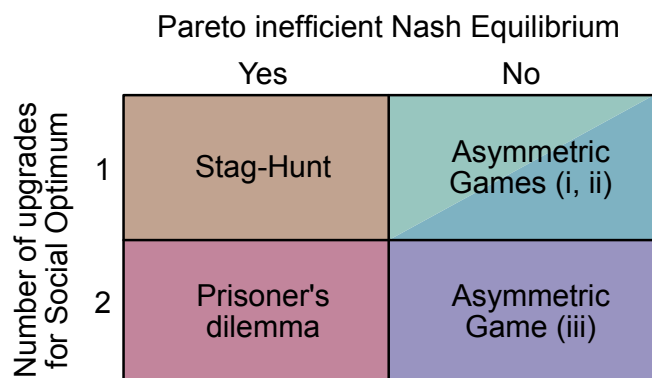
Figure 8. Pareto efficiency and upgrades required for the Social Optimum. The five types of dilemmas can be mapped according to whether or not there is a Nash equilibrium that is Pareto *inefficient*, and the number of players that would have to upgrade to achieve a social optimal outcome (PD and AD games). In the Stag-Hunt game, if one player can be convinced to upgrade then the other player will be incentivized to upgrade as well.

and these situations could become social dilemmas. The 5 ppm threshold is below the EPA MCL for nitrates, and therefore C_x/C_σ could be overestimated. However, this ratio captures only the internalized costs to the homeowner and not additional public health or environmental externalities that could affect the socially optimal utility. This scenario is therefore illustrative

305 of what could happen when such externalities are incorporated. Heterogeneity in groundwater contamination still plays a large role. For instance, in some neighborhoods the rates of contamination were as high as 50% over 10 ppm, whereas the calibrated model estimated a contamination rate of about 12% (Fig. 7a, ii and iv). Thus the model is conservative in some cases and, if these differences could be resolved, then social dilemmas could be evaluated with greater precision. For instance, some wells tap into the deep aquifer, but only 10% of wells in the dataset came with well depth, therefore it is possible that wells in the

310 shallow aquifer have higher rates of contamination. Other factors include localized abnormalities. For instance, septic design and maintenance practices play a role in septic water quality and well contamination, and lakes exist in some neighborhoods that may be recharging and diluting groundwater.

5 Discussion

The results demonstrate that multiple types of social dilemmas can arise in the context of groundwater contamination of

315 private water supply and sanitation systems. When considering two-player games with uncertainty in the mean direction of groundwater flow, we identified five types of social dilemmas including a Prisoner's Dilemma, Stag-Hunt game, and three types of Asymmetric Dilemmas. The type of social dilemma can serve as a guideline to understanding barriers to cooperation and policy opportunities to shift from the Nash equilibrium to the Social Optimum (Fig. 8).

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The *Prisoner's dilemma* is, in essence, a free-rider problem: a market failure that occurs when people might benefit from
320 services without having to pay the associated cost (Fischbacher and Gachter, 2010). Here, the decision keep a basic system (B)
strictly dominates the decision to upgrade to an enhanced system (E), and each player benefits the most when only the other
player upgrades. This allows the player in question to utilize the cleaner water associated with the other player's upgraded septic
without having to pay for an upgrade themselves. A variety of market design approaches have been identified to address the
free-rider problem in the context of public goods, including assurance contracts (Tabarrok, 1998), Coasian bargaining (Farrell,
325 1987) and incentives for cooperation (Balliet et al., 2011). The Nash equilibrium in the *Prisoner's dilemma* game is not Pareto
efficient, meaning that all players can benefit if everyone upgrades their septic system. The free-rider problem can therefore
also be addressed through altruistic social norms (potentially combined with enforcement and sanctions) to support collective
action (Kerr, 1992). In other words, despite the various obstacles to overcoming the Prisoner's Dilemma, there exist multiple
governance approaches to address this challenge and initiate community-wide upgrades to enhanced septic systems, allowing
330 everyone to benefit from cleaner groundwater and reduced contamination costs.

In contrast, the *Stag-Hunt* game (also known as assurance game) is a problem of strategic uncertainty, where players might
fail to achieve a socially-optimal equilibrium by not being able to coordinate their decision-making. Here, either player can
only benefit from upgrading if the other player upgrades as well. Under these conditions, they will only endure the cost of
upgrading if they are reasonably sure that the other player is also upgrading. Strategic uncertainty can be resolved through
335 trust and reliable information (Jansson and Eriksson, 2015). In contrast with the Prisoner's Dilemma, where *all* players must
be incentivized to upgrade, the assurance game only requires *any* player to buy in (e.g., through targeted subsidies). The other
player will reciprocate if she has sufficient assurance of the other player's buy in. As such, public programs that provide some
measure of transparency or assurance that some households have upgraded their septic systems would encourage additional
households to also upgrade.

340 In each of the *Asymmetric dilemmas*, the Nash equilibrium is Pareto optimal but one player receives outsize benefits at
the expense of the other player. A greater social optimum can be achieved by one player sacrificing some of their utility.
Asymmetric Dilemmas i and ii are akin to the Stag-Hunt game in that the social optimal is one upgrade away from the
Nash equilibrium. However, unlike the Stag-Hunt game, achieving the social optimal requires convincing a *specific* player to
upgrade. Any subsidy must therefore specifically targeted to the appropriate player, which requires reliable information on all
345 players' utility parameters. Finally, Asymmetric Dilemma iii is partially similar to a Prisoner's dilemma because the social
optimal requires both players to upgrade. However, unlike the Prisoner's dilemma where both players increase their utility by
achieving the Social Optimal, one player is worse off in the social optimal compared to the Nash Equilibrium. In this situation,
targeted subsidies or side payments might be needed, in addition to social or market approaches to address potential free-rider
problems.

350 Social dilemmas in N-player games can be understood by non-dimensionalizing the expected utility when everyone upgrades
(i.e., the cooperation benefits) and expected utility when only one player upgrades (i.e., the maximum loss of upgrading). Social
dilemmas arise when both are positive. Situations akin to the Prisoner's dilemma are likely to arise when the cooperation
benefits are modest and the maximum loss of upgrading is high. Dilemmas akin to a Stag-Hunt game are more likely when the

cooperation benefits are high and the maximum loss of upgrading is low and $p_{ii} \cap p_{ij} > 0$, meaning that an individual's upgrade

355   becomes more appealing after another player upgrades. The three asymmetric dilemmas only emerge in situations where (known) specific players have undue influence on the contamination of other players' wells. We assume that the N-players are homogeneously located throughout the neighborhood and do not have perfect information on the flow direction of groundwater, and that all households face similar costs and emit comparable pollution loads. Under these conditions, asymmetric dilemmas would only emerge near the edges of the neighborhood and therefore, assuming the neighborhood is sufficiently large, only

360   concern a small fraction of the households. Although both types of symmetric social dilemmas (Prisoner's Dilemma and Stag-Hunt) are possible, the Prisoner's dilemma situation is more likely because the case study in St. Joseph County suggests that our model potentially overestimates Δp_{ii} and the maximum loss of upgrading (Fig. 4). However, the specific benefits and costs of such upgrades are likely to be location-specific and depend on a variety of factors. While we show that such dilemmas are possible in St. Joseph County, additional groundwork would be needed to more clearly identify the type of situation that exists

365   within the county, including the specific locations where housing and groundwater behavior give rise to such dilemmas.

6   Conclusions

Contamination of domestic wells by septic leachate is a public health concern in residential areas with high housing density. The issue has been particularly difficult to resolve for public health officials and residents alike. We develop a theoretical framework to understand how misaligned incentives can give rise to social dilemmas within such private water systems. A variety of social

370   dilemmas can occur in such situations, depending on the groundwater hydrology, costs of various treatment technologies, and configurations of households. These dilemmas include the classic Prisoner's Dilemma and Stag-Hunt game, as well as an Asymmetric Dilemma that favors some players over others. These dilemmas can occur even if all households face the same economic costs of contamination and treatment. As such, this manuscript provides a theoretical basis to identify when social dilemmas could be occurring and offers a new perspective through which to approach management of such systems. A better

375   understanding of the challenges for any specific location could be achieved using more sophisticated groundwater and transport models combined with location-specific estimates of the associated costs of contamination and septic upgrade. Such analyses would better resolve the details pertaining to social dilemmas, but the overarching framework would remain unchanged.

Code and data availability.   Code for the two-player games and groundwater model is available in an R package (Penny, 2021) and can be accessed online at https://github.com/gopalpenny/nitratesgame. Household nitrates data are available from the corresponding public agencies.

380   *Author contributions.*   G.P., D.B., and M.F.M. designed the research. G.P. conducted the analyses. G.P. and M.F.M. wrote the manuscript.

Competing interests. The authors declare that they have no conflict of interest

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