We thank the reviewer for careful consideration of our manuscript, and thoughtful suggestions which we believe will improve the manuscript in important ways. We have addressed each of the comments in-line, below. Please see our in-line responses below, which include:

Our response, in blue
Manuscript text, in maroon

Sincerely,
Gopal Penny, on behalf of the authors

Comments from Reviewer 1

Summary

In this paper, the author stressed a very important water issue. The private systems and wells contamination issued by septic systems, and this might cause many types of social dilemmas. The author. Has developed a water game theory for private water systems starting with 2 and then with N-players applied then a symmetric as well as an asymmetric game with more uncertainty related mainly with the groundwater flow direction and the different possibility of contamination. All this has been applied to learn more about the interlinkages between the choice of the septic system upgrading, wells contamination, and social dilemmas. To do so, the author applied a groundwater model. To have more clearance about. The different probabilities are related to the uncertainty around the groundwater flow direction and the possibility of contamination (self-contamination and cross-contamination) by the septic systems.

At the end of the game (study), we expect to have a straightforward decision (policy solutions) that can help in solving this social dilemma with less cost.

General comments:

1) Title: reflect very well the main question of the paper

Thank you. Please note that we intend to revise the title to “Social dilemmas and poor water quality in ~~private~~household water systems” in response to a comment from the other reviewer.

2) Introduction: well, framed, and organized, but the author needs to check for more recent references.

Thank you for this suggestion. We will add a number of recent references throughout the introduction. These include papers referring to disparities in water quality (Schaider et al, 2019; Meehan et al, 2020a,b), household water contamination in developing countries (Ngasala, 2019), nitrate sources (Bastani and Harter, 2019) and source identification

(Zendehbad, 2019), water quality hazard identification (Li et al, 2019; Juntaku et al, 2020), and temporal variation of water quality in domestic wells (Ornelas Van Horne et al, 2019).

Bastani, M., & Harter, T. (2019). Source area management practices as remediation tool to address groundwater nitrate pollution in drinking supply wells. Journal of contaminant hydrology, 226, 103521.

Juntakut, P., Haacker, E. M., Snow, D. D., & Ray, C. (2020). Risk and cost assessment of nitrate contamination in domestic wells. Water, 12(2), 428.

Li, P., He, X., & Guo, W. (2019). Spatial groundwater quality and potential health risks due to nitrate ingestion through drinking water: a case study in Yan'an City on the Loess Plateau of northwest China. Human and ecological risk assessment: an international journal, 25(1-2), 11-31.

Meehan, K., Jepson, W., Harris, L. M., Wutich, A., Beresford, M., Fencl, A., ... & Young, S. (2020a). Exposing the myths of household water insecurity in the global north: A critical review. Wiley Interdisciplinary Reviews: Water, 7(6), e1486.

Meehan, K., Jurjevich, J. R., Chun, N. M., & Sherrill, J. (2020b). Geographies of insecure water access and the housing–water nexus in US cities. Proceedings of the National Academy of Sciences, 117(46), 28700-28707.

Ngasala, T. M., Masten, S. J., & Phanikumar, M. S. (2019). Impact of domestic wells and hydrogeologic setting on water quality in peri-urban Dar Es Salaam, Tanzania. Science of the total environment, 686, 1238-1250.

Ornelas Van Horne, Y., Parks, J., Tran, T., Abrell, L., Reynolds, K. A., & Beamer, P. I. (2019). Seasonal variation of water quality in unregulated domestic wells. International journal of environmental research and public health, 16(9), 1569.

Schaider, L. A., Swetschinski, L., Campbell, C., & Rudel, R. A. (2019). Environmental justice and drinking water quality: are there socioeconomic disparities in nitrate levels in US drinking water?. Environmental Health, 18(1), 1-15.

Zendehbad, M., Cepuder, P., Loiskandl, W., & Stumpp, C. (2019). Source identification of nitrate contamination in the urban aquifer of Mashhad, Iran. Journal of Hydrology: Regional Studies, 25, 100618.

3) Two household contamination games: this part is very well described.

- However, there is a need to clarify if the game is cooperative or not cooperative before heading to the Nash equilibrium (non-cooperative).

- The author needs to explain why he has chosen to go with the non-cooperative choice, even if it was very clear that the author wanted to stress out the social dilemma cause. But it would be great to clarify the rationality behind the choice.
- Why the author did not consider all the parts of the game: elements of action (finite or infinite), information set (complete information or incomplete information game), numbers of the same play in a game (one-shot game and repeated game).

Thank you. We have rewritten the text to make explicit our rationale behind the setup of the two-household game. This includes that the game is a non-cooperative, static (one-stage of play), one-shot (not repeated), game of complete information (the payout structure of all players is common knowledge). Note that the action space is limited to two actions (upgrade or do not upgrade). We use a one-shot game because the decision to build infrastructure locks players into future behavior given the capital cost and long lifespan of the infrastructure. These details will be clarified in the revised text as:

We first consider a two-player static game with complete information, wherein the payout structure of both players is common knowledge. Note that we employ non-cooperative game theory to determine the presence or absence of social dilemmas, rather than the manner in which players build coalitions (as in cooperative game theory). As described below, this approach is realized by comparing outcomes under individual optimization (the Nash equilibrium) and full cooperation (the social optimum). Because the payout structure for all players is common knowledge, it is a game of complete information. In the game, each player chooses whether to upgrade their septic system 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. Although the game can be played at any time, it is a static one-shot game because the action to upgrade a septic system only occurs once via capital investment and multiple stages (as in a dynamic game) are not necessary to determine the possibility of a social dilemma.

And just below:

$\sigma_i \in \{0,1\}$ represents the action space of each household, which can choose to maintain a basic septic system (B, $\sigma_i = 0$) or upgrade to an enhanced system (E, $\sigma_i = 1$).

4) Symmetric two-player games: from lines 113 to 121: the paragraph is a bit complicated, there is clear contradiction and redundancy in explaining the upgrading and non-upgrading choice.

This paragraph describes Figure 2c and 2d, which show 2x2 payout structures and equilibria (both Nash and social optimum) for the two-player game. The two games (in Fig 2c and 2d) are similar but with key differences. We have modified the paragraph to address this comment while striving to seek a balance between clarity, brevity, and redundancy.

A social dilemma occurs when individual optimization leads to a different outcome than would be achieved if players work together. This can only occur when players potentially contaminate each other (as in Fig. 2c and 2d). When both players only contaminate the other player's well without contaminating their own well (Fig. 2c), the best response for each player would be not to upgrade (B), regardless of the decision of the other player. While neither player directly gains by upgrading their own septic system, each player would benefit if the other player upgrades. This leads to a classic Prisoner's dilemma (see Kollock, 1998) where neither player upgrades in the Nash equilibrium despite the mutual benefits of doing so. In the final situation (Fig. 2d), players contaminate both their own and the other players' well. This game yields two Nash Equilibria, including one where neither player upgrades (B, B) and another where both players upgrade (E, E). This structure follows an Assurance or Stag-Hunt game (Kollock, 1998), where players only wish to upgrade to an enhanced system when the other player also upgrades.

5) Groundwater model: the author mentioned that the modeling part could be determined by any groundwater model, but he did not explain the rationale behind selecting /using the MODFLOW model.

We will revise this section to clarify that we do *not* use a MODFLOW model, but rather a simplified groundwater model based on the analytical element method. Our intention behind mentioning MODFLOW is to be clear that the non-cooperative game described in this paper can be implemented with *any* groundwater model that generates probabilities of contamination. We will clarify this within the manuscript.

6) Case study:

- The existing groundwater data are mainly based on assumptions, does the author performed any data collection or had access to any national database?
- It is important to have the year of any collected data
- Does wells capture radius (rs) is sufficient to calibrate a groundwater model? In my knowledge in the case of groundwater flow modeling we need more than the Rs parameter, we need for example the recharge and hydraulic conductivity supported by field data.
- The model validation is absent, does the author validate the model data?
- The author took too much space to explain the game (almost 10 pages), however, he didn't well calibrate and validate his groundwater model and he didn't clearly explain and apply the game for the case study.

The data were collected from the St. Joseph County Public Health Department, in the years (2012-2019). We realize this information was only mentioned at the beginning of the case study and not where we described data preparation and calibration. We agree this needs to be clearer, and we now explicitly describe the testing data and preprocessing in the manuscript in conjunction with calibration.

Although groundwater behavior and flowpaths can be extraordinarily complex, the intention of the groundwater model is not a complete representation of groundwater flow, but rather an estimate of the probabilities of contamination of any domestic well due to pollution from any septic system, as required by the game theoretic model. This probability depends only on whether or not a pollutant will be captured by the well and (importantly) should capture the perceptions of the players. Under steady state and the simplified assumptions of our model, the capture radius and direction of flow are the key determinants of this probability. We assume the probability of flow direction is fixed, and therefore the well capture radius is the only calibration parameter. Note that the capture radius is the result of multiple hydrogeological features of the aquifer, including recharge rates, hydraulic conductivity, and well depth.

There are, of course, many other hydrogeological features that would determine whether or not a pollutant would be captured by a well. However, it is worth restating: in this paper we are *not* interested in a precise estimate that would determine whether or not a pollutant enters the well, but rather the appropriate estimate on the probability *based on the information available* to the players. In general, that information would be very limited because hydrogeological surveys and modeling are expensive. This feature of our study leads us to the simple model and calibration approach presented.

We will revise the manuscript text to read:

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 and is the result of multiple hydrogeological features including recharge rates, hydraulic conductivity, and well depth. Therefore, the value could potentially change for different regions of the aquifer and different thresholds of contamination. Note that the model should capture the perceived probability of contamination based on information available to the players, rather than reflect the most precise estimate based on complete knowledge of the groundwater system. As such, our stylized model and calibration procedure associates this probability with household density and observed probabilities of contamination.

St. Joseph County requires that water quality of private wells be tested any time a new well is installed or a property with a private well is sold (St. Joseph County, 2020). We obtained records of nitrate contamination from these tests for both Centre Township (N = 724) and Granger CDP (N = 3457) from the St. Joseph County Department of Health, spanning the years 2012--2019. From these tests, we determined the probability of contamination as the fraction of tests in 16-acre pixels that exceeded a particular contamination limit, and matched each pixel with an associated housing density from publicly available county shapefiles.

We then calibrated the groundwater model in both Centre Township and Granger CDP for contamination thresholds of 5 ppm and 10 ppm. The calibration procedure led to an estimate of the probability of contamination based on housing density and the stylized groundwater model (Fig. 7a).

St. Joseph County, IND, Code of Ordinances, Ch. 52: Water Regulations, § 52.011 (2020)

7) Discussion: the discussion is good, but it is too general and does not directly reflect the results from the selected case study. The author here only explained more about the different types of social dilemmas.

Thank you for this comment, we will add to the discussion the following text:

The model identifies how social dilemmas arise through tension between the cost of well contamination and inability of individual households to prevent contamination. In particular, wealthier households may be able to collectively organize to prevent contamination through enhanced septic treatment. This approach can be facilitated by homeowners associations, and public education about the consequences of contamination. As the model demonstrates, the drawback of this framing is that lower-income households may be averse to participation in such projects because the costs of enhanced septic treatment exceed the economic benefits associated with home prices. This creates an obvious conundrum for local governments whereby the most equitable health outcomes cannot be achieved through community collective action because lower-income households are reluctant to participate in collective initiatives for enhanced septic treatment.

The above analysis suggests three potential policy approaches depending on the disposition of local residents. First, promoting homeowners associations that require enhanced septic treatment would be acceptable to wealthier households provided this initiative is combined with sufficient public education. Lower-income households are likely to oppose such requirements because the economic burden of installing enhanced treatment likely exceeds the perceived benefits. Second, local governments can require wastewater treatment, either via enhanced septic systems or public sewerage. This option will likely lead to more equitable public health outcomes but potentially inequitable economic outcomes that disadvantage lower-income households who rent or own property with lower values. Third, the local government can use a combination of taxes and fees to incentivize (i.e., subsidize) wastewater treatment via enhanced septic systems or community sewerage. The game theoretic model provides a first estimate of the subsidies that would be required such that the cost of treatment would match the reduction in property value from nitrate contamination. Public outreach could be used to refine the taxation structure and value of subsidies so that residents are amenable to this approach.

8) Conclusion: we expected after applying the game to a case study to have some applicable policy recommendations/solutions, but the author didn’t provide any straightforward solutions.

We have added policy recommendations in response to comment #7. We will briefly summarize these recommendations within the conclusions.

Specific comments:

1) Symmetric two-player games: from the line 113 to 121: the paragraph is a bit complicated, there is clear contradiction and redundancy in explaining the upgrading and non-upgrading choice

See response to #4, above.

2) Line 337: The other player will reciprocate if she (he) has sufficient assurance of the other player's buy-in.

We will make this correction.

3) I think that the references listed below worth to be sited in this publication:

- Raquel S, Ferenc S, Emery C Jr, Abraham R. Application of game theory for a groundwater conflict in Mexico. J Environ Manage. 2007 Sep;84(4):560-71. DOI: 10.1016/j.jenvman.2006.07.011. Epub 2006 Sep 22. PMID: 16996197.
- Ariel Dinar and Margaret Hogarth (2015), "Game Theory and Water Resources: Critical Review of its Contributions, Progress and Remaining Challenges", Foundations and Trends® in Microeconomics: Vol. 11: No. 1–2, pp 1-139. http://dx.doi.org/10.1561/0700000066

Thank you, both are relevant citations and we will include them in the revision.