We appreciate the careful consideration and constructive feedback the reviewer has provided for this manuscript. We believe these suggestions will improve key aspects of the manuscript. Please see our in-line responses below and ourplan to revise the manuscript text, including:

Our response, in blue
Manuscript text, in maroon

Sincerely,
Gopal Penny, on behalf of the authors

Comments from Reviewer 2
https://doi.org/10.5194/hess-2021-312-RC2

General comments:

The article combines game theory with groundwater modelling to analyse social dilemmas and potential policy solutions related with groundwater contamination. This is a timely contribution given that groundwater contamination remains a widespread challenge. The authors' detailed description of the the game theoretical model and the groundwater modelling is informative and helpful - especially for readers not familiar with the framework proposed. I also find the application of the framework to a real-world scenario interesting. I believe further work on the case study and the discussion section would contribute to strengthen the paper. To this end, I provide some suggestions below.

The authors show the relevance of the methodology presented by applying it to the case of St. Joseph County. I would suggest the authors to further contextualize the case study. For instance, it would be of interest to include more data about the socio-economic status of residents of the two sites considered (Centre Township and Granger CDP) and housing density as well as some more information about environmental policies in place to tackle groundwater use/contamination. This would be helpful to assess the potential of the framework to understand real-world cases. Recent work on water security in the context of the US has highlighted significant inequalities that I believe it is worth discussing either in the presentation of the case study or in the discussion session, see for instance:

- Meehan, K., Jurjevich, J.R., Chun, N.M. and Sherrill, J., 2020. Geographies of insecure water access and the housing–water nexus in US cities. Proceedings of the National Academy of Sciences, 117(46), pp.28700-28707.
- Meehan, K., Jepson, W., Harris, L.M., Wutich, A., Beresford, M., Fencl, A., London, J., Pierce, G., Radonic, L., Wells, C. and Wilson, N.J., 2020. Exposing the myths of household water insecurity in the global north: A critical review. Wiley Interdisciplinary Reviews: Water, 7(6), p.e1486.

The suggested references are highly pertinent and we will include both of them to provide additional perspective, in particular by shedding light on our additional discussion of policy as it pertains to St. Joseph County. As noted in the manuscript, both Centre Township and Granger Census Designated Place (CDP) exhibit high prevalence of nitrate contamination at the 5 ppm and 10 ppm levels. We will now also highlight additional similarities and differences between the two in the manuscript with the following text:

We obtained income distributions from the censusreporter.org website, which aggregates census statistics by geographical areas and provides median income and four income groups ($0-50k, $50k-100k, $100k-200k, >$200k). Centre Twp has a median household income of $64k and the most common income bracket is $0-50k (39% of households), whereas Granger CDP has a median income of $102k and the most common income group is $100k-200k (35% of households).

We will also note:

As both regions are located within unincorporated areas of St. Joseph County, they face the same regulations with respect to housing density and well placement.

The discussion is limited to describe different social dilemmas and propose (rather vague) policy solutions. The author could work to further develop the discussion section with specific reference to the case study. For instance, I am missing a clear statement indicating to which extend the framework proposed is helpful to i) describe real-world social dilemma, ii) identify (applicable) policy solutions.

Thank you for this important comment, which was also reflected in the comments of the other reviewer. We now structure the discussion to (a) describe theoretical interpretations of the game (as before), (b) include policy considerations for local governments such as St. Joseph County (new text below), and (c) discuss limitations of the model and applications to other regions (new text in response to subsequent comment). We will include the following text in the revised manuscript to address this comment:

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.

I would also suggest to further reflect on the limitations of the proposed framework especially in relation to policy solutions in a real-world scenario and to the uncertainties in the modelling. For instance, the authors assume the players are homogeneously located, do not have perfect information and they face similar costs and emit comparable pollution (l.356). How does such assumptions influence the results, especially in terms of identifying policy solutions? Loss in home value is considered as an estimate for the cost of contamination, while in the conclusion the authors suggest that more data are needed, they could also explain how does this assumption influence the findings. Moreover, I was wondering if and how the choice to focus on a case study located in the US (and not for instance a case in the Global South where groundwater contamination is also a pressing challenge) would influence the author's assessment of the potential of the framework to understand social dilemmas and advice policy making.

We agree that additional context would be beneficial. We will add text to the manuscript that incorporates the following points to address how the assumptions of our modeling approach relate to policy implications in St. Joseph County (and similar regions) in addition briefly describing how the model could be applied to scenarios that would be more likely to arise in low- and middle-income countries.

This approach must take into consideration the assumptions and context in which the model was applied in St. Joseph County, including that (a) houses were uniformly distributed on a grid, (b) contamination occurred due to nitrate pollution, and (c) the cost of contamination was determined as the associated reduction in home prices.

The assumption of homogeneity yields situations of symmetry where the payouts are identical for all players. There are two features of heterogeneity that could affect model outcomes and therefore policy considerations. First, heterogeneity in the hydrogeology or housing density would create situations where some households are located upstream of the majority of the neighborhood and therefore would be less interested in contributing to collective action schemes that required enhanced septic treatment, as these households would be unlikely to be contaminated regardless of the behavior of other households. However, these theoretical limitations are unlikely to affect the policy process for the following reasons. To our knowledge, the majority of situations with high community nitrate contamination occur in hydrogeological settings with unconsolidated aquifers and flat topography, meaning that the direction of groundwater flow may not be obvious. It would therefore place local governments in a tenuous position to attempt to adequately assess the groundwater flow paths in order to customize policy to such asymmetries, and although they may exist they can be effectively ignored in most situations. Second, heterogeneity in property values would create a dynamic environment where wealthier households are willing to pay more than less wealthy households for improved water quality. This should be taken into account when implementing policy, and may facilitate implementation of the third policy approach, described above.

The cost of contamination could just as well arise from any range of household contaminants. We focused on nitrate contamination, which is prevalent in St. Joseph County and many other locations in the United States, but other situations may arise with other types of pollutants and treatment strategies. The game can just as well be applied to these scenarios, accounting for different costs of contamination and treatment. For instance, pathogenic contamination is more prevalent in low- and middle-income countries, and the associated economic consequences include loss of work and income (Prüss-Üstün, 2016). Similarly, treatment strategies are likely to differ, both in terms of domestic water treatment and waste treatment. A complete assessment is beyond the scope of this manuscript, but the game theoretic model could readily be applied to such situations using the R package developed for this manuscript (Penny, 2021).

Prüss-Üstün, A., Wolf, J., Corvalán, C., Bos, R., & Neira, M. (2016). Preventing disease through healthy environments: a global assessment of the burden of disease from environmental risks. World Health Organization.

Minor comments:

Title: the authors might want to consider to specify that the study focuses on a case study located in the US.

We have made a minor change in the title, switching “private water systems” to “household water systems” in response to the comment below. We decided to keep the remainder of the current title because the theoretical aspects of the manuscript, including game theory and R package, apply generally to water quality in household water systems. We now briefly describe (in the discussion) how the approach could be applied to scenarios with other pollutants and economic considerations (as might arise in low- and middle-income countries).

l.9 – Repetition of ‘three’

Thank you, we will fix this.

l.25 – Here and in other sections the authors refer to “private water systems”. Perhaps the term household water systems or domestic water systems would be more appropriate in order to distinguish the water systems considered in the paper and avoid confusion with i.e. a privatized pipe-born networked systems.

We agree with this suggestion and will revise the paper to refer to household water systems rather than private water systems.

l. 320-321 – It is unclear to what the letters B and E refer to.

We will clarify that B refers to a “basic” (i.e., traditional) septic system and E refers to enhanced septic treatment that would remove contaminants of concern. For instance, advanced septic systems (e.g., the Aquapoint, Inc., Bioclere™ 16/12 system, noted in the case study) can remove nitrate contamination from septic leachate.