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Hydrology and Earth System Sciences Discussions

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Interactive Comment

Interactive comment on "Natural vs. artificial groundwater recharge, quantification through inverse modeling" *by* H. Hashemi et al.

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The authors thank the reviewer for constructive comments to improve the quality of the manuscript. Time and effort spent on the manuscript is highly appreciated.

1) In page 9769 lines 6-11, the authors states that transmission losses in stream channels are inefficient with respect to recharge of the alluvial aquifers. This statement is not accurate. Several studies demonstrated that the capacity of the recharge from stream channels is very high and efficient. Moreover several other studies indicated inefficiency of spreading reservoirs to recharge ground water. In fact many flood water spreading zones in arid lands abandon after several years of operation due to acknowledgement of their mal functioning as ground water recharging mechanism. Therefore

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such statements as a starting point for the manuscript is miss leading and require a broader discussion on the this subject.

→ The authors agree with the opinion of the reviewer. However, the objective here is to increase the recharge by increasing the area of flooding. If from the start we assume that soil and subsurface conditions are similar for both the stream channel and the artificial recharge area, then the area governs the recharge volume. Assuming similar recharge per area for both channel and artificial area means that the volume recharged by far would be the prepared artificial recharge areas. If similarly the areas are maintained then again recharge must be greater in the recharge areas. However, even if there is no doubt that many of the stream channels may have a high capacity of recharge, and as mentioned on page 9769 lines 4-6, then ''lower magnitude flood events generally do not result in complete channel submersion. Therefore, the infiltration and consequently the recharge are limited". Thus, recharge through the river channel is a natural phenomenon and most probably with a high infiltration rate but with limited and often insufficient (NOT inefficient) volumes for domestic use due to the limited infiltration surface area. There are two common ways for providing water for the rural community 1) storage dams about which several studies have indicated their inefficiency due to the high potential for evaporation, silting, the filling up of the reservoir with sediments, the costs of construction, the environmental impact, etc.; and 2) artificial recharge. The authors agree that studies have demonstrated that many floodwater harvesting systems in arid areas were abandoned after several years of operation due to clogging, but, for most of them the author(s) did not give any reason for site selection, inspection, and maintenance of the system. As it is mentioned in the manuscript, the system constitutes a low-cost passive technology that may give high return in terms of increased groundwater supply. Owing to that, the floodwater spreading system, as well as all water/hydraulic infrastructure projects and techniques need regular inspection and maintenance. In other words, as in the case of all floodwater harvesting, breaches occur, especially in the early stages of operation, and also siltation occurs in the first basins and almost all channels through the entire system. Hence, continuous maintenance is a basic requirement to have a fully functional system. Sediments, just like other problems, can be managed, for example silt can be removed every few years. One reason among many for abandoning floodwater spreading systems is improper site selection. The water harvesting method applied strongly depends on local conditions and includes widely differing practices, such as bunding, pitting, micro-catchments water harvesting, flood water and ground water harvesting (Prinz 1996, Critchley and Siegert 1991). In order to find the most appropriate technique, the area must be studied in terms of soil properties, geology of the upstream catchment, topography, flood water quantity and quality, climatology, hydrology, etc., before establishing such systems. In addition, since the floodwater spreading system requires an extensive area, the sediment may spread over a large area with relatively small thickness. However this property creates some limitations for site selection, which tends to be site specific, but this is not the main concern of this study. Another point that the authors would like to raise in this discussion is the unspecified budget at the government level for such projects in many arid/semiarid countries. Unfortunately, once the system has been established, no budget or an insufficient budget may be allocated to maintain the system. Our studies show that after the first year of operation about 20% of the initial cost of the project should be allocated for maintenance and from then, 10% is required for the yearly maintenance. However, it may increase after each significant flood.

2) In the same page line 15 the authors state that underground storage is an important alternative to overcome seasonal water deficiency. Indeed it is a preferred solution in arid environments. Yet, flood water in arid environments is usually characterized with very high load of suspended material. Reduction in the stream water energy in the spreading zone derives accumulation of clay particles on the reservoir bottom. As such the infiltration capacity of reservoirs in arid environments is a known to be reduced dramatically. Practically the bottom of the reservoir is sealed off, and significant infiltration is very limited. Unfortunately Examples for such inefficient reservoirs in arid environments exist all over the world's arid countries. Moreover in many cases it has been proved that the infiltration reservoirs created sever damaged the groundwater due to

reduction in natural infiltration in the stream channel.

→ The reviewer is right about the high load of suspended material in the floodwater of arid areas. This is why the authors emphasize floodwater spreading over an extensive area rather than a smaller pond, injection well, and even storage dam. A floodwater spreading system consists of several different basins, the first two basins act as sedimentation basins and the rest act as infiltration basins. Our studies for a system consisting of 6 different basins shows that the sediment thickness in the first basin reached up to 30 cm after 25 years of operation, whereas the sediment thickness decreased to 0.5 cm in the third and 0 cm in the last two basins. Also, a mixture of trees and shrub land helps significantly to increase the infiltration rate. Siltation also depends on how upstream areas are managed.

3) Further on in line 18 of the same page the authors state "Artificial recharge is a method to balance and recover groundwater resources through floodwater spreading systems and injection wells". In most cases (of which I am familiar with) recharging reservoirs in arid environments are very shallow and spread over large area. As such, the ability to collect the stored water after sediment settling for direct injection through wells is very limited due to the very large surface area to depth ratio. Therefore only small fraction of the reservoir water may be diverted for recharge through well and the rest is left for intensive evaporation that ends up in salinization of the reservoir sediment. Throughout the entire introduction chapter and further through the results the manuscript almost completely ignores operational issues related to siltation on clogging of flood water reservoirs in arid environments. The only place where the author mentions the clogging phenomena of reservoirs is in a vague sentence the in chapter 3.2.2. as an explanation to observation on reduced recharge.

→ The authors agree with the reviewer. However, we cannot generalize and only emphasize problems encountered in artificial recharge systems. Each system has its own unique features, which are a result of physiographical and topographical conditions. On page 9785 lines 26–28, and page 9786 lines 1-22, we emphasize that ‘’Less water

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is recharged through AR 2 (area of 970 ha). This is probably due to poor vegetation cover (observed in the field, Fig. 11) or the clogging in this zone and consequently less recharge occurred as compared to AR 1 (a,b). In order to stabilize and increase the infiltration rate in the FWS systems, indigenous trees adapted to this environment have been tested, but as their growth is too slow, two species belonging to the exotic genera (Eucalyptus and Acacia) have been planted experimentally, mainly in AR 1, along with three indigenous trees and bushes (Khanmirzaei et al., 2011). The trees were planted on 5 plots of 4×4m spacing covering about 15% of AR 1 and also behind each embankment in the entire area of AR 1 and part of the area of AR 2 in 1986 (Fig. 11). The Agha Jari formation covers most of the Tchah-Qootch basin and represents early to middle Miocene and greater sediment volumes, as compared with the Bisheh-Zard basin, being transported to the GBP during flood periods. Since AR 2 receives water from both Tchah-Qootch and Bisheh-Zard Ephemeral Rivers, sediments also are transported that can be a cause of clogging and infiltration reduction in this recharge zone. To address this issue, the research carried out by Mohammadian and Kowsar (2003) shows an increase in the concentration of three different types of clay at the depth of 7.5 m after 13 yrs operation of the system which shows gradual impermeability and eventual clogging of the vadose zone by translocation of extremely small particles. Also, research reveals that the average infiltration rate of an afforested system was 9.3 cm h−1 as opposed to 3.8 cm h−1 for a treeless system, and 7.7 cm h−1 for the area outside of the FWS systems (Kowsar, 2005). As a result, after development in 1996, more water recharged through the artificial recharge system rather than through the river channel, and AR 1 (a,b) is the main recharge zone among all FWS zones." It is well known that plant roots together with organic material increase infiltration rates through physical and biological processes. Consequently, reforestation of areas also means that the effects of siltation on permeability to some extent are balancing the recharge rates.

4) The objective of this study and its model are primarily addressed toward assessing infiltration issues. Nevertheless, the research approach is totally based on ground

water modeling. As such the level of uncertainty regarding the actual process the take place through the vadose zone to ground water is extreme and so is the sensitivity to recharging values. Technically, using groundwater level fluctuation to estimate recharge is a common and valid approach. Nevertheless, results should have been validated (even conceptually in qualitative manner) through independent other parameters that are independent of the fluctuation in groundwater level. For instance, floodwater infiltration and groundwater recharge inherently impact the chemical composition of groundwater (or in a more simplistic way salinity or EC). Since those parameters are very easy to be measures I have a personal feeling that the model results regarding the recharge process could well be validated through simple independent parameter as variation groundwater EC during recharge events. This is only one option out of many independent ways to get a "better feeling" of the actual infiltration process that could have finally support the results. Somehow this work did only little to validate results on infiltration process.

→ The authors agree. As mentioned in the Introduction, ”the scarcity of data in many arid regions, especially in the Middle East, has necessitated the use of combined mathematical models and field observations to estimate recharge. Mathematical groundwater models are used to simulate aquifer conditions, to estimate aquifer parameters, and to predict groundwater conditions. In addition, as groundwater is essentially a hidden resource, studies on groundwater under both natural and artificial boundary conditions require modeling techniques (Scanlon et al., 2002)”. Unfortunately, the only available groundwater data are observed water levels for about 6-7 monitoring wells (the oldest installed around 1993). For this reason, an inverse modeling approach was developed in which confidence interval of the estimated parameters and sensitivity to the observations and parameters carefully were checked in all model steps in order to decrease the level of uncertainty. Our aim was to provide an approach capable of estimating the recharge parameters in such complex systems even with the scarcity of available data. At present we are installing new pressure transducers and salinity sensors that can be used in line with the suggestions by the reviewer. Thus, we hope soon to be able to compare modeling results with salinity changes due to infiltrating water.

5) In page 9775 line 7, the authors explain reduction in groundwater level by over exploitation by pumping. On one hand this may be a viable explanation. On the other hand it could well be aggravated by a decreased recharge due to reduced infiltration from the spreading zones. This phenomenon has been observed in many infiltration reservoirs in arid zones.

→ The number of wells in the area has increased tenfold or more. We are rather certain that groundwater decline is due to over-pumping. We will clarify the text by including: ''As a consequence of the floodwater spreading system, the number of legal and illegal pumping wells in the area increased to over 120 wells in 1996 (Ghahari and Pakparvar, 2007), about 10 times the number before establishing the system. However, this number decreased to 85 in 2006."

6) In page 9775 line 18, the authors state that 10% of the irrigation water is assumed to be back infiltrated (as agricultural return flow). It is a vague number that require better be explanation, or at least some discussion. For drip irrigation this value is reasonable, on the other hand if farrow irrigation is practices than return flow may exceed 50%. This is a significant difference that requires elaboration. Moreover, if 10% is a solid value than the authors should be concerned of an expected dramatic increase in solute concentration of the return flow. The return flow concentration may increase by 5-10 times fold of the concentration of the groundwater that is pumped and used for irrigation. This may be resulted in dramatic deterioration of ground water quality. Examples for that process may be found in all arid countries. Though this is not the main subject and objective of this manuscript in my view the authors should discuss this issue, even in brief.

→ The authors agree with the reviewer that more explanation of irrigation return water is required. The text is too short and confusing. Therefore, the following text will be added to the manuscript. ''Since there was no available data for agricultural return flow,

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10% of total discharge from pumping wells first was subtracted as a discharge input to the unsteady model (Jafari et al., 2012a). However, it was changed during the calibration process of each unsteady-state model in order to achieve the best agreement between observed and simulated value." In order to substantiate return flow volumes more studies are needed on irrigation techniques, pumped volumes, crop types and irrigation requirements. We feel that this is needed in continuing studies, but at present this is beyond the scope of the manuscript. We also agree that return flow quality is important for groundwater sustainability but that perhaps this also is a bit beyond the scope of the paper.

7) In page 9784, lines 9-13, the authors state that "the river channel recharge estimation represents relatively more uncertainty, which can be due either to less model sensitivity for parameters of ER or to major influence of extreme flood events on the estimated recharge in the channel". To my experience it is obvious that the level of uncertainty under the river channel zone is much higher simply because infiltration rate and percolation velocities under the active channel are inherently higher compare to the unavoidable much low infiltration rate under the clogged flooding zones. There are many studies showing very quick response time of ground water to flooding events under stream channels. This is a localized phenomenon that is expected to act in short duration and therefore will be reflected as uncertainty.

→ The authors appreciate the reviewer's comment and consider it in the discussion section of the manuscript.

8) My argument that artificial recharge of flood water in spreading zones in arid lands is "not as efficient" as planned (and presented in this manuscript), mainly due to clogging, is getting stronger upon analyzing the "Recharge contribution to groundwater" chapter 3.2.2. (page 9785,lines 2-25). Figure 10 shows clearly that the recharge rate through the early stages (years 1993-1996) was significantly more efficient compare the later years, though no significant change in rain pattern was recorded. The authors do not provide reasonable explanation to that and provide only vague explanation in page

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9785 lines 20-25.

→ The authors would like to extend the discussion on possible reasons for interannual variation. As is seen in Fig. 10, there is, however, no significant difference in the precipitation for either the 1993-1997 or the 2003-2006 period, but the recharge in 2003-2006 was about double that in 1993-1997 with the exception of one event in very early 1993. However, it is noted that the artificial recharge area 1 (AR 1), was developed from 420 to 1020 ha in 1997. In case of clogging of the system, the recharge difference between the AR (1 and 2) and ephemeral river (ER) should be at maximum, which is not the case, because even more water recharged through the AR (1 and 2) e.g., during 2006. In conclusion, clogging and siltation in all artificial recharge systems as well as all water structures are inevitable and result in less efficiency. According to this, the system in the beginning was assigned a 12 to 15 years life time. But our studies and particularly the one presented here show that the system is still working well after about 30 years. The authors believe that, with regular inspection and maintenance of such systems, their life-time and efficiency will be much longer, and they will yield a high return in terms of small yearly investments. In addition, one of the objectives of the system is also to bring to the originally poor soil some more fertile soil for agriculture from intermountain-upstream catchments where there is no possibility for farming. Our recent results (unpublished yet) show double efficiency of rainfed crops in a FWS system in comparison with a natural control plot outside the system. The above text will be added to the manuscript.

9) Than in the next paragraph of this chapter the authors state that "in order to stabilize and increase infiltration rate eucalyptus trees were planted, ignoring the huge transpiration capacity of these trees. In fact in few places around the world these trees were planted in order to dry swamps. Transpiration factor of a dense Eocalyptus forest (as appear in figure 11) may have a significant impact on the total recharge as well as direct groundwater abstraction, especially from shallow groundwater.

→ The authors agree. One problem that we have been facing for several years is the

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high evapo-transpiration of the Eucalyptus trees. For this reason, five different varieties of Palm trees and a Jojoba tree species have been tested in order to replace the Eucalyptus. Palm trees have not been successful due to their low resistance against flooding and algae infection and the Jojoba project has not been finalized yet. As stated in the manuscript, page 9786 lines 1-19, Eucalyptus was planted, particularly in the first basins as it was already predicted to be clogged, as its growth is fast, in order to combat wind erosion in the region, increase the infiltration capacity, and stabilize soil etc. To address this issue, the text below is given in the manuscript, page 9786 lines 17-19, ‘’Also, research reveals that the average infiltration rate of a reforested system was 9.3 cm $h{-1}$ as opposed to 3.8 $cmh{-1}$ for a treeless system, and 7.7cm $h{-1}$ for the area outside of the FWS systems (Kowsar, 2005)”. It should be noted that this is a decision which was made in the beginning of the project and perhaps the right decision considering all crucial conditions at the time. However, very deep Eucalyptus' roots also contribute to increasing the infiltration rate.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 9767, 2012.