Interactive comment on “Analysis of groundwater flow and stream depletion in the L-shaped fluvial aquifer” by Chao-Chih Lin et al.

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The paper under review presents a semi-analytic method for describing groundwater flow in an irregular (L-shaped) unconfined aquifer bounded on two sides by contributing streams. The authors have presented a solution for groundwater flow in a steady-state condition, and, using the steady-state solution as a boundary condition, under the influence of a single pumping well. The authors’ work is developed from the work of Kihm et al. in the 2007 paper “Three-dimensional numerical simulation of fully coupled groundwater flow and land deformation due to groundwater pumping in an unsaturated fluvial aquifer system” and draws heavily from the conceptual model developed therein.

Substantive Praise-Worthy Aspects:

1. In this paper, the authors present a novel method for solving for the groundwater flow field for a complex hydrogeology problem. As noted by anonymous referee #1, few papers address groundwater flow in multi-unit aquifers with complex shape, so by presenting a semi-analytic solution to groundwater flow under these conditions, this paper provides insight into methodology for representing hydrologic processes. The problem addressed by the authors also provides insight into modelling the relative contribution of aquifer storage and stream filtration water to the total water abstracted from a pumping well. The authors’ work also contributes to an understanding and awareness of the interaction of surface hydrology and groundwater, a topic that should be further addressed and developed. By developing a solution for the groundwater flow field in a system incorporating these factors, the authors have made a worthy contribution to the field of hydrology and engineering.

Response:

Thanks for the comment. We provide a point-by-point response to each of your comments listed below. The page and line numbers mentioned in our responses are referred to those in the revised manuscript.

Substantive Considerations:

2. This paper draws heavily on the work of Kihm et al. (2007), and I am concerned that not all the material presented has been cited correctly. Several examples of incorrectly cited material are provided below:

The sentence on P.4, L.9-10 is cited as a summary, but the wording may not be sufficiently different from the original sentence in Kihm et al. (2007, P.4).

Response:

The sentence in lines 16-17, page 4 has been modified as: "The annual average heads above the bottom of the aquifer are respectively identified as 5.18 m, 4.06 m and 5.29 m at points A, B, and D (Kihm et al., 2007)."

3. A direct quotation from Kihm et al. (2007, P.4) that was not properly indicated or cited was detected on P.4, L.17-18.

Response:

The citation has been added in lines 28-31, page 4 as: "The annual average depth from the ground surface to the water table is 1.26 m with a spatial variation from 0.57 m to 1.95 m in accordance with the average water stages in the streams AB and BD (Kihm et al., 2007). This depth was estimated under the hydrostatic equilibrium condition for the aquifer system before pumping and subject to the effect of net annual average rainfall."

Prior to the start of groundwater pumping, the aquifer system is assumed to be at a hydrostatic equilibrium condition corresponding to the net annual average rainfall rate (i.e., 20%×1287 mm/year = $8.16\times10^{-9}$ m/s), the annual average depth to the water table from the ground surface (i.e., 1.26 m), and the annual average water stages above the bottom of the aquifer in the two surrounding perennial streams (i.e., 5.18 m at Point A, 4.06 m at Point B, 5.29 m at Point C), which are all mentioned above.

4. Figure 6 is an updated reprint of Kihm et al.'s Figure 12 (2007, P.12), but is not directly cited in the figure caption.

Response:

Part of Figure 6 is from Kihm et al. (2007) (i.e. observation and FEM simulation at piezometers $O_1$, $O_2$ and $O_3$) and therefore the citation of Kihm et al. (2007) has been added in the figure caption as

"Figure 6: Temporal distributions of hydraulic head $H_{io}$ observed at piezometer $O_i$ and $H_{iF}$ simulated by the FEM simulations both reported in Kihm et al. (2007) and $H_{iA}$ and $H_{iM}$ predicted by the present solution and MODFLOW, respectively, for $i$ = 1 - 3."

5. Important assumptions made in the development of the conceptual model have not been discussed. These assumptions follow those made in Kihm et al. (2007) and include the assumption that hydrostatic conditions exist in the vertical profile

through both units of the aquifer (i.e. the piezometric surface is equal to the water table at all points along the vertical profile) and that recharge to the system from vertical percolation or precipitation is negligible. These assumptions, and others, may represent significant deviations from real-world conditions, and should be explicitly stated.

Response:

Thanks for the comment. The pumping well in this study is considered as a fully penetrating well as mentioned in Kihm et al. (2007), and thus the hydraulic gradient in the vertical direction is neglected. Furthermore, the effect of rainfall recharge on the water table had been considered as stated in our response to the third comment. We have modified some sentences in the revised manuscript to make them clear:

In Sect. 2.1:

"Pumping wells in the conceptual model are assumed to fully penetrate the aquifer near the perennial stream AB as those did in Kihm et al. (2007), and therefore the hydraulic gradient in vertical direction is neglected." (lines 24-26, page 4)

In Sect. 2.2:

"Consider that there are totally M pumping wells in region 1 and N pumping wells in region 2, and all the pumping wells fully penetrate the aquifer." (lines 2-3, page 5)

6. Although the piezometer data presented in Kihm et al. 2007 appears to support the modelled solutions, it should be noted that piezometer observations are only available over a period of 5 days; no information is presented to validate the modelled response to pumping beyond this period. Considering Figure 6, the 5-day observation period appears insufficient to observe any response to pumping at piezometer 3 (O3). This indicates that these data are irrelevant for the purpose of validating the transient solution for hydraulic head distribution presented by the authors.

Response:

In general, field observations for groundwater pumping are not easy to obtain and the measurement period is usually limited in a short time (Hunt et al., 2001; Fox, 2004; Lough and Hunt, 2006). We have compared the predicted results of proposed solution to the field data in a period of 5 days and the largest relative difference 1.74% occurs at $O_2$. This result indicates that the present solution gives fairly good predictions in the early pumping period. In addition, the comparison of the temporal head distributions predicted by the present solution and two different numerical approaches ensures that the present solution also provides reasonably good results in predicting the head distribution after long term pumping. We have rewritten the sentence in lines 8-10, page 12 as:

"In addition, the largest relative differences between measured heads and predicted heads by the present solution at $O_1$ to $O_3$ during 0.1 to 5 day are respectively 1.64%, 1.74% and 0.62%, indicating that the present solution gives good predictions in the early pumping period."

7. It is also to be considered that at a time period of less than 5 days, the majority of the modelled contribution of abstracted water is from aquifer storage (SRR), with the contribution from stream filtration (SDR) increasing after this point. The absence of observed piezometer response to pumping after a time of 5 days would seem to prevent any conclusions from being drawn as to the application of the method presented by the authors in predicting aquifer response to pumping in situations with a large stream filtration component.

Response:

In the short time pumping period (in 5 days), the present solution has been validated by measured data provided by Kihm et al. (2007). Unfortunately, there is no more observation about the pumping response beyond 5 days. The simulation result from FEM for the aquifer system has been verified by Kihm et al. (2007). Figure 6 shows a good match for the predictions of the present solution with the FEM simulations for pumping after 5 days, indicating that the present solution provides a fairly good prediction and is applicable in engineering practice.

8. It is my opinion that the results presented in this paper are insufficient to draw conclusions as to the validity of the methodology presented in predicting aquifer response to pumping. The results presented, however, demonstrate consistency between the semi-analytic method presented by the authors and the numeric model developed by Kihm et al. for the same aquifer system. Likewise, it is my opinion that the results presented are insufficient to draw conclusions regarding the significance of unsaturated flow and land deformation due to the limited observed data.

Response:

The text ", implying that the effects of unsaturated flow and land deformation on the groundwater flow in Yongpoong aquifer are small and may be negligible" in the conclusion has been slightly modified and moved to line 10, page 12 after "in the early pumping period." as

"Moreover, the effects of unsaturated flow and land deformation on the groundwater flow in Yongpoong aquifer are small and may be negligible."

9. The authors present the semi-analytic solution as a design tool for determining well location. The demonstrated applicability of the numeric simulations presented by Kihm et al. 2007 and the authors' solution developed in MODFLOW, validated by the semi-analytic method presented in this paper, would seem to be more flexible and appropriate tools for the design of well location.

Response:

One of the objectives in this study is to interpret the flow interaction between the aquifer and nearby streams, which can be used as a design tool to determine well location with a specific pumping rate for required amounts of SDR from nearby stream. Thus, the calculation of stream depletion rate (SDR) is necessary to determine the well locations based on the estimation of distance to the stream for extracting a specific amount of water from a nearby stream. Basically, the SDR can be easily estimated by taking the derivative of analytical solution with respect to the related direction, then integrating along the stream. However, the numerical approaches presented by Kihm et al. (2007) and MODFLOW are not available to calculate the SDR directly.

Further to the substantive observations which I have made above, there are several additional observations of a less critical nature that I would like to make.

Strengths:

10. The derivation of the analytic solution appears well documented and described. This paper provides the reader with a clear description of the analytical methods used by the authors, theoretically allowing for the results to be reproduced. The literature review presented by the authors also appears to be detailed, and well-structured, providing valuable information to other scientists interested in studying groundwater flow in aquifers with complex boundaries and that are bounded by contributing streams.

Response: Thanks.

Areas of Improvement:

11. The assumption was made that all flow is horizontal, including the flow through the overlying clay loam aquitard unit, which has been assigned a hydraulic conductivity two orders of magnitude lower than the underlying loamy sand unit. This assumption is necessary for the simplification of the groundwater flow

equation to 2-dimensions, but is non-realistic and the implications of this assumption have not been addressed by the authors.

Response:

As described in Kihm et al. (2007) for Yongpoong 2 Agriculture District, the streams almost fully penetrate the aquifer system and a fully penetrating well is installed and screened in the entire aquifer near one of the streams. Accordingly, it is reasonable to treat the flow as horizontal in the aquifer. Furthermore, the equivalent hydraulic conductivity for the loam aquitard and loamy sand units with different conductivities is estimated and used to simulate the flow through these two units.

12. The equivalent hydraulic conductivity for horizontal flow (Eq. (48)), discussed on P.10, L.3-4, is calculated as the weighted arithmetic mean of the two units assuming the full thickness (2.5 m) of the overlying unit is available for groundwater flow. Since the overlying unit is only saturated to a maximum seasonal average thickness of 0.79 m (as described on P.4, L.9), it may be more appropriate to use the saturated thickness of the upper layer when calculating the equivalent hydraulic conductivity for the aquifer.

Response:

Thanks for the comment. We suppose that the thickness of 0.79 m for the overlying unit is a typo and should read 1.79 m (i.e., 5.29 m - 3.5 m=1.79 m). We use 1.79 m for the upper layer thickness to estimate the equivalent hydraulic conductivity ($K_h$). The estimated $K_h$ is $1.3\times10^{-4}$. The difference between this figure and the value used in the study (i.e., $1.2\times10^{-4}$) is insignificant, implying that the influence of different thickness of overlying unit on the $K_h$ is small.

The logic regarding the required well setback from a stream is incomplete (P.12, L.7-9), and the connection between the required well setback distance from possible contaminants and the well setback distance from a stream is not clear.

Response:

The sentence in lines 4-6, page 13 is rewritten as: "Driscoll (1986, p. 615) mentioned that a well shall be installed at least 45.7$m$ from areas of spray materials, fertilizers or chemicals that contaminate the soil or groundwater. Hence, the distance from the pumping well to the stream is considered at least 50 m to guarantee the quality of extracted water."

13. As noted by anonymous referee #2, the solution presented by the authors is semianalytical. The first use of the term "semi-analytical" by the authors is in the

conclusion on P.12, L.25. The solution presented by the authors should be consistently described throughout the paper, as appropriate.

Response:

Thanks for the suggestion. The steady state solution derived in this study is analytical and the transient solution is semi-analytical because it needs a numerical tool to obtain the time-domain solution. To avoid confusion, we therefore use the word "semi-analytical" in lieu of "transient" before the time-domain solution in the revised manuscript.

Several minor grammatical issues were found within the paper, and are listed as follows:

P.2, L.9 typo: "arbitrarily", should be "arbitrary"

Response: Thanks, it has been corrected.

P.2, L.12-15 ambiguous references; it is not clear that the authors are referring to the work of Kihm et al. (2007)

Response:

We have modified the sentences in lines 14-17, page 2 as: "The domain of the aquifer in their study is in L shape and bounded by streams and impermeable bedrocks. They performed FEM simulations for steady-state spatial distributions of hydraulic head before aquifer pumping and then for the distributions of hydraulic head and land displacement vector after one-year pumping. Their simulation results were compared and validated with the field measurements of hydraulic head and vertical displacement in the transient case."

P.2, L.12 inconsistent hyphenation of "L-shape"

Response: Thanks, it has been corrected.

P.2, L.15 missing "the": "in <the> transient case"

Response: Done as suggested.

P.2, L. 20 poor grammar: "to solve a regional groundwater in an…"

Response:

We have rewritten the sentence in lines 22-24, page 2 as: Serrano (2013) illustrated the use of Adomian's decomposition method to solve a regional groundwater flow problem in an unconfined aquifer bounded by the main stream on one side, two tributaries on two sides, and an impervious boundary on the other side.

P.3, L.31 “perennial stream<s>…”

Response: Corrected.

P.4, L.22 syntax error: “Consider that there are totally M pumping wells…”

(Throughout paper) inconsistent use of italics to denote units, and spaces between values and units (i.e. 6m, 6 m, 6 m)

Response: We have carefully checked and revised the manuscript.

P.2, L.34 ambiguous reference to “irregular boundaries” – what are irregular boundaries?

Response:

We have modified the sentences in lines 1-3, page 3 as:

“Kuo et al. (1994) applied the image well theory and Theis’ equation to estimate transient drawdown in an aquifer with irregularly shaped boundaries. The aquifer is an oil reservoir bounded by three tortuous faults. However, the number of the image wells should be largely increased if the aquifer boundary is asymmetric and rather irregular.”

P.3, L.18 ambiguous reference: “principle direction aligned with the border of the sub-region”; which border?

Response: The sentence in lines 24-26, page 3 has been rewritten as: “The aquifer is divided into two rectangular sub-regions. The aquifer in each sub-region is homogeneous but anisotropic in the horizontal plane with principal direction aligned with the borderline of the rectangular sub-regions.”

P.13, L.6-7. Awkward transition. This should either be a new paragraph, or these sentences should be rewritten.

Response:

We have divide the second paragraph in pages 13-14 of conclusion into two parts as:

“The 3D finite difference model MODFLOW is first used to check the accuracy of hydraulic head predictions by the present solution for the L-shaped two-layered aquifer system. The hydraulic head distributions predicted by present solutions agree fairly well over the entire aquifer except the heads nearing the no-flow boundary. The solution for hydraulic head distribution in the L-shaped aquifer without pumping has been used to investigate the effect of anisotropic ratio ($Kx\ /Ky$) on the steady-state flow system. It is interesting to note that the flow pattern in terms of lines of equal hydraulic head is strongly influenced by the value of anisotropic ratio for the region near the turning point of the L-shaped aquifer.

The transient solution proposed by this study is employed to simulate the head distribution induced by pumping in the aquifer within the agriculture area of Gyeonggi-Do, Korea. The aquifer is approximated as L-shaped in this study. The simulation results indicate that the largest relative difference in predicted temporal head distributions at three piezometers by the present solution and Kihm et al.'s (2007) FEM simulation is less than 1.74%, implying that the effects of unsaturated flow and land deformation on the groundwater flow in Yongpoong aquifer are small and may be negligible."

Suggestions:

A careful and detailed review of the entire paper should be conducted by the authors to ensure all material is appropriately cited. The authors should revisit the description of the conceptual model and either further develop and detail the assumptions made in the development of the conceptual model or clearly state that the conceptual model and assumptions have been taken from the work of Kihm et al. (2007) and refer the readers to that paper for details.

The authors should address the implications of the simplifying assumptions when applying the results of the semi-analytic and numeric solutions for groundwater flow in this aquifer to the real world. The limitations of the 5-day observation period should be noted by the authors. The conclusions drawn by the authors should be reconsidered. The results appear to demonstrate consistency between the semi-analytical method presented by the author and the numeric model presented by Kihm et al. (2007), and raise questions as to the significance of unsaturated flow and land deformation. Conclusions regarding real-world aquifer response to groundwater abstraction appear unsupported. It is recommended that the authors reframe their work as a method of validating the numeric simulations and as a method of developing a better understanding of the physical processes governing groundwater flow.

Response:

Thanks for the suggestion. We have revised our work according to the comments herein and the comments from two anonymous referees for manuscript improvement.

Reviewer Experience:

It should be noted that I am a Master of Science candidate in the field of engineering, with minimal experience in either analytical or numerical methods for describing groundwater flow. I have no prior experience refereeing academic submissions. The observations and opinions I have expressed herein should be considered with my inexperience in mind.

Proposed Fate:

The authors are to be commended for their approach to this complex problem. It is my opinion that the methods and results presented by Lin, Chang, and Yeh makes a valuable contribution to the field of hydrology and engineering and are of interest to the scientific community. However, the issues noted above are significant. I recommend that this paper be resubmitted for review following the revisions suggested above. I would further recommend that extreme caution be exercised by both the authors and by the editor in vetting the submission for incorrectly cited material.

Response: Thanks.

References:

Fox, G. A.: Evaluation of a stream aquifer analysis test using analytical solutions and field data, Journal of the American Water Resources Association, 40(3), 755-763, 10.1111/j.1752-1688.2004.tb04457.x, 2004.

Hunt, B., Weir, J., Clausen, B.: A stream depletion field experiment, Ground Water, 39(2), 283–289, doi/10.1111/j.1745-6584.2001.tb02310.x, 2001.

Lough, H. K., and Hunt, B.: Pumping Test Evaluation of Stream Depletion Parameters, Ground Water, 44(4), 540-546, doi:10.1111/j.1745-6584.2006.00212.x, 2006.

Kihm, J.-H., Kim, J.-M., Song, S.-H., and Lee, G.-S.: Three-dimensional numerical simulation of fully coupled groundwater flow and land deformation due to groundwater pumping in an unsaturated fluvial aquifer system, Journal of Hydrology, 335, 1-14, http://dx.doi.org/10.1016/j.jhydrol.2006.09.031, 2007.

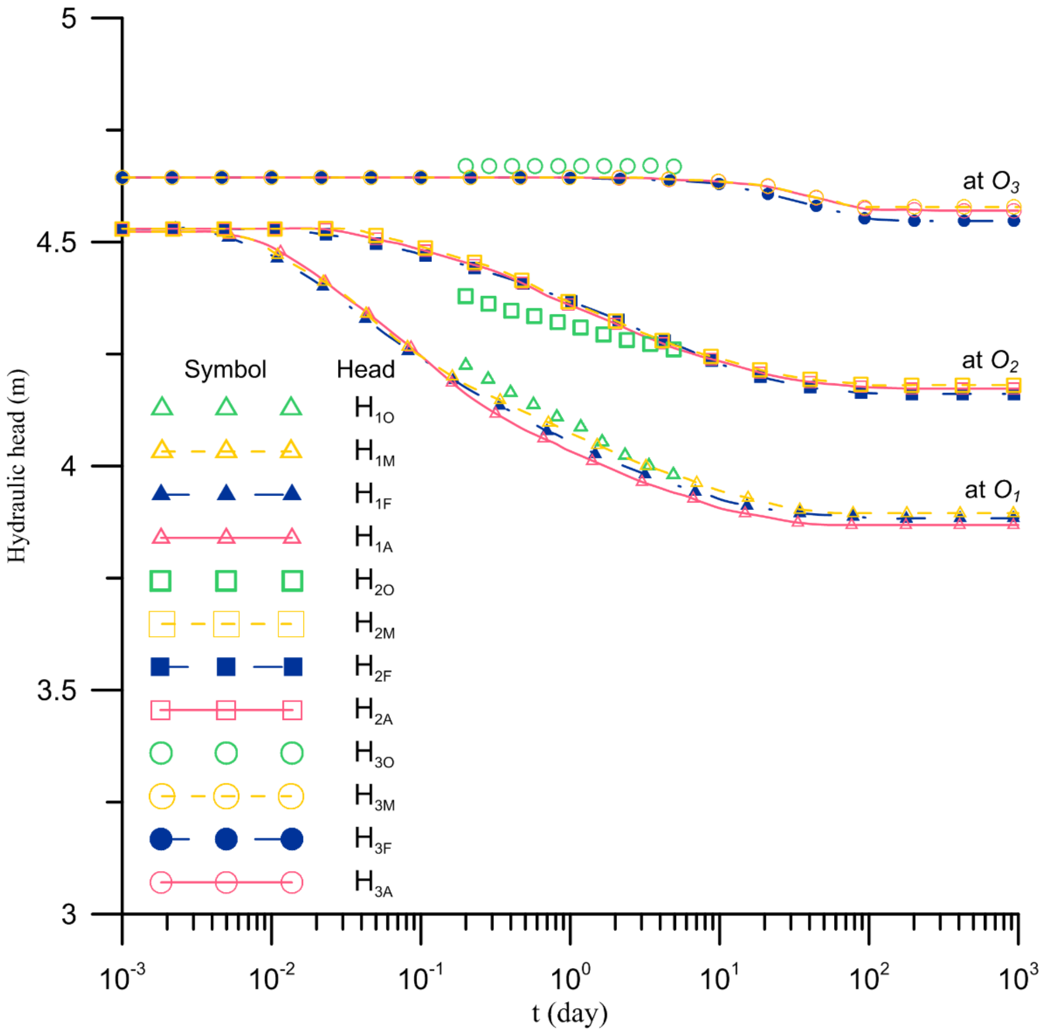


**Figure 6: Temporal distributions of hydraulic head $H_{io}$ observed at piezometer $O_i$ and $H_{iF}$ simulated by the FEM simulations both reported in Kihm et al. (2007) and $H_{iA}$ and $H_{iM}$ predicted by the present solution and MODFLOW, respectively, for $i$ = 1 - 3.**