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Hydrology and Earth System Sciences Discussions

Interactive comment on "Predictability, stationarity, and classification of hydraulic responses to recharge in two karst aquifers" *by* A. J. Long and B. J. Mahler

J. Von Asmuth (Referee)

Jos.von.Asmuth@kwrwater.nl

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General comments

The paper by Long and Mahler provides interesting data, methods and results on the simulation of groundwater levels and spring and stream flows in karst aquifer systems. It presents a method for simulating time series of these parameters through the combination of a simple unsaturated zone model and a convolution model that accounts for the response of the saturated, karst aquifer. In addition, they present a method for dealing with non-stationarity, and for classifying the results or responses thus ob-

tained. The performance of the approach, judging from the Nash-Sutcliffe coefficients, appears to be generally very good (although even reaching a value of one, implying the absence of model errors, which could use some clarification).

In general, the material is very interesting but I feel that there are also improvements to be made. The title of the paper is appealing, but it suggests that the issues of predictability, stationarity and classification are discussed in a more fundamental way. The paper as it is presents a lot of material, where each issue perhaps deserves more attention and a more in depth treatment. On the other hand, the paper could also be presented as a case study, rather than as a fundamental discussion of these terms. In both cases, the paper may benefit by placing the methods and terminology in a more general framework.

To give an example, convolution is related to linear systems theory and (of origin) statistical methods like time series analysis and system identification. In related literature and in general in statistics, e.g.:

Box, G. E. P. and G. M. Jenkins, 1970. Time Series Analysis: Forecasting and Control. Holden-Day, San Fransisco.

Dooge, J. C. I., 1973. Linear theory of hydrologic systems. Technical Bulletin 1468, Agricultural Research Service, U.S. Department of Agriculture, Washington D.C.

Ljung, L., 1999. System Identification, Theory for the user. Prentice Hall, Upper Saddle River.

stationarity has a somewhat different but distinct meaning (see also http://en.wikipedia.org/wiki/Stationary_process) and the 'stationarity' treated in this paper is generally called 'time-invariance' therein. Also, in the field of time series analysis, the method presented here is not unknown. See, e.g., chapter 5 'Models for Time-varying and Nonlinear Systems in (Ljung, 1999) or the periodic models in:

Hipel, K. W. and A. I. McLeod, 1994. Time series modelling of water resources and environmental systems. Elsevier, Amsterdam.

The term 'nonstationary' is not explicitly defined in this paper, and no reference is made to the issue of non-linearity, nor to its difference with 'stationarity' or time-invariance. For non-linearity or non-linear models see, e.g.:

Berendrecht, W. L., Heemink, A. W., Van Geer, F. C., Gehrels, J. C., 2004. State-space modeling of water table fluctuations in switching regimes. Journal of Hydrology . 292 249-261.

Berendrecht, W. L., Heemink, A. W., Van Geer, F. C., Gehrels, J. C., 2006. A non-linear state space approach to model groundwater fluctuations. Advances in Water Resources. 29 959–973.

Knotters, M., De Gooijer, J. G., 1999. Tarso modelling of water table depths. Water Resources Research. 35(3), 695-705.

Tong, H., 1990. Non-linear Time Series: A Dynamical System Approach. Clarendon, Oxford.

As for the metrics used, they are related to the general, statistical concept of moments of distribution functions. The use of moments for characterizing IRFs was suggested in e.g.:

Nash, J. E., 1959. Systematic Determination of Unit Hydrograph Parameters. Journal of Geophysical Research. 64(1), 111–115, doi:10.1029/JZ064i001p00111.

Jury, W. A. and K. Roth, 1990. Transfer functions and solute movement through soil: theory and applications. Birkhäuser Verlag, Basel, Switzerland.

Maas, C., 1994. On Convolutional Processes and Dispersive Groundwater Flow. PhD Thesis, Delft University of Technology, Delft.

An advantage of moments is that they provide an elegant link to the underlying physics of a system via so-called moment-generating differential equations, see e.g.:

Bakker, M., Maas, K., Von Asmuth, J. R., 2008. Calibration of transient groundwater models using time series analysis and moment matching. Water Resources Research. 44(W04420), doi:10.1029/2007WR006239.

Govindaraju, R. S. and B. S. Das, 2007. Moment analysis for subsurface hydrologic applications. Water Science and Technololgy Library, vol. 61. Springer, Dordrecht.

Harvey, C. F., Gorelick, S. M., 1995. Temporal moment-generating equations: Modeling transport and mass-transfer in heterogeneous aquifers. Water Resour. Res. 31(8), 1895-1911.

Von Asmuth, J.R. and Maas, K. The method of impulse response moments: a new method integrating time series-, groundwater- and eco-hydrological modelling. Impact of Human Activity on Groundwater Dynamics (eds Gehrels, J.C., Peters, N.E., Hoehn, E., Jensen, K., Leibundgut, C., Griffioen, J., Webb, B., and Zaadnoordijk, W.J.), IAHS Press, Centre for Ecology and Hydrology, Wallingford, 51-58, 2001.

The use of moments for aquifer characterization was addressed in:

Von Asmuth, J. R., Knotters, M., 2004. Characterising spatial differences in groundwater dynamics based on a system identification approach. Journal of Hydrology. 296(1-4), 118-134.

As for predictability (later in the paper 'Predictive strength' is used, is that the same?), the approach could be formalized and be made more explicit, where it now appears to be somewhat heuristic and as stated sometimes relies on 'trial and error'. An interesting additional issue, apart from the estimated metrics themselves, would be their covariance or in other words the identifiability of the metrics. According to table 1, the model may contain 10 parameters that need to be estimated from the data. In my experience, in convolution models with only three or four parameters, the parameters are often already highly correlated and may not be uniquely identifiable.

For more detail, see the specific comments.

Specific comments

p9579-21: There have been developments in the use of convolution for modelling groundwater head series, the use of characteristics or moments of impulse response functions and their physical interpretation. Although these methods are formulated in a time series analysis framework, they are closely related and may be relevant for the contents of this paper. See for instance:

Von Asmuth, J. R., Bierkens, M. F. P., Maas, K., 2002. Transfer function noise modeling in continuous time using predefined impulse response functions. Water Resources Research. 38(12), 1287-1299, doi:10.1029/2001WR001136.

Bakker, M., Maas, K., Schaars, F., Von Asmuth, J. R., 2007. Analytic modeling of groundwater dynamics with an approximate impulse response function for areal recharge. Advances in Water Resources. 30(3), 493-504, doi:10.1016/j.advwatres.2006.04.008.

Von Asmuth, J. R., Maas, K., Bakker, M., Petersen, J., 2008. Modeling time series of groundwater head fluctuations subjected to multiple stresses. Ground Water. 46, doi: 10.1111/j.1745-6584.2007.00382.x(1), 30-40.

Bakker, M., Maas, K., Von Asmuth, J. R., 2008. Calibration of transient groundwater models using time series analysis and moment matching. Water Resources Research. 44(W04420), doi:10.1029/2007WR006239.

Convolution is now widely used for groundwater heads also, see e.g.:

Von Asmuth, J. R., Maas, C., Knotters, M., Bierkens, M. F. P., Bakker, M., Olsthoorn, T. N., Cirkel, D. G., Leunk, I., Schaars, F., Von Asmuth, D. C., 2012. Software for hydrogeologic time series analysis, interfacing data with physical insight. Environmental Modelling & Software. 38 178-190, http://dx.doi.org/10.1016/j.envsoft.2012.06.003.

p9580-3: At this point, also a reference to the use of spectral analysis may be relevant, as also that is used for aquifer characterization and the methods are related. It would

aid the reader if the advantages of convolution over alternatives like spectral analysis or their link are addressed. Please see for instance:

Larocque, M., Mangin, A., Razack, M., Banton, O., 1998. Contribution of correlation and spectral analysis to the regional study of a large karst aquifer (Charente, France). Journal of Hydrology. 205 217-231.

Lee, J.-Y., Lee, K.-K., 2000. Use of hydrologic time series data for identification of recharge mechanism in a fractured bedrock aquifer system. Journal of Hydrology. 229 190-201.

Manga, M., 1999. On the timescales characterizing groundwater discharge at springs. Journal of Hydrology. 219 56-69.

Von Asmuth, J. R., Knotters, M., 2004. Characterising spatial differences in groundwater dynamics based on a system identification approach. Journal of Hydrology. 296(1-4), 118-134.

p9581-13: Is groundwater recharge the same as effective precipitation or precipitation surplus?

P9582-6: The sentence appears to list the assumptions when using convolution. As such, it may help to state that convolution may be used for linear, time-invariant systems in general.

P9582-12: In this formulation of a convolution integral, y(t) depends on u(ïĆţ) which may be confusing.

P9582-13: system response function for y(t) may be a confusing term, as the impulse, step, block, and frequency response functions are also system responses. Why not use 'output' when u(t) is named input?

P9582-17: Please define N

P9582-19: What is the length of the IRF? Isn't 'the time that the impulse persists' in principle and/or in equation (5) infinite?

P9582-20: Please share some thoughts on the use of exponential and/or lognormal IRFs. In:

Maas, C., 1994. On Convolutional Processes and Dispersive Groundwater Flow. PhD Thesis, Delft University of Technology, Delft.

Nash, J. E., 1958. Determining runoff from rainfall. Proc. Inst. Civ. Eng. 10 163-184.

Von Asmuth, J. R., Bierkens, M. F. P., Maas, K., 2002. Transfer function noise modeling in continuous time using predefined impulse response functions. Water Resources Research. 38(12), 1287-1299, doi:10.1029/2001WR001136.

the Gamma or PearsonIII distributions are used. In:

Jury, W. A. and K. Roth, 1990. Transfer functions and solute movement through soil: theory and applications. Birkhäuser Verlag, Basel, Switzerland.

several are compared, also to an impulse response solution to the convection-dispersion equation. See also:

Veling, E. J. M., 2010. Approximations of impulse response curves based on the generalized moving Gaussian distribution function. Advances in Water Resources. 33 546-561.

See:

Von Asmuth, J. R., 2012. Groundwater System Identification, through Time Series Analysis. Ph.D. thesis, Delft University of Technology, Delft.

for a treatment of physically based responses of several elementary groundwater systems.

P9584-23: Here, the issue of non-stationarity is addressed by citing references where non-stationary IRFs are used. As stationarity is one of the main issues of the paper,

it would benefit by defining stationarity more clearly and/or discussing the term time-invariance used elsewhere and/or the difference with non-linearity.

P9585-6/7: These sentences postulate that the characteristics change and that is useful to separate the precipitation record, but this postulation is not really corroborated.

P9585-10: Please define CDMP mathematically

P9585-15: It is stated that this method is not previously used (for this, see also the general comments). Is it physically justified and what errors are made by doing so?

P9586-4: the paper would benefit if the authors refer to other publications where the use of metrics or characteristics of IRFs is treated. In the field of statistics, distribution functions are commonly characterized by their moments. Moments may provide a more general framework than the metrics presented here. For instance, what is and what isn't a ratio depends on the definition of the metrics. The use of moments is suggested in:

Nash, J. E., 1959. Systematic Determination of Unit Hydrograph Parameters. Journal of Geophysical Research. 64(1), 111–115, doi:10.1029/JZ064i001p00111.

Jury, W. A. and K. Roth, 1990. Transfer functions and solute movement through soil: theory and applications. Birkhäuser Verlag, Basel, Switzerland.

Maas, C., 1994. On Convolutional Processes and Dispersive Groundwater Flow. PhD Thesis, Delft University of Technology, Delft.

P9587-8: 'There is less confidence.....' Are or can the confidence intervals of the parameters and/or the simulation be used to quantify this?

p9587-13: What exactly were the selection rules?

P9590-9: Are the parameters adjusted or estimated by trial and error or automatic parameter optimization? I think I don't really understand the process described

P9590-17: The Nash criterion ranges up to 1. This implies a model without error. How can that be? Please explain.

P9591-5: Trial and error is not really explicit. What were the criteria?

P9596-4: Are the metrics novel, or are they comparable to the use of moments?

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 9577, 2012.