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Discussions

Interactive comment on "A partially-coupled hydro-mechanical analysis of the Bengal Aquifer System under hydrological loading" *by* Nicholas D. Woodman et al.

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General comments

This paper addresses an important aspect of groundwater management: the fact that groundwater levels do not reflect only the changes of groundwater storage but also reflect groundwater pressure changes due to mechanical loading by changes of total water storage above the formation. For deep confined aquifers, such as the deeper layers of the Bengal Aquifer System, conventional estimates of groundwater recharge based on changes of groundwater levels may be in error if moisture loading effects are ignored. In turn recognition and analysis of such loading effects can provide valuable

constraints on the evaluation and simulation of surface water processes such as runoff and evapotranspiration. These loading effects are only starting to be acknowledged in groundwater management practice and this paper therefore can make an important contribution to the literature in groundwater and surface water hydrology. However, the paper can be considerably strengthened and focused and major revisions are recommended with regard to the review of poromechanical theory, the simulation of various loading scenarios, and the presentation and interpretation of field data from the Bengal Aquifer System..

Specific comments

The introduction provides an extensive general review of poro-elastic coupling and only gradually reaches the idea that changes in "terrestrial water storage" (TWS) result in changes of groundwater pressure. But the phenomenon of groundwater pressure changes due to changes of atmospheric pressure, as expressed through the concept of "barometric efficiency", is well-known in hydrogeology and is an obvious example of groundwater pressure changes caused by surface loading. It is only mentioned later in the paper (L 199) although it is most directly relevant to the focus of the paper.

The barometric efficiency of observation wells in deep confined aquifers also can used to determine an in situ value of specific storage that is directly applicable to the interpretation of short-term moisture loading events. Such analyses are briefly mentioned in the text (L 186-194) with reference to Burgess et al (2017), but are not further described or used in the paper although they are surely relevant. At the very least a more detailed explanation should be provided of why these results are not used.

L 102 onward – Poromechanical equations. This section starts off with a lengthy review of general 3D poro-elastic equations and then arrives back to the 1D differential equation that is used in the subsequent simulations and interpretations. This general review can be largely eliminated from the paper because it does not present anything new that cannot be found in the literature as cited. The paper could then perhaps go directly to the 1D equation (# 9) including the discussion, more or less as give,n on when and why the 1D equations provide an adequate description of the poro-elastic interactions between stress and groundwater pressure. The appropriate equations for the loading efficiency and specific storage should be included - they are not given in the text as it stands.

L 148-359. The simulations of the three different loading scenarios can all be considered together as one, by treating the loading effects and the hydraulic head changes at the upper boundary separately. This approach is described and illustrated in detail by Anochikwa et al (2012) a reference that is important for this paper because it presents a somewhat similar analysis of poroelastic effects induced by moisture loading [Anochikwa, C.I., G. van der Kamp and S.L. Barbour, 2012. Interpreting pore-water pressure changes induced by water table fluctuations and mechanical loading due to soil moisture changes. Canadian Geotechnical J, 49(3): 357-366.]

With such an approach the Loading effects are manifested as pore pressure changes throughout the domain which then dissipate to the upper boundary, generally with very little and negligible effect on the hydraulic head at the upper boundary. Hydraulic head changes at the upper boundary propagate downward and dissipate. The two can be simply added to arrive at the total head changes throughout the domain. Such a decomposition is legitimate because it satisfies the boundary and domain conditions and the basic differential equations The advantage of such an approach to understanding and analyzing the combined effects of loading and flow is that the loading effects can be simulated and described separately from the effects of flow induced by changes of hydraulic head at the boundary. Such an approach may at first seem counter-intuitive, but it is mathematically and theoretically legitimate (given reasonably low compressibility of the formations), and can enhance understanding and visualization of the poroelastic processes.

L 229. Why ignore barometric effects? They can be easily dealt with by direct subtraction from the observation well records, and also provide a good estimate of loading

efficiency and compressibility of the formations. L 260. The assumption that loading efficiency is $\sim$ 1.0 is questionable and needs more justification, considering that the loading efficiency for barometric loading is an in-situ field measurement that closely corresponds in magnitude to the loading due to changes of TWS. Likely the instantaneous responses observed by the piezometers represent the short-term pore pressure changes in sands, whereas over the long term the pressure changes in clays may predominate. Thus the long-term value of specific storage, as applicable for changes of total water storage on an annual basis, may be $\sim$1.0 since such a long-term response of the entire groundwater system may be dominated by the more compressible aquitard portions of the basin. This is an important and poorly resolved issue in geolysimetry and merits attention.

L 298-299. The “counter-intuitive” amplitude response to the LD is likely due to a “traveling wave” effect of the transient sinusoidal flows. In fact the flows for this case can be mathematically decomposed as the superposition of the imposed groundwater head changes due to loading (but without flow) and an equal but opposite sinusoidal transient imposed at the water table which induces a downward traveling wave that is dissipated as it moves, but may also be “reflected” from the horizontal boundaries represented by different hydraulic properties, thus giving rise to amplitude and phases that appear anomalous and counter-intuitive. LL 337-458 Field data. The reality of the loading effects due to changes of Total Water Storage could likely be demonstrated more strongly by including description and analysis of the short-term loading effects due to individual rain events. Such events are mentioned in the text and appear to be present in the hydrographs shown in figure 6 and especially in figure 7. The sharp spikes with subsequent decay that appear in the rising limbs of the hydrographs are presumably due to large rain events and subsequent runoff and evapotranspiration. Certainly such short-term responses to individual events should be apparent in the hydrographs if the hypothesis of water loading effects is at all correct.

There is no detailed discussion of the climate of the region and of whether seasonal changes of total water storage of up to 1 meter, as implied by the records for the deep piezometers, are reasonable and realistic. The paper should therefore include a detailed presentation and discussion of the climate and water balance of the region, including estimates the water storage changes based on rainfall, runoff and evapotranspiration. L 449 the speculative uncertainty with regard to loading efficiency could perhaps be resolved by inspection of the responses at each depth to episodic rainfall events. As mentioned previously a description and analysis of barometric loading effects for the same piezometers would further establish the reality of the poroelastic responses to changes of total water storage.

Technical corrections

The reference information for Burgess et al (2017) is incomplete and requires more information as to the publisher and if necessary, how the report can be accessed.

LL 110-115 Can't have some units as Pa and others as MPa. That would require introduction of factors of 106 in the equations.

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