# Replies to comments on "A revisit of drawdown behavior during pumping in unconfined aquifers" by Neuman and Mishra

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## 1. Introduction

[1] We welcome the comments from *Neuman and Mishra* [2012]. It provides us the opportunity to state our position more clearly. Our reply to *Neuman and Mishra* [2012] is according to each paragraph of their comment.

### 1.1. Reply to Comments in Paragraphs 1 and 2

[2] Heterogeneity as investigated in our paper, presences of perched water table aquifers, limited leakage sources, boundary conditions, and many other factors that may modify the shape of a drawdown-time curve. Likewise, groundwater flow is driven by the energy gradient but it can be influenced by many different factors. It is not the intent of our paper to discuss them all. We merely emphasize the fact that the fundamental mechanisms causing the S-shaped curves are the transition of water release mechanisms and the vertical flow components. More importantly, our paper advocates that a multidimensional variably saturated flow model, which considers the transition of water release mechanisms and accounts for heterogeneity, would provide a more realistic representation of flow processes in unconfined aquifers during a pumping test. These conclusions are independent from the number of experiments we examined.

### 1.2. Reply to Comments in Paragraph 3

[3] *Tartakovsky and Neuman* [2007] and *Mishra and Neuman* [2010, 2011] consider unsaturated flow. However, realistic flow processes due to a lowering of the water table are simplified such that analytical solutions are tractable. For example, *Tartakovsky and Neuman* [2007] and *Mishra and Neuman* [2010 in equation (7)] assume that the unsaturated hydraulic conductivity and moisture capacity depend on the elevation not on the pressure head, which change dynamically. This assumption implicitly ignores the real flow process during the lowering the water table and in the unsaturated zone although it is justified as an approximation. Effects of such an approximation are vivid in Figures 7–9 of *Mishra and Neuman* [2011], even for the case they selected. An approximation is always an approximation; it is not the true solution to the variably saturated flow equation. Significant inaccuracy would occur if different initial and boundary conditions, and materials with rapid reductions in unsaturated hydraulic conductivity or moisture content as the pressure head becomes more negative (i.e., highly nonlinear unsaturated hydraulic properties) are considered. It is our opinion that to be rigorous, *Tartakovsky and Neuman* [2007] and *Mishra and Neuman* [2010, 2011] should have compared their analytical model with the numerical models, such as STOMP [*White and Oostrom*, 2000], VSAFT2 [*Yeh et al.*, 1993], VSAFT3 [*Srivastva and Yeh*, 1992], FEMWATER [*Lin et al.*, 1997], TOUGH2 [*Pruess et al.*, 1999], and others, for a variety of scenarios and soils. This would allow a full assessment of robustness and limitations of their linearized model.

### 1.3. Reply to Comments in Paragraph 4

[4] Regarding the sentence, "That a transition from compression-dominated ... is not new..."; yes, as stated in paragraph 12 of *Mao et al.* [2011], previous studies have either implicitly or explicitly related the S-shaped drawdown-time curve observed during pumping in the unconfined aquifer to a transition in water release mechanisms. Nevertheless, the exact nature of this behavior has been a source of confusion and debate. The confusion and debate, we believe, are a result of difficulty in solving analytically the governing equation for multidimensional flow through variably saturated media, which has been known for decades [e.g., *Neuman*, 1973]. This difficulty has promoted creation of simpler and practical mathematical models for the flow system (such as *Boulton* [1954, 1963], *Kroszynski and Dagan* [1975], and *Neuman*[1972] to mimic the S-shaped drawdown time curves commonly observed during pumping tests in unconfined aquifers).

[5] Because of the use of simpler models, without fully considering inherent transition in water release mechanisms during flow through variably saturated media, previous studies have to invent the delayed yield, the delayed gravity response, or the delayed water table response concept to explain the formation of the S-shaped drawdown-time curve. One of such popular simplified models is the delayed

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water table response model by *Neuman* [1972], which solves the saturated flow equation for media below the water table, uses a free surface boundary equation for the water table, and ignores the initially unsaturated zone above the water table. In addition, the release of water from initially saturated pores due to the falling of the water table is assumed to be instantaneous. In spite of these simplified assumptions, this model implicitly includes the transition of the water release mechanisms, i.e., elastic release of water from the saturated zone and instantaneous drainage of pores due to falling of the water table. Although the transition of water release mechanisms is not completely implemented, the model mimics the S-shaped drawdown-time curve observed during pumping tests in the unconfined aquifer. More importantly, it seems to provide a logical explanation of the formation of the S-shaped curve in terms of horizontal (Theis flow, elastic release), vertical (non-Theis), and horizontal (Theis, specific yield) flow during early, intermediate, and late time stages of a pumping test. Furthermore, it has led to practical-type curves for analyzing pumping tests in unconfined aquifers.

[6] Application of Neuman's model to drawdown-time data collected from field pumping tests, however, generally results in specific yield (effective porosity) values that are substantially below those that would be expected on the basis of other methods of measurement [see *Nwankwor et al.*, 1984; *Endres et al.*, 2006]. For example, *Nwankwor et al.* [1984] obtained specific yield values $\sim$0.07 for a predominantly medium-grain sand aquifer using the model by *Neuman* [1975]. *Nwankwor et al.* [1984] attributed the low values of specific yield obtained from the type-curve methods to an inadequate representation of the drainage processes occurring near the water table. *Neuman* [1987] argued whereas that specific yields obtained in the laboratory are generally not relevant to the problem of relating groundwater level fluctuations to pumpage. More recently, the importance of variably saturated flow has been recognized. For example, *Moench* [2008] and *Tartakovsky and Neuman* [2007] developed analytical models that consider the impacts of unsaturated zone and flow. *Bunn et al.* [2010] investigated the effects of the spatial variability of the saturated hydraulic conductivity in the unconfined aquifer on the capillary fringe extension observed in the field.

[7] While the concept of a transition of the water release mechanism is not new, the progression of the research discussed above (including Neuman's works) clearly resonates the intent of our paper. That is, a multidimensional variably saturated flow model, which considers the transition of water release mechanisms and accounts for heterogeneity, would provide a more realistic representation of flow processes in unconfined aquifers during a pumping test.

### 1.4. Reply to the Vertical Flow Comments in Paragraph 4

[8] We did not exclude the 3-D flow field created due to pumping in unconfined aquifers. Figures 1a and 1b of *Mao et al.* [2011] compare the simulated S-shaped curves during pumping in a partially perforated well in a fully 3-D unconfined aquifer and the drawdown-time curves in the confined aquifer. Because of the partially perforated pumping well, horizontal and vertical flow components exist in both scenarios. Figures 2a–2c relate the transition of water release mechanisms to the deviations in Figure 1. The one-dimensional vertical column experiments by *Mao et al.* [2011] aim to illustrate the necessity of the vertical flow (not the horizontal flow) in conjunction with the transition of water release mechanisms to yield the S-shaped drawdown-time curve. That is, the S-shaped drawdown-time curve will take place even if horizontal flow is not involved, in contradiction to the statement by *Neuman and Mishra* [2012].

### 1.5. Response to the Comments in Paragraphs 5 and 6

[9] We believe that the terms "delayed yield," "delayed gravity response," and "delayed water table response" are misleading and inappropriate. In comparison with the drawdown-time curve and flow field in a confined aquifer under the same pumping situation, the flat section of the S-shaped drawdown-time curve during the intermediate stage of a pumping test is merely a manifestation of "additional" or "excess" water migrating downward as recharge. This water comes from the drainage of pores in the initially unsaturated zone as well as pores due to falling of the water table. The amount of water released by drainage is much larger than that released by the elastic effect of the aquifer under confined situations. This explains the "additional" water and the reduction in the drawdown in comparison to that in confined aquifer. The pressure and flow as well as release of water from the aquifer are continuous in time and space. The amount of water released due to different mechanisms is different during the transition process as illustrated in Figure 4b of *Mao et al.* [2011]. In other words, we do not see any delaying process during the transition of the water release mechanisms. As a matter of fact, the model by *Neuman* [1972], which assumes instantaneous drainage of pores during falling of the water table, also produces a similar flat drawdown-time curve during the intermediate stage of the pumping test. We fully agree with *Neuman and Mishra* [2012] that the shape of the S curve may depend on parameters as demonstrated in Figure 8 of *Mao et al.* [2011] as well as Figures 2 and 3 and 6 and 7 of *Mishra and Neuman* [2010]. However, the transition of water release mechanisms remains the underlying process that differs from that in fully saturated aquifers.

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