Reply to Comment on "Analysis of pumping test data for determining unconfined-aquifer parameters: Composite analysis or not?": paper published in *Hydrogeology Journal* (2009) 17:1133–1147, by Hund-Der Yeh and Yen-Chen Huang

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The Comment focuses on the model usage and analysis procedures of the pumping test data obtained from 20 observation wells at the Cape Cod site. The following two fundamental issues need to be addressed before proceeding:

1. The Comment states that "… the Cape Cod aquifer is relatively homogeneous to flow …" and "… the Cape Cod aquifer was shown by Moench et al. (2001) to be remarkably homogeneous". However, the abstract of Moench (2004a) states "… in Cape Cod, Massachusetts, in a slightly heterogeneous, coarse-grained glacial outwash deposit …". Moreover, "The Cape Cod aquifer …in slightly heterogeneous and anisotropic, coarse-grained alluvial aquifers" (Moench 2004a). The aquifer test (Moench et al. 2001) was performed at the Cape Cod Toxic Substances Hydrology Research Site in Falmouth, Massachusetts. The tracer test site near Otis Air Force Base at Cape Cod, referred to in LeBlanc et al. (1991), is about 15 km to the north of Falmouth. LeBlanc et al. (1991, p. 898) gave a figure, which shows a geological profile with stratified sand and gravel formation, for an unsaturated zone about 5 m above the water table at the tracer test site. LeBlanc et al. (1991, p. 897) mentioned that the estimated hydraulic conductivity of the outwash varies about one order of magnitude and this variation results from the interbedded lenses and layers of sands and gravels. So it is not appropriate to state that the aquifer formation at Cape Cod is relatively homogeneous or remarkably homogeneous.
2. Physically, the time-drawdown distribution due to pumping in an unconfined aquifer can be divided into three segments. In the early stage, water is instantaneously released from storage by the compaction of the aquifer and the expansion of the water. In the second stage, the vertical gradient near the water table causes flow of the porous matrix. The gravity drainage starts to replenish the depression and the rate of decline in the hydraulic head slows or stops after a period of time. The second stage is also called 'the delayed yield stage' in Batu (1998, p. 459). Finally, the flow exhibits Theis behavior and most of the pumping is supplied by the specific yield in the third stage. Boulton's model (Boulton 1954) can reproduce all three segments of the delayed process by introducing an empirical constant α with specific yield in the confined aquifer flow equation. However, the physical meaning of the constant remains unclear, as mentioned in the groundwater literature. One example is the comment given by Neuman (1979, p. 899) as "Although Boulton's model appears to fit data quite well, it nevertheless fails to provide insight into the physical nature of the delayed yield phenomenon." On the other hand, Neuman's model (Neuman 1972, 1974), which replaces the term 'delayed yield' with a more general concept called 'delayed water-table response' (Neuman 1972, p. 1033), leads to a solution that is also capable of reproducing all three segments of the time-drawdown curve. Batu (1998, p. 492) wrote a comment on Boulton's and Neuman's models: "The main difference between the two models is that the Neuman model is based on well-defined physical parameters of the aquifer system." Truly speaking, Neuman's model can successfully predict delayed water-table response and gives very good fit to the Cape Cod aquifer test data using single-well data analysis as demonstrated in the subject article (Yeh and Huang 2009).

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The authors of this Reply do not agree with the Comment suggestion that inappropriate model and improper procedures have been used, to obtain inaccurate parameter estimates and to reach erroneous conclusions regarding the efficacy of composite analysis. The problem about the data-analyzing approach using composite analysis (CA) or nonCA, addressed in the Comment, had been discussed in Moench (2004b) and Leng and Yeh (2004). A part of the conclusion in Leng and Yeh (2004), which is still applicable to this Reply, is drawn as follows: "In conclusion, Moench's criticisms on the inaccurate results of estimated parameters by extended Kalman filter (EKF) and other single-well data analyses (i.e., nonCA) by Neuman (1975) and Batu (1998) are mainly based on his assertion that one should use composite analysis."

As mentioned in the second issue given in the previous, Neuman's model is capable of reproducing the three segments for a time-drawdown curve with a delayed response in the intermediate stage for pumping in an unconfined aquifer. Additionally, in Yeh and Huang (2009), it was demonstrated that the estimated parameters from nonCA, along with Neuman's model, gave very good fits to the test data of Cape Cod aquifer. The estimated parameter values based on nonCA for Cape Cod data and the SEE (standard error of estimate) values were listed in Table 2 in Yeh and Huang (2009, p. 1137). Most of the SEE values obtained from nonCA are on the order of millimeters and the estimated hydraulic conductivities are very consistent indicating the nonCA based on Neuman's model works very well.

In regard to the suggestion of use of an inappropriate model or model error, the problem in Neuman's model is in handling the drainage from the unsaturated zone to the saturated zone. Neuman's model does neglect the capillary effects above the water table and, thus, water is released instantaneously from the unsaturated zone in response to pumping. In Neuman's model, a time-dependent free-surface equation (Neuman 1972, Eq. 6, p. 1033) is used to simulate the process of gravity drainage. In fact, this free-surface equation plays the role of producing the delayed response for the water table and results in the second segment of the time-drawdown curve. The first reason given in the Comment that opposes the use of the Neuman model for analyzing Cape Cod data is that "The model assumes that drainage from the unsaturated zone to the saturated zone occurs instantaneously, not gradually as has been shown to occur experimentally." Obviously, this statement is not correct or is questionable. The Comment's criticism is that inaccurate parameter estimates were obtained because of the use of the Neuman model. This comment is based on analyses using 'the Moench model', presented in Moench (2004a, b). Basically, the Moench model was developed based on Neuman's model and used a delayed yield term (Moench 2004a, b, Eq. 2), like Boulton's approach (Boulton 1954), to replace the specific yield term in Neuman's free surface equation. Similar to Boulton's model, the Moench model (Moench 2004a, b) includes empirical delayed yield constants for which physical meanings are still unclear. In addition, Neuman's model can fully describe the delayed water-table response. The need or validity of using the delayed yield term in lieu of the specific yield term in Neuman's model is also questionable.

The suggested application of improper procedures infers that the use of nonCA to analyze Cape Cod data is not appropriate. This criticism is without foundation. As demonstrated in the subject article, the estimated results for pumping data from those 20 observation wells based on nonCA are all very promising. The values of standard error of the estimate (SEE) ranging from 1.53×10^{-3} m to 8.55×10^{-3} m (Yeh and Huang 2009, Table 2, p. 1137), indicating that the nonCA approach, along with the Neuman model (Neuman 1974), can accurately determine the hydraulic parameters. In addition, the subject article also shows in a figure (Yeh and Huang 2009, Fig. 4, p. 1144) that the predicted time-drawdown curves based on the estimated parameters determined from nonCA have good match with the observed drawdown data obtained from wells F505-080 and F505-032. The CA gives a good fit for observed data of F505-080 well but a lower predicted drawdown in the intermediate-time period (roughly from 1 to 100 min) for well F505-032. (Note, there is an error in Fig. 4 of the subject article—the horizontal axis scale is not correct and an Erratum has been created). A figure in Moench (2004a, b, Fig. 4, p. 229) shows four sets of observed drawdown data and their predicted drawdown based on Neuman's model and the estimated parameters determined from CA (dashed line). The CA also gives lower predicted drawdowns in the intermediate-time period for wells F505-032, F504-032, F377-037, and F347-031. The estimated parameters from nonCA for those four wells and the related SEE values can be seen in Table 2 of the subject article (Yeh and Huang 2009, p. 1137). The SEE values are roughly on the order of millimeters and those four sets of estimated hydraulic conductivities are very consistent indicating the nonCA based on Neuman's model works very well. In contrast, the CA gives only one set of aquifer parameters for those four wells. It is not likely that the predicted time-drawdown curves from this set of aquifer parameters can give good fits to those four observed drawdown data sets, especially if the Cape Cod aquifer is heterogeneous, as discussed in the first issue mentioned previously, and the data may contain measurement errors.

The final problem highlighted in the Comment is the neglect of pumped well storage and skin. It is true that Neuman's model (Neuman 1974) does not consider the effects of wellbore storage and well skin (see, e.g., Yeh et al. 2003; Chiu et al. 2007). However, it was expected that these two effects are negligible in analyzing the Cape Cod test data, since those 20 observation wells are located at distances about 6–70 m away from the pumping well and the radius of the pumping well is 0.1 m.

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