

Study on the Hydraulic Connectivity between Holocene and Pleistocene Aquifers and the Red River in Hung Yên City Area

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Abstract: The groundwater system in Bắc Bộ plain in general and in Hung Yên province in particular consists of Holocene aquifers and Pleistocene aquifers. Analysis of the hydraulic connectivity between the Holocene and Pleistocene aquifers plays an important decision on that which conceptual groundwater model is. The latter then decides various analyses regarding the groundwater hydraulic and dynamic regime, the formation of groundwater chemical compounds resulted from different mixing mechanisms, the structure of the groundwater system to be used in numerical simulation etc. This paper focused on the clarification of the hydraulic connectivity between the Holocene aquifer and lower Pleistocene aquifers and their hydraulic connectivity with the main rivers in the area. Comprehensive analysis of the groundwater monitoring water levels with use of the hydraulic parameters of the aquifers, river water level fluctuation had been carried out. The results have shown that there is a negligible hydraulic connectivity between the Holocene and Pleistocene aquifers in Hung Yên province. The fluctuation of groundwater level of lower Pleistocene aquifer has been proved to be dominated by the large river such as the Red river and Đuống river by an analytical analysis and finite element modeling. The results of application of finite element modeling had been compared with the analytical results and demonstrated a good match. An important conclusion was made that groundwater resources potential thanks to the Red river for the water needs of the area.

Keywords: Groundwater, Bắc Bộ plain, Holocene, Pleistocene, Spearman correlation, Pearson Correlation, Hydraulic Connectivity, Hydraulic Parameters, FEM.

1. Introduction

In groundwater resources assessment in the Bac Bo plain in general and in Hung Yen province in particular (the study area), the hydraulic connectivity between the Holocene and Pleistocene aquifers and the rivers plays an important decision on that which conceptual

groundwater model may be used. This is especially important for cost effective regional groundwater modeling when a large domain must be dealt with. There are upper and lower Holocene aquifers (or one undivided Holocene aquifer) and upper and lower Pleistocene aquifers (or one undivided Pleistocene aquifer) existing in the study area. They usually had been considered hydraulic connected by most Vietnam hydrogeologists. However, what is the degree of the connectivity, very tied

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connectivity are very weak connectivity which completely may be neglected? The following contents of the paper had tried to clarify this hydraulic connectivity and its degree (magnitude of the connectivity). The approach used for this purpose is direct, i.e., a comprehensive quantitative analysis of the exchange of water between Holocene and Pleistocene aquifers and the dynamics of water level fluctuations in the aquifers under the Red river water level fluctuation. The methods used are both exact groundwater analytical analysis and finite element modeling. This clarification is also as a key fundamental for recharge estimation of the groundwater. The other outcome of the study is the estimate of the dynamic groundwater resources thanks to the recharge from the Red river.

2. Groundwater system and GW monitoring of the study area

There are three major Quaternary aquifers in the study area: Holocene aquifer (qh) in the

top, upper Pleistocene aquifer (qp_2) in the middle and lower Pleistocene aquifer (qp_1) in the bottom. Between the Holocene and upper Pleistocene aquifers there is a continuous aquitard, while between the upper and the lower Pleistocene aquifers there is a discontinuous aquitard. For more details of the hydrogeological conditions of the area some publications are mentioned [1,2]. In Hung Yen city and its suburb there are two national groundwater monitoring stations QT129 and QT130 [2].

The monitoring Red river water level and the Holocene and lower Pleistocene aquifers in Hung Yen city in the period 1995-2006 at the monitoring well QT129 is presented in Figure 1. The monitoring data are available until the present time, however our intend analysis is focused on the yearly period when there were less artificial affecting conditions on the groundwater system regime.

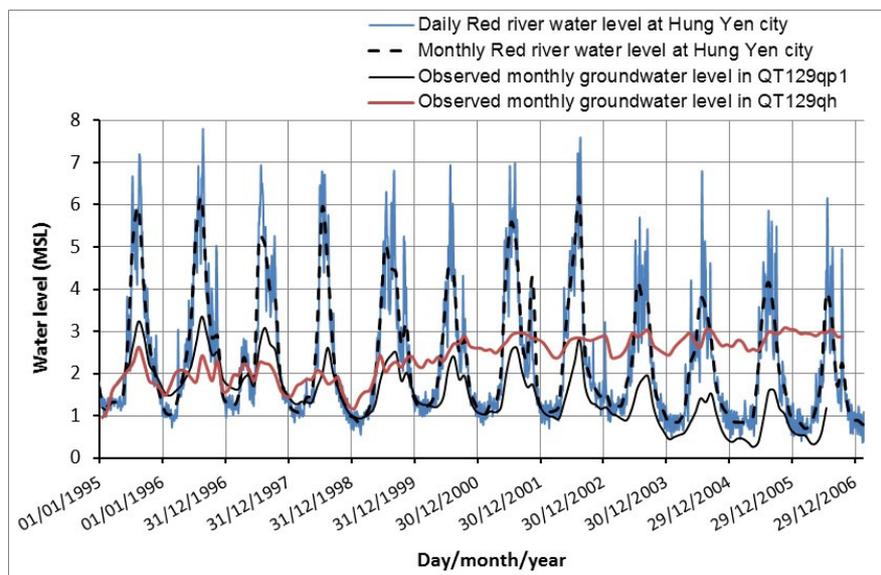


Figure 1. Ground water level in Lower Pleistocene aquifer (qp_1) in well QT129.

3. Analysis of hydraulic connectivity between aquifers and rivers

3.1. Statistical analysis

Statistical analysis has been carried out for examining the correlation between the Red river water level and the GW level. The Spearman correlation has been used for that purpose since the trending nature is to be analyzed here.

a. Holocene aquifer

From the monitored water level of Holocene aquifer qh, there are two distinguished parts of the water level trend. The first part is from 1995 to the end of 1998 where the water level had a lower trend and changed in the range of 1-1.6m, and the second part is from the middle of 2000 to 2006 where the water level had a higher trend and is mostly in the range of 2.5-3.0m. During the time from beginning 1999 to the middle of 2000 the water level had increasing trend from the lower level to the higher level. The most likely reason is that before 1998 there was no pipe domestic water supply in the area and most households had shallow dug wells or drilled wells in Holocene aquifer to supply domestic water need. Since 1998 that household abstraction decreased, and mostly stopped in 1999 thanks to pipe domestic water supply since 1998. Therefore, the statistical analysis had been made for those two distinguished parts. The Spearman correlation analysis has given:

- 1995-1998: Spearman correlation coefficient: 0.690

- 2000-2006: Spearman correlation coefficient: 0.331

That means that the Red river and Holocene aquifer WL are of mathematical correlation for the period 1995-1998. Whether or not that

mathematical correlation is thanks to physical connectivity between the Red river and Holocene aquifer shall be considered later.

b. Pleistocene aquifer

The observed monthly water level data of the upper and lower Pleistocene aquifers have been compared. The results have shown that the absolute difference between water levels of the two aquifers is 3cm in average. This is because the two aquifers are of a tight hydraulic connectivity as the aquitard in-between them is discontinuous in many places. Therefore, only lower Pleistocene aquifer is presented in Figure 1, the term Pleistocene aquifer is used. From the monitored water level of aquifer qp₁, there are three distinguished parts of the water level trend. The first part is 1995-1997 where the water level had highest level trend and changed in the range of 1.5m-3.2m, and the second part is 1998- 2002 where the water level had medium level trend and changed in the range of 1-2.7m, and the third is from 2003 where the water level has continuous decreasing trend. Before 1998 most household wells are in Holocene aquifer, not in the lower Pleistocene aquifer. During the time from the end 1998 to the 2002 more small-scale domestic water wells in the Pleistocene were constructed. Since 1998 the pipe domestic water supply system's groundwater wells had pumping rate of 5,000m³/day, and since 2003 have pumping rate of 10,000m³/day from the Pleistocene aquifer [3]. The Spearman correlation analysis has given:

1995-1997: Spearman correlation coefficient: 0.714

1998-2002: Spearman correlation coefficient: 0.897

2003-2006: Spearman correlation coefficient: 0.820

That means that the Red river and qp aquifer WL are of a very tight mathematical correlation. The factor controlling that mathematical correlation is actually the physical connectivity between the Red river and Pleistocene aquifer and shall be considered in the next.

3.2. Analytical determination of GW level

a. Analytical method

The water level fluctuation of a river, which has hydraulic connectivity with aquifer, leads to the fluctuation of GWL. The magnitude ΔH of the GWL fluctuation of a semi-infinite aquifer at a point located with distance x from the edge of a straight river water is in accordance with the following formula (Mironenco V.A. and Shestakov V.M., 1974) [4]. The interested reader may refer to Polubarinova-Kochina, 1977 [5] for various analytical solutions of more hydrological boundary conditions.

$$\Delta H = V_0 t R(\lambda) + \sum_{i=1}^n (V_i - V_{i-1})(t - t_i) R(\lambda_i) \quad (1)$$

where ΔH -magnitude of increased or decreased groundwater level (m), V_0 -the river water level change rate during the first time interval t_1 (m/day), t -time counted from the moment the river water level started to change (day).

$$R(\lambda) = (1 + 2\lambda^2) \operatorname{erfc}(\lambda) - \frac{2}{\sqrt{\pi}} \lambda e^{-\lambda^2} \quad (2)$$

$$\operatorname{erfc}(\lambda) = 1 - \frac{2}{\sqrt{\pi}} \int_0^\lambda e^{-\lambda^2} d\lambda \quad (3)$$

$$\lambda = \frac{x + \Delta L}{2\sqrt{at}}; \lambda_i = \frac{x + \Delta L}{2\sqrt{a(t - t_i)}}; a = \frac{Km}{S} \quad (4)$$

where x -distance from the river water edge to the point of calculation (m), ΔL -the increased distance value characterized for river bed hydraulic resistance to the aquifer (m); K -permeability of aquifer (m/day); m -thickness of aquifer (m); S -storage coefficient; V_i -river water level change rate from moment t_{i-1} to t_i (m/day) (plus sign if water level increases and vice versa); a -coefficient of water level (for unconfined aquifer) or pressure (for confined aquifer) transmissivity (Russian terminology).

Therefore, we have formula (1) for GWL change in the following form:

$$\Delta H = V_0 t R\left(\frac{x + \Delta L}{2\sqrt{at}}\right) + \sum_{i=1}^n \left[(V_i - V_{i-1})(t - t_{i-1}) R\left(\frac{x + \Delta L}{2\sqrt{a(t - t_i)}}\right) \right] \quad (5)$$

b. Holocene aquifer

The river bed hydraulic resistance-equivalent distance ΔL to Holocene aquifer would be negligible for the reason that during the high river water level most material of the silt river bed is washed away due to high water flow velocity, and also the river had cut through most Holocene aquifer thickness. However, in order not to mathematically ignore it, here we implicitly use $(x + \Delta L)$.

The Holocene aquifer has transmissivity of $96.5 \div 355 \text{ m}^2/\text{day}$. The specific yield of the Holocene aquifer determined in the hydrogeological survey is varying from 0.01 to more than 0.1 [6-8]. If the common used value is 0.1, then the coefficient of water level transmissivity $a = 965 \div 3,550 \text{ m}^2/\text{day}$. Let us semi-quantitatively consider the change of the Holocene aquifer WL at monitoring well QT129. Let us use the average $a = 2,250 \text{ m}^2/\text{day}$ and two values of $(x + \Delta L)$ of 200m and 1,800m for illustration. The values of function $R(\lambda)$ in time are given in Figure 2.

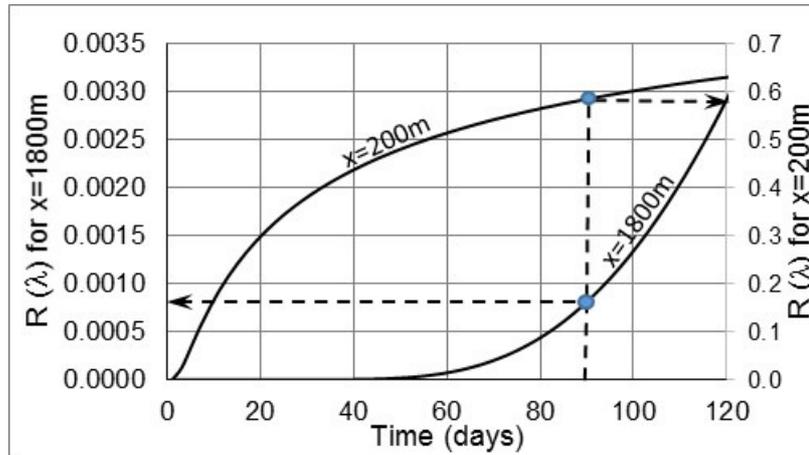


Figure 2. Function $R(\lambda)$ in time.

If the river water level starts to rise, then after three months the Holocene aquifer WL at monitoring well QT129 at $(x+\Delta L)=1,800\text{m}$ would only increase 0.075% of the river water level rise during that three months, while at a $(x+\Delta L)=200\text{m}$ the GWL would increase 58%. However, as the monitored Holocene aquifer WL shows that the fluctuations of the river WL and the GWL are of cyclical, and even are of Spearman correlation of 0.690. Therefore, the river WL and the Holocene aquifer WL at monitoring well QT129 are only of mathematical correlation (but not thanks to hydraulic connectivity) for 1995-1998 years.

Other factors would cause the two fluctuations be correlated, for example the rainfall to increase river water level and recharge the Holocene aquifer to increase its WL.

c. Pleistocene aquifer

The aquifer transmissivity is around $1,426\div 3,650\text{m}^2/\text{day}$, in average $2,540\text{m}^2/\text{day}$, and let take common average storativity of 0.001 [6-8]. Therefore, the coefficient of water pressure transmissivity $a=2,540,000\text{m}^2/\text{day}$. Regarding the river bed hydraulic resistance-equivalent distance ΔL to Pleistocene aquifer, ΔL may be calculated as follows [9]:

$$\Delta L = \sqrt{\frac{m_0}{k_0} KM} \left[\operatorname{cth} \left(\frac{2b}{\sqrt{\frac{m_0}{k_0} KM}} \right) \right]; \operatorname{cth}(\alpha) = \frac{1 + e^{-2\alpha}}{1 - e^{-2\alpha}} \text{ with } \alpha > 1.6; A_0 = \frac{m_0}{k_0} \quad (6)$$

in which: b - the river width; m_0 - thickness of semipermeable soil layer above the aquifer; k_0 - equivalent vertical permeability of semipermeable soil layer above the aquifer; and A_0 - the river bed hydraulic resistance, and is about 130day^{-1} [10]. With the average Red river width of 500m and $KM=2,540\text{m}^2/\text{day}$ it gives $\Delta L \approx 600\text{m}$.

Since the above equations (1)-(5) are for semi-infinite aquifer, which means the aquifer has only boundary with the river. However, in our case, the aquifer is bounded with upper Pleistocene aquifer, with Neogene aquifer below, side boundary in the ocean in the East and is abstracted by many GW abstractions facilities in Hung Yen, Hai Duong, Thai Binh...

provinces. Therefore, some GWL decrease is due to the effect of all those factors, and the ultimate effect shall be given to some net out flow per unit of of area.

Since the monitoring well was constructed at the end of 1994. The WL data during 1995-1998 shall be used for the analysis. In order to have the solution of the analytical equations, the "due" equivalent distance from the Red river the the monitoring well QT129 needs to be determined for the semi-infinite aquifer. The short distance from the Red river to the monitoring well is around 1,700m for the more or less straight river part. However, the "due" equivalent distance needs to estimate. Let us approximately linearize the Red river in order to be able to the conceptual semi-infinite aquifer scheme. The average distance from the well to the "linearized" Red river water edge of plus ΔL is 4,000m as shown in Figure 3. Therefore, that distance is used for the analysis.

From Figure 1 it can be seen that the monthly monitored GWL of the lower

Pleistocene aquifer (the 15th day of every month) is very smooth, while the Red river WL is recorded every day with many high and low peaks during one year. Therefore, if the daily river WL are used for calculation of the GWL, then the GWL would also have many high and low peaks as shown by continuous red line in Figure 4. Also, the GWL calculated by the Red river daily WL has rather greater fluctuations (the high calculated values are higher than the high observed values, and the low calculated values are smaller than the low observed values) than the recorded monthly GWL. This is most likely due to the reason of that the extreme river WL are much shorter in time than the other intermediate WL. Therefore, the averaging the river WL over some days would eliminate this effect. Actually, using the weekly (7-day averaged) river WL the calculated GWL has a better shape match with the observed data as shown by dotted line in Figure 4. Therefore, the weekly river WL data have been used for the presentation.

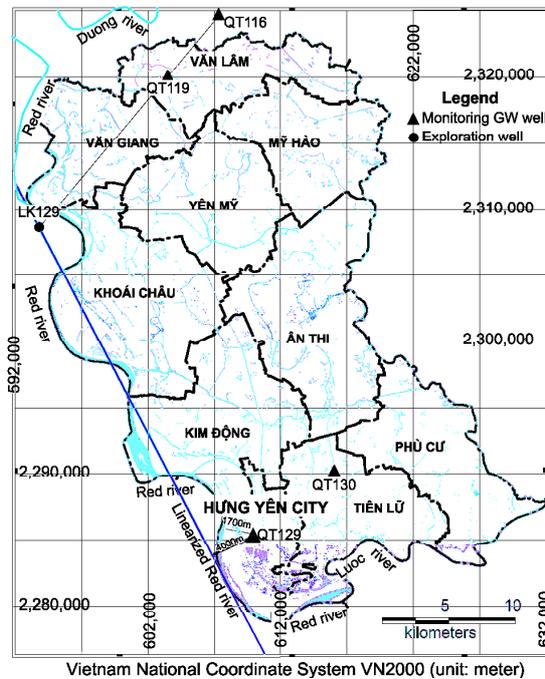


Figure 3. Map of locations of GW monitoring wells and equivalent distance.

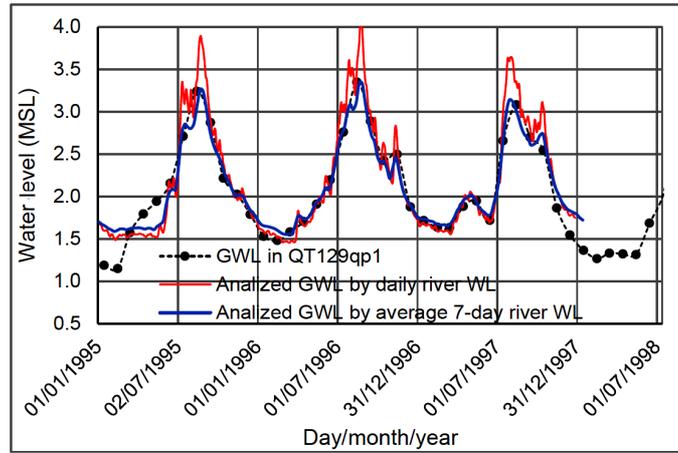


Figure 4. Analyzed groundwater level with daily and 7-day average river water level.

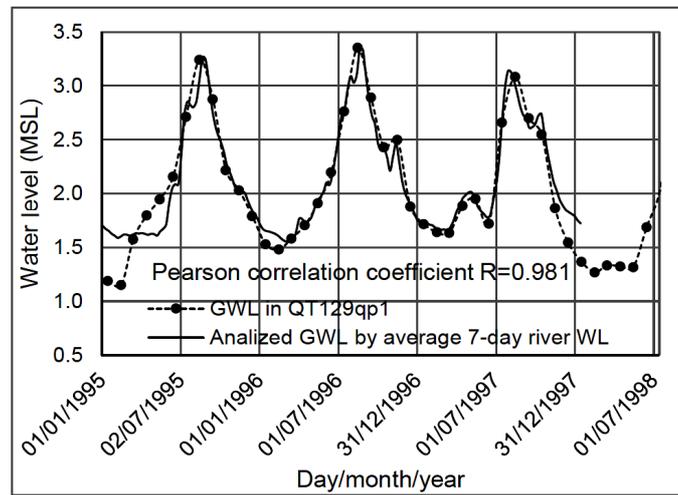


Figure 5. Analyzed (with out flow) groundwater level.

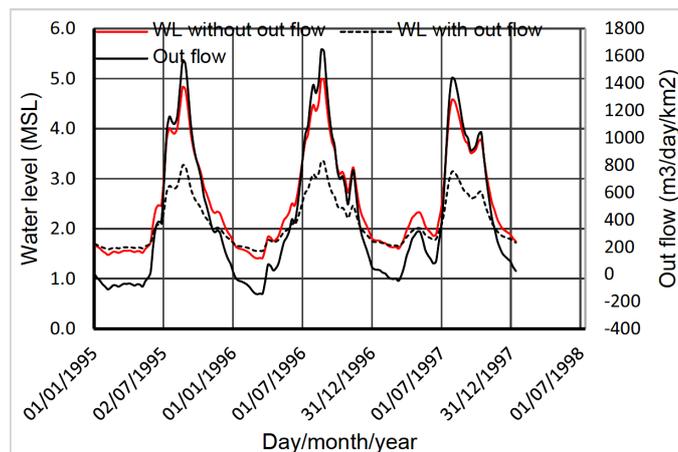


Figure 6. No-out flow, with out-flow groundwater level and out flow.

Since the monitored WL is resulted from the Red river WL and that ultimate out flow, and the monitored GWL is cyncronical with the Red river WL, the unknown ultimate out flow must be proportional to the magnitude of the value of GWL change determined by equation (5) above. We shall assume a constant proportion (the most likely proportion) difference between the monitored GWL and of calculated by equation (5). That a constant proportion is multiplied by unit area (for example 1km^2) and the storativity to give the unit ultimate out flow.

The analysis results for the period from the Jan. 1995 (the time when the Red river water level started to rise) to the Dec. 1997 are given in Figure 6. The analized out flow is presented in Figure 6, which has average out-flow in the area of the minitoring well QT129 of about $425\text{m}^3/\text{day}/\text{km}^2$ for that period, which may mean the annual 1996-1997 groundwater recharge by the Red river. The Pearson correlation coefficient between the Red river and analized GWL is 0.977, which means a perfect mathematical correlation resulted from essential physical hydraulic connectivity.

b. Finite element modeling

The above analytical analysis is applicable only for homogenous and semi-infinite aquifer and strictly straight infinite Dirchlete boundary of horizontal specified WL, otherwise

numerical modeling should be applied. Within the practical directional fundamental scientific project coded ĐT.NCCB-ĐHUD.2012-G/04 [Nguyen Van Hoang, 2014-2016][11] a groundwater flow finite element model had been compiled. Let us use that numerical simulation to the above case as programming verification in order to apply to any other aquifer conditions. The finite element method used is the Galerkin method using four-node linear weighting and shape functions [12].

The model parameters are: The aquifer transmissivity is $2,540\text{m}^2/\text{day}$, the storativity is 0.001, and the out flow at the right boundary side during the model time is as in Figure 6.

The model domain is 20 meter width (along the river) and 8,000m (perpendicular to the river). Different element sizes (from 20m to 2m) and time step (from 1 day to 5 hours) have been tested for accuracy with the changing domain sizes of the total number of nodes within $3,000\div 5,000$. All the cases have given small discrepancies in water level results (relative difference is not greater than 5%). Therefore the element sizes of 10m in x direction and 5m in y direction and time step of 1day were used. The river side of the model has specified WL of the river, the opposite side in prescribed hydraulic gradient (hydraulic gradient is calculated from the hydraulic head), the two 8,000m-long sides are no-flow boundaries (Figure 7).

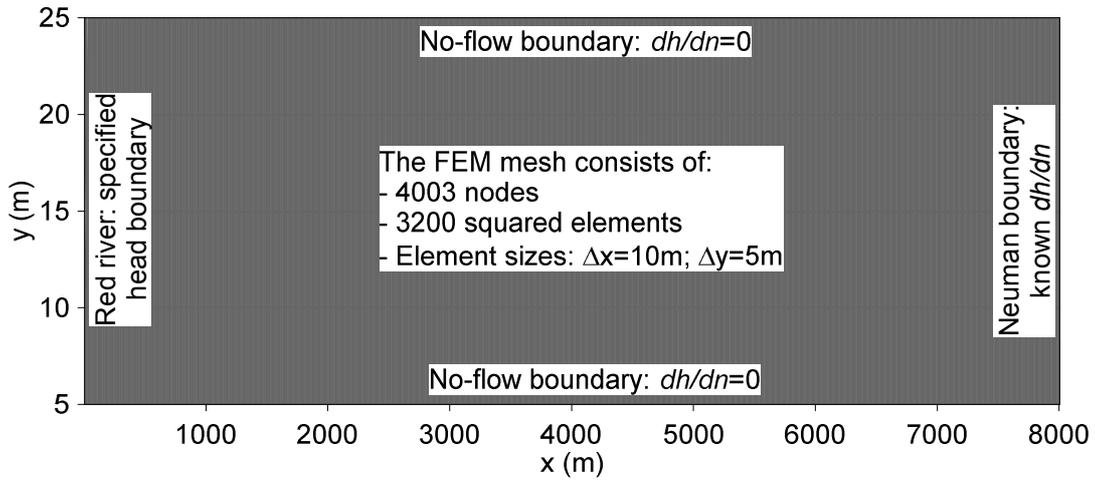


Figure 7. Model domain and boundary conditions.

The FEM provides water level in time and space which may be used for prediction of water level in response to the Red river water level changes. Figures 8 presents water level at differences distances from the Red river water

edge, and Figure 9 presents the water level at the monitoring well QT129. The Pearson correlation is very high with correlation coefficient of 0.915.

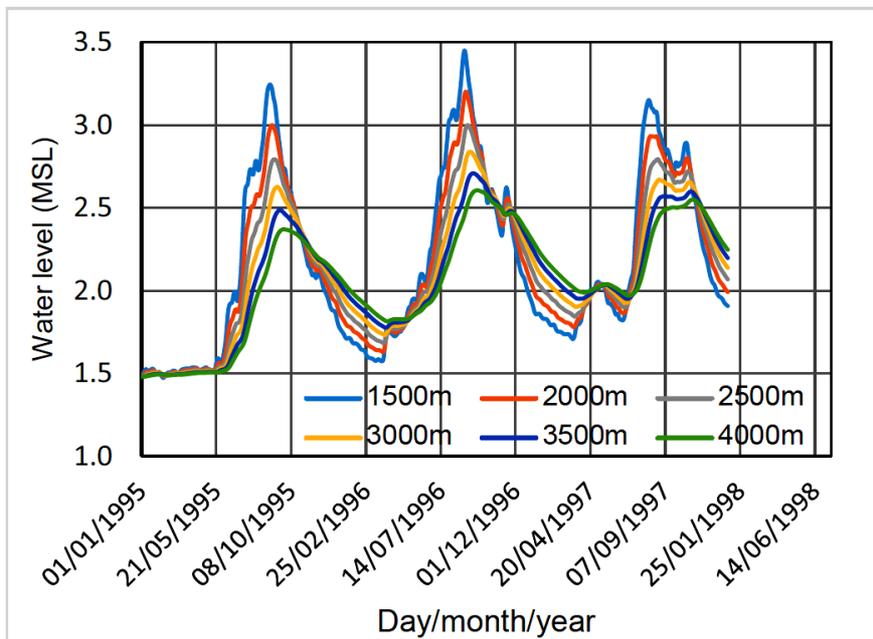


Figure 8. Water level at different distances from the Red river.

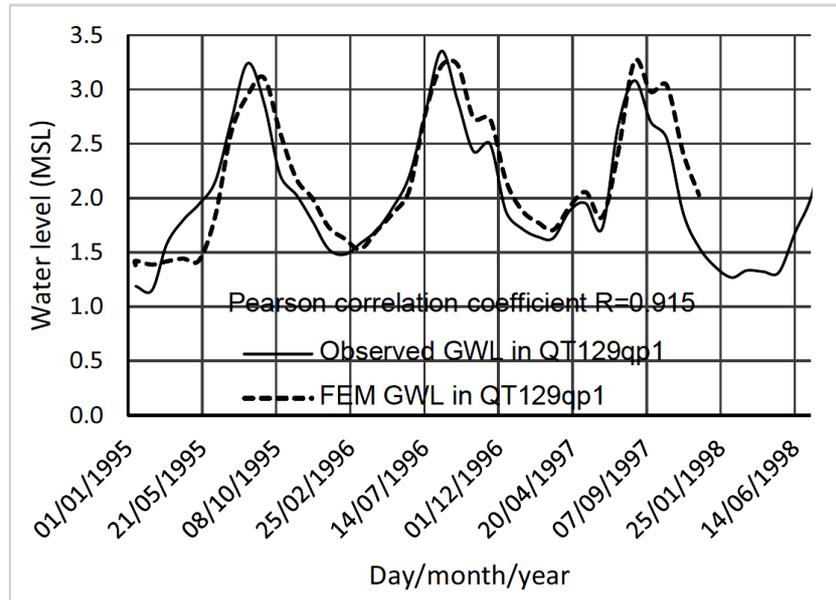


Figure 9. Observed and FEM water level at monitoring well QT129.

4. Concluding remarks

From the above arguments and results, the following conclusions may be made:

- Water level fluctuation of the Holocene aquifer is mostly effected by the small river and streams, irrigation system, irrigated water, rainfall, evapotranspiration etc. The Holocene aquifer water level is infected by the stream water level in very short distance of less than 500m. The mathematical high correlation between the Holocene aquifer WL and the Red river WL at the long distance from the Red river is not due to the physical hydraulic connectivity;

- The Holocene and Pleistocene aquifers almost has no hydraulic connectivity where the semipermeable layer is existing in between them. That condition exists in most area of Hung Yen province;

- In the analysis of the GWL due to the river WL fluctuation, the recorded river WL at certain time of day would cause highly

inaccurate values if the daily average river WL is much different from that recording certain time. It is recommended that the river WL be recorded in hourly and be used for calculating the daily WL, and that the GWL be recorded in 5÷7 days instead of the 15th of each month;

- The Red river has a tight hydraulic connectivity with Pleistocene aquifer and the WL pressure of the aquifer is effected by the WL over distance of several kilometers. The release of the Pleistocene aquifer water piezometric level due to miscellaneous discharge of water from the aquifer is the key factor in decreasing the physical water piezometer increase potential by the Red river WL increase;

- The Red river has very high capacity of recharging directly from the Pleistocene and indirectly from above and lower water bearing strata, which during the high Red river water level may reach a high value around $1,500\text{m}^3/\text{day}/\text{km}^2$, and annually is $425\text{m}^3/\text{day}/\text{km}^2$. This figure is a good water

resource potential value in water supply to the area and is worthwhile to be considered for the water resources development in the area.

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Nghiên cứu quan hệ thủy lực giữa tầng chứa nước Holocen và Pleistocen với sông Hồng khu vực TP. Hưng Yên

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Tóm tắt: Hệ thống các tầng chứa nước dưới đất ở đồng bằng Bắc Bộ nói chung và tỉnh Hưng Yên nói riêng bao gồm tầng chứa nước Holocen và các tầng Pleistocen. Phân tích quan hệ thủy lực giữa

tầng Holocen and Pleistocen có vai trò quan trọng trong quyết định sử dụng mô hình khái niệm đúng đắn- nhất. Mô hình khái niệm sẽ quyết định sử dụng các phương pháp phân tích khác nhau về thủy lực và động thái nước dưới đất, về sự hình thành phần phân hóa học nước dưới đất theo các cơ chế pha trộn, về cấu trúc hệ thống các tầng chứa nước được sử dụng trong mô hình số... Bài viết tập trung nghiên cứu làm sáng tỏ quan hệ thủy lực giữa tầng chứa nước Holocene và Pleistocen và giữa chúng với sông Hồng ở khu vực nghiên cứu. Đã tiến hành phân tích tổng hợp mực nước dưới đất được quan trắc bằng việc sử dụng các thông số thủy lực của tầng chứa nước và dao động mực nước của sông Hồng. Kết quả cho thấy quan hệ thủy lực giữa tầng Holocen và Pleistocen tại khu vực TP. Hưng Yên rất yếu. Bằng phương pháp giải tích và mô hình số đã chứng minh được rằng dao động mực nước tầng Pleistocen bị quyết định chủ yếu bởi mực nước các sông lớn như sông Hồng, sông Đuống. Kết quả của mô hình số được so sánh với kết quả giải tích cho thấy rất phù hợp. Đã rút ra kết luận quan trọng về tiềm năng trữ lượng động nước dưới đất từ sông Hồng có ý nghĩa lớn phục vụ nhu cầu nước của khu vực.