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ESTIMATION OF GROUNDWATER FLOW VELOCITY USING RADON IN SINGLE WELL TESTS

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Abstract: *Radon has been used to determine groundwater velocity in this research, applied to two case studies, in France and Vietnam. By using the Hamada "single-well method", Darcy velocity was estimated using comparison of radon activities in well waters and in the aquifer, itself). Measurements done at three depths in a single well (shallow, intermediate and deep) provided velocity ranging from a few mm/day to more than 20 cm/day with highest velocities observed at the 15-m depth in Crau aquifer. In Dan Phuong holocence aquifer, groundwater flow velocity ranging from 0.178 to 8.57cm/day. Resulting hydraulic conductivities agree with the known geology of Crau aquifer. In Dan Phuong area, the result from this method response to the estimated values from pumping tests and slug tests.*

Keywords: *groundwater flow velocity, Radon, single well test, Crau, Dan Phuong*

1. Introduction

Groundwater flow velocity (Darcy velocity) is one of the most important parameters of the aquifer which is needed to study groundwater movement and the contaminant processes. This parameter could be estimated by using experience equations, experiences in laboratory or in situ. In this study, radon activity in groundwater was used to assess groundwater flow rates, hydraulic conductivities in Crau aquifer (southeastern France) and in Dan Phuong area (Hanoi, Vietnam). Radon (^{222}Rn) is a radioactive gas produced by the decay of radium (^{226}Ra). In groundwater, radon activity originates essentially from ^{226}Ra adsorbed on mineral surfaces in the aquifer with little contribution from dissolved ^{226}Ra. Natural radon is a good groundwater tracer because of its inert chemical behavior, its elevated concentrations in groundwater and its "lack of memory" after a few days (half-life = 3.824 days). Several recent studies used radon activity surveys in a single well test to estimate groundwater velocity by comparing radon activity in borehole waters and in groundwater found in the aquifer (Hamada, 2000, Schubert et al., 2011, Adriano et al.,2016). Aquifer hydraulic conductivities were calculated using the radon-determined groundwater velocities and the observed hydraulic gradients.

2. Methods

Radon activity was measured in water using RAD7 radon monitors (Durridge Co. Inc.) and RAD H_2O water exchanger (Figure 1).

Figure 1. RAD7 radon monitors with RAD H20 water exchanger (Durrige Co.Inc)

To assess groundwater velocity (here, this is the Darcy velocity as used by previous authors and not the mean pore velocity) using radon, the method of Schubert et al. (2011) was adapted. The basic principle of this method is that inside an observation well, dissolved radon is no longer supplied by the decay of ^{226}Ra adsorbed on mineral surfaces of the aquifer. Therefore, water in the borehole has a lower radon activity in respect to that in the groundwater outside of the well. Neglecting degassing, the steady-state radon activity in the borehole water depends on the initial activity of the groundwater coming from the aquifer and the water residence time in the borehole. The water residence time in the borehole depends on the velocity of groundwater in the aquifer and on the hydraulic characteristics of the borehole. Velocity of groundwater in the aquifer can thus be estimated by comparing radon activity in borehole water with that in the aquifer. The latter may be obtained by sampling water after a complete purge of the borehole. According to Schubert et al (2011), groundwater velocity (Darcy velocity) is calculated from the ratio of the measured activity of water in the well (C_{ww}) to that in aquifer (C_{gw}):

$$\frac{C_{\mathrm{ww}}}{C_{\mathrm{gw}}}=\frac{v}{\pi\lambda r}\int_{-\pi/2}^{\pi/2}\left(1-e^{-\lambda 2r\cos\theta/v_{\mathrm{ww}}}\right)\cos\theta\,\mathrm{d}\theta$$

(1)

where λ is the radon decay constant, v_{ww} is the velocity of water in the borehole, r is the borehole radius (3 cm in this case) and θ the variable of integration. This integral is solved by an iterative, numerical approach to obtain v_{ww}. The value of C_{gw} was obtained by measuring activity in well water after a complete purge, i.e. after complete renewal of the water volume in the well.

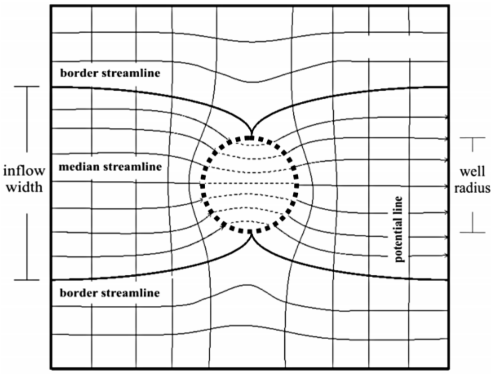


Figure 2. Schematic horizontal flow pattern (top view) within and around a well (after Englert, 2003)

In addition, this study attempts to highlight the effects of the freshwater/saltwater interface for coastal aquifer in Crau area (southern France) and the effects of the heterogeneity in Holocene aquifer in Dan phuong (Hanoi, Vietnam) by repeating the measurements of C_{ww} and C_{gw} at three depths. For this purpose, a series of boreholes was selected, situated near the front of the saltwater intrusion in Crau aquifer and near the Red river in Dan phuong area (Fig.3 and Fig.5 respectively). Before collection of the water samples, the water-table and borehole depths were measured. The depths of sample collection were defined by dividing the water column into three regularly-spaced depth intervals. In Crau aquifer, the water samples were taken depends on the distribution of electrical conductivity, therefore in the middle (at mean depth) of each interval (i.e. at 1/6, 3/6 and 5/6 of the borehole water column). The range of mean depths of sample collection was 5 to 8 m for the shallow interval, 15 to 17 m for the intermediate interval, and 21 to 22 m for the deep interval. When the well is located above the saltwater front, as for X26, XD and L3, the intermediate interval is close to the freshwater/saltwater interface. In these cases, the deep interval is located within saltwater. The shallow interval is always in fresh water, i.e. above saltwater. Meanwhile in Dan Phuong area, the sample depths have difined base on the lithological distributed (see the cross section in Fig.5). The shallow, intermediate and deep samples have taken in the middle of clay, sandy clay layer, fine sand and medium sand, respectively.

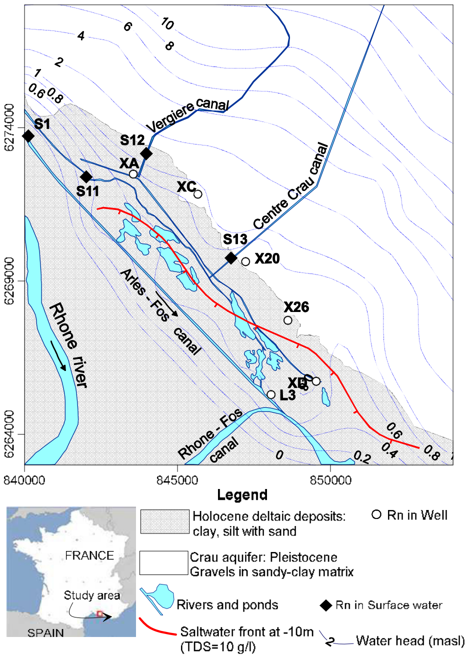


Figure 3. Geological sketch map of the south-west termination of the Crau aquifer. Water-table contour lines (fine blue lines) were obtained from piezometric surveys done during this study. The limit of the saltwater front (thick red line) was obtained from electrical conductivity logs.

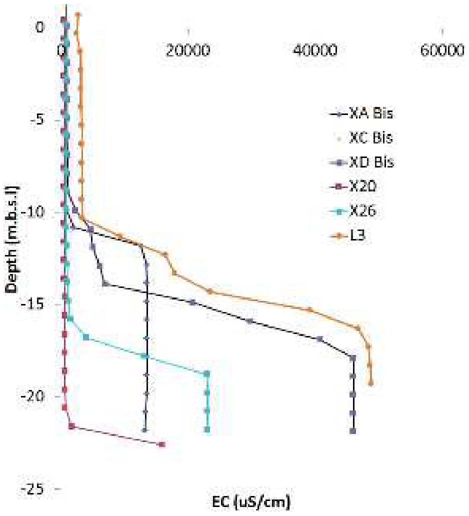


Figure 4. Variation of electrical conductivity by depth in Crau aquifer

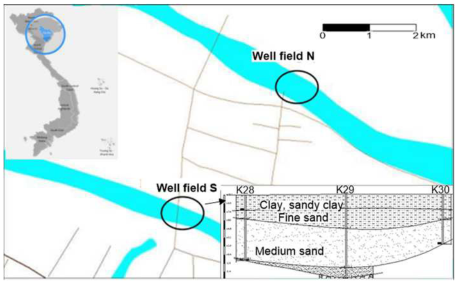


Figure 5. Sketch map of Dan Phuong well field. Radon samplings have been taken in Well Field S (Southern). The cross section shows the heterogeneity of Holocene aquifer in this area (lithological description collected from well K28, K29 and K30 taken by VietAs project, 2007)

The water samples for C_{ww} were collected first. To collect samples at the three depth intervals (Fig. 6), the intake of the pump was lowered at the requested depth starting from the shallower interval to avoid water mixing. The water was pumped at a rate of 2 l/min into a 2.5 l bottle. To minimize degassing, the sample bottle was kept upright and the bottle was filled from the bottom to the top. The water volume in the bottle was renewed one time to assure that the sampled water was not degassed.

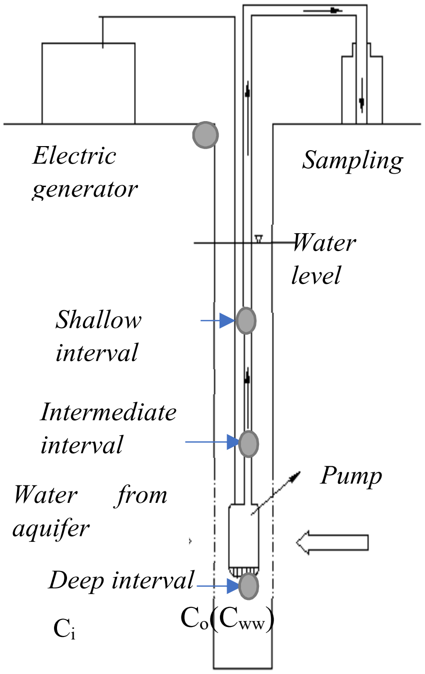


Figure 6. Schematic of water sampling in a well for Radon experiment. Each well has been collected samples at three difference intervals (shallow, intermediate and deep)

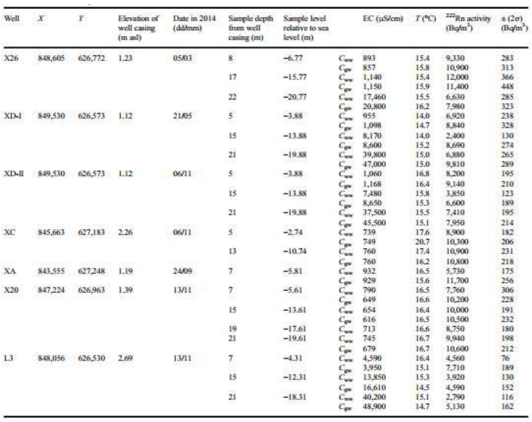
After that, water was sampled to measure C_{gw}. The intake pump was lowered at the same depths as for C_{ww}, starting from the shallow interval. Before collecting the sample, the water-volume of the depth-interval of the borehole was purged three times at a rate of 2.5 l/min. It was considered that the aquifer permeability in front of the tested interval is sufficient to supply water and that the pumping rate is low enough to prevent water coming from shallower or deeper intervals. It was assumed therefore that the permeability is sufficient to maintain a linear sub-horizontal flow during purging as it is in natural conditions. Finally, the sample for C_{gw} was collected. Also in this case, water was renovated one time in the bottle to minimize degassing.

To compute groundwater velocity v_{gw} from v_{ww}, the v_{ww} value was divided by a geometric correction coefficient α to consider the convergence of water streamlines into the well. The value of α was calculated according to Cook et al. (1999) and the reference therein:

$$\alpha = \frac{4}{1+\left(\frac{r_1}{r_2}\right)^2 + \left[\frac{K_2}{K_1}\left(1-\frac{r_1}{r_2}\right)^2\right]} \qquad (2)$$

In equation 2, K_1 is the hydraulic conductivity of the filter screen, K_2 is the hydraulic conductivity of the aquifer, r_1 is the inside radius of the filter screen, r_2 is the borehole radius. Assuming that the permeability of the borehole screen is much higher than the permeability of the aquifer, and that the borehole is constructed without a filter pack, the α coefficient has a value of 2.

Table 1. Radon activities in groundwater at different depths in wells at the Crau aquifer. Cww radon activity in well water; Cgw radon activity in groundwater after purge and renewal of well water



Well	X	Y	Elevation of well casing (m asl)	Date in 2014 (dd/mm)	Sample depth from well casing (m)	Sample level relative to sea level (m)		EC (µS/cm)	T (°C)	^{222}Rn activity (Bq/m^3)	± (2σ) (Bq/m^3)
X26	848,605	626,772	1.23	05/03	8	−6.77	C_{ww}	893	15.4	9,330	283
							C_{gw}	857	15.8	10,900	313
					17	−15.77	C_{ww}	1,140	15.4	12,000	366
							C_{gw}	1,150	15.9	11,400	448
					22	−20.77	C_{ww}	17,460	15.5	6,630	285
							C_{gw}	20,800	16.2	7,980	323
XD-I	849,530	626,573	1.12	21/05	5	−3.88	C_{ww}	955	14.0	6,920	238
							C_{gw}	1,098	14.7	8,840	328
					15	−13.88	C_{ww}	8,170	14.0	2,400	130
							C_{gw}	8,600	15.2	8,690	274
					21	−19.88	C_{ww}	39,800	15.0	6,880	265
							C_{gw}	47,000	15.0	9,810	289
XD-II	849,530	626,573	1.12	06/11	5	−3.88	C_{ww}	1,060	16.8	8,200	195
							C_{gw}	1,168	16.4	9,140	210
					15	−13.88	C_{ww}	7,480	15.8	3,850	123
							C_{gw}	8,650	15.3	6,600	189
					21	−19.88	C_{ww}	37,500	15.5	7,410	195
							C_{gw}	45,500	15.1	7,950	214
XC	845,663	627,183	2.26	06/11	5	−2.74	C_{ww}	739	17.6	8,900	182
							C_{gw}	749	20.7	10,300	206
					13	−10.74	C_{ww}	760	17.4	10,900	231
							C_{gw}	760	16.2	10,800	218
XA	843,555	627,248	1.19	24/09	7	−5.81	C_{ww}	932	16.5	5,730	175
							C_{gw}	929	15.6	11,700	256
X20	847,224	626,963	1.39	13/11	7	−5.61	C_{ww}	790	16.5	7,760	306
							C_{gw}	649	16.6	10,200	228
					15	−13.61	C_{ww}	654	16.4	10,000	191
							C_{gw}	616	16.5	10,500	232
					19	−17.61	C_{ww}	713	16.6	8,750	180
					21	−19.61	C_{ww}	745	16.7	9,940	198
							C_{gw}	679	16.7	10,600	212
L3	848,056	626,530	2.69	13/11	7	−4.31	C_{ww}	4,590	16.4	4,560	76
							C_{gw}	3,950	15.1	7,710	189
					15	−12.31	C_{ww}	13,850	15.3	3,920	130
							C_{gw}	16,610	14.5	4,590	152
					21	−18.31	C_{ww}	40,200	15.1	2,790	116
							C_{gw}	48,900	14.7	5,130	162

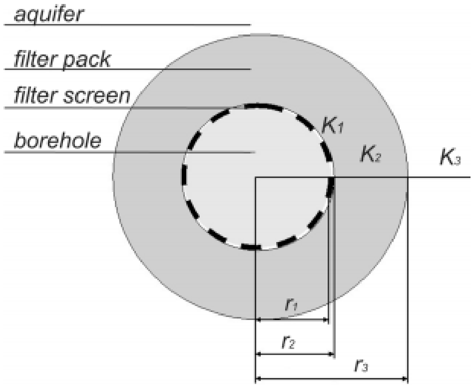


Figure 7. Schematic horizontal cross section of a screened borehole with filter pack (after Drost et al. 1968 and Schubert et al,.2011).

3. Results and discussion

3.1 Groundwater velocity from radon measurements

- Crau aquifer

The radon activities measured in well waters (C_{ww}) are presented in Table 1, Fig. 6 for the three depth intervals. Calculated groundwater velocities are presented in Table 1.

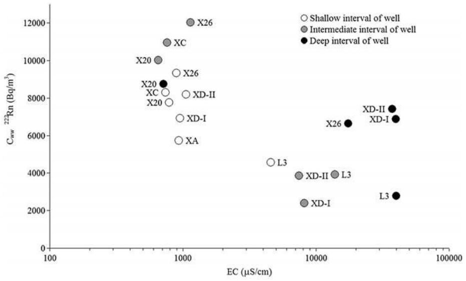
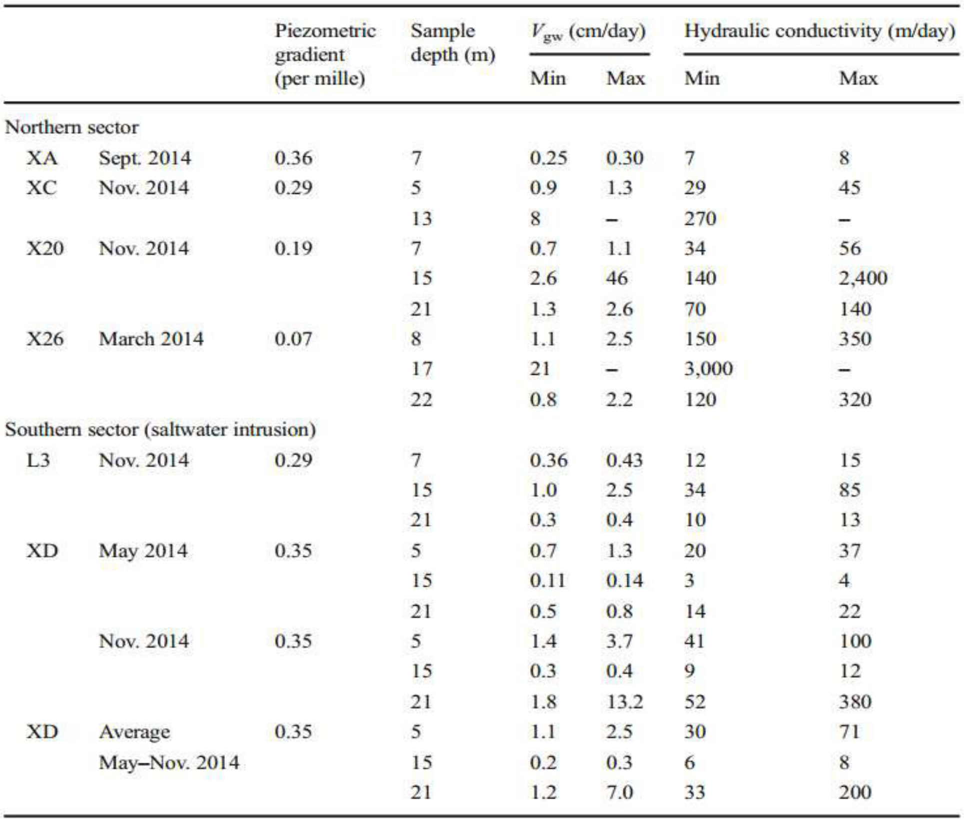


FIG. 8 RADON ACTIVITY AND ELECTRICAL CONDUCTIVITY (EC) OF WELL WATERS OF THE CRAU AQUIFER, SAMPLED BEFORE WELL PURG

Table 2 Groundwater velocity in Crau aquifer and permeability estimated from radon data and piezometric gradient. V_{gw} is the calculated groundwater velocity. Ranges (min– max) are estimated on the basis of 2σ errors of groundwater radon activity measurements



		Piezometric gradient (per mille)	Sample depth (m)	V_{gw} (cm/day)		Hydraulic conductivity (m/day)	
				Min	Max	Min	Max
Northern sector							
XA	Sept. 2014	0.36	7	0.25	0.30	7	8
XC	Nov. 2014	0.29	5	0.9	1.3	29	45
			13	8	–	270	–
X20	Nov. 2014	0.19	7	0.7	1.1	34	56
			15	2.6	46	140	2,400
			21	1.3	2.6	70	140
X26	March 2014	0.07	8	1.1	2.5	150	350
			17	21	–	3,000	–
			22	0.8	2.2	120	320
Southern sector (saltwater intrusion)							
L3	Nov. 2014	0.29	7	0.36	0.43	12	15
			15	1.0	2.5	34	85
			21	0.3	0.4	10	13
XD	May 2014	0.35	5	0.7	1.3	20	37
			15	0.11	0.14	3	4
			21	0.5	0.8	14	22
	Nov. 2014	0.35	5	1.4	3.7	41	100
			15	0.3	0.4	9	12
			21	1.8	13.2	52	380
XD	Average May–Nov. 2014	0.35	5	1.1	2.5	30	71
			15	0.2	0.3	6	8
			21	1.2	7.0	33	200

In the shallow interval (5-8 m) the difference in activity before (C_{ww}) and after (C_{gw}) the purge is large, indicating that groundwater velocity is low. This result well agrees with the nature of the sediments in the upper part of the deposits. Borehole logs made around the ponds indicate that the aquifer is partially confined by less permeable sediments of the Rhône River, mixed with lacustrine deposits. The lowest velocities (XA and L3, table 4) are obtained for the boreholes situated on the two opposite sides of the study area (Fig. 1). Water level in these boreholes merges with the water level in the pond.

For the intermediate interval (14-17 m), in the northern sector the radon activities before and after the purge are almost identical implying high groundwater velocities. These high velocities are explained by a much higher permeability, i.e. by the presence of coarse-grain material corresponding to alluvial pebbles and gravels. Another reason for the high groundwater velocity may be the rise of the saltwater interface. The more elevated the saltwater interface, the thinner the fresh-water layer. Velocity must thus increase to accommodate the thinning of the freshwater cross-section. The salinity interface in X26 and X20 occurs at depths of 17 m and 21 m respectively, just below the depths obtained for the maximum velocities. For XC, the saltwater interface has not been found because this borehole reaches only 13 m depth. However, since in the nearby XA borehole the saltwater interface is at 12 m depth, it is assumed that in XC, slightly upstream relative to XA, the saltwater interface is somewhat lower than 13 m depth.

Borehole L3, located within the saltwater intrusion (Fig. 1), shows moderate velocities (table 4) in agreement with a water table essentially controlled by surface waters (Arles-Fos Canal and Vigueirat Marsh). A minor increase in velocity occurs in the intermediate interval, as observed in the northern boreholes. Also in this case, the increase in velocity is accompanied by a sudden increase in salinity in the interval below. On the other hand, the borehole XD yields the lowest velocity in the intermediate interval. A probable reason is that XD is located in the water divide area (or stagnation point) of the groundwater capture zone of the Pissarotte pumping well (average pumping rate of 2,600 m^3/d). On this downstream boundary of the pumping well capture zone, velocity becomes zero (stagnation). The measurement made in May 2014 clearly reflects the existence of stagnant groundwater in the intermediate interval. In November 2014 velocity is lightly higher in XD, probably due to the displacement of the stagnation point after the period of high water-pumping rate.

For the deeper interval, radon data suggest that, except for XD, groundwater velocity is lower than in the intermediate layer.

In Dan Phuong aquifer

As described before, the samples in Dan Phuong area were selected to highlight the heterogeinety of aquifer. A group of borehole in the same area but with difference depth have been chose and the samples at three difference depths were defined base on the lithological descriptions of each boreholes (Table 3).

Table 3. Radon activities in groundwater at different depths in wells in Holocene aquifer (Dan phuong well field, Hanoi, Vietnam). Cww radon activity in well water; Cgw radon activity in groundwater after purge and renewal of well water

Sample/ Well name	Lat.	Long.	Depth of well m	Altitude of piezometer casing m	Sampling date	Depth from piezometer casing m	Depth from sea level m		T °C	^{222}Rn Bq/m^3	+/- (2σ) Bq/m^3
K28	2338505	565186	10.7	10.228	23/3/2017	6	4.228	before	19.4	2002	198
								after	19.8	7296	219
						8	2.228	before	19.4	1185	256
								after	19.9	4500	313
						10	0.228	before	19.5	5872	199
								after	20.2	10260	226
K29	2338506	565188	19.8	10.367	11/4/2017	10	0.367	before	18	6835	167
								after	18.7	12523	230
						14	-3.633	before	18	4552	91
								after	19.2	9030	192
						18	-7.633	before	19	7642	186
								after	19	9809	202
K30	2338507	565188	8.2	10.384	11/4/2017	6	4.384	before	20.8	10996	137
								after	20.4	15125	147
						7	3.384	before	19.8	8605	86
								after	19.3	13582	132
						8	2.384	before	19.5	7407	136
								after	19.1	7951	150

Table 4 Groundwater velocity in Dan Phuong aquifer. V_{gw} is the calculated groundwater velocity.

Sample /Well name	Sampling date	Sampling depth from casing m	Vgw cm/day
K28	3/23/2017	6	0.18
		8	0.18
		10	0.35
K29	11/4/2017	10	0.48
		14	0.43
		18	9.07
K30	11/4/2017	6	1.03
		7	0.68
		8	5.70

3.2 Estimate of hydraulic conductivity

Table 4 and Fig. 5 present the values of hydraulic conductivity (*K*) calculated as the ratio between the (Darcy) groundwater velocity obtained from radon activity and the hydraulic gradient. The calculation assumes that groundwater flow is horizontal (no vertical component) and that the hydraulic gradient is constant at any depth, i.e. flow is two-dimensional (2D). The hydraulic gradient was determined from the water table map drawn using 45 water level measurements (locations on Fig.1). Measurements have been corrected for density changes in the water column due to water salinity. For X20 and X26, located in the central zone, the hydraulic gradient is very low (0.07-0.19 ‰, against 0.35 ‰ at the border).

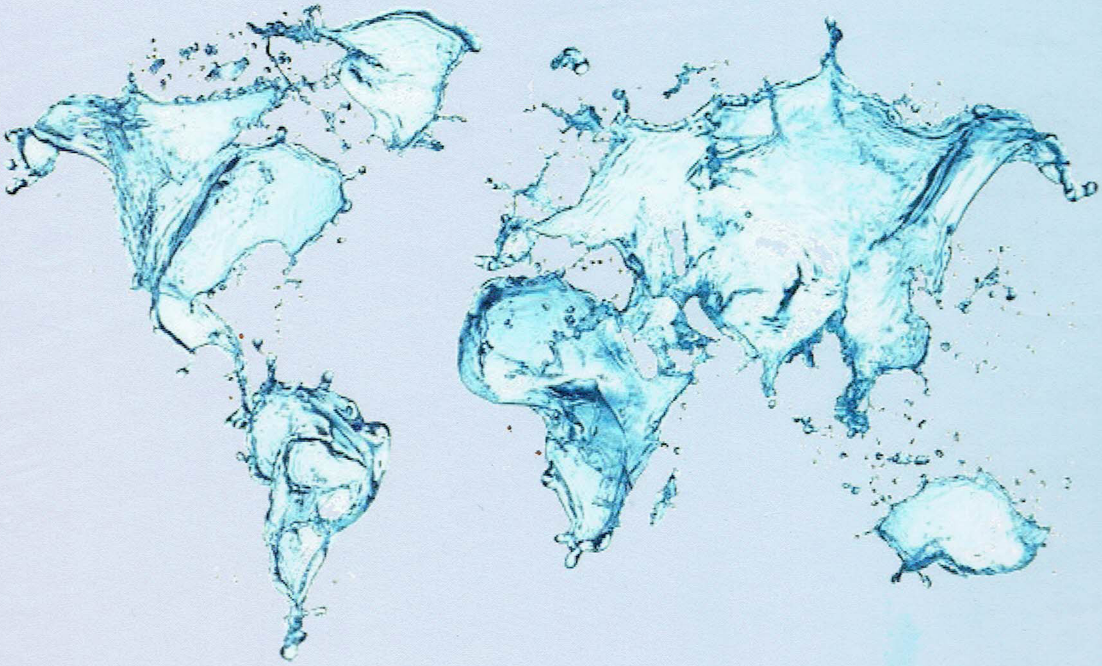
The high hydraulic conductivity found in the intermediate interval indicates that this interval is very permeable, i.e. probably composed by very coarse material. The top of the Rhône river gravels, mapped by Vella et al (2005), corresponds to the high-permeability intermediate interval found with radon in this study.

The value of *K* in the shallow interval is much lower and is consistent with the occurrence of fine sediments of the Rhône River mixed with lacustrine deposits. A monotonic increase in *K* value is observed in the shallow depth interval from North to South in the sequence XA, XC, X20 and X26. For XD, estimates of *K* are given for May and November 2014, and averaged in Fig. 5. For both estimates, the intermediate interval appears to be less conductive. However, as discussed above, these estimates are probably influenced by the variable hydraulic gradient near the pumping station (water table depression and hydraulic-gradient inversion). For this specific location, it is probably not correct to calculate *K* using a hydraulic gradient that is not determined at the same time as the radon sample collection. Fig. 5 shows the extrapolation of hydraulic conductivities obtained with radon-determined velocities and hydraulic gradient. The spatial distribution of *K* values well agrees with the geology known from borehole logs. High-permeability zones are found at depths corresponding to unconsolidated pebbles and sands.

4. Conclusions

Radon has been used to assess groundwater velocities in two difference cases study. Study in the coastal Crau aquifer (France) to highlight the effect of saltwater and freshwater interface to the velocity of groundwater, meanwhile the study in Holocene aquifer of Dan phuong well field (Vietnam) to highlinght the effect of lithological pattern to groundwater velocity.

Groundwater Darcy velocities have been measured using the method proposed by Schubert et al (2011). The measurements were repeated at three depth intervals in boreholes situated close to the saltwater interface (salinity front) and in boreholes with heterogeneity formation. In coastal aquifer of Crau area, Darcy velocities are in the range of a few cm/day to more than 20 cm/day. The results highlight the existence of high groundwater velocity (few m/day) at a depth of about 14 m below surface in the central part of the study area. These high velocities, related to a low hydraulic gradient, imply the existence of a highly permeable layer at this depth. Such a highly conductive layer is supported by the presence of pebbles and un-cemented coarse sediments as described by borehole logs. Hydraulic conductivities were also calculated as the ratio between the groundwater velocity and the piezometric gradient. Shallower and deeper intervals provide lower velocities. This characterizes the less permeable sediments indicated by the borehole logs: fine sediments of the Rhône river at shallow level and cemented conglomerates at deeper level. Reduced velocities are also observed in zones of low hydraulic gradient due to the effect of water pumping. The high velocities may also



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The conference is to mark the 50th anniversary of the Vietnam Hydrogeology education (1967-2017), the special event of Vietnamese Hydrogeologist. The conference theme SGD is an invitation to researchers, academics and professionals to present their research results and exchange their new ideas and application experiences face-to-face.

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