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Combining shallow hydrogeological characterization with borehole data for determining hydrofacies in the Valin River paleodelta

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ABSTRACT

A hydrogeological characterization of hydrofacies in the Valin River paleodelta, in the Saguenay region (Quebec), has been conducted based on the identification of lithofacies and the estimation of their hydrogeological properties, such as the hydraulic conductivity. One of the objectives of this study was to develop a conceptual model of the granular aquifers constituting the paleodelta. The approach begins by characterizing the internal architecture of the aquifers using the lithofacies documented from the excavated faces of sand-pits in the study area. As part of this work, it was proceeded to exploit the deeper lithological data from the wells and piezometers localised in the study area to complete the conceptual model. Accordingly, two different approaches have been proposed and adopted to determine hydrofacies from wells and piezometers data. Both approaches are based on combining shallow hydrogeological information, collected on the exposed faces of the sand-pits investigated in the study area, with the geological information obtained from wells and piezometers. This paper describes the steps for determining hydrofacies, as well as the results obtained with each approach.

RÉSUMÉ

Une caractérisation hydrogéologique des hydrofaciès dans le paléodelta de la rivière Valin, dans la région du Saguenay au Québec, a été réalisée en se basant sur l'identification des lithofaciès et l'estimation de leurs propriétés hydrogéologiques telles que la conductivité hydraulique. Un des objectifs de cette étude était de développer un modèle conceptuel des aquifères granulaires constituants le paléodelta. L'approche débute par la caractérisation de l'architecture interne des aquifères à l'aide des lithofaciès documentés sur les faces excavées de certaines sablières localisées dans la zone d'étude. Dans le cadre de ce travail, il a été procédé d'exploiter les données lithologiques plus profondes des puits et des piézomètres localisés dans la zone d'étude pour compléter le modèle conceptuel. En conséquence, deux approches différentes ont été proposées et adoptées pour déterminer les hydrofaciès à partir de données de puits et de piézomètres. Les deux approches reposent sur la combinaison d'informations hydrogéologiques peu profondes, recueillies sur les faces fraiches des sablières examinées dans la zone d'étude, avec les informations géologiques provenant des puits et des piézomètres. Cet article décrit les étapes permettant de déterminer les hydrofaciès, ainsi que les résultats obtenus avec chacune des approches.

1 INTRODUCTION

Granular deposits are increasingly used around the world for many activities, such as sand extraction, construction of airports or other facilities, as well as water supply given their potential to provide good quality groundwater. Therefore, knowledge of the hydrogeological properties of these granular deposits is very important, especially in developing regions. The characterization of granular deposits systems is a key step for the construction of conceptual hydrogeological models and for the understanding of groundwater flow conditions (e.g. Quaternary basin of southwestern Quebec in Canada (Ross et al. 2005), Savannah River Site in South Carolina of USA (Rine et al. 2006), West of Bengal in India (Mukherjee et al. 2007), Miocene succession in Denmark (Scharling et al. 2009), Darling River Valley in Australia (Triantafilis and Santos 2011), and Tiber Valley in Italia (Di-Salvo et al. 2012)). Also, conceptual hydrogeological models are required for adequate understanding of contaminant transport problems, as well as the management and protection of water resources. However, the predictive function of conceptual hydrogeological models is dependent on the quality and quantity of geological data used in the characterization of granular aquifer systems (Di-Maio et al. 2014). Consequently, hydrogeological studies, including the transport of contaminants in such heterogeneous aquifer systems, require a thorough investigation. Indeed, the variability in physical structure and texture of sediments often result in a complex spatial distribution in hydrogeological properties (Hsien-tsung et al. 2010, Vienken and Dietrich 2011). This complexity results in a great variability of hydrogeological parameters such as hydraulic conductivity and porosity. A resulting challenge is the determination of preferential pathways of groundwater flow in these heterogeneous granular aquifer systems.

This paper proposes two approaches for the hydrogeological characterization of the internal architecture of granular aquifers. These two approaches combine the geological information gathered from a shallow hydrogeological characterization study with geological data provided by boreholes. The result could be used to develop more exact hydrogeological conceptual models.

2 REVIEW ON DETERMINING THE INTERNAL ARCHITECTURE OF GRANULAR AQUIFERS

Sedimentological analysis and interpretation can provide a systematic framework for the reconstruction of the architectural elements of the paleodelta and its spatial continuity (Heinz et al. 2003). The use of this knowledge is fundamental to obtain a sound geological description of the heterogeneity and to determine units of high hydraulic conductivity (Anderson 1989, Iversen et al. 2008). Hydrogeological studies (Heinz et al. 2003, Kostic et al. 2005) have shown that the determination of the internal architecture of granular aquifers could follow an approach consisting of an initial sedimentological characterization based on the identification of lithofacies, defined as lithological units characterized by a particular combination of lithologies and physical structures (Walker 1992). The process would then be finalised by estimating hydrogeological parameters, i.e. hydraulic conductivity and porosity, of the identified lithofacies to determine the hydrofacies. By definition, a hydrofacies combines lithological units that have a relative homogeneity in their hydrogeological properties (Poeter and Gaylord 1990).

According to Elshall et al. (2013), the conceptualization of the internal architecture of granular aquifer systems is relatively dependent on the type and density of hydrofacial data as well as the heterogeneity characterization scale. Indeed, some studies consider the hydro-stratigraphic sequences as the appropriate scale (Miller et al. 2000, Scharling et al. 2009); some authors consider the hydrofacies assembling scale (Trevisani and Fabbri 2010); other researchers refer, more specifically, to the hydrofacies unit (Zappa et al. 2006); and finally, some hydrogeological characterizations are carried out by combining different scales (Proce et al. 2004). One of the difficulties in these investigations appears when the envisaged conceptual hydrogeological models consider a larger scale. This involves the use and/or completion of a sufficient number of boreholes or investigation points over the study area in order to obtain sufficient geological information to be used for developing an appropriate conceptual model. In fact, the detailed hydrogeological characterization of the internal architecture of an aquifer systems improves considerably the reliability of the hydrogeological conceptual models (Fogg 1986, Johnson and Dreiss 1989).

3 THE NECESSITY FOR UPSCALING DATA

A hydrogeological characterization study of hydrofacies in the Valin River paleodelta in Saguenay region (Quebec) was conducted by Boumaiza (2008). One of the objectives of this study was to construct a conceptual model of the granular aquifers of this paleodelta. The followed approach was to describe the internal architecture of the aquifers by characterizing lithofacies units exposed at fresh faces in operating sand-pits. These artificial depressions provide easy access to lithofacies, and the direct determination of their sedimentary and hydrogeological characteristics. The fresh sand-pit faces offer the possibility to conduct in situ hydrogeological testing for estimating the hydraulic conductivity and porosity, as well as to collect soil samples for conducting grain size analysis.

The envisaged conceptual model was a 3D description of the spatial distribution of the hydrofacies determined in this study. However, the large extent of the Valin River paleodelta (about 60 km^2; Figure 1), combined with the limited number of operating sand-pits, posed some difficulty in modeling the entire aquifer system. However, a portion of this paleodelta in the south of the Saint-Honoré airport present an adequate number of operating sand-pits (indicated as 1, 2, 3 and 4 in Figure 1), as well as an appropriate number of wells and piezometers that are well documented. This portion that covers an area of 5.76 km^2 was finally chosen to develop a smaller conceptual model based on both surface exposures and data from wells and piezometers. However, the raised problem was to find an approach allowing to combine the hydrogeological information collected on the faces of the investigated sand-pits and the data collected from wells and/or piezometers (boreholes). This combination was proposed for determining the hydrofacies along the boreholes, and incorporates them within the envisaged conceptual model.

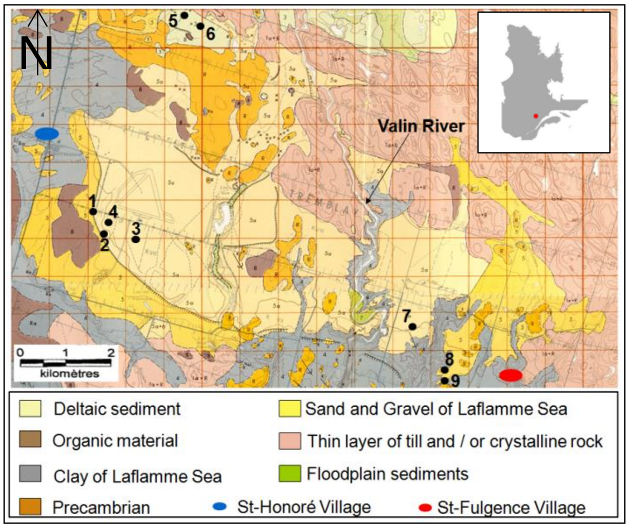


Figure 1. Granular deposits of Valin River paleodelta in the Saguenay region (According to Lasalle and Tremblay 1978).

4 REVIEW OF UPSCALING APPROACHES

Numerous tools for acquiring lithological information and the stratigraphic characteristics of granular deposits at different scales are available (Galloway 2010). An application was carried out by Scharling et al. (2009) based on a large database of geophysical surveys and drilling reports. Geophysical methods are increasingly used in the characterization of the internal architecture of granular aquifers (Huggenberger et al. 1994, Rea and Knight 1998, Hinnell et al. 2010). However, these indirect methods can only provide an approximate assessment of underground structures, and do not permit an accurate analysis of hydrogeological parameters (Brauchler et al.

2010). Geophysical methods for assessing the hydrodynamic parameters of complex aquifer systems are yet to be developed (Roy et al. 2008). Consequently, they were not used in the hydrogeological characterization study of Boumaiza (2008).

A number of studies (e.g. Klingbeil et al. 1999; Heinz and Aigner 2003, Heinz et al. 2003) have used small-scale hydrofacial analysis in large-scale applications, assuming that the determined stratigraphic units constitute the key step allowing to determine the heterogeneity of aquifers. Indeed, this method offers the possibility of adopting specific available geological information concerning a part of a study area for a better assessment of sedimentological processes that were involved, and to extrapolate these results to aquifer characterization at different scales. This approach is strictly qualitative and can be used to improve the model of the spatial distribution of hydrofacies in granular deposits (Kostic et al. 2005). However, the application of this approach to the conceptual modeling of large scale granular aquifer systems implies combining geological data from surface exposures in the study area, with geological data on deeper sediment units obtained from borehole logs (Scharling et al. 2009). Two approaches have been adopted by Boumaiza (2008) as part of this data combination process, for the purpose of determining hydrofacies along boreholes, as explained in the following section.

5 SELECTED APPROACHES

As described in Boumaiza et al. (2017), an intermediate step was introduced between the identification of lithofacies and the determination of hydrofacies. This step consists in determining the operative lithofacies according to the approach proposed by Zappa et al. (2006). For this purpose, the identified lithofacies characterized by the same classes and the same grain size fractions were grouped into operative lithofacies. Each determined operative lithofacies therefore is described by a set of hydraulic conductivity values; the magnitude of these values is related to the particle size fraction, and also to the method used for estimating this parameter. Moreover, a number of identified lithofacies belong to the same class and present similar particle size fraction (Boumaiza et al. 2015).

According to Anderson (1989), a hydrofacies can be defined as an anisotropic medium that is characterized by its size, geometry and hydrogeological properties, primarily hydraulic conductivity, whose values can vary by several orders of magnitude. It is assumed therefore that a hydrofacies can ultimately be characterized by a range (interval) of hydraulic conductivity values. Once this interval is determined for each operative lithofacies, those with similar hydraulic conductivity intervals are then grouped to determine the corresponding hydrofacies. This approach was adopted to determine the hydrofacies of the granular deposits of the Valin River paleodelta, wherein four hydrofacies (A, B, C and D) were determined. Each of these hydrofacies was characterized by a single representative value of hydraulic conductivity; it is the arithmetic mean of all the values obtained for the operative lithofacies that are considered (Boumaiza 2008, Boumaiza et al. 2017). Moreover, the domain to be modeled has been investigated by a number of boreholes that were realized in previous hydrogeological studies (Dessureault 1977, Laboratoires S.L. 2000a, 2000b, 2003). The two approaches that were followed for determining the hydrofacies along boreholes are described below using borehole N1 (Dessureault 1977) as an example. During the realization of borehole N1, soil samples were collected continuously for regular intervals of 1.5 m to a depth of 31.5 m., for a total of 21 soil samples. Grain size analyzes were also carried out on the soil samples.

5.1 Approach A

The grain size distribution graphs for the 21 soil samples collected in borehole N1 were used to determine the percentiles corresponding to d_{10} and d_{60} (Boumaiza 2008). Thus, hydraulic conductivity was estimated using Beyer (1964) empirical formula (eq. 1).

$$K = C.d_{10}^2 \qquad [1]$$

where:

K : Hydraulic conductivity (m/s)
d_{10} : Effective diameter (mm)
$C = 4.5 \times 10^{-3} \log 500/Cu$
Cu : Uniformity coefficient (d_{60}/d_{10})

The hydraulic conductivity value was estimated (in cm/s) for each grain size curve representing a soil sample collected at a given depth over a 1.5 m borehole length. The obtained value was then compared to the hydraulic conductivity values of hydrofacies A, B, C and D to select the one whose conductivity is the closest to the estimated value. For example, for the range of 0 to 1.5 m depth of N1 borehole, the hydraulic conductivity estimated from the grain size curve of the soil sample is 8.18×10^{-2} cm/s. When compared with the hydraulic conductivity values of the determined hydrofacies, it appears that hydrofacies C shows a hydraulic conductivity value that is the closest to the estimated value for the sample. Therefore, the depth interval from 0 to 1.5 m deep along borehole N1 is considered as corresponding to the hydrofacies C. As shown in the last column of Figure 2, this approach (Approach A), was applied throughout borehole N1 for determining the corresponding hydrofacies.

5.2 Approach B

Each soil sample collected from borehole N1 is considered as representing a single lithofacies. It was consequently necessary to determine first the lithofacies corresponding to each soil sample. This was done by determining the similarity between the grain size curve of the sampled soil along the borehole, and the curve obtained for the lithofacies identified in sand-pit faces, assuming that this similarity would lead to a value of hydraulic conductivity that could be considered similar.

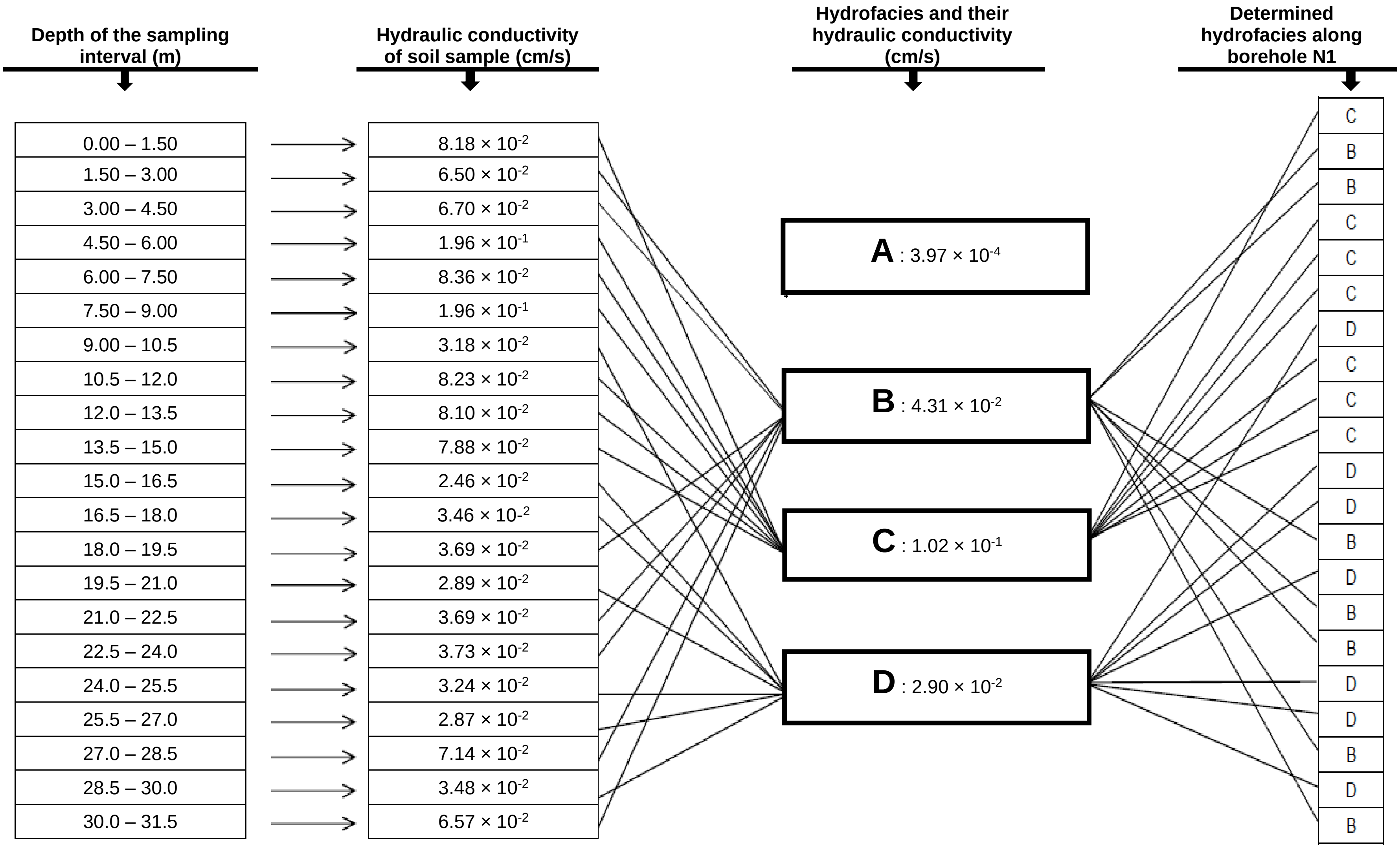
Although the hydraulic conductivity of the identified lithofacies in the sand-pits was estimated according to several methods (Boumaiza et al. 2015), only the values estimated by Beyer's (1964) empirical equation were considered for consistency with the estimate obtained from the borehole samples. In a few cases during field investigation, the same lithofacies, which was observed at more than one place, has yielded different values of hydraulic conductivity. In these cases, that lithofacies is represented by a single value of hydraulic conductivity representing the arithmetic mean. This later value was compared with the values obtained on the soil sample from borehole N1. For example, the lithofacies fSr was identified in sand-pits 1, 4 and 6, for respective values of hydraulic conductivity, estimated with Beyer's (1964) expression, of 2.17×10^{-2}, 2.90×10^{-2} and 2.11×10^{-2} cm/sec. The value of the hydraulic conductivity considered for this lithofacies is 2.39×10^{-2} cm/s, the arithmetic mean of the three values above. The set of lithofacies considered and their calculated hydraulic conductivity values are presented in Figure 3 (in the third column). Note that for some of the lithofacies identified on sand-pits faces, the hydraulic conductivity could not be estimated using Beyer's (1964) expression because of the application limits of this expression. For this reason, only 13 lithofacies with their hydraulic conductivity values are presented on Figure 3. Once the lithofacies corresponding to the borehole soil samples are determined (Figure 3), the corresponding hydrofacies are determined, as explained at the beginning of Section 5, by following the intermediate step for determining the operative lithofacies (Boumaiza et al. 2017). As shown in Figure 3, this approach (Approach B) was applied throughout borehole N1 for determining the hydrofacies that correspond to the sampled soils intervals along this borehole. The determined hydrofacies over the 31.5 m depth are presented in the last column in Figure 3.

6 RESULTS AND DISCUSSION

To facilitate the comparison of the results concerning the determination of the hydrofacies along borehole N1 according to the two proposed approaches, the end results are presented in two adjacent columns in Table 1. Note that hydrofacies A wasn't identified for any soil sample according to both approaches. This is explained by the low hydraulic conductivity value of this hydrofacies (3.97×10^{-4} cm/s; Boumaiza 2008) as compared to the estimated values for the 21 soils samples, varying from 8.36×10^{-2} cm/s to 1.96×10^{-1} cm/s. Moreover, it is noted in Table 1 that the two approaches led to same hydrofacies for the two soils samples collected at intervals of 4.50-6 m and 7.5-9 m. For the other samples, the two approaches lead to a few different results, because each approach has its own conditions of application. In fact, the hydraulic conductivity values for the soil samples obtained according to the approach A were compared directly with those of the hydrofacies; while these values, according to the approach B, were compared with those of the lithofacies before determining the hydrofacies. In addition, the sensitivity of the two approaches, in particular approach A, depends on the difference between the hydraulic conductivity values of the hydrofacies (hydrofacies B: 4.31×10^{-2} cm/s, hydrofacies C: 1.02×10^{-1} cm/s, hydrofacies D = 2.90×10^{-2} cm/s). Given the small difference between the representative hydraulic conductivity values of hydrofacies, the process of selecting hydrofacies becomes very sensitive. On the other hand, it should be noted that the hydraulic conductivity values of the borehole soil samples were obtained using Beyer's (1964) empirical expression, and that the hydraulic conductivity values attributed to the lithofacies in approach B represent the average of values also obtained using this empirical expression. However, the representative values of hydrofacies A, B, C and D have been estimated by combining several expressions (Boumaiza 2008). The multitude of methods used for estimating hydraulic conductivity (Boumaiza et al. 2015) could explain the divergence between the two approaches. However, the comparison performed between the two approaches is only informative and the two approaches remain reliable, since they follow logical successive steps. Approach A is simpler than approach B, but the two approaches are useful for a deeper hydrogeological characterization of hydrofacies. As the physical structures of soil is destroyed during currently used techniques of soil sampling along borehole, a shallow hydrogeological characterization on surface exposures provides the possibility of interpreting information obtained from disturbed soil samples collected in boreholes. As a result of the PACES projects (*Projets d'Acquisition de Connaissances sur les Eaux Souterraines;* MELCC 2019), a large amount of hydrogeological data are become available over Quebec territory, including grain-size curves of the soil samples collected from water-wells boreholes. In this way, the two proposed approaches could be applied with these geological data for developing better hydrogeological conceptual models, which could be used to address contaminant transport problems and water resources protection.

Table 1. Results comparison

Soils sampling depth (m)	**Approach A**	**Approach B**
0.00 – 1.50	C	B
1.50 – 3.00	B	C
3.00 – 4.50	B	C
4.50 – 6.00	C	C
6.00 – 7.50	C	B
7.50 – 9.00	C	C
9.00 – 10.5	D	B
10.5 – 12.0	C	B
12.0 – 13.5	C	B
13.5 – 15.0	C	B
15.0 – 16.5	D	B
16.5 – 18.0	D	C
18.0 – 19.5	B	C
19.5 – 21.0	D	B
21.0 – 22.5	B	C
22.5 – 24.0	B	C
24.0 – 25.5	D	B
25.5 – 27.0	D	B
27.0 – 28.5	B	C
28.5 – 30.0	D	C
30.0 – 31.5	B	C



Depth of the sampling interval (m)	Hydraulic conductivity of soil sample (cm/s)	Determined hydrofacies along borehole N1
0.00 – 1.50	8.18×10^{-2}	C
1.50 – 3.00	6.50×10^{-2}	B
3.00 – 4.50	6.70×10^{-2}	B
4.50 – 6.00	1.96×10^{-1}	C
6.00 – 7.50	8.36×10^{-2}	C
7.50 – 9.00	1.96×10^{-1}	C
9.00 – 10.5	3.18×10^{-2}	D
10.5 – 12.0	8.23×10^{-2}	C
12.0 – 13.5	8.10×10^{-2}	C
13.5 – 15.0	7.88×10^{-2}	C
15.0 – 16.5	2.46×10^{-2}	D
16.5 – 18.0	$3.46 \times 10\text{-}^{2}$	D
18.0 – 19.5	3.69×10^{-2}	B
19.5 – 21.0	2.89×10^{-2}	D
21.0 – 22.5	3.69×10^{-2}	B
22.5 – 24.0	3.73×10^{-2}	B
24.0 – 25.5	3.24×10^{-2}	D
25.5 – 27.0	2.87×10^{-2}	D
27.0 – 28.5	7.14×10^{-2}	B
28.5 – 30.0	3.48×10^{-2}	D
30.0 – 31.5	6.57×10^{-2}	B

Figure 2. Determining hydrofacies throughout borehole N1 according to the approach A (A, B, C and D: hydrofacies).

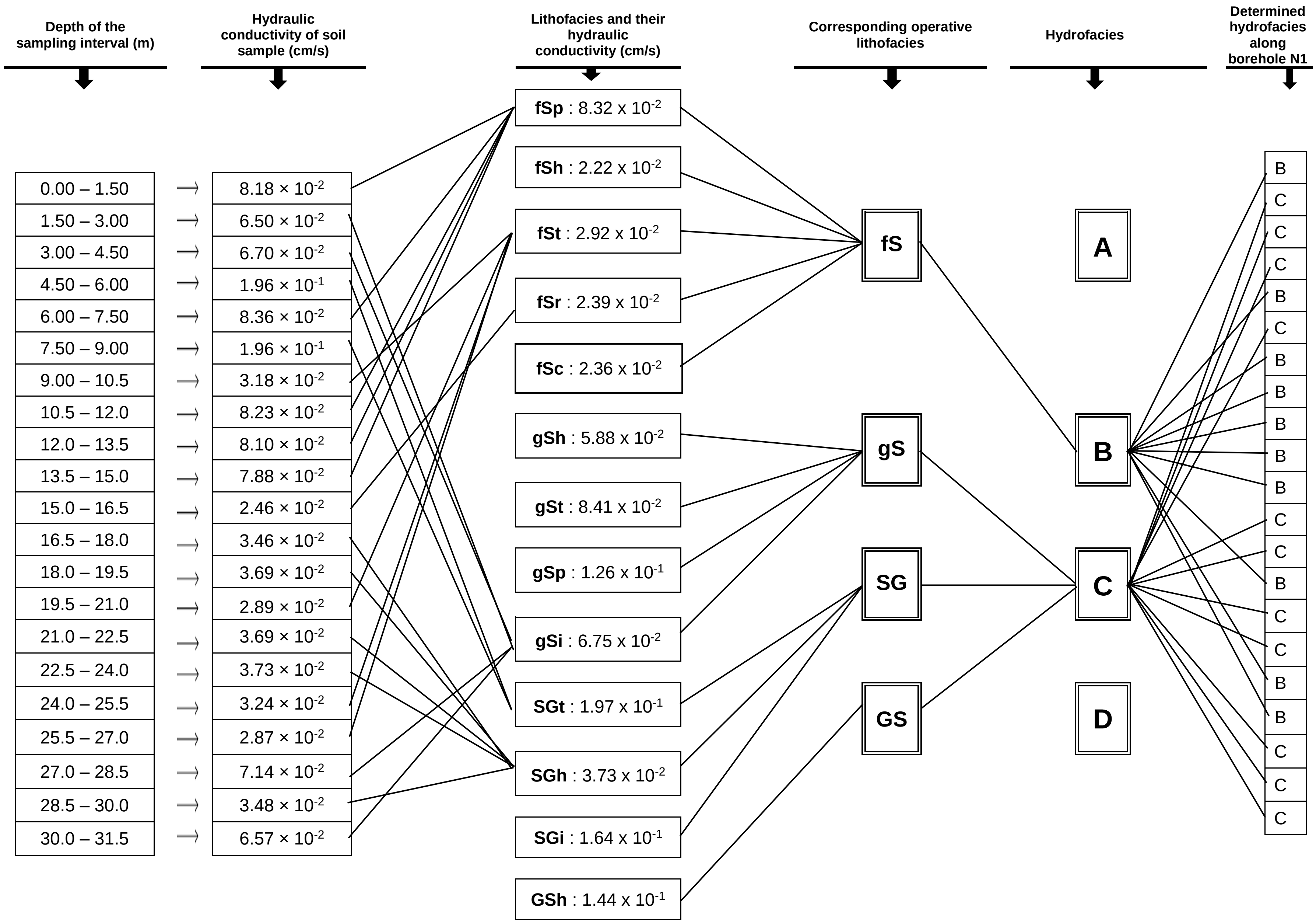


Figure 3. Determining hydrofacies throughout borehole N1 according to the approach B (fSp, fSh,…: lithofacies; A, B, C and D: hydrofacies).

7 CONCLUSION

As part of a hydrogeological characterization study of hydrofacies in the granular aquifers of the Valin River paleodelta, two approaches allowing to determine hydrofacies throughout a borehole have been proposed. These two approaches are based on combining shallow hydrogeological information from sand-pit faces with geological data obtained from boreholes (wells and piezometers). The advantage of these two approaches lies in the simplicity of their sequential steps. On the other hand, the concept of these approaches could be used for local and/or regional hydrogeological characterization studies. Indeed, in many cases, a number of boreholes (wells, piezometers and drilling boreholes) have been conducted for previous studies of the subsurface over an area of interest. The information collected from these boreholes could be used for determining the internal architecture of granular deposits, and to develop more accurate hydrogeological conceptual models of aquifers.

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