Comparative non-linear regression - case of infiltration rate increase from upstream in valley

Amadou Keita[1]*, Hamma Yacouba[1], Laszlo G. Hayde[2], and Bart Schultz[2]

[1]Department of Hydraulics, International Institute for Water and Environmental Engineering (2iE),
Ouagadougou, 01 BP 594 Ouaga 01, Burkina Faso
[2]Department of Water Science and Engineering, International Institute for Hydraulic and Environmental Engineering
(UNESCO-IHE- Institute for Water Education), Delft, PO Box 3015, 2601 DA Delft, the Netherlands

A b s t r a c t. In Tropical Savannah flooded valley soils, very low infiltration rates often result in acidic conditions favourable to high concentrations of metallic ions, toxic for rice. Determination of the under-phreatic infiltration rate is important in drainage design to reclaim degraded soils. Several studies have addressed the mapping of the infiltration rate. Yet, its relationship with the toposequence of the valley is not clarified. This paper has investigated such a possibility, examining the case of the irrigated rice valley of Tiefora, Burkina Faso. Nine boreholes – from 1 to 5 m deep – were implemented from upstream to downstream. The Lefranc permeability test of the under-phreatic level in water-logged soils – used when the impervious layer is close to soil surface or absent – was conducted. First, a comparative regression was applied to the data, including all the parameters of the regression curves. In the case of dissimilarity of the infiltration processes, the comparison focused on the final permeability. The results show a permeability increase from upstream (0.10 ± 0.10 cm h^{-1}) to downstream (greater than 20 ± 10 cm h^{-1} in some places). Taking into account such a permeability increase in the subsurface drainage system design would result in implementation of more efficient and cost effective systems.

K e y w o r ds: drainage, Lefranc test, regression, one-phase-decay, permeability, Savannah

INTRODUCTION

Given the crucial role of the valley bottom in ensuring food security, soils in these areas have been submitted to intensive research and development (Nguu *et al*., 1988; Oosterbaan *et al*., 1986). In fact, valley bottoms – where the most sophisticated and rich traditional farming systems in Africa are found - represent less than 10% of the total crop production areas (Oosterbaan *et al*., 1986). However, valley

bottoms constitute privileged zones for various physico-chemical processes such as sedimentation and precipitation of toxic and non-toxic ions. For example, poor drainage capacity or very low permeability is closely linked to the increase in acidity and rice iron toxicity (Chérif *et al*., 2009).

Much research addressed the permeability characterization issue in valley bottoms. For this purpose, regional cartographic mapping of soil permeability and sensitivity were conducted (Cam *et al*., 1996; Sharma *et al*., 1987). Attempts were also made to assess the soil infiltration rate using remote sensing in arid regions (Ben-dor *et al*., 2004). In addition, regression fittings have been applied to describe infiltration in Savannah valley bottom soils (Fagbamia and Ajayia, 1990). Though all these studies cover more or less wide zones, none of them examines the relationship between the under-phreatic level permeability and the toposequence at which it is located. Nevertheless, discriminating permeability values throughout a valley, where a subsurface drainage project is planned, can lead to a drastic reduction of the implementation costs, and much greater efficiency. The present study contributes in this area by making a comparative regression analysis of three cross sections of the valley of Tiefora in Burkina Faso (West Africa), from upstream to downstream.

MATERIALS AND METHODS

Located in southwestern Burkina Faso, at the heart of the Tropical Savannah area, the position of the irrigated rice valley bottom of Tiefora has considerably evolved during the implementation process. The geographic coordinates of

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*Corresponding author e-mail: amadou.keita@2ie-edu.org

the site are 4°33'13.19' W and 10°37'33.56' N. The valley is located some 800 m downstream from an earthen dam. This irrigation scheme was formerly intended to be constructed immediately downstream the dam, where the local population, composed essentially of Karaboro (Institut National de la Statistique et de la Démographie (INSD-BF)], 1985), was producing even though rustically a certain quantity of rice. The first idea was naturally to develop the lands into an irrigation scheme (SOGETHA, 1963). However, it appeared that not only those lands downstream of the dam were composed of isolated pieces of soils with no surface water interconnection, but also that the soils were not so suitable for rice production (Office National des Barrages et des Aménagements Hydroagricoles (ONBAH)], 1987). After soil and topographic surveys, the 16 ha irrigation scheme was finally developed at the current site, where soils were more clayey and where the slopes and the axes of the valley were more accentuated. Afterward farmers were relocated to this new site.

In order to get as much as possible a complete picture of the permeability in the valley, a topographic survey was conducted and nine borehole locations determined. The survey provided a contour lines map of the area, with the indication of the limits of the irrigation scheme. The main axis and, perpendicularly to it, the upstream, the middle, and the downstream cross-sections of the valley were identified. Subsequently, on each of the cross sections, three points – one along the axis of the valley and two at the edges of the cross section but inside the irrigated area – were marked and their geographic coordinates determined by a topographic survey and re-checked with a Global Positioning System (Fig. 1).

In the 50-year old valley bottom, anticipating a heterogeneous soil requiring several boreholes, two main types of boring machines were prepared. When passing through a clayey and cohesive but non-saturated soil, the Edelman auger with a 70 mm diameter was used. The body of this auger is made of two blades that tapered into two linked 'spoons' at the bottom, while they are connected at the top *via* a bracket to an extension rod operated by a handle (Royal Eijkelkamp, 2009). Across saturated soils under the groundwater table, in layers with sand or gravelly non-cohesive material, the Riverside auger with a 70 mm diameter was used. The body of this auger consists of an open tube at the bottom of which there are two soldered spoon-shaped pieces. Here also a bracket connects the top of the open tube to the bottom part of the extension rod operated by a handle.
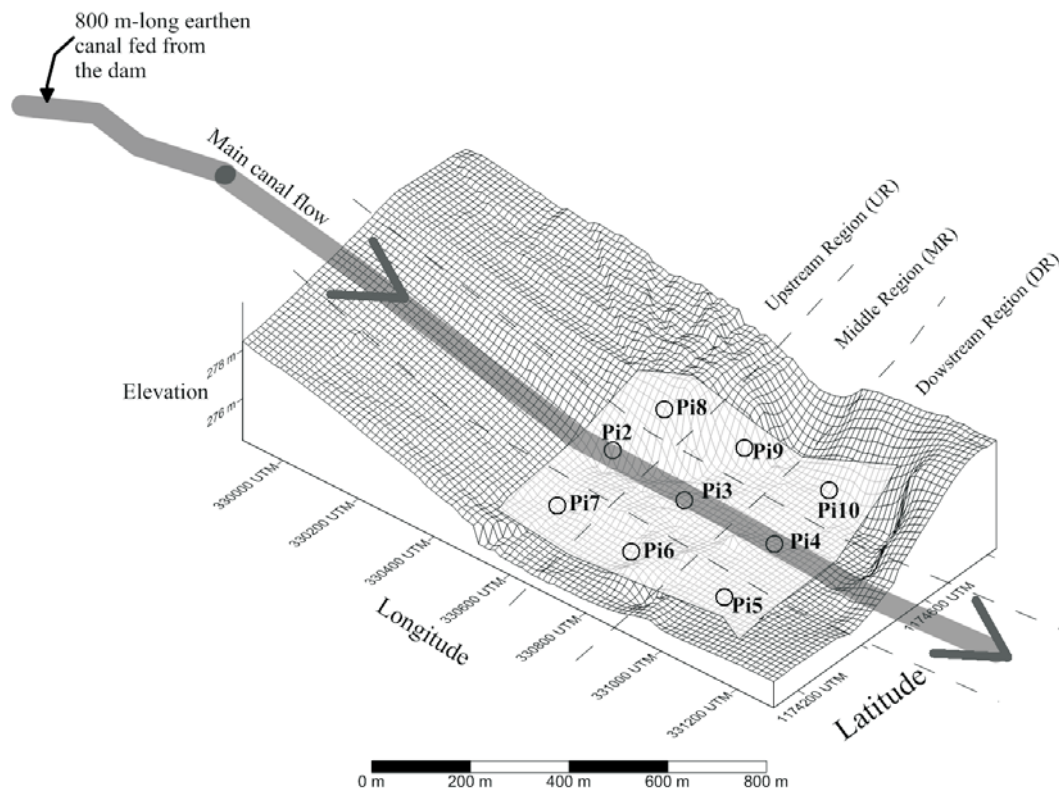
Fig. 1. The three cross sections and the location of the nine boreholes of Tiefora valley bottom. The main canal receives water from a 'transport' earthen canal, which is fed by an earthen dam located 800 m upstream. The circles represent the piezometers (boreholes) installed along three cross-sections in the Tiefora valley bottom (Burkina Faso). Pi2 stands for Piezometer No. 2, Pi3 is the Piezometer No. 3 *etc*. The cross sections are located some 300 m from each other (Keita *et al*., 2013a).

The extension rods of one-meter length with coupling sleeves were connected to the auger at the bottom, and were operated on the top using a screwable handle (Royal Eijkelkamp, 2009). The boring would be ended any time a clear fine sand layer was found. The fine sand layer would create a higher infiltration rate at the bottom – not reflecting the permeability of the soil top layers-rapidly filling or emptying the borehole. Therefore, the borehole was clogged back with clay until complete covering of that layer. These non-lined boreholes - with depths ranging from 1 to 5 m – were used for under-phreatic level permeability measurements.

The main canal receives water from a 'transport' earthen canal, which is fed by an earthen dam located 800 m upstream. The circles represent the piezometers (boreholes) installed along three cross-sections in the Tiefora valley bottom (Burkina Faso). Pi2 stands for Piezometer No. 2, Pi3 is the Piezometer No. 3 *etc*. The cross sections are located some 300 m from each other. Source: Keita *et al*. (2013a).

Though several permeability measurement methods exist (Bouwer and Jackson, 1974; Peter, 1990), only two of them allowing the measurement of the under-phreatic level permeability were planned: the Hooghoudt method and the Lefranc method. The Hooghoudt method (Schilfgaarde, 1957) was not applicable because the impervious layer, supposed to be at a depth of 2 m, was simply absent. Conversely, the first boreholes revealed the existence of an impervious

layer on the top of a pervious one. Consequently, the Lefranc method (Cassan, 2005) was used. Referring to an initial phreatic level in a soil, this method is implemented by producing a differential hydraulic head inside a cavity of known dimensions. The cavity is created at the basis of a borehole. This way, the flow towards the borehole, generated by the hydraulic head, happens only through the cavity (Fig. 2). The evolution of the differential hydraulic head – created by pumping or injecting water at a constant discharge – was measured against the time at observable decreases of the water level. The resulting times t and hydraulic head Hi intervals were used to compute the infiltration rate per time interval as it follows in Eq. (1):

$$I_t = -\frac{Hi_{t+\Delta t} - Hi_t}{\Delta t}, \qquad (1)$$

where: I_t is the infiltration rate (cm h^{-1}), $Hi_{t+\Delta t}$ represents the hydraulic head at instant $t+\Delta t$ (cm), and the Hi_t is the corresponding value at instant t (Fig. 2). The negative symbol is used in the current pumping Lefranc test (instead of injecting) from the borehole ($Hi_{t+\Delta t}$ smaller than Hi_t). Statistical analysis was applied to the resulting data.

The statistical analysis strove, first, to determine two suitable regression best-fit models, and to select among them the one with the most physically meaningful parameters. For this purpose, two non-linear regression models were put to the test: the quadratic and the exponential one-
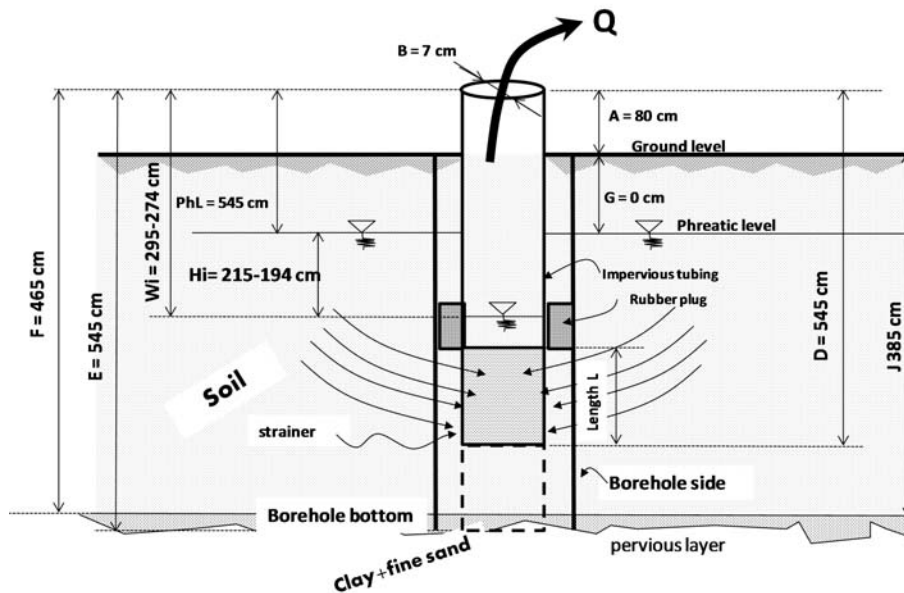
Fig. 2. Lefranc test implemented at Tiefora. The Lefranc test for under-phreatic permeability measurement is explained here using the case of the piezometer called Pi8. The equipment was installed using rubber plugs between the plastic tubing of the borehole and the impervious PVC tubing that holds a strainer at its extremity. This system composed of PVC tubing and rubber plugs forces the water - coming from the soil layers which permeability was being measured - to flow into the strainer. Once the tubing has been prepared, a borehole with an 80-85 mm diameter is implemented using 70 mm diameter augers till just before the fine sand layer. The tubing is introduced inside the borehole and the following parameters are either measured or computed. Measured parameters: coordinates (*X, Y*) of the borehole, tube length above ground *A*, tube diameter *B*, distance from the tube start to the strainer bottom edge *D*, length of the strainer *L*, depth of the pervious layer J, and the water level *Wi* depending on the time. Computed parameters: phreatic level *PhL*, borehole edge depth *E*, pervious layer start *F*, borehole section *S*, phreatic depth *G* from the soil surface, and the hydraulic head *Hi*.

phase decay equations. The first selection criterion between the two models was their goodness of fit, and the second their simplicity when both displayed an equivalent first criterion. Finally, the last criterion was the physical meaningfulness of the model parameters. The considerable amount of time required for digging every borehole and achieving stabilization of the hydraulic head (Fig. 2) restricted the amount of data collected per borehole to generally less than ten. Nevertheless, the goodness of the model was assessed using three sets of key parameters:

– the goodness of fit (especially the coefficient of determination R^2 and the standard deviation of the residuals Syx) (Montgomery and Runger, 2011);
– the normality test of residuals of Shapiro-Wilk (1965),
– the assessment of the deviation of the data from the curves by the Runs test method (McWilliams, 1990).

Once the most suitable models were selected, the analysis focused on comparing the infiltration processes on a cross sectional basis. The major surface flow - governing sediment transports and depositions (Selley, 2000) during the flood period - suggested dividing the valley bottom into three cross sections for permeability analysis: upstream, middle, and downstream. Accordingly, the complete set of regression models found for the three boreholes of a considered cross section are statistically compared. This comparison checks whether the infiltration processes were equivalent or a unique permeability can be chosen for the cross section. This was down by hypothesis testing of variance of the regression parameters (Härdle and Mammen, 1993; Neumeyer and Dette, 2003). When the comparison failed for the entire set of parameters, the models were once more compared on the only basis of the most meaningful parameter: the permeability.

RESULTS AND DISCUSSION

In spite of the goodness of fit of both quadratic and exponential one-phase decay models (Fig. 3), they could be discriminated based on physical meaningfulness of their parameters. For example, both models fitted with a coefficient of determination R^2 greater than 0.70 (Rumsey, 2009). In fact, for each of the nine boreholes, both quadratic and one-phase decay models had the same degree of freedom and therefore the p-value allowing the rejection of one of the two hypotheses could not be computed. However, while the coefficients in the quadratic Eq. (2) had no real physical meaning, the exponential one-phase decay Eq. (3) did. The two equations are:

$$I_t = B_0 + B_1 t + B_2 t^2, \qquad (2)$$

$$I_t = (Y_0 - \text{Plateau})\exp(-Kt) + \text{Plateau}, \qquad (3)$$

where: B_0 (cm h^{-1}), B_1 (cm h^{-2}), B_2 (cm h^{-3}) as the coefficients in the quadratic equation, and t, the time variable (h); It - the infiltration rate (cm h^{-1}) at instant t; the coefficients

Y_0 and Plateau (cm h^{-1}); K – the coefficient (1 h^{-1}), and the instant t (h). Plateau represents the limit of the function I_t when the time t becomes infinite.

At most, the quadratic function admits one extremum corresponding to the point where the first derivative is null. There is no limit to this function when the time t tends to infinite, and the zero intercept equal B_0 possesses no physical meaning as far as groundwater flow is concerned. By contrast, the exponential one-phase decay function was successfully used in many cases. It is applicable anytime the rate, at which one variable is altered, depends on the remaining amount of that same variable. Well-known examples include already the soil infiltration rate determination (Horton, 1941), the decay of radioactive isotope atoms (Gardner *et al.*, 1959; Varani *et al.*, 1990), and the turnover of blood cells in HiV-1 infection (Ho *et al.*, 1995). In other words, it is most appropriate in the present case where there is a decrease in time (deceleration) of the flow rate dI/dt at a velocity that can be considered proportional to the infiltration rate I. In these conditions, the equation can be expressed as:

$$\frac{dI}{dt} = KI, \qquad (4)$$

where: dI/dt (cm h^{-2}) is the average flow rate change (deceleration) in the soil medium during a short duration dt; K is a constant of proportionality (1 h^{-1}), and I is the infiltration rate (cm h^{-1}).

It can be verified that the following improper integral is a solution of Eq. (4):

$$I = C_1 \exp(-Kt) + C_2, \qquad (5)$$

where: C_1 (cm h^{-1}) the 'span' of variation of the infiltration rate with t increasing from zero to infinite (it corresponds to Y_0-Plateau in Eq. (3)). The coefficient C_2 (cm h^{-1}) is the 'Plateau', the limit of the function when t increases infinitely.

All the parameters of Eq. (3) – which is the same as Eq. (5) – possess a clear physical meaning in the groundwater flow. That explains why this model was selected. At the beginning of the measurements in the saturated soil, when $t = 0$ and the hydraulic head and hence the infiltration rate over the first minutes are the highest, the initial infiltration rate equals 'span+plateau' ($C_1 + C_2$). Then, while the experiment progresses, the hydraulic head decreases, reducing the infiltration rate. The infiltration rate depends on the remaining water layer and the process can therefore be described by an exponential one-phase decay regression. At greater values of the time t, the infiltration rate is smaller. Theoretically, when t tends to infinite, the asymptote of the function provides the value of the under-phreatic level permeability, plateau expressed in Eq. (3). Therefore, the value of the plateau can be used as the key parameter for subsurface drainage if any solute (*eg*. excess of aluminium, ferrous iron, sulphur *etc*.) has to be removed from the submerged soil (Suryadi, 1996).

Although many measurement points could not be obtained, the one-phase decay fitting to Tiefora permeability data provided rather good results. As can be observed from

Table 1, the coefficient of determination R^2 for example ranged from 0.70 to 1.00. However, as is known, R^2 is not sufficient to conclude on the goodness of fit of a model (Boslaugh and Watters, 2008). The normality test of the residuals gave p-values also greater than the significance level $\alpha=5\%$ (except for boreholes Pi3 and Pi5), allowing a conclusion for the normality of the residuals. Finally, the results yielded also an adequate distribution of the data around the curves, as shown by the values of the Runs test and Fig. 3 (Härdle and Mammen, 1993).

The three piezometric boreholes Pi7, Pi2, and Pi8 data on top represent the upstream cross section; the data of Pi6, Pi3, and Pi9 the middle cross section, and the data of Pi5, Pi4, and Pi10 the downstream cross section. The exponential one-phase decay regression curves represent the individual best fit curves, when no comparison is made among the borehole infiltration processes.

The one-phase decay regression modelling from upstream to downstream revealed a great variability not only in the infiltration processes, but also in the value of the stabilized permeability or plateau (Fig. 3). The attempt to make three regression equations with one related to each of the three cross sections (upstream, middle, and downstream), led to the rejection of this null hypothesis of similar processes with respective p-value of 0.01% for upstream, and 0.09 and 0.01% for the middle and downstream, respectively. Therefore, for all the cross sections the coefficients Y_0, K, and plateau of Eq. (3) were different and hence the infiltration processes dissimilar.
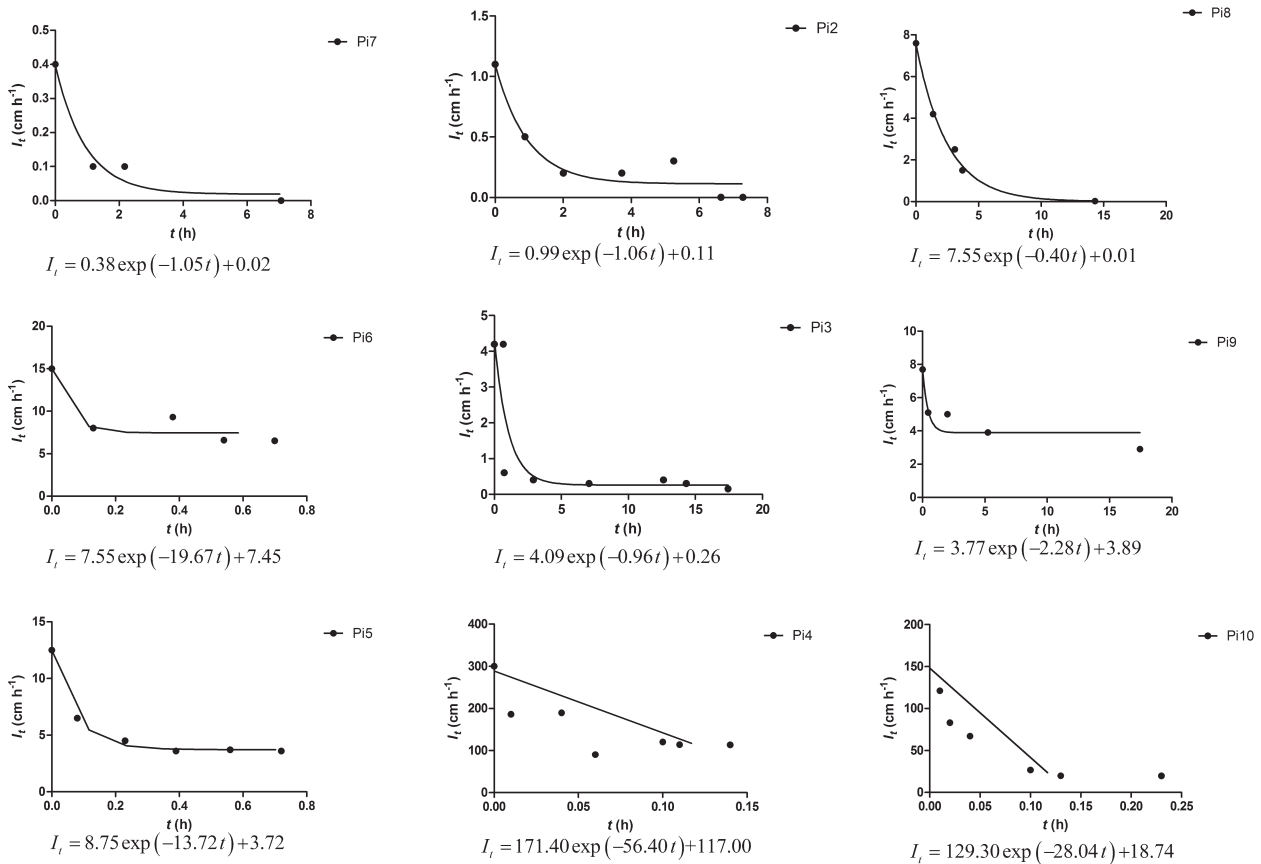
The important variability in the permeability – not very convenient for drainage engineering – can be lessened on valid statistical basis. In fact, the subsurface drainage design uses a small number of permeability values to implement projects in swampy areas (Keita *et al.*, 2013b; Wesström *et al.*, 2001). Hence, in the case of Tiefora, one can loosen the constraints upon the infiltration processes and statistically compare only the plateau values (under phreatic permeability) in each cross section. This examination reveals that the under-phreatic level permeability is similar (p-value greater 5%) for the three boreholes (Pi7, Pi2, and Pi8) in the upstream cross section. Their plateau equals 0.10 ± 0.10 cm h^{-1}. They are also similar for the three boreholes (Pi6, Pi3, and Pi9) in the middle section, where the plateau equals 0.30 ± 1.30 cm h^{-1} (Table 2). Therefore, though the infiltration processes are different, a single permeability can be used for the upstream cross section on the one hand and the middle cross section on the other hand. However, the variability is so important in the downstream cross section that a unique permeability cannot be chosen.

The remarkable increase in the permeability from upstream to downstream in the valley bottom (Fig. 1 and Table 2) cannot simply be explained by soil alteration. Two major phenomena are generally considered to explain valley bottoms genesis (Schaetzl and Sharon, 2005). First, it is assumed that valley bottoms and streams generally appear on the top of deep fractures of the sound rocks (CIEH, 1987) as the consequence of rock chemical alteration driven by

T a b l e 1. Goodness of the models

Piezometer	Pi7	Pi2	Pi8	Pi6	Pi3	Pi9	Pi5	Pi4	Pi10
				Goodness of fit*					
Degree fo freedom	1	4	2.00	2	5	2	3	4	3
Regression coefficient R^2	0.97	0.93	0.99	0.90	0.73	0.83	1.00	0.84	0.98
Absolute sum of squares (Ab SS)	0	0.06	0.18	5.03	6.05	2.15	0.23	5 019.00	153.40
Standard deviation of residuals	0.05	0.13	0.30	1.59	1.10	1.04	0.28	35.42	7.15
				Normality test of residuals (%)					
Shapiro-Wilk p-value (%)	51	47	48	18	3	59	4	36	63
				Runs test					
Points above the curve	2	3	2	2	4	3	2	3	4
Points below the curve	2	4	3	3	4	2	4	4	2
p-value (runs test) (%)	100	54	90	90	63	90	80	97	100
Deviation from the model				not significant					

*Null hypothesis – the most suitable regression equation is exponential one-phase decay (expntl). Alternative hypothesis – the best fit function is a quadratic (quad) function (second order polynomial).

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$$I_t = 0.38\exp\left(-1.05t\right)+0.02$$

$$I_t = 0.99\exp\left(-1.06t\right)+0.11$$

$$I_t = 7.55\exp\left(-0.40t\right)+0.01$$

$$I_t = 7.55\exp\left(-19.67t\right)+7.45$$

$$I_t = 4.09\exp\left(-0.96t\right)+0.26$$

$$I_t = 3.77\exp\left(-2.28t\right)+3.89$$

$$I_t = 8.75\exp\left(-13.72t\right)+3.72$$

$$I_t = 171.40\exp\left(-56.40t\right)+117.00$$

$$I_t = 129.30\exp\left(-28.04t\right)+18.74$$

Fig. 3. Regression best fit curves and equations of the boreholes. The three piezometric boreholes Pi7 Pi2, and Pi8 data on top represent the upstream cross section; the data of Pi6, Pi3, and Pi9 the middle cross section, and the data of Pi5, Pi4, and Pi10 the downstream cross section. The exponential one-phase decay regression curves represent the individual best fit curves, when no comparison is made among the borehole infiltration processes.

acidic water (Jackson and Sherman, 1953). Then, the fracture develops transversal and longitudinal slopes and clay tends to accumulate. The second phenomenon, simultaneous to the first, consists of periodic or continual deposits of thin layers of colluvial, alluvial, or eolian sediments (Moormann and Breemen, 1978). That deposit changes the profile. These theories do not address the change in permeability from upstream to downstream.

From a different standpoint, the sedimentation process can greatly help explain the toposequential increase in permeability. The sediment transport and deposition processes have been object of several important studies (Selley, 2000). As shown by the results (Table 2), the permeability is much higher downstream with over 20±10 cm h^{-1} than upstream with 0.10 ± 0.10 cm h^{-1}. This observation can be explained to some extent by heterogeneity of downstream. The borehole soil data showed a thicker clay layer upstream and in the middle than downstream, where a quartzic stony soil is found more rapidly near the soil surface. However, in lakes and dams, the water flow conveys water from a relatively narrow irregular channel to an extended area, causing the

drop of velocity. Heavier particles like sand deposit first, while fine clay particles will deposit in the reservoir bed later but in a greater amount near the dam located farther. The permeability would therefore be lower near the dam. The phenomenon is inverted in flood plains: when the sediment loaded water invades the area, fine clay particles are deposited farther, upstream. Therefore, the permeability will tend to be lower upstream. We think this last process applies to the case of Tiefora, where the irrigated valley bottom continues to be flooded from downstream twice a year by the Lafonde River (Kanté, 2011).

The practical implications of such a toposequential variation of the permeability are important. In effect, it is well known (Skaggs, 2007) that the spacing of subsurface drainage pipes is smaller when the under-phreatic permeability is small, in order to be able to intercept more important flow. Therefore, drain pipe density in a valley bottom with a significant permeability increase from upstream to downstream will also conversely decrease from upstream to downstream. This consideration can lead to a more effective drainage at lower cost in comparison to a uniform piping of a swampy area.

T a b l e 2. Regression parameters with 90% confidence interval

Piezo-meter	Pi7	Pi2	Pi8	Pi6	Pi3	Pi9	Pi5	Pi4	Pi10
					Section				
		Upstream			Middle			Downstream	
Y_0	0.40±0.31	1.09±0.30	7.56±0.30	13.02±2.29	4.35±2.78	6.16±1.74	12.47±0.65	288.5±73.20	148.10±33.3
K	1.94±8.53	0.93±0.13	0.40±0.72	1.21±0.62	0.99±1.73	0.06±0.08	13.72±3.12	56.4±78.80	28.04±15.74
Span[1]	0.32±0.33	1.02±0.29	7.50±0.32	12.70±2.61	4.30±3.00	5.84±2.14	8.75±0.73	171.40±79.5	129.30±30.7
Plateau	0.07±0.13	0.07±0.13	0.07±0.13	0.32±1.30	0.32±1.30	0.32±1.30	3.72±0.36	117.00±40.80	18.74±12.95
					Goodness of models				
R^2	0.93	0.92	0.99	0.68	0.73	0.68	-0.01	0.70	0.97
					Absolute sum of square				
	0.01	0.07	0.18	15.55	6.07	4.17	61.13	0.92	246.70

Unique plateau for cross section p-value (%)

84.40   5.20

Unique plateau for cross section p-value (%)		Individual plateau values for each borehole
0.07 ± 0.13	0.32 ± 1.30	3.72±0.36[2] 117.00±40.80 18.74±12.95

[1]Span $=Y_0$ - plateau, [2]this high value of plateau is due to quartzic stony layer found in the Pi4 borehole.

CONCLUSIONS

1. Comparative regression analysis can be used to assess the equivalence of infiltration processes and to determine a toposequential distribution in a valley bottom with very positive economic implications for subsurface drainage.

2. The results show that no unique infiltration process is valid for the whole valley. However, confining the comparison criterion only to the under-phreatic permeability reveals that it increases for upstream with 0.10±0.10 cm h^{-1} to more than 20±10 cm h^{-1} in some areas downstream, in spite of the differences of the infiltration curves.

3. Taking into account that subsurface drainage pipe spacing is bigger – and then the density of implantation is smaller – when the permeability increases, greater efficiency and money saving in the drainage system design and operation of valley bottoms can be achieved.

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