(1)_Spatial variability of soil saturated hydraulic conductivity in paddy field in accordance to subsurface percolation

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Paddy Water Environ (2010) 8:113–120
DOI 10.1007/s10333-009-0190-x

ARTICLE

Spatial variability of soil saturated hydraulic conductivity in paddy field in accordance to subsurface percolation

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Received: 23 June 2009 / Accepted: 15 November 2009 / Published online: 1 December 2009

Abstract Insufficient puddling with inappropriate implements or imprecise time/intensity may alter saturated water flow in paddy soil spatially or temporary due to change in aggregate size distribution, dry bulk density, saturated hydraulic conductivity, and percolation rate of the soil. In this study, spatial variability of saturated hydraulic conductivity (K_s), a key parameter of the saturated water flow, in Fuchu Honmachi paddy plot (100 m × 28 m) was characterized based on dielectric or ADR dry bulk density ($\rho_{b\text{-}ADR}$) with help of non-similar media concept (NSMC) and geostatistics model to meet its correlation to subsurface percolation. A 100 cc core and an ADR data were sampled from each sub-plot (7 m × 7.5 m), and then were used for measuring and predicting ρ_b and K_s. The predicted data agreed with the measured ones, in which they fitted well the $x = y$ line with RMSE of 0.029 $cm^3\ cm^{-3}$ ($R^2 = 0.68$), 0.027 $g\ cm^{-3}$ ($R^2 = 0.71$) (ρ_b), and 0.098 $cm\ d^{-1}$ ($R^2 = 0.45$) for θ, ρ_b, and K_s, respectively. The predicted ρ_b and K_s had similar trend in spatial variability to the measured ones particularly within the distance of 46.3–51.9 m and 26.2–27.9 m, respectively. The spatial variability of the predicted K_s coincided to that of the subsurface percolation rate, in which they had similar distance of dependence. The results indicated that the presenting method can be reasonably accepted.

Keywords Spatial variability · Saturated hydraulic conductivity · Paddy field · Dielectric dry bulk density · Subsurface percolation

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Introduction

Saturated water flow is an important factor in understanding the dynamic process of water and solute movement in soil. Although in most cases of upland field, saturated water flow is often used to designate an appropriate internal drain-ability for better crop growth (Arya et al. 1998). However, in paddy field it is considered to be undesirable since it may affect water balance instability, fertilizer inefficiency, and results in groundwater contamination by pesticide through subsurface percolation (Malone et al. 2003; Vu et al. 2003). Therefore, characterizing the saturated water flow and its distribution pattern in the paddy field is vital and worthy to be conducted to support better cultivation as well as to conserve aquatic environment.

Saturated hydraulic conductivity is a representative key parameter of the saturated water flow in soil. A number of direct methods have been applied for determining saturated hydraulic conductivity (Reynolds and Elrick 1991; Clothier and Smethem 1990; Wooding 1968). However, most of the methods are difficult to use and often time consuming (Libardi et al. 1980). This triggered many researchers to develop prediction model for determining saturated hydraulic conductivity from some basic soil physical properties (Julia et al. 2004; Regalado and Carpena 2004; Zhuang et al. 2001; Miyazaki 1996; Ahuja et al. 1989).

Wijaya and Kuncoro (2008), Wijaya et al. (2004, 2003), and hereafter Setiawan et al. (2004) developed a simple method for predicting volumetric water content and dry bulk density based on dielectric constant data produced by amplitude domain reflectrometer (ADR). By using five types of upland field soils, namely TUAT's Andisol, Fukaya's Alluvial, Bogor's Latosol, Cidanau-Banten's Brown Alluvial, and Pratin-Purbalingga's soil, it was found that the predicted values of such physical properties agreed well with the measured ones. Accordingly, employing the predicted data to NSMC model of Miyazaki (1996) to determine saturated hydraulic conductivity as well as its spatial variability in the fields was acceptable (Wijaya and Kuncoro 2008; Wijaya et al. 2005; Nishimura et al. 2007). However, in case of wetland field soils such as paddy field, the method has not been excessively applied yet.

This study was aimed to predict and to characterize spatial variability of saturated hydraulic conductivity in a paddy field based on dielectric (ADR) properties of dry bulk density as well as volumetric water content, and then to correlate the results to the field-distributed subsurface percolation.

Methodology

Experimental plot and soil properties

The experimental plot of 100 m × 28 m in large was prepared at Fuchu Honmachi paddy field (35°41′ N, 139°29′ E, 59 MSL) of Tokyo University of Agriculture and Technology (TUAT), Japan in the end of summer 2003. A number of 39 undisturbed soil and ADR samples were collected from every 7 m × 7.5 m subplots (Fig. 1) at the depth of about 15 cm by using 100 cc core and ADR probe, respectively. Additional disturbed soil samples were randomly taken from the plot for determining some soil properties as described in Table 1, and for ADR calibration purpose.

Calibration of ADR probe

The disturbed soil samples were packed into acrylic cylinder of 11 cm in inner diameter and 8 cm in height (Fig. 2). After the sample was weighed by using electric balance, the ADR probe was inserted vertically into the sample, and its output voltage was then recorded by using a digital voltmeter. Volumetric water content and the output voltage were plotted and fitted by using simple least-square method to obtain the calibration equation.

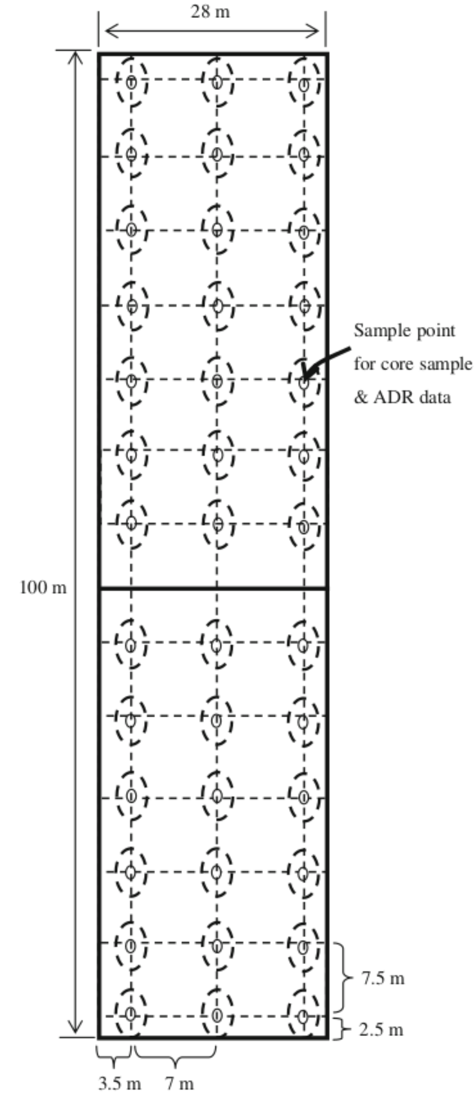

Fig. 1 Experimental plot of Fuchu Honmachi paddy field

Procedure to predict saturated hydraulic conductivity

The obtained calibration equation was used to predict soil volumetric water content ((), and the predicted data was then substituted in Eq. 1 (Wijaya et al., 2003) to calculate the dry bulk density (ρ_b) as follows:

Table 1 Physical properties of TUAT's Fuchu Honmachi paddy field soil

Parameters (unit)	Value
Texture (g kg^{-1}), sand:silt:clay	0.38:0.32:30 (light clay, LiC)[a]
Organic carbon content (g kg^{-1})	39.6
Particle density (g cm^{-3})	2.50
Dry bulk density (g cm^{-3})	0.77–1.01
Total density (g cm^{-3})	1.19–1.48
Cation exchange capacity, CEC (cmol kg^{-1})	22.5

[a] Textural class was defined based on the Japanese System of Textural Classification (Kawaguchi and Kyuma 1974)

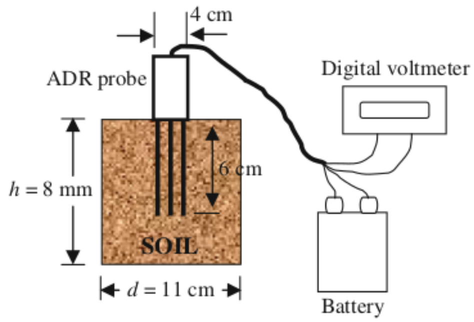

Fig. 2 Calibration of ADR probe

$$\rho_{b-ADR} = \rho_t - (\theta_{ADR} \cdot \rho_w) \quad (1)$$

where θ_{ADR} is the predicted volumetric water content by ADR (g cm^{-3}), ρ_t is the total density (g cm^{-3}), and $\rho_w$is the density of water (1 g cm^{-3}).

Saturated hydraulic conductivity (K_s) was predicted from the ADR dry bulk density ($\rho_{b\text{-}ADR}$) by using the non-similar media concept (NSMC) model of Miyazaki (1996) (Eq. 2) with certain parameters, i.e., K_{so}, τ, ρ_s, and ρ_{bo}, fitted prior to the prediction.

$$K_s = K_{so}\left[\frac{\left(\frac{\tau\rho_s}{\rho_{b-ADR}}\right)^{1/3} - 1}{\left(\frac{\tau\rho_s}{\rho_{bo}}\right)^{1/3} - 1}\right]^2 \quad (2)$$

where K_{so} is the measured saturated hydraulic conductivity of reference sample with a dry bulk density, ρ_{bo}, τ is the shape factor (it is limited by $\rho_b/\rho_s < \tau \leq 1$), and ρ_s is the measured particle density of the reference sample.

For laboratory scale, the volumetric water content and the dry bulk density were measured gravimetrically, while the saturated hydraulic conductivity was determined by falling head method. The data were used to validate the results of the predicted parameters obtained from the field observation.

Distribution of the predicted and the measured parameters, and also the subsurface percolation rate through puddled layer (0–15 cm in depth), monitored by Souphasay et al. (2003) under ponding condition, at 20 and 70 days after puddling were plotted in contour map. Their spatial variability were then analyzed by using semivariogram (Eq. 3), a well-known geostatistic tool (Clark 1979). Finally, those data were compared and corresponded one to another.

$$\gamma(h) = \frac{1}{2N(h)}\sum_{i=1}^{N(h)}[z(x_i) - z(x_i + h)]^2 \quad (3)$$

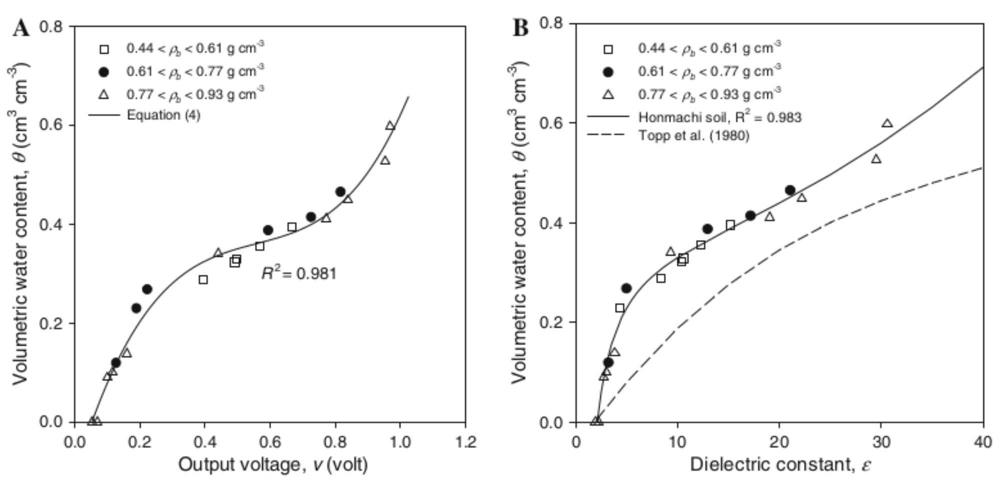

Fig. 3 Relationship between volumetric water content with: ADR output voltage (**a**) and dielectric constant (**b**)

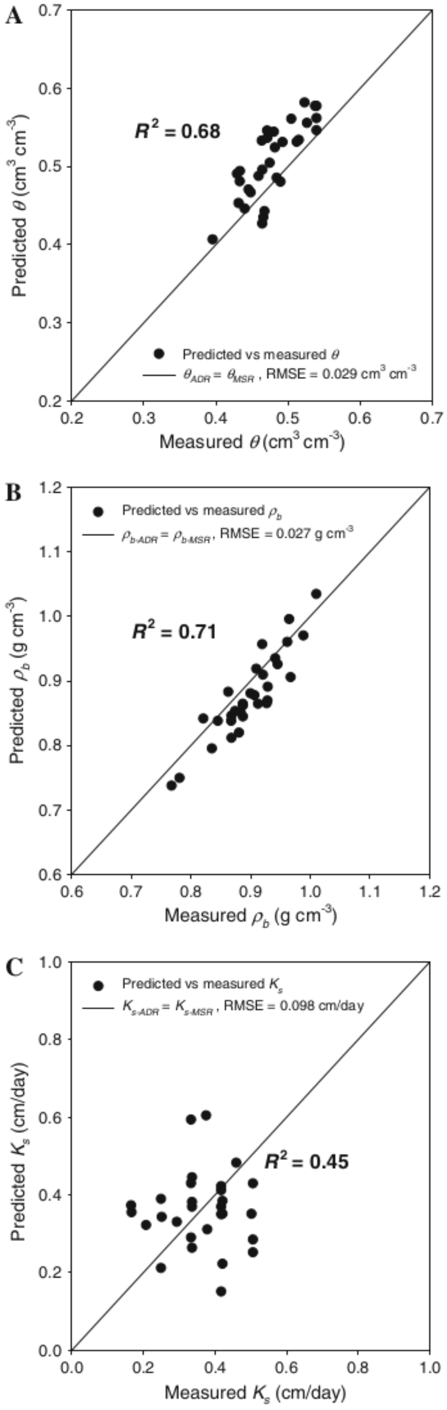

Fig. 4 Comparison between the predicted and the measured parameters: volumetric water content (**a**), dry bulk density (**b**), and saturated hydraulic conductivity (**c**)

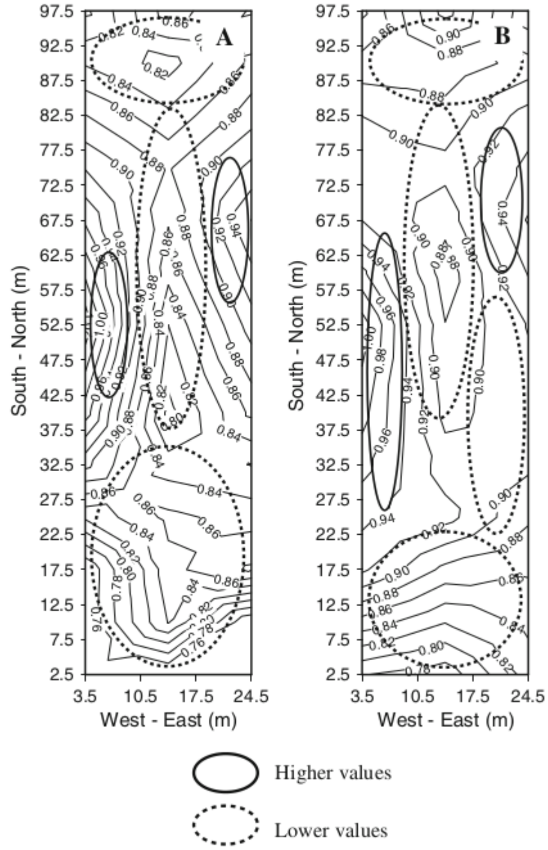

Fig. 5 Contour map of: predicted (**a**) and measured ρ_b (**b**)

where $N(h)$ is the number of sample pairs separated by a distance h, $z(x_i)$ is the measured sample value at point x_i, and $z(x_i + h)$ is the measured sample value at a distance h from x_i.

Results and discussion

Figure 3a presents the relationship between volumetric water content (θ) and output of the ADR probe (v) for Fuchu Honmachi soil, which mathematically can be expressed in Eq. 4. This equation was reliable mainly in the range of 0–0.6% volumetric water content. For such range, the result gained from Eq. 4 overestimated that of Topp et al. (1980) (Figure 3b); thus the specific ADR calibration was properly applicable for this study.

$$\theta_{ADR} = -0.104 + 2.158v - 3.567v^2 + 2.132v^3 \quad (4)$$

Comparison between the predicted and the measured parameters of the field experiment are shown in Fig. 4a

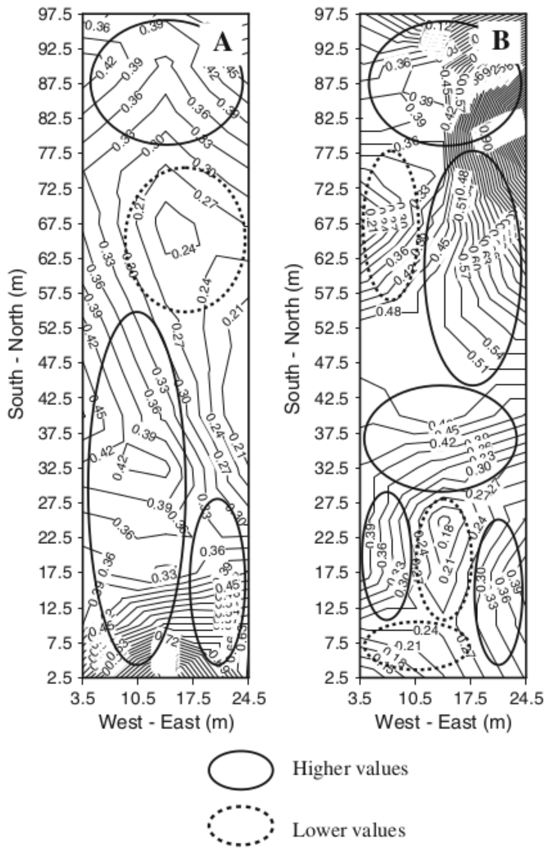

Fig. 6 Contour map of: predicted (**a**) and measured K_s (**b**)

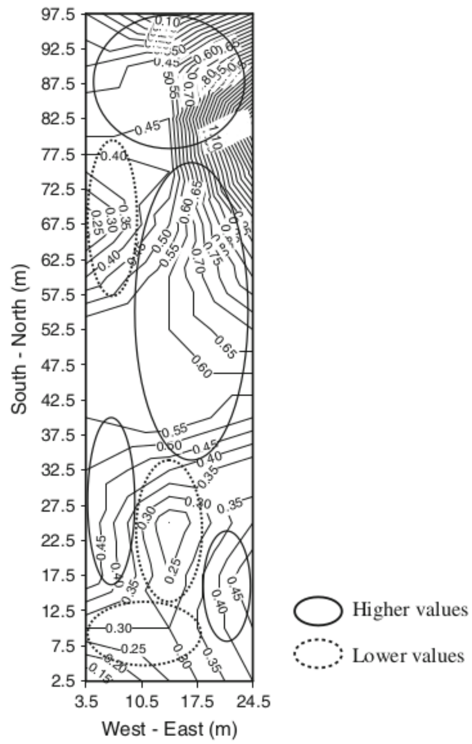

Fig. 7 Contour map of subsurface percolation rate

(volumetric water content), b (dry bulk density), and c (saturated hydraulic conductivity). The predicted data agreed with the measured ones, in which those followed the trend line $x = y$ with R^2 of 0.68 (RMSE = 0.029 g cm^{-3}) and R^2 of 0.71 (RMSE = 0.027 g cm^{-3}) for volumetric water content and dry bulk density, respectively. Since the errors were less than the average ADR error, i.e., 3% (Gaskin and Miller 1996) and the error for common soils, i.e., 4–15% (Tominaga et al. 2002), the results can be acceptable. On the other hand, although the predicted (by NSMC model with $K_{so} = 0.49$ cm d^{-1}, $\tau = 0.54$, $\rho_s = 2.79$ g cm^{-3}, and $\rho_{bo} = 0.79$ g cm^{-3}) and the measured saturated hydraulic conductivity seemed to be less fitted the line ($R^2 = 0.45$), the error (RMSE = 0.098 cm d^{-1} or 23% deviated from the average data) was considerably lower than its common error, i.e., 58–116% (Ciolarro and Romano 1995). Therefore, the result was still reasonable.

In spatial case, the agreement between the predicted and the measured parameters can be visually observed from their contour maps, as shown in Figs. 5 and 6, for dry bulk density and saturated hydraulic conductivity, respectively. The lower dry bulk densities covered almost the entire field, except the western part around the coordinate of [5, 52.5] m and the eastern part around the coordinate of [21, 67.5] m, where the values was higher (Fig. 5a, b). Accordingly, the higher saturated hydraulic conductivities distributed in most part of the field excluding the part around the coordinate of [15, 67.5] m (predicted data), also the coordinate of [5, 67.5] m, [15, 22.5] m, and [10.5, 7.5] m (measured data), where it was lower (Fig. 6a, b). This indicated that the distribution of the predicted data agreed with that of the measured ones, and the distribution of the saturated hydraulic conductivities closely related to that of the dry bulk densities.

Correlating the contour map of both the dry bulk densities and the saturated hydraulic conductivities to that of the subsurface percolation rate (Fig. 7) showed that they corresponded one to another. The location with higher dry bulk densities correlated to that with lower saturated hydraulic conductivities and lower subsurface percolation rates, and vice versa, particularly in the part ranged from the middle to the northern of the field.

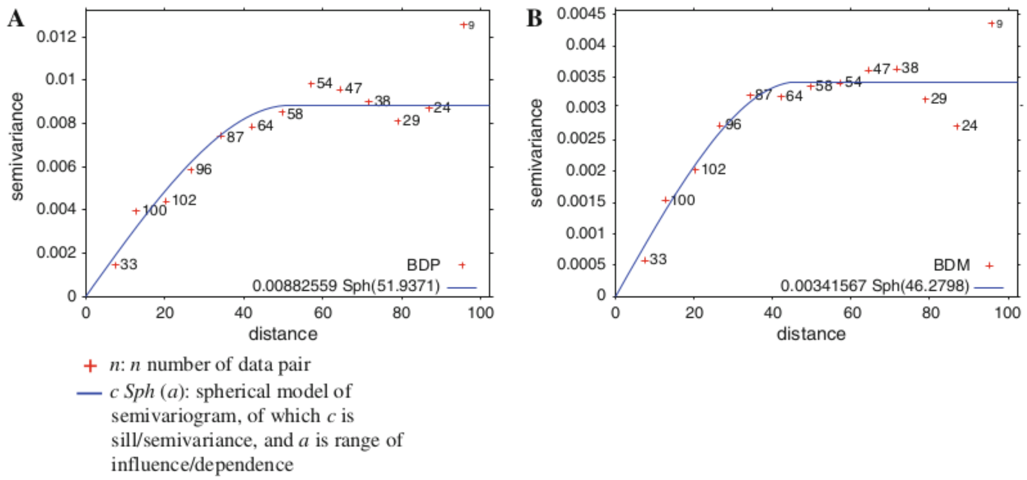

Fig. 8 Semivariogram of: predicted (**a**) and measured ρ_b (**b**)

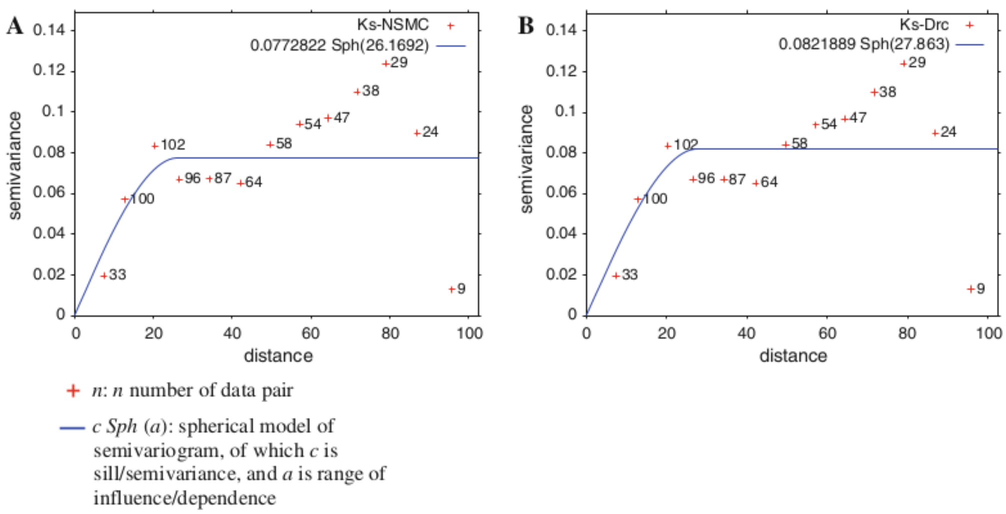

Fig. 9 Semivariogram of: predicted (**a**) and measured K_s (**b**)

The coincidence between the predicted and the measured parameters, and the close correspondence of those parameters to the subsurface percolation rate can be explicitly identified from their semivariograms shown in Figs. 8a, b (dry bulk densities), 9a and b (saturated hydraulic conductivities), and 10 (subsurface percolation rate). The predicted and the measured dry bulk densities had similar semivariogram trend in which the data were spatially correlated up to 46.3 and 51.9 m, respectively. The semivariogram of the predicted saturated hydraulic conductivity was also agreed well with that of the measured one, and the data were spatially depended within the distance of 26.2–27.9 m. Accordingly, the subsurface percolation rate showed the similar pattern in semivariogram as well as its range of influence to the saturated hydraulic conductivity.

Among the presented results above, the spatial variability of the dry bulk densities and the subsurface percolation rate had the lowest correspondence. Nevertheless, according to Bagarello and Sgroi (2004), Mulla and McBratney (2000), and Mohanty et al. (1994) reported that the variation of the saturated flow rate tended to be significantly greater than others soil properties, i.e., 36–372%, thus the results in general can be accepted and might be

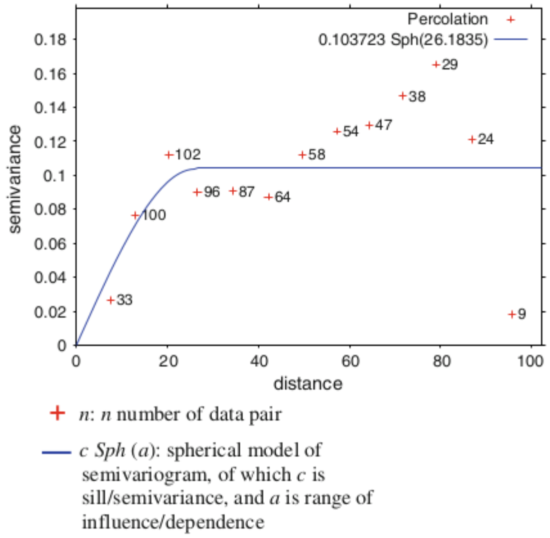

Fig. 10 Semivariogram of subsurface percolation rate

useful for supporting better cultivation practices like as puddling preparation, and water and/or pesticide fate management in the paddy field.

Conclusion

The spatial variability of saturated hydraulic conductivity in a paddy field was successfully predicted and characterized from the dielectric (ADR) properties of the dry bulk density as well as the volumetric water content by using NSMC and geostatistic model. And, it was closely corresponded to the spatial variability of the subsurface percolation rate in which both the data were spatially correlated within the same distance of 26.2–27.9 m.

Acknowledgment The authors thank Mr. Souphasay Komany, a former master student of Department of International Environmental and Agricultural Sciences (IEAS), TUAT, Japan for his permission to use the subsurface percolation data and for his cooperation in conducting the experiment. We also would like to thank Dr. Hirozumi Watanabe, an assistance professor of IEAS Department of TUAT for his valuable support during the study.

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