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Investigating Surface Water and Groundwater Interactions using Ground Electrical Conductivity Measurement in the Bassac River Floodplain

Vuthy Chork[1,2*], Kong Chhuon[1], Khy Eam Eang[1,2], Sambo Lun[1], Ratha Doung[1,2], Sylvain Massuel[3]

[1] *Faculty of Hydrology and Water Resources Engineering, Institute of Technology of Cambodia, Russian Federation Blvd., P.O. Box 86, Phnom Penh, Cambodia*

[2] *Water and Environment Research Unit, Research and Innovation Center, Institute of Technology of Cambodia, Russian Federation Blvd., P.O. Box 86, Phnom Penh, Cambodia*

[3] *G-Eau, IRD, AgroParisTech, Institut Agro, Cirad, INRAE, University of Montpellier, 361 rue J.F. Breton, BP 5095, 34196 Montpellier Cedex 5, France*

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Abstract: *In Koh Thom district, people mostly rely on agriculture for their incomes. The irrigation systems are based on prek namely small channels diverting the water of the Bassac River in the floodplain. This system potentially contributes to changing the flood dynamics in the area by reducing the period of submersion and its amplitude. This may change the relationships between surface and groundwater flow, with potential pollutant accumulation in aquifers, but this has never been studied in detail. Very few hydrological observations are available in the area, but ground electrical conductivity (EC) measurements can provide some answers about infiltration processes or water transfers because it depends on the water content, mineralization and matrix type. For a given lithology, any change in ground EC can be interpreted as changes in terms of water movement or mixing. A detailed geophysical survey using frequency electromagnetic method (FEM) was conducted to measure the apparent ground EC from the surface. The soundings were conducted between two preks, one rehabilitated (deepened and equipped with a gate), prek Chann, and one traditional, prek Touch. The geophysical equipment (CMD-explorer) provides simultaneous soundings at 3 depths but is limited to 6 m deep. Apparent ground EC sounding were carried out, the 2D maps were calculated, and ground EC vertical panels were simulated using IX1D inversion of the soundings. The apparent ground EC ranged from 0 to 210mS/m, clearly increasing with depth and towards the low-lying areas. Inversion modeling produced cross-section panels suggesting the presence of a conductive layer at 4m below the ground surface overlain by a resistive layer with lateral variation of the conductivity, namely more resistive in the low-lying areas. This layer could be interpreted as vadose zone leaching from percolated water since it corresponds to areas where water from excess irrigation return flow accumulates on the surface. This mechanism contributes to the connection between surface water and groundwater in the area in the dry season and may imply pollutant dissemination and transfer from the surface to groundwater. Since groundwater is largely used for domestic purposes, more investigations should be conducted to evaluate the potential health risks.*

Keywords: Irrigation Canal; Groundwater; prek; Electromagnetic sounding; ground electrical conductivity; Cambodia

1. INTRODUCTION

Cambodia is a country in the southern central subregion of the Indochina peninsula. The country covers a total area of 181,035 km^2 and is bordered by Thailand and Laos, Vietnam and the Gulf of Thailand [1].The Kravanh Range, also present in the west, roughly reaches from Pailin southward to Kampot. The northern border with Thailand is marked by the watershed of Dangrek Range [2]. Hydrological models have been used to evaluate and determine appropriate water management policies and water availability [3], but in the prek system area, hydro(geo)logical models have been applied at a fine scale in order to know about the groundwater flow and availability [4]. According to Uhlemann et al. [5] , an area of 44 km^2 on the right bank of the Bassac River, one of the Mekong's deltaic

* Corresponding author: Vuthy Chork
E-mail: vuthy_chork@gsc.itc.edu.kh; Tel: +855-96 464 5239

distributaries, was chosen to do geophysics in order to know the aquifer properties that affected groundwater. In floodplain area, Koh Thom, Kandal province, the area where flood dynamics have already been studied in detail [6,7]. This area shows rapid changes in land use following flood rise and recession and strong annual variability in cropping calendars and cultivated areas.

Flooding is one of the most troublesome and frequent natural hazards, resulting in environmental damage, temporal displacement and loss of life and livelihood [8]. In Cambodia, flooding is a serious concern during the rainy season. Chantarat et al. [9] showed that the mega flood in 2011 affected household behaviors, some of which could affect long-term economic development and be flexible to future flood. Groundwater potentially plays a role in this system as surface and groundwater exchanges were observed in the area [7,10]. However, little information exists about the effect of the aquifer systems on the surface flow regime and flood dynamics.

The interaction between groundwater and surface water has been shown that is a major concern in many situations. For instance, polluted aquifers that discharge to streams, rivers, or prek can cause surface water to become contaminated over time. On the other hand, streams may be a significant source of aquifer pollution. Surface water and groundwater are frequently hydraulically related, but since these interactions are difficult to monitor and quantify, they are frequently disregarded in decisions and policies about water management [11]. This trade may be a basic portion of the hydrologic cycle [12]. Surface water supplies recharge to the fundamental aquifer, where the groundwater can stay in storage for days, months, years, centuries, or even centuries. Inevitably the groundwater releases back into the stream depending on how much time the water spends underground and the geochemical conditions within the aquifer [13].

Ground electrical conductivity (EC) is a physical parameter that integrates many ground properties. These properties includes water content, soil texture, soil organic matter, depth to claypans, cation exchange capacity, salinity, and exchangeable Ca and Mg [14].

Ground EC is a complex function of the soil characteristics (mineralogy, texture, and structure) and of its water and solute contents. The Archie's law [15] originally expressed for saturated formations can be transformed for the unsaturated zone as follows [16]:

$$EC_g = \frac{1}{a}.EC_w.S_w^n.\phi^m$$

where EC_g is the ground electrical conductivity ($S.m^{-1}$), EC_w is the conductivity of the pore water ($S.m^{-1}$), Φ is the porosity (dimensionless), S_w is the pore space saturation (dimensionless, L^3/L^3), a is the tortuosity factor (dimensionless), m is the cementation factor (dimensionless), and n the saturation exponent. For the sandy formation, Keller [16] propose the values of 0.88, 1.40, and 2 for a, m and n, respectively.

Geophysical surveys which measure apparent ground EC have been used since the early 20th century to map geological features and heterogeneities [17]. Practical applications include the determination of bedrock type and depth, location of cavities or aggregate and clay deposits, measurement of groundwater extent and salinity, detection of pollution plumes in groundwater, location of geothermal areas, and characterization of archaeological sites [18]. The conduction of electricity in soils occurs through the moisture-filled pores between individual soil particles. Therefore, the EC of soil is influenced by the interactions between the following soil properties such as water content, soil texture, soil organic matter, depth to claypans, cation exchange capacity, salinity and exchange (Ca, Mg, K, Na, NH_4) [19].

This study aims to understand the interactions between surface water and groundwater. The objective of this study is to determine the presence of superficial and deep aquifers separated by clay lenses and to what extent the surface hydrological network can interact with these aquifers.

2. METHODOLOGY

2.1. Study area

The study area is located in Koh Thom, Kandal Province, around 60 km south of Phnom Penh. The survey was conducted near prek Touch and prek Chann that connect with the Bassac River and drain the flow to submerge the floodplain during the high flow regime of the river (see Fig. 1).

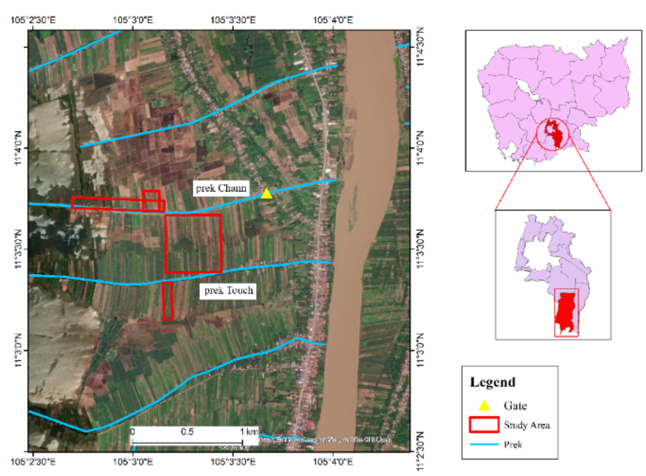

Fig. 1. Study Area (prek Chann and prek Touch)

In dry season, during the low flow regime, the water is pumped from the preks for irrigating rice fields and vegetables. The excess irrigation return flow is drained back to the preks or flows into ponds located in the low-lying areas between the preks. At the study site, the water level of the Bassac river, canals, flooded areas and groundwater are continuously measured and water electric conductivity is measured on a regular basis. The measurement of apparent ground EC was used as a preliminary study. It allows the mapping of possible soil heterogeneities in the prek area, their location and scale for further interpretation.

2.2. Ground electrical conductivity and data collection

The apparent ground EC was measured using the frequency electromagnetic method (FEM). The CMD Explorer (GF Instrument) was used to investigate ground EC with 3 coil spacings, giving approximate penetration depths up to 0-2, 0-4 and 0-6m. The instrument was operated by 3 people. It was carried at both ends to ensure perfect horizontality at all times (1m above the ground surface) and the third operator was checking the monitor of the device and the DGPS positioning, by using continuous measurement every 2 seconds and horizontal dipole configuration (F-1m, high range).

Geologists and geophysicists have used this technology to map glacial deposits, bedrock surfaces and permafrost, estimate the thickness of clay deposits, locate sand and gravel deposits, predict soil water content, and for groundwater investigations and it is well suited for investigating shallow aquifers [20].

Table 1 Ground EC values found in different soil types [21]

Material	Soils and Clays	Ground EC (mS.m^{-1})
Soil Types	Clay (general term)	10 - 1000
	Loam	25 - 250
	Top Soil	5 - 25
	Clay-rich Soil	2.5 - 10
	Sandy Soil	0.25 - 2.5
	Loose Sand	0.01 - 1

Interconnected clay layers are another source of low soil resistivity or high conductivity (Table 1). Clay is a result of chemical alteration of rock or soil-forming minerals, and is due to various weathering and mechanical transport processes. It is distributed throughout a soil column, often forming layers of different concentrations [22].

The depth to which EC measurements penetrate the soil depends on the spacing width of coulter mounted electrodes for contact methods and on the orientation (vertical vs. horizontal) and height and spacing of the source electrical coils for the non-contact methods. While geological testing can be done to a depth of several hundred meters. The CMD-explorer serve for fast contactless measurement of ground conductivity and in-phase (closely depending on magnetic susceptibility). Measured data can be used for conductivity maps from one or several depth levels and for conductivity sections. Thus, it can be used for many tasks in the frame of geological and civil engineering survey, agriculture, environmental monitoring, groundwater protection, raw material prospecting, archaeology, metal objects and networks detection. Walking and vehicle applications of CMD instruments allow performing measurements even in exacting conditions like dry or icy soil.

The data will collect and follow step of the framework in Fig. 2, which 2D mapping will generate with Surfer software to do grid file between 0-2m, 0-4m, 0-6m depth and plot the grid file in QGIS to interpret the Ground EC. 2D mapping is interpreted only apparent conductivity ranging from 0-2m, 0-4m, 0-6m. Then, IX1Dv3, the inversion modelling, were performed to plot with 3 layers for every profile of ground EC and generate real ground conductivity from 0-6 m depth with every sounding of apparent conductivity from the tool (CMD-explorer). Two hypotheses were suggested for interpreting ground EC in IX1Dv3 modelling:

- **Conductivity Fixing:** conductivity at the 3rd layer will be fixed at 300mS.m^{-1} in order to see how the conductivity thickness changes in the first and second layer.
- **Depth Fixing:** horizontal layer will fix at -0.5m below sea level in order to to see what is changing when putting same elevation value for every location.

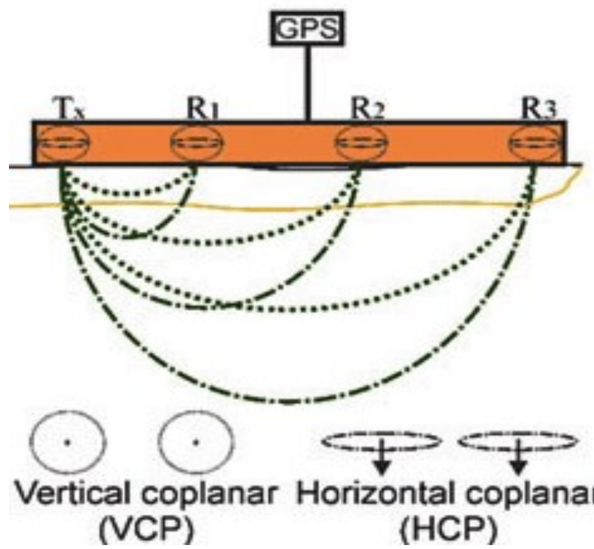

Fig. 2. Collecting ground EC with electromagnetic sounding

In December 2021, a first survey was conducted along prek Chann with 4 profiles of 1 km from upstream to downstream. On the left bank of prek Touch, 4 profiles towards the low-lying area in the south were conducted. In April 2022, the inter-prek area was investigated, and six profiles (north-south) between prek Chann and prek Touch were conducted, and then, another measurement in the early rainy season was conducted in June 2022 with 10 profiles (see Fig. 5).

3. RESULTS AND DISCUSSION

3.1. 2D ground EC mapping

The profile made in December 2021 along prek Chann indicates no noticeable gradient of apparent ground conductivity from the river to the floodplain. The ground EC distribution of the low conductivity varies from 15 to 75 $mS.m^{-1}$, 35 to 115 $mS.m^{-1}$, and 55 to 145 $mS.m^{-1}$ at 0-2, 0-4, and 0-6 m depth, respectively (see Fig. 3). The 2D mapping shows that heterogeneities are in the order of 20 to 30m, so the measurement lines can be spaced accordingly in the area for future surveys.

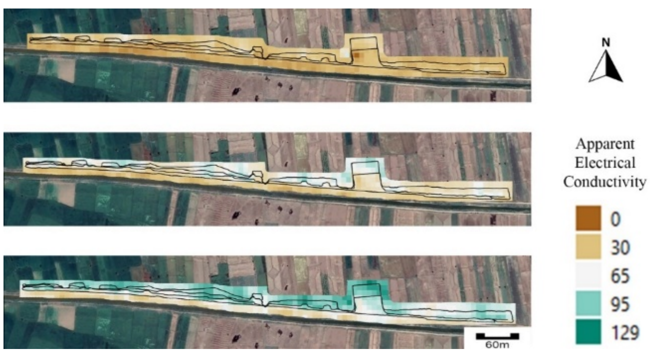

Fig. 3. Apparent ground EC in prek Chann (December, 2021)

The apparent ground EC in the left bank of prek Touch varies from 0 to 80 $mS.m^{-1}$ 30 to 150 $mS.m^{-1}$, and 50 to 200 $mS.m^{-1}$ for 0-2, 0-4 and 0-6m depth, respectively. There is a noticeable increase in the apparent ground conductivity towards the low-lying area (almost twice as high) and with depth (Fig. 4).

A tube well in Fig. 4 showed the EC 3500 $\mu S.cm^{-1}$ in groundwater. The groundwater level was 3.62m amsl (1.9m below the ground level) whilst the water level in the prek was 2.92m amsl. This means that the prek could only drain the groundwater at this period. The water EC of the pond in the low-lying area was 436 $\mu S.cm^{-1}$.

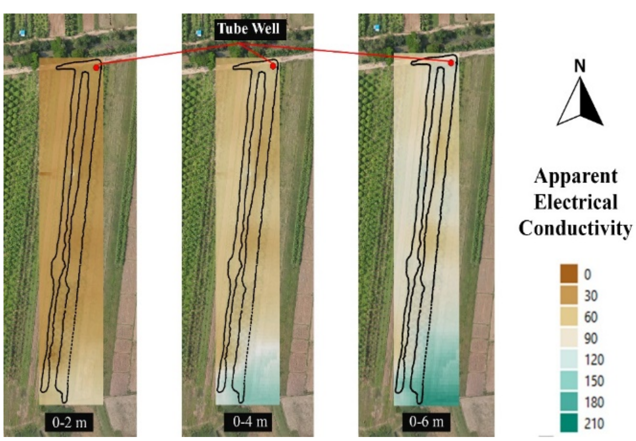

Fig. 4. Results of ground EC in prek Touch (December, 2021)

Three hypotheses can be made to explain the observed increase of the apparent ground conductivity in low-lying areas (Fig. 5):

1- The soil type in the area is mostly represented by sandy soil and loam. The sedimentation process can deposit the finest particles in the low-lying areas where the clay content can cause high ground EC.

2- The water table is closer to the surface in the low-lying areas; the relatively high groundwater EC can also increase the apparent ground EC measured on the surface.

3- The ponds in the low-lying areas can collect excess irrigation return flow in the dry season; the water can then percolate and increase the water content of the vadose zone and, thus, the measured apparent ground conductivity.

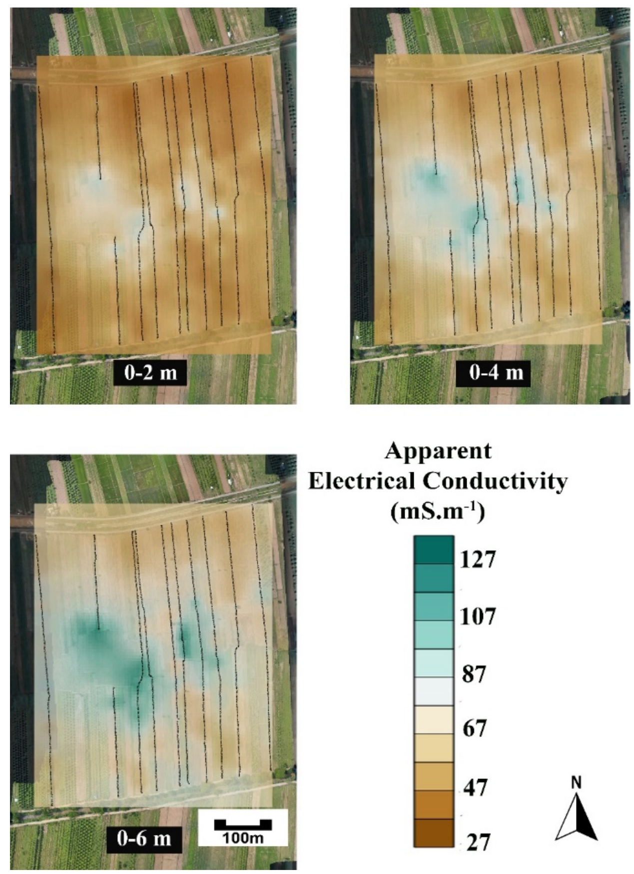

Fig. 5. 2D mapping of the ground EC between prek Chann and prek Touch (June, 2022)

The present survey does not provide enough material to support the contribution of each hypothesis, but some elements from the survey in the inter-prek area in the early rainy season provide some answers.

The 10 profiles of the apparent ground EC values range from 27 to 127 $mS.m^{-1}$, and clearly increase between the preks, in the lowest elevation zone. The apparent ground EC at 0-2 m depth range from 27 $mS.m^{-1}$ to 87 $mS.m^{-1}$. The two other coil spacings confirm the same thing with conductivity values twice as high. At 0-4 m depth, the values range from 35 $mS.m^{-1}$ to 110 $mS.m^{-1}$. At 0-6 m, the values range from 45 $mS.m^{-1}$ to 127 $mS.m^{-}$

[1]. The increase in the apparent ground EC in the vicinity of the main pond suggests that the water from the excess irrigation return flow potentially percolates though the vadose zone and acts as groundwater recharge. Water samples were taken for further stable isotope analysis to determine if the evaporated signal from the surface can be found into groundwater.

3.2. 1D inversion mapping

There was an attempt to propose a model of ground electrical conductivity using IX1D software (Interpex Limited). The inversion shows that there are potentially 3 layers to explain the apparent ground EC measured on the surface.

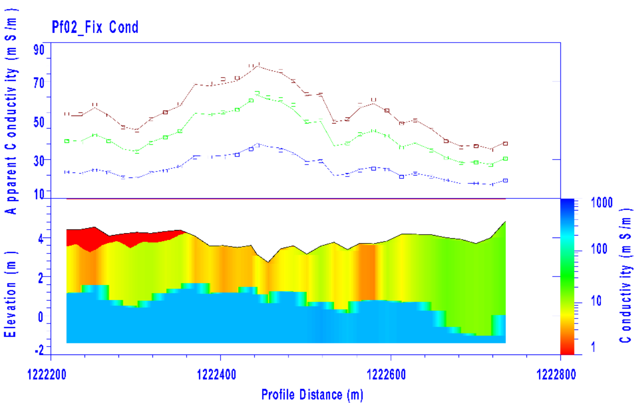

Fig. 6. Apparent ground EC inversion with a 3 layers model for 1 profile (P02-Fixing cond) between prek Chann and prek Touch in IX1D software

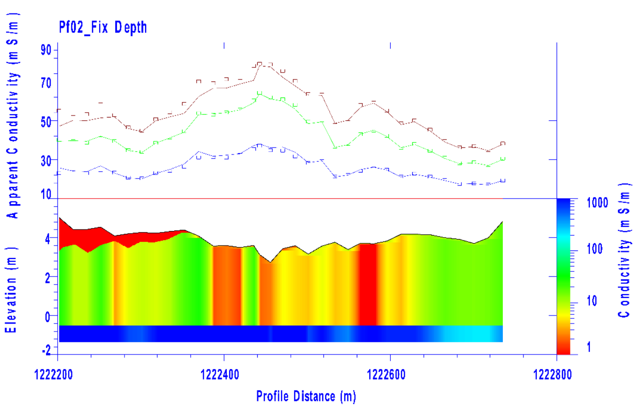

Fig. 7. Apparent ground EC inversion with a 3 layers model for 1 profile (P02-Fixing depth) between prek Chann and prek Touch in IX1D software

A model was simulated for a horizontal layer (fixed depth) corresponding to the ancient sedimentation process in the floodplain (i.e. before prek construction). A second model was simulated for a more conductive layer (fixed ground EC to 300mS.m^{-1}) underlying the area (i.e. saturated zone). Results showed that both models could fit the measured apparent ground EC (Figs. 6 and 7), but both models suggest that the ground EC of the second layer below the low-lying areas was lower. This layer could be interpreted as vadose zone leaching from percolated water since it corresponds to areas where water from excess irrigation return flow accumulates on surface. The result of apparent ground conductivity is globally higher due to the proximity of the water table in the low-lying areas are near to the surface.

4. CONCLUSIONS

In conclusion, the area of prek Chann and prek Touch, ground EC values range from 27 to 127 mS.m^{-1}. The 2D mapping show relatively large homogeneous areas but with an increase in ground EC in the low-lying areas (inter-prek zone). There is a noticeable increase in the apparent ground conductivity towards the low-lying area (almost twice as high) and with depth. This heterogeneity is difficult to explain using only preliminary results and 2D maps. The inversion shows potential leaching of the vadose zone below the ponds formed by the excess irrigation return flow suggesting the occurrence of groundwater recharge. The increase in apparent conductivity would be then the result of the proximity of the water table in the low-lying areas.

To confirm these results, more investigations are needed, especially crossing geophysics and hydrochemistry tools like stable isotopes of water able to trace evaporated water from the ponds into the groundwater. EC logger installation is also suggested to investigate groundwater electrical conductivity changes. Other tools could be also used to measure ground EC at a lower depth than 6m (TDEM, ERT, VES, etc).

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