A new method in determining bulk hydraulic conductivity of mangrove forest sediment

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Abstract

The flow of groundwater from mangrove swamp sediment to mangrove creeks is likely to be an important pathway in mangrove swamps, particularly for the removal of salt excluded at the mangrove root. The swamps are generally saturated with water, and are perforated with animal burrows, allowing a significant groundwater flow to mangrove creeks to occur. The hydraulic conductivity of the sediment is thus an important physical parameter but is very difficult to measure in-situ. This paper describe a simple method for determining the hydraulic conductivity of mangrove sediment, including the effect of macropores such as crab burrows, that use the existing animal burrows as piezometers. Experiments to measure the hydraulic conductivity of the sediment were carried out in a variety of mangrove forests. It was found that hydraulic conductivity varied from around 1 m/day–10 m/day, which is at least 10 times greater than would be expected if there were no burrows. In order to check the validity of this method, conventional piezometers were used to determine the free water table level in an area of mangroves fringing a creek. The hydraulic conductivity determined from these experiments was found to be consistent with the new methodology.

Keywords: hydraulic conductivity, mangroves, burrow, piezometer.

1 Introduction

The salinity of the groundwater has a significant influence on the growth of mangrove trees. Mangroves that grow in areas that are frequently inundated by the tide, or that grow in lower salinity regions of the estuary, are likely to grow more rapidly than those living in regions where the swamp is rarely inundated, and where groundwater salinity is very high [1].
Mangrove trees can increase soil salinity around their roots [2]. Freshwater evaporates at the leaves but, unlike terrestrial plants, the roots are surrounded by saltwater. Typically the roots exclude 90% or more of salt from the water absorbed, so that with time, there is a potential for buildup of salt around the roots. The removal of the excluded salt is an important mechanism that must occur if the groundwater salinity is to remain below lethal level. Two mechanisms exist which can remove the salt accumulated within the mangrove soil. The first process is diffusion of the salt across a short distance from the roots to an animal burrow and then flushed by lower salinity water during tidal inundation [3–5]. The other process that can reduce local groundwater salinity is groundwater flow back to the creek or estuary. The flow of groundwater back to the creek is also affected by the presence of animal burrows as they significantly reduce the hydraulic conductivity of the soil [6].

The measurement of hydraulic conductivity including the influence of the burrows, must ideally be carried out in situ because it is usually impossible to take a sufficiently large sample of soil that would include a significant number of burrow systems. Stieglitz et al. [7] found that burrow systems may have horizontal and vertical scales of over a meter and a sample significantly bigger than this would need to be extracted for analysis. In this work a new method is presented for measuring hydraulic conductivity in-situ, that takes into account the animal burrows, and which does not disturb the soil. In addition the method can be applied rapidly and does not require the employment of piezometers that are difficult and costly to install in mangrove swamps.

2 Methods

2.1 Measurement of the bulk hydraulic conductivity of mangrove soils using crab burrows

Bulk hydraulic conductivity was determined by utilising crab burrows as natural piezometers. This involved pumping a small quantity of water out of the burrows and measuring the flow rate back into the burrow from the sediment porewater. This is similar to the traditional method of pump testing of piezometers [8], but in this case, I used the natural burrows that were already in the system. Pump testing involved pumping water from a piezometer and noting the rate at which water returns to some fraction of its original level.

It is common in mangrove swamps that the crab burrow systems overlap and intermingle with each other as shown in Figure 1. Because of this burrows intermingling, the distance of one burrow chamber to another chamber in an adjacent burrow system may be only a few centimeters. Figure 1a shows three separate burrow systems. If the water is pumped out from burrow B, it will return through the mangrove soil from the surrounding burrow systems, burrow A and burrow C. This will occur in a similar manner to the way the water will flow during natural groundwater flow i.e. due to a pressure gradient (Figure 1b).

Although the adjacent burrow systems intermingle, the water level in each burrow will be slightly different. Essentially, the water flow from one burrow to
another burrow is determined by the sediment’s high resistance to the flow. It should be noted that Figure 1b represents the case during neap tides when the swamps are not inundated by high tides. Figure 1c is the top view of the burrow system.

Figure 1: Schematic diagram of crab burrows that are intermingled with, but separate from each other. (a) The case when a quantity of water is pumped out from burrow B (b) the normal relative water levels in the burrows. (Note that the burrow size is greatly exaggerated compared to the size of the creek), and (c) the plan (top) view of the three burrow systems.

The flux of water into the burrow domain is given by:

\[ q = K \frac{\Delta z}{\Delta r} \]  

where

- \( K \) = bulk hydraulic conductivity of the sediment (to be determined)
- \( \Delta z \) = drop in water level compared to adjacent burrows
- \( \Delta r \) = characteristic distance between centers of adjacent burrow domains.

The parameter \( \Delta r \) requires some further explanation. As the water naturally flows through the ground towards the creek, in the direction of the hydraulic gradient, it will pass from one burrow to another (Figure 1b). Because the flow within the burrow chambers has effectively zero resistance, the net flow rate is determined by the resistance to the flow in the sediment between chambers of adjacent burrow systems. As the water flows towards the creek, it experiences a succession of discrete water pressure drops as it passes from one burrow system to another, i.e., the water level drops by \( \Delta z \) in the distance between the burrows (\( \Delta r \)). This value of \( \Delta r \) has a scale equivalent to the horizontal scale (radius) of the burrow systems (see Figure 1c).
Equation 1 allows the calculation of $K$. A small quantity of water was pumped out from a burrow and the drop in water level $\Delta z$ (in the order of centimetres) was measured with a ruler to an accuracy of 1 mm. We determined $\Delta r$ from the geometry of the burrow, and the flux by measuring the time and the amount of the water that returned to the burrows. The flux of the water $q$ was determined by

$$q = \frac{\Delta V_1}{\Delta t}$$  \hspace{1cm} (2)

where $\Delta V$ is the volume of water that flowed into the burrow in time $\Delta t$, and $A$ the area of the curved surface surrounding the burrow domain. This surface is assumed to be a cylinder of radius $\Delta r$ and height equal to the burrow depth $H$. The area $A$ is given by

$$A = 2 \pi \Delta r H$$  \hspace{1cm} (3)

$\Delta V/\Delta t$ is the rate of flow into the burrow. Ideally $\Delta V/\Delta t$ must be measured instantaneously but in practice it is measured over some time interval (usually a few minutes). In this work, a convenient period of averaging was to set $\Delta t$ to the time for the water to return halfway back to its original position. $\Delta V$ is thus approximately half the volume of the water removed. The burrow depth $H$ was determined using the method described in [3], which is around 1 m.

The procedure for measuring $K$ was carried out 1 or 2 hours after tidal inundation to ensure that the burrows are full of water and was repeated on numerous burrows in order to get the average bulk hydraulic conductivity for the region in question. In this work, approximately 5 burrows were used in each region, each burrow being within a few tens of meters of each other.

### 2.2 Measurement of bulk hydraulic conductivity using a piezometer array

In order to verify the method to measure hydraulic conductivity described above, an independent method is required. This was done using an array of piezometers in a transect perpendicular to a mangrove creek. The piezometers consist of a pipe that was inserted into the soil with an opening near the bottom of the pipe. The groundwater flowed into the pipe and the water level in the pipe gave the value of the water pressure. Provided that there are no significant vertical water flows, or impermeable layers, the water level in the piezometer also represents the free water table height.

By measuring the water table level (from the piezometers) during neap tides, the fluxes of groundwater between each piezometer can be determined. In addition, the piezometers also measure the water table surface slope and thus pressure gradient. With flow rate and slope, Equation 1 can be used to determine the hydraulic conductivity.

In order to apply the above method to calculate the hydraulic conductivity from the three piezometers data, I made an assumption that the bulk of the water flow occurs in the upper zone of the sediment that is perforated by animal burrows (Figure 2). Consider the slab of sediment shown in Figure 2 that is (a)
above the impermeable lower layer, (b) between piezometers A and B, and (c) has a dimension parallel with the axis of the creek of $\Delta y$. The volume of water in the slab below the water table is dependent on $h$, the distance from the water table to the impermeable layer, $p$ the porosity of the soil, and $F_B$ the fraction of this layer occupied by burrows, which are full of water in this zone. I presume that for small water slopes, $h$ is constant over the length, $dx_b$ of the slab. The volume of water above the water table depends upon the degree of saturation of this layer, $F_s(t)$, and also the fraction of this layer, $F_b$, that is occupied by animal burrows, which are empty in this zone. $F_s$ equals to 1 for fully saturated soil and equals to zero for completely dry soil. Hence the volume of water in the slab is given by:

$$V = h \Delta x_i \Delta y \ p \left(1 - F_b\right) + (H - h) \Delta x_i \Delta y F_s(t) \ p \left(1 - F_i\right) + h \Delta x_i \Delta y F_b$$  \hspace{1cm} (4)$$

Figure 2: Model of groundwater flow in the mangrove swamp during neap tides.

Equation 4 is derived by considering the volume of water contained in the porewater and in the burrows. The first term on the right hand side of Equation 4 represents the pore water in the region below the water table surface, the second term represents the porewater in region above the water table, and the third term represents the water in the burrow.

By considering the flux entering and leaving the slab, the rate of change of water volume in the slab of sediment between piezometer $A$ and $B$ is given by the following equation:

$$\frac{\Delta V}{\Delta t} = -q_a h \Delta y + q_b h \Delta y - E \Delta y \Delta x_i$$  \hspace{1cm} (5a)$$

and similarly for the sediment between piezometers $B$ and $C$:

$$\frac{\Delta V}{\Delta t} = -q_b h \Delta y + q_c h \Delta y - E \Delta y \Delta x_2$$  \hspace{1cm} (5b)$$
where $E$ is the evapotranspiration rate. On the right hand side of equations 5(a) and 5(b), the first term represents the groundwater flowing out of the volume towards the creek, the second term represents the flow into the volume, and the third term represents the loss of water due to evapotranspiration. Hollins and Ridd [9] found $E$ to range from 1 to 5 mm/day with a typical value for mangroves of around 2 mm/day.

It was assumed in this analysis that the flux $q_c = 0$ because of field conditions (discussed later) with presumed low hydraulic conductivity due to the absence of animal burrows. Equation 4 was used to calculate the volume of the stored water in the sediment between piezometer sites C – B. $q_b$ was calculated from equation 5b, i.e.

$$q_b = \frac{\left( \frac{\Delta V}{\Delta t} \right) - E \Delta x_2 \Delta y}{(h_0 \Delta y)} \quad (6)$$

Using the Darcy law, and assuming that the flux midway between piezometers B and C is the average of the fluxes $q_c$ and $q_b$, the value of $K$ between sites C and B was determined using

$$K = \frac{q_b \Delta x_2}{2 \Delta h_{CB}} \quad (7)$$

where $\Delta h_{CB}$ is the water level difference between piezometers C and B.

However, to calculate $q_a$, the value of $q_b$ must be taken into account, i.e.

$$q_a = \frac{-\left( \frac{\Delta V}{\Delta t} \right) + q_b (h_0 \Delta y - E \Delta x_1 \Delta y)}{h_a \Delta y} \quad (8)$$

Finally, the calculation of $K$ value between site B and A was accomplished using

$$K = \frac{(q_b + q_a) \Delta x_1}{2 \Delta h_{BA}} \quad (9)$$

where $\Delta h_{BA}$ is the water level difference between piezometers B and A.

In order to use this method it is necessary to determine $F_x$, $F_b$, and $p$. $F_x$ is defined as the ratio of the water content of the sediment to the water content when the sediment is fully saturated experimentally, which on average was 85% or 0.85, $F_b$ from previous experiment, 0.1 and $p$ ranges from 0.41 to 0.51.

3 Descriptions of the field sites

The field sites were chosen in the upper reaches of Cocoa Creek, Gordon Creek and Three Mile Creek, which are all small mangrove fringed estuaries in tropical North Queensland, Australia (see Figure 3). Piezometer experiments were carried out at Cocoa Creek area, while burrow experiment were conducted at all three locations.

The Cocoa Creek is an undisturbed area within the Cape Bowling Green National Park. The total length of this Creek is about 7 km and its width ranges
from approximately 50 meters at the mouth of the estuary to less than 10 m at the head. Mangrove trees grow along the creek and the width of the mangrove fringe varies considerably along its length from a few meters to 50 m. Burrow density in this area is about 10 to 13 holes/m³ of sediment surface.

The second site, the Gordon Creek, is a small creek about 5 km length and its width ranges from 25 m at the mouth of the creek to less than 5 m at the head of the creek. There are two types of mangrove plants at this site, i.e. *Rhizophora stylosa* and *Ceriops spp.* The *Rhizophora stylosa* forest grows close to the creek and its sediment surface is relatively lower than *Ceriops spp.* area. The density of the number of crab burrow openings in the *Rhizophora stylosa* forest is about 14 holes per m², which is higher than in the *Ceriops spp.* forest which is around 6 holes per m².

![Figure 3: The location of experiments at Cocoa Creek, Gordon Creek and Three Mile Creek. Piezometer experiments were carried out at Cocoa Creek only, while burrow experiment were at all three locations.](image)

The final experimental area was conducted at the Three Mile Creek which is about 15 km North-West of Townsville. Only burrow experiments were conducted. The total length of this creek is about 2.5 km and is around 20 m wide at the mouth of the creek and less than 5 m at the head of the creek. Mangrove forest grows on both sides of the creek, dominated by *Rhizophora stylosa* growing along the edge of the creek, and *Ceriops spp.* forest farther landward where the sediment surface is higher. The number of burrows openings for each burrow system ranges from 5 to 15 holes and the density is about 25 holes/m².
4 Sediment physical properties in the field area

Materials composing the sediment affect the effective porosity of the sediment and are a relatively important factor in determining the hydraulic conductivity. Particle size analysis of the sediment at each site was determined using a Malvern Instruments Mastersizer analyzing the 7 \( \text{mm} \) to 1000 \( \text{mm} \) size fraction. The mean for each site was 10 \( \text{mm} \), 25 \( \text{mm} \), and 53 \( \text{mm} \) for Cocoa Creek, Gordon Creek, and Three Mile Creek, respectively.

5 Results

5.1 Measurement of hydraulic conductivity of sediment using animal burrows

The results of measurement of hydraulic conductivity for the four different field sites are shown in Table 1. The error was determined from the variability of individual measurement and was a very large fraction of the measured value.

Table 1: Hydraulic conductivity at different field sites measured by removing water from the animal burrows.

<table>
<thead>
<tr>
<th>Location</th>
<th>Average Hydraulic Conductivity ( K ) (m/day)</th>
<th>Standard error (m/day)</th>
<th>Number of measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gordon Creek ( Rhizophora )</td>
<td>7.4</td>
<td>3.5</td>
<td>7</td>
</tr>
<tr>
<td>Gordon Creek ( Ceriops spp. )</td>
<td>0.8</td>
<td>0.6</td>
<td>4</td>
</tr>
<tr>
<td>Cocoa Creek ( Rhizophora )</td>
<td>3.7</td>
<td>2.7</td>
<td>5</td>
</tr>
<tr>
<td>Three Mile Creek ( Rhizophora )</td>
<td>9.9</td>
<td>5.4</td>
<td>4</td>
</tr>
</tbody>
</table>

5.2 Calculation of hydraulic conductivity using the piezometer array

Groundwater level recordings were used to calculate volumes \( V \), fluxes \( q \) and hydraulic conductivity \( K \) in the mangrove area (between sites C and B, and A and B). The water levels from the piezometers at the Cocoa Creek site from 25 July to 10 August 2001 (Julian day, from 206 to 222) are shown in Figure 4. During this period the neap and spring tides were evident. The neap tides were characterized by a slow and monotonic reduction in the water level, in this case from day 207 to 210 and from day 218 to 222.

Hydraulic conductivity using groundwater level was calculated from piezometer data at sites A, B and C. Days processed were 208, 218 and 220, i.e. when there was no inundation due to neap tides. During each of these days, the value of \( K \) was estimated over four 6-hour time intervals. In order to give an idea of the dependence of the calculation on evaporation rate \( E \), calculations were done with two values of \( E \) i.e. 1 mm/day and 2 mm/day, the latter probably representing a typical value whereas 1 mm/day would be an extremely low value [9]. The results of \( K \) from this calculation is shown in Table 2.
Figure 4: Fluctuation of groundwater and creek water levels at site A, B and C at Cocoa creek recorded using pressure sensors.

Table 2: Average and standard deviation (in brackets) of hydraulic conductivity calculation of mangrove sediment using Evapotranspiration 1 mm/day and 2 mm/day and porosity, $p$, of $0.46 \pm 0.05$.

<table>
<thead>
<tr>
<th>Julian days</th>
<th>$K_{CB}$ (m/day) $(E = 2 \text{mm/day})$</th>
<th>$K_{CB}$ (m/day) $(E = 1 \text{mm/day})$</th>
<th>$K_{BA}$ (m/day) $(E = 2 \text{mm/day})$</th>
<th>$K_{BA}$ (m/day) $(E = 1 \text{mm/day})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>208</td>
<td>1.27 (0.24)</td>
<td>1.45 (0.24)</td>
<td>0.32 (0.06)</td>
<td>0.28 (0.06)</td>
</tr>
<tr>
<td>218</td>
<td>1.29 (1.15)</td>
<td>1.49 (1.17)</td>
<td>0.40 (0.23)</td>
<td>0.38 (0.23)</td>
</tr>
<tr>
<td>220</td>
<td>1.58 (0.43)</td>
<td>1.78 (0.43)</td>
<td>3.74 (0.78)</td>
<td>0.89 (0.25)</td>
</tr>
</tbody>
</table>

It can be seen that a wide range of values of $K$ calculated from this method using $E = 1 \text{mm/day}$ ranges from 1.1 to 3.4 m/day and using $E = 2 \text{mm/day}$ ranges from 1.0 to 3.0 m/day. Based on these results the average value of $K$ are $(2.5 \pm 0.8)$ m/day and $(2.2 \pm 0.7)$ m/day for $E = 1 \text{mm/day}$ and $E = 2 \text{mm/day}$, respectively.

6 Discussion and conclusion

The results of the measurements of the bulk hydraulic conductivity, $K$, using the new method reveals that $K$ is highly variable spatially at any one site. At Gordon Creek in a *Rhizophora stylosa* forest, measurements of $K$ varied from 2.5 to 10.5 m/day over 7 samples with an average value of 7.4 m/day and a standard deviation of 3.6 m/day. In an adjoining *Ceriops spp.* forest the calculated values of $K$ averaged 0.81 m/day with a standard deviation of 0.61 m/day. This significant reduction in the average value of $K$ looks reasonable as the burrow density in the *Ceriops spp.* forest was much less than in the *Rhizophora* forest (14 and 6/m$^2$, respectively). An area of *Rhizophora* forest in Cocoa Creek yielded an average $K$ of 3.8 m/day with a standard deviation of 2.2 m/day (5
samples). At Three Mile Creek a very high value of $K$ was found (average 9.9 m/day and standard deviation of 5.4 m/day). This may have been the result of the significantly coarser, and therefore more permeable sediment found at the Three Mile Creek site. At the Cocoa Creek site, measurements of $K$ using piezometer data were also carried out. Assuming an evapotranspiration rate of 1 mm/day, this method gave $K$ of $2.5 \pm 0.8$ m/day. If the evapotranspiration was 2 mm/day, the corresponding value of $K$ was $2.2 \pm 0.7$ m/day. This is comparable with the result from the burrow method of 3.7 m/day and standard deviation of 2.7 m/day. These methods are consistent with each other taking into account of the large error bars on both methods.

The measurement of hydraulic conductivity of sediments is problematic requiring piezometers which are expensive and difficult to install. This paper presents a new and innovative method that allows a rapid assessment of hydraulic conductivity using existing crab burrow networks. Measurement on one burrow took approximately 40 minutes and typically five to 10 burrows should be measured to allow averaging of a significant area of the swamp. The field results show that the new method compares well to more traditional estimates using piezometers.

References