Spatial scaling of soil salinity indices along a temporal coastal reclamation area transect in China using wavelet analysis

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\textbf{ABSTRACT}

High spatial variability of soil salinity in coastal reclamation regions makes it difficult to obtain accurate scale-dependent information. The objectives of this study were to describe the spatial patterns of saline-sodic soil properties (using soil pH, electrical conductivity (EC\textsubscript{1:5}) and sodium ion content (SIC) as indicators) and to gain knowledge of the scaling relationships between those variables. The soil pH, EC\textsubscript{1:5} and SIC data were measured at intervals of 285 m along a 13,965-m temporal transect in a coastal region of China. The spatial variability of soil pH was weak but it was strong for soil EC\textsubscript{1:5} and SIC at the measurement scale. There was a significant positive correlation between soil EC\textsubscript{1:5} and SIC, while correlations between soil pH and either EC\textsubscript{1:5} or SIC were weak and negative. For each saline-sodic soil parameter, the variability changed with the decomposition scales. The high-variance area at the larger scales (≥570 m) occupied less than 10% of the total area in the local wavelet spectrum, which meant that the spatial variations of the salinity indicators were insignificant at these scales. For local wavelet coherency, at a scale of 1500–2800 m and a sampling distance of 0–4500 m, the covariance was statistically significant between any two of the saline-sodic soil parameters.

\textbf{INTRODUCTION}

Tidal areas represent an important land resource (She et al. 2014; Liu et al. 2015). Rich tidal area resources encourage worldwide coastal reclamation where feasible, and the development of coastal areas is an important strategy for most coastal countries, and notably so for China. The soils in tidal areas of the coastal regions are saline-sodic soils. In this article, this term was used to refer to a group of soils that were either saline or sodic to varying degrees, or were both saline and sodic. Due to incursion by seawater, Na\textsuperscript{+} largely replaces Ca\textsuperscript{2+} and Mg\textsuperscript{2+} on the exchangeable surfaces of soil colloids. Subsequent dispersion of soil clay particles in the presence of fresh water and the puddling of soil lead to the destruction of soil structure and a low void ratio resulting in poor permeability (Suarez et al. 2006; Chappell et al. 2013). Desalinization of saline-sodic soils includes leaching the salts from the soil matrix, a process that is impeded by the low permeability...
of the soils. Thus, severely degraded soils are common in coastal areas and pose an obstacle to the development and utilization of tidal area resources for agriculture and open spaces (She et al. 2014). Therefore, sufficient and accurate information about the sodium salt content of soils is crucial to the understanding of the soil quality and to soil reclamation management in these areas. Obtaining this information through direct methods demands a great deal of time and expenditure, and some sampling strategies neglect the complexity of local soil distributions. Similarly, obtaining the information through indirect methods is also challenging due to the high spatial variability of soil saline-sodic parameters and their scale dependency in the coastal regions (Douaik et al. 2005). A number of physical, chemical and biological processes acting in combination affect the spatial variations of soil properties at different scales and locations. This can lead to very complex patterns of spatial heterogeneity of soil saline-sodic parameters and their relationships with other variables (Si 2003).

The spatial heterogeneity of soil properties has been studied using geostatistical methods, fractal and multifractal approaches, and wavelet analysis (Olive 1987; Kachanoski & Jong 1988; Hu & Si 2013). Although there are advantages in using these methods, they all have some disadvantages. The semivariance in geostatistics can describe the changes in variance as the distance between a sampling site and other sites increases. However, it can identify only one range value within which most of the variance in a property can be explained and that is considered to represent the cycling or frequency of the changes in that property. Furthermore, it is not suitable for nonstationary spatial series (Nielsen & Wendroth 2003). Although fractal and multifractal approaches can be applied for nonstationary spatial series, they cannot describe localized features (Zeleke & Si 2007).

Using wavelet analysis enables the variations in stationary/nonstationary spatial series to be divided into multiple scale and location variations (Lark et al. 2004). The wavelet transform can be categorized into continuous wavelet transforms (CWT) and discrete wavelet transforms (DWT), and they can be applied on different occasions or under different circumstances. Wavelet coefficients at different scales and locations of DWT are orthogonal but this does not apply to CWT. The redundant information among different coefficients at different scales and locations in the CWT makes a statistical significance test problematic (Grinsted et al. 2004). However, the CWT can reveal enhanced information about the original data series and it is better for extracting signal/noise and analyzing both the scale and location dependency of a spatial series (Lau & Weng 1995). The independent information provided by the DWT is useful when making comparisons between different coefficients, and in the decomposition and reconstruction of spatial series (Lark & Webster 1999). In the wavelet analysis, cross wavelet transforms (XWT) and wavelet coherency (WTC) can be applied to describe the correlation between two variables in a scale-location space, but the XWT relies on both the common power and the individual powers, making it difficult to analyze the relationships (Grinsted et al. 2004).

Studies related to the spatial variability of soil properties have rarely focused on characterizing the spatial distribution of soil salinity, especially in coastal reclamation regions. Due to vast destruction of natural wetland vegetation caused by long-term human reclamation activities and frequent alternation of soil desalination and re-salinization processes, revegetation systems in the temporal coastal reclamation area were established in a patchwork or mosaic pattern of land use (She et al. 2014). The distribution characteristics and dynamics of soil salinity at a large scale (e.g. the coastal reclamation region) covered with various land uses become more complex, thus giving rise to scale-dependent nonstationary patterns in soil salinity. In this situation, the study of multi-scale distribution of soil sodium salt contents along a temporal coastal reclamation transect can be very important, especially for soil desalination and melioration during the reclamation of a coastal region. Therefore, the purpose of this present study was to investigate the multi-scale distribution of soil saline-sodic properties and to gain an understanding of the relationships between the variables in terms of scale-location variation in coastal reclamation regions using wavelet analysis.
Materials and methods

Site description

The soil samples were collected from coastal land undergoing reclamation in Rudong County, Jiangsu Province, China (32°12′ to 32°36′ N, 120°42′ to 121°22′ E) (Figure 1). The study site is located on the shores of the Yellow Sea. The altitude of this area is 3.5–4.5 m. The groundwater level ranges from 0.6 to 1.8 m. Consequently, saline water has inundated this low-lying flat tidal area and soil salinity is high. The climate is predominantly subtropical with a hot monsoon season. The mean annual rainfall is 1026 mm and 68% of the rainfall is concentrated between May and September. The mean daily temperature and the annual potential evapotranspiration are 14.8°C and 1343.5 mm, respectively. Soils in the study area are predominantly sullage-puddle soils with poor structure due to the high sodium ion content (S/C) (She et al. 2014). Initial infiltration rates can
exceed 125 mm h\(^{-1}\) but decline rapidly to almost zero. The rate of decline depends on the sodicity of the soil as well as upon the electrical conductivity of the infiltrating water. To facilitate reclamation, a series of steep-banked drainage ditches have been constructed in the area (She et al. 2014).

Reclamation in the study area has resulted in changes to the morphology of the landscape, soil properties and land use. Reclamation has been achieved by first constructing a series of dikes (in 1916, 1940, 1950, 1960, 1981, 2000 and 2007) to prevent inundation of the land by tidal seawater (Figure 1). A system of drainage ditches channeled water to outlets set within the dikes that were opened at low tide permitting drainage water to exit and were then closed to prevent seawater re-entering (She et al. 2014). Pumping could be used to increase the rate of drainage from the land. Natural vegetation regeneration in the reclamation area initially created salt meadows that were largely left undisturbed by humans, while rainwater percolating through the soil removed excess salts. After about 10–15 years, farmers could begin to grow crops on the land, tilling the upper 20-cm layer, and the intensity of cultivation increased over time as the soil improved. Irrigation was provided for the cropland, further facilitating the leaching process while the application of fertilizers could reduce alkalinity.

**Soil sampling and analysis**

Soil saline-sodic parameters were measured at 50 points, with a sampling interval of 285 m, along a transect that extended for 13,965 m in an East-West direction from the most recently reclaimed farmland (behind the most recent dike) to the Fan-Gong Dike (Figure 1). The eastern end of the transect was designated as the sampling origin point.

The transect passed through areas with different vegetation types and different degrees of vegetation coverage (ranging from 0% to 95%). The two more common land use types were salt meadows and farmland. Farmland was the most common land use type and occupied the older reclaimed areas (1916–1981 at sampling distances >2500 m), where cover ranged from 5% to 85%. Salt meadows tended to occupy the more recently reclaimed areas (2000–2007 at sampling distances <2500 m) and cover ranged from 0% to 90%. The greatest degree of cover (95%) was found in an area of shrubland that, along with bare soil and drainage ditch slopes, comprised a much smaller proportion of the land uses along the transect. During reclamation, soil organic matter contents increased from about 2.3–24.7 g kg\(^{-1}\).

In October 2013, three disturbed soil samples were collected in steel cylinders (5 cm long, and 5 cm in diameter) from the soil surface layer (0–10 cm) at a depth of about 2.5–7.5 cm, and were then mixed to create one representative sample at each sampling point. The soil was air-dried and crushed to pass through a 2-mm mesh prior to the following analyses. Soil electrical conductivity of a 1:5 soil to water extract (EC\(_{1:5}\)) was determined using a DDS-307 conductivity meter (Shanghai Precision Scientific Instrument Co. Ltd., Shanghai). Exchangeable cations were extracted by ammonium acetate (Bao 2005), and SIC was determined by a flame photometer (Bao 2005). Soil pH was measured at a soil-to-water mass ratio of 1:2.5. Soil particle size was analyzed using a MasterSizer2000 laser particle size analyzer (Malvern Instruments, UK). For each site, the altitude, longitude and latitude were determined by a portable GPS (Mobile Mapper).

**Data analysis**

Using SPSS 20.0 software, data sets were analyzed to provide the summary descriptive statistics. A Kolmogorov–Smirnov (K–S) test was used to examine the statistical distribution types of soil pH, EC\(_{1:5}\) and SIC data. Pearson correlation coefficients were calculated to assess the correlations between the different variables.

Even though it was beyond the scope of this study, a geostatistical analysis was conducted in order to determine if the parameters of the fitted semivariogram models could complement the
wavelet analysis. The description of the methodology, results and discussion are given in the Supplemental data.

MATLAB 7.1 software was used for the wavelet analysis including that of the DWT, CWT and WTC. For each of the three salinity indicators, four-layer wavelet decomposition was used in order to obtain the five scale components of the DWT, which was then used to analyze localized details and global (i.e. overall) features of variables at the corresponding scales. The CWT was used to provide enhanced information at various application scales and was presented as a continuous wavelet spectrum covering the length of the transect at the different scales. The WTC was used to find significant coherence between two variables at different scales and locations. A wavelet coherence spectrum was constructed for each pair of the salinity indicators. Lark and Webster (1999) have given a review of the theory of wavelet analysis while Si and Zeleke (2005) have given details of the calculations used in this study.

Results and discussion

Descriptive statistics of soil salinity along the transect

Table 1 presents the descriptive statistics of the soil pH, EC_{1:5} and SIC data along the study transect. The mean soil pH was 8.15, which reflected the weak alkalinity of the soils. Furthermore, the low coefficient of variation (CV) value of 3.0% for the soil pH data indicated weak variability (Nielsen & Bouma 1985). In contrast, the much higher CV values for soil EC_{1:5} (247.3%) and soil SIC (170.4%) meant that this data exhibited strong variability along the transect. The single-sample K–S normality test of these saline-sodic soil parameters showed that soil pH had a normal frequency distribution, and the skewness and kurtosis were both close to zero. In contrast, the EC_{1:5} and SIC data were not normally distributed but a natural logarithm transformation of the data resulted in normal distributions. There was a significant positive correlation between EC_{1:5} and SIC, while between soil pH and either EC_{1:5} or SIC there were weak negative correlations (Table 1). Traditional statistics could only reveal information on the overall variation of the three soil properties and the relationships among them at the measurement scale (285 m), but not at specific locations or scales. Accordingly, it was necessary to analyze the variations of the three parameters and their relationships among each other at different scales and locations in order to identify their scaling properties to better understand the spatial distribution of the soil sodium salt contents.

Table 1. Descriptive statistics of saline-sodic soil parameters in the coastal reclamation region.

|          | pH | EC_{1:5} (μS cm⁻¹) | EC_{1:5}ᵃ | SIC (g kg⁻¹) | SICᵃ |
|----------|----|-------------------|----------|--------------|------|
| Minimum  | 7.72 | 113.2            | 0.96     |              |      |
| Maximum  | 8.92 | 18,300.0          | 1.97     |              |      |
| Mean     | 8.15 | 1444.0           | 0.25     |              |      |
| SD       | 0.25 | 3607.5           | 0.43     |              |      |
| CV (%)   | 3.0  | 247              | 170      |              |      |
| Skewness | 0.41 | 3.50             | 1.66     | 2.73         | 0.90 |
| Kurtosis | 0.44 | 12.10            | 1.97     | 7.04         | 0.36 |
| K–S      | 0.93 | 0.00             | 0.01     | 0.00         | 0.09 |
| Distribution type | N  | NN  | n | NN | N |
| Correlation coefficient | pH | – | –0.11 | –0.03 |
| | EC_{1:5} | – | – | 0.78** |
| | SIC | – | –0.03 | 0.78** |

ᵃVariables after natural logarithm transformation.

**Variability is significant at the significance level of 0.01.

N indicates a normal distribution; NN represents a non-normal distribution; n indicates that the variable approximately follows the normal distribution; K–S, Kolmogorov–Smirnov test; CV, coefficient of variation; SD, standard deviation EC_{1:5}; electrical conductivity of a 1:5 soil to water extract; SIC, sodium ion concentration.
**Geostatistical analysis**

An autocorrelation analysis indicated that the current sampling interval was sufficient to identify the spatial autocorrelation between adjacent observations of each index. The range of the semivariograms indicated that the sampling distance would suffice to describe the variation in the parameter (see Supplemental data).

**Discrete wavelet transforms of soil salinity along the transect**

Wavelet coefficients can be calculated at different scales and locations through DWT. In general, a spatial series with a length of \( n \) and an interval of \( x \) contains scales that range from \( 2x \) to \( nx \) (Lark & Webster 1999). The scales, such as \( 2x-4x, 4x-8x, 8x-16x, \) etc., can represent nonoverlapping information. The original spatial series of the saline-sodic soil parameters were decomposed into predefined five scale components \((d_1, d_2, d_3, d_4 \text{ and } a_4)\) after four-layer wavelet composition (Figures 2–4). Wavelets coefficients such as \( d_1, d_2, d_3 \) and \( d_4 \) were referred to as detail coefficients or high-frequency coefficients, which reflected the localized variation of the soil properties at the corresponding scales, while \( a_4 \), which was called the approximation coefficient or low-frequency coefficient, reflected the overall trends of variables along the transect. In this study, the wavelet coefficients of \( d_1, d_2, d_3, d_4 \) and \( a_4 \) separated the spatial variances at scales of 570–1140 m, 1140–2280 m, 2280–4560 m, 4560–9120 m and >9120 m, respectively. Following the wavelet decomposition, the signal of soil pH in \( a_4 \) was divided into three stable phases (Figure 2). The \( a_4 \) coefficient contributed to most (30.7%) of the total variance (Table 2). This meant that large-scale (>9120 m) or low-

![Figure 2](image-url). Four discrete wavelet transforms of soil pH measured at the 285-m scale as a function of the sampling distance along a transect. The signal (S) indicates the original soil pH data.
frequency processes (e.g. soil-related farming activities) had the greatest influences on the total variance of soil pH. The oscillation amplitude of soil pH along the transect decreased with the increase in sampling distance, i.e. as the reclamation status evolved to cultivated farmland when the application of fertilizers reduced alkalinity. In the detail coefficient of $d_1$, the amplitude of the signal reached a maximum at a sampling distance of $0$–$4275$ m, indicating that this section was the one most influenced by outside interferences (e.g. excavated ditch distributions, rainwater percolation), while the signal was least influenced at a sampling distance of $4275$–$13,965$ m. These two sections corresponded to locations at which the reclamation processes of drainage and leaching were being applied and at which the farmland was being developed with increasing use of fertilizers, respectively. The detail signals of $d_2$ and $d_3$ exhibited shapes that gradually became an irregular ladder. For the detail signal of $d_4$, the signal remained near zero at a sampling distance of $0$–$8835$ m, indicating little influence by outside factors, such as human activity. In this section, the evolution of salt meadows via drainage and leaching proceeded under natural conditions (rainfall) to farmland under less intense cultivation was occurring. In contrast, the signal was more greatly influenced by outside interference at a sampling distance of $8835$–$13,965$ m where farming became more intense. The variance contribution of $d_4$ to the total variance was $20.5\%$, which was the fourth largest and represented large-scale variance. The contributions of $d_1$ and $d_2$ were close to that of $d_4$, accounting for $21.7\%$ and $21.0\%$ of the total variance, respectively (Table 2). While the contribution of $d_3$ accounted for $6.1\%$, which was the smallest portion of the total variance. The wavelet coefficients of $d_1$, $d_2$ and $d_3$ could represent small-scale processes, which

Figure 3. Four discrete wavelet transforms of soil EC$_{1:5}$ (electrical conductivity of a 1:5 soil to water extract) measured at the 285-m scale as a function of the sampling distance along a transect. The signal (S) indicates the original EC data.
meant that relatively small-scale (570–1140 m, 1140–2280 m, 2280–4560 m) processes, such as biological activity, had moderate effects on the total variance.

After four-layer wavelet decomposition, the signal of EC\(_{1:5}\) exhibited two stable phases as identified in the distribution of \(a_4\) (Figure 3). At a sampling distance of 0–4275 m, EC\(_{1:5}\) values were maintained at 3871 \(\mu\)S cm\(^{-1}\), and at a sampling distance of 4560–13,965 m, they were reduced sharply to 278 \(\mu\)S cm\(^{-1}\). The EC\(_{1:5}\) was comparatively high in the most recently reclaimed part of the transect, where the main vegetation type was salt meadow. In spite of leaching, the salinity might change slowly during the initial phases of reclamation due to tidal water movement through subsurface soil layers that maintained the salinity of groundwater, while precipitated salts may act as a buffer. The EC\(_{1:5}\) was comparatively low in the middle and older reclaimed sections of the transect, where the main vegetation type was farmland. In these sections, saline groundwater

\[\text{Table 2. The power of wavelet coefficients of saline-sodic soil parameters.}\]

| Components       | pH      | EC\(_{1:5}\) | SIC    |
|------------------|---------|--------------|--------|
| \(d_1\) (570–1140 m) | 21.7    | 19.8         | 24.6   |
| \(d_2\) (1140–2280 m) | 21.0    | 17.8         | 19.4   |
| \(d_3\) (2280–4560 m) | 6.1     | 7.8          | 6.4    |
| \(d_4\) (4560–9120 m) | 20.5    | 20.2         | 22.3   |
| \(a_4\) (>9120 m) | 30.7    | 34.4         | 27.2   |

EC\(_{1:5}\), electrical conductivity of a 1:5 soil to water extract; SIC, sodium ion concentration.
would cease to have an influence, while precipitated salts were being dissolved and leached by percolating rain and irrigation water. The variance contribution of $a_4$ to the total variance was 34.4% (Table 2), which was the highest among all of the wavelet coefficients for EC$_{1.5}$. The oscillation amplitude was comparatively large at the eastern end of $d_4$, which indicated that EC$_{1.5}$ had a large spatial variability and was greatly influenced by outside interference in this section. The variance contribution of $d_1$ was 19.8% (Table 2). For the detail signals of $d_2$ and $d_3$, oscillation amplitudes of the signals were relatively large at a sampling distance of 0–3700 m along the transect while, in the detail signal of $d_4$, the oscillation amplitudes were relatively large at a sampling distance of 0–4275 m. This indicated that large variances occurred at these locations and were greatly influenced by outside interferences. The variance contributions of $d_2$ and $d_3$ were relatively low, accounting for only 17.8% and 7.8%, respectively, while $d_4$ accounted for 20.2%, which was the second highest contribution (Table 2).

The soil SIC also presented two stable phases after four-layer wavelet decomposition as shown by the distribution of $a_4$ (Figure 4), which was similar to that of the $a_4$ of EC$_{1.5}$. At a sampling distance of 0–4275 m, the SIC was constant at 0.60 g kg$^{-1}$ but, at a sampling distance of 4560–13,965 m, it was greatly reduced to only 0.08 g kg$^{-1}$. The variance contribution of $a_4$ to the total variance was 27.2% (Table 2), which was the highest contribution among those of all of the wavelet coefficients of SIC. The analysis of $d_1$, $d_2$, $d_3$ and $d_4$ can be related to the analysis of the corresponding coefficients of EC$_{1.5}$, which had the same demarcation locations. The second highest variance contributor was $d_1$ (24.6%) and the third highest was $d_4$ (22.3%) (Table 2). The variance contributions of $d_2$ and $d_3$ were relatively low, accounting for only 19.4% and 6.4%, respectively.

For soil pH, large-scale components made greater contributions to the total variance and low-frequency processes, such as farming activities, played a primary role in the spatial variance. In contrast, for EC$_{1.5}$ and SIC it was the high-frequency processes such as biological activities that affected both of their spatial variances. There were decreasing trends in the values of the saline-sodic soil parameters (pH, EC$_{1.5}$ and SIC) with increases of the sampling distance. These could be explained by the greater amount of salt leaching that had occurred in the soils that had been reclaimed for longer and were farther from the coast (She et al. 2014). Soil pH and EC$_{1.5}$ were determined by the species and contents of different ions. Theoretically, they should decrease with increases in the sampling distance. However, the variance at different locations might be influenced also by different physical, chemical and biological processes. As mentioned above, salinity would initially be buffered by the effects of tidal water and precipitated salt reserves. Soil pH in the middle section of the transect increased slightly due to different types of vegetation growing there, such as beans, corn and watermelons. However, in general, once the buffering effects in the initial reclamation phase ceased, human farming activities dictated the degree of desalination in the reclamation area over time, which declined along the transect toward the coast (She et al. 2014). The DWT helped us to understand localized details and overall trends of the various wavelet signals. It was a convenient means by which to acquire their degrees of variation at corresponding scales. However, there might be a leakage of information through the DWT, so we used the CWT to give more intensive information about the variation.

It was noteworthy that the $d_4$ scale exceeded the range values for pH and SIC determined by the geostatistical analysis indices (see Supplemental data), while $a$ does so for all three salinity indicators. This suggests that these range values did not fully take into account all of the processes involved in reclamation. This might be attributed to the non-stationary nature of the soil properties in the reclamation area.

**Continuous wavelet transform of soil salinity along the transect**

The local wavelet spectrum of soil salinity (pH, EC$_{1.5}$, and SIC) is shown in Figure 5. There was a strong variance region (indicated by the black parts) of soil pH, i.e. at scales of 570–800 m and a
sampling distance of 0–2500 m. At other scales and locations, the variance was moderate or weak. For soil EC$_{1:5}$, there were three scales of major variations: (i) at a scale of 570–750 m and a sampling distance of about 12,000 m; (ii) at a scale of about 1300 m and a sampling distance of approximately 9000 m and (iii) at a scale of 1800–2500 m and a sampling distance of 500–5500 m (black shading). For SIC, there were two scales of major variations: (i) at a scale of 720–1024 m and a sampling distance of 11,600–12,400 m; and (ii) at a scale of 1800–2300 m and a sampling distance of 10,000–11,600 m (black shading). However, the area of each major variance was less than 10% of the total area, which means that the variance may be statistically insignificant. For EC$_{1:5}$ and SIC, high variances existed at a scale of 720–750 m and a sampling distance of around 12,000 m. For the correlations between soil pH and EC$_{1:5}$ and between soil pH and SIC, there were no regions of strong variance at the same scales and locations.

Figure 5. Local wavelet spectrum of soil salinity indicators (soil pH, electrical conductivity (EC$_{1:5}$), and sodium ion content (SIC)) along a transect at multiple scales and locations. (a) pH. (b) EC$_{1:5}$. (c) SIC. The x-axis represents the sampling distance along the transect and the y-axis indicates wavelet decomposition scales. Thick solid lines represent 5% significance level and thin solid lines indicate the cone of influence. The color bar from white to black indicates the size of the variances (normalized to 1/8 ~ 8).
There were additional factors that affected soil heterogeneity at different scales in the study area. For example, large numbers of excavated slopes, such as the banks of ditches or streams, were present in the coastal region as part of the water conservancy construction. In addition to the vegetation types and coverage, the excavated slopes also affected the spatial heterogeneity of soil properties (She et al. 2015). The degree of salinity in the groundwater was the main factor limiting soil quality, which resulted in large differences in soil salinity at the different sampling locations (Mondal et al. 2001). Uneven ground within the sampling micro-zones could cause lateral movement of sodium. Soil texture, soil minerals and pedogenic processes were also factors that affected soil spatial variability (Wang et al. 2009; She et al. 2013). At the 285-m sampling scale, soil pH varied weakly, while EC_{1:5} and S/C varied strongly (Table 1). However, their variabilities changed at other scales, which were greater than 570 m. This was because the type and extent of the influence of external factors changed at different scales. When sampling scales were small, sampling frequencies were high and high-frequency processes, such as microbial activity, acted as major factors. When sampling scales were large, sampling frequencies were low and low-frequency processes, such as farming activities, played a leading role (Liu et al. 2012). Spatial variabilities of the saline-sodic soil properties along the transect were insignificant at scales larger than 570 m. Therefore, it is appropriate to analyze the spatial heterogeneity at scales that are smaller than 570 m. The CWT can enhance the information on variations, and it is suitable for extracting signal/noise and analyzing variations of spatial series at different scales and locations.

Wavelet coherency of soil salinity along the transect

The local WTC between soil pH and either EC_{1:5} or S/C is shown in Figure 6. There were three scales of variations at which the correlation between soil pH and EC_{1:5} was relatively high: (i) at a scale of 570–800 m and a sampling distance of 0–3000 m; (ii) at a scale of 1024–2800 m and a sampling distance of 0–4500 m and (iii) at a scale greater than 4096 m and a sampling distance of 0–8500 m. The area of section (ii) accounted for almost 13% of the total area, indicating that the covariance was statistically significant, while the areas in sections (i) and (iii) were less than 10% of the total area, and might indicate a spurious covariance (Lark & Webster 1999). The arrows pointing toward the left in the first two scaling partitions indicated that their coherency was out of phase and that there was a negative correlation between them. Arrows pointing to the right in the third zone indicated their coherency was in phase and the correlation between soil pH and EC_{1:5} was positive.

For the correlation between soil pH and S/C, there were three scales with significant coherency: (i) at a scale of 570–1024 m and a sampling distance of 10,000–13,965 m; (ii) at a scale of 1024–2800 m and at sampling distances of 0–4500 m and of 10,400–13,965 m and (iii) at a scale greater than 4096 m and a sampling distance of 0–7500 m. The area of section (ii) accounted for almost 13% of the total area, indicating that the covariance was statistically significant, while the areas in sections (i) and (iii) were less than 10% of the total area, indicating a possible spurious covariance. Similarly to the related properties between soil pH and EC_{1:5}, the correlation between soil pH and S/C was negative in the first two sections and positive in the third section. There were four regions of scales in which the coherency between EC_{1:5} and S/C was relatively strong: (i) at a scale of 570–1024 m and at sampling distances of 0–4000 m and of 12,000–13,965 m; (ii) at a scale of 1024–1500 m and a sampling distance of 0–6000 m, (iii) at a scale of 1500–3000 m and at sampling distances of 0–8000 m and of 12,500–13,965 m and (iv) at a scale greater than 3000 m and in the overall section. The areas of sections (iii) and (iv) accounted for 27% and 22%, respectively, of the total area, indicating that the covariance was statistically significant for both areas, while the areas in zones (i) and (ii) were both less than 10% of the total area, indicating a possible spurious covariance. In all the scale partitions except for section (ii), the arrows pointed toward the right, and the in-phase arrows indicated a positive correlation at these scales and locations. However, in section (ii), the direction of arrows was sometimes toward the left and at
other times toward the right, indicating that an unstable correlation between EC\textsubscript{1:5} and SIC existed at these scales and locations.

The significant correlation area of WTC between EC\textsubscript{1:5} and SIC was the largest, and the correlation had an increasing trend with scale increases. Therefore, it is more appropriate to use a larger scale to analyze the relationship between EC\textsubscript{1:5} and SIC. However, in the analysis of the relationship between soil pH and SIC, and between soil pH and EC\textsubscript{1:5}, it might not always be better to adopt larger sampling scales. At a scale of 1500–2800 m and a sampling distance of 0–4500 m, their covariances were all statistically significant. Therefore, it is more appropriate to analyze their coherency at these scales and locations.

Figure 6. Local wavelet coherency of soil salinity indicators (pH, electrical conductivity (EC\textsubscript{1:5}) and sodium ion content (SIC)) along a transect at multiple scales and locations. (a) pH-EC\textsubscript{1:5}. (b) pH-SIC. (c) EC\textsubscript{1:5}-SIC. The x-axis represents the sampling distance along the transect and the y-axis indicates wavelet decomposition scales. Thick solid lines represent 5% significance level and thin solid lines indicate the cone of influence. The color bar from white to black indicates the size of the covariance.
### Table 3. Descriptive statistics of wavelet coherency between components of soil salinity at different scales.

| Coherency       | Scale (m) | Mean   | Maximum | Minimum | SD    |
|-----------------|-----------|--------|---------|---------|-------|
| Soil pH-EC<sub>1:5</sub> | 570–1140  | 0.37   | 0.98    | 0.01    | 0.19  |
|                 | 1140–2280 | 0.56   | 0.96    | 0.00    | 0.32  |
|                 | 2280–4560 | 0.51   | 0.99    | 0.00    | 0.53  |
|                 | 4560–5400 | 0.95   | 0.99    | 0.86    | 0.04  |
| Soil pH-SIC     | 570–1140  | 0.51   | 0.99    | 0.08    | 0.29  |
|                 | 1140–2280 | 0.48   | 0.95    | 0.00    | 0.32  |
|                 | 2280–4560 | 0.36   | 0.75    | 0.01    | 0.12  |
|                 | 4560–5400 | 0.76   | 0.86    | 0.62    | 0.07  |
| EC<sub>1:5</sub>-SIC | 570–1140  | 0.51   | 0.99    | 0.08    | 0.26  |
|                 | 1140–2280 | 0.69   | 0.99    | 0.00    | 0.27  |
|                 | 2280–4560 | 0.83   | 0.98    | 0.91    | 0.10  |
|                 | 4560–5400 | 0.96   | 0.98    | 0.94    | 0.01  |

EC<sub>1:5</sub>, electrical conductivity of a 1:5 soil to water extract; SIC, sodium ion concentration.

In order to investigate further the correlations between saline-sodic soil properties at different scales, we calculated the WTC at scales of 570–1140 m, 1140–2280 m, 2280–4560 m and 4560–5400 m as indicated by the DWT (Table 3). At a scale of 4560–5400 m, the correlations between any two of the saline-sodic soil properties were the highest, but the areas of the significant correlations were all less than 10% of the total area, indicating statistical insignificance at this scale (Figure 6). For soil pH and EC<sub>1:5</sub>, the significant area was at a scale of 1024–2800 m (Figure 6), and the mean coefficients of coherency at scales of 570–1140 m, 1140–2280 m and 2280–4560 m were 0.37, 0.56 and 0.51, respectively (Table 3). Hence, soil pH and EC<sub>1:5</sub> may exhibit medium and negative correlations at these scales. For the WTC between soil pH and SIC, the significant area was also at the scale of 1024–2800 m (Figure 6), and the mean coefficients of their coherency at scales of 570–1140 m, 1140–2280 m and 2280–4560 m were 0.51, 0.48 and 0.36, respectively (Table 3). At scales of 1500–3000 m and 3000–5400 m, there existed significant areas for EC<sub>1:5</sub> and SIC (Figure 6). The mean coefficients of their correlations were relatively high (0.69, 0.83 and 0.96) as shown in Table 3. At scales of 1140–2280 m and 2280–4560 m, the standard deviations of the coefficients of the correlations between soil pH and EC<sub>1:5</sub> were 0.32 and 0.53, respectively. For soil pH and SIC, they were 0.32 and 0.12, respectively, and for EC<sub>1:5</sub> and SIC, they were 0.27 and 0.10, respectively (Table 3). These standard deviations of the coefficients were relatively higher than those at other scales; thus, it was more appropriate to analyze their relationships at a scale of 1140–4560 m, as mentioned above. Through WTC, we generally obtained the relationships among any two saline-sodic soil properties at different scales and locations.

### Conclusions

In this study, the spatial heterogeneity of soil salinity, as indicated by three soil variables (soil pH, EC and SIC) along a 13,965-m temporal transect in a coastal reclamation area, was investigated. Results showed that, at the observation scale (285 m), the three salinity indicators decreased with increasing reclamation time and ultimately stabilized. Soil pH changed only slightly over time. There was a significant positive correlation between EC<sub>1:5</sub> and SIC, and weak negative correlations between pH and either EC<sub>1:5</sub> or SIC, which had similar distribution patterns.

The wavelet analysis identified the multiple scales at which the salinity indicators were influenced and helped identify factors that were influencing their spatial variability. Some of these factors would operate at scales much greater than the measurement scale or the range identified by a geostatistical analysis (Supplementary data).

The DWT at the large scale (>9120 m) helped identify where abrupt transitions occurred in the reclamation process as indicated by the EC<sub>1:5</sub> salinity parameter. This corresponded to a land use change of salt meadow into farmland and further indicated where EC<sub>1:5</sub> had been buffered by undissolved salts for a significant length of time after the land use had changed. Further studies into...
the effects of and persistence of solid salts in reclamation area soils should be undertaken. Scales of lesser magnitude indicated that other soil physical, chemical and microbiology properties influenced salinity.

The local wavelet spectrum indicated that at the decomposition scale (≥570 m), spatial variations in the salinity indicators were insignificant. Local WTC, at a scale of 1500–2800 m and a sampling distance of 0–4500 m, indicated that covariance was significant between any two of the saline-sodic soil parameters. Therefore, the more appropriate scales at which to analyze their relationships were either 1500–2800 m or at less than 570 m.

Distributions of salinity indicators were proven to be scale-dependent. Knowledge of scale-location information is important to determine distribution characteristics. It helps to identify areas where certain processes are occurring and indicates the need for further investigation, as well as ways in which they could be changed by appropriate land management practices that would enhance coast reclamation and improve soil quality.

**Disclosure statement**

No potential conflict of interest was reported by the authors.

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