The Effects of Timing of Inundation on Soil Physical Quality in the Water-Level Fluctuation Zone of the Three Gorges Reservoir Region, China

Junfang Cui, Xiangyu Tang,* Wei Zhang, and Chuandong Liu

With the completion of the Three Gorges Dam, soils between the elevations of 145 and 175 m are exposed or submerged seasonally. Soil hydrological and physical properties are changed. A detailed investigation was performed to examine the influence of the timing of inundation on soil physical quality. Samples were collected in the water level fluctuation (WLF) zone and non-WLF zone in Zhongxian County, Chongqing. Soil samples were taken from depths of 0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm. Soil structural quality was assessed by the visual evaluation of soil structure (VESS) method in situ; mean weight diameter (MWD) and mass fractal dimension ($D_m$) were measured to represent soil aggregate stability; and the soil water retention curve and computed microtomography (micro-CT) images were used to show soil pore networks. Our findings show a deterioration of soil physical quality through decreased porosity and a shift of drainable micropores (0.1 < radii < 125 μm) to non-drainable micropores (radii < 0.1 μm) in the WLF zone of the Three Gorges Reservoir. The potential of environmental hazards of soil in WLF zone was also investigated.

Abbreviations: AC, air capacity; CEC, cation exchange capacity; CT, computed tomography; MWD, mean weight diameter; PAWC, plant-available water capacity; SOM, soil organic matter; Sq, soil quality; TGR, Three Gorges Reservoir; VESS, visual examination of soil structure; WLF, water level fluctuation.

The Three Gorges Dam, which is located in central China, is one of the largest water projects ever built. The Three Gorges Reservoir (TGR) covers a total area of 349 km² along the Yangtze River (Bao et al., 2015). Water pooling began in June 2003; it was impounded to elevations of 135, 156, and 175 m asl in November 2003, October 2006, and October 2010, respectively (Wu et al., 2016). On a hydrological year basis, the reservoir water level fluctuates between the base level of 145 m during the wet season (May–September) for flood control and the peak level of 175 m during the dry season (October–April) for power production (Yu et al., 2017). Seasonal water level fluctuation (WLF) has created a reservoir fluctuation zone, representing a unique artificial landscape that was originally composed of terrestrial upper lands with diverse land uses. The WLF zone has been transformed into a transitional area undergoing seasonal flooding and exposure. Furthermore, the timing of the fluctuation is opposite to the natural inundation regime (Subklew et al., 2010).

As a populated area, the environmental issues induced by the TGR have centered on land use change and erosion (Seeber et al., 2010; Subklew et al., 2010; Wei et al., 2017), interaction of sediment and water quality (Bing et al., 2016; Jiang et al., 2018; Ma et al., 2011; Shi et al., 2017; Tang et al., 2014, 2016b), and revegetation (Peng et al., 2014; Ye et al., 2015). Numerous studies have concluded that soil issues including soil erosion, transportation of soil nutrients and pollutants, and interactions between the soil and the water body are strongly controlled or regulated by soil physical properties (i.e., soil texture, soil porosity, bulk density, and the soil pore network) (Arrouays et al., 2006; Chan et al.,...
Yangtze River. The mass movement of soil brings a change in soil properties; the SWRC is also useful to investigate the soil pore network at the microscale. Micro-CT has been affirmed to produce images of the soil pore structure (Munkholm et al., 2012; Pires et al., 2010). It is under the water level from late September to April of the following year. Each year, right after the water level drops to the base level of 145 m, a soil surface crust may develop in the lower land as temperatures go up in the spring. Subsequently, some grass and shrubs grow well in the summer season, with Xanthium sibiricum Pat. ex Widder as the dominate vegetation.

**Sampling Design and Soil Analysis**

Five sampling points, approximately equal distance apart (4–5 m), were laid out with random orientation in representative parts of each elevation, with uniform soil and land cover (based on a visual assessment on arrival in the field) (Fig. 1).

For determination of SWRCs and soil pore size distribution, undisturbed soil core samples (5 cm in height and 5 cm in inner diameter) were taken at each sampling point from four soil depths of 0 to 5, 10 to 15, 20 to 25, and 35 to 40 cm, representing 0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm, respectively, in April 2015 (five cores from each depth, 20 cores from each elevation, and 60 cores in total). The soil cores were stored at 4 °C before conducting analyses for the SWRC, bulk density, and porosity.

A group of loose soil samples was also collected at each sampling point at 0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm and sealed in a single plastic box for laboratory measurements. Loose soil samples were air dried and divided into two subsamples. One
subsample was stored carefully in a plastic box for soil aggregate size distribution measurement, and the other subsample was ground and passed through a 2-mm sieve for basic analyses (pH, soil organic matter content, particle size distribution, cation exchange capacity, etc.).

To explore the effects of soil minerals on soil aggregate stability, the soil mineralogical composition was analyzed by X-ray diffraction (D/max-2500, Rigaku Corporation). Soil organic matter (SOM) content (expressed as g kg\(^{-1}\) soil) was determined using the wet combustion method of Walkley and Black (1934). Particle size distribution was measured using the pipette method (Gee and Or, 2002). The cation exchange capacity (CEC) was determined by the Sumner and Miller (1996) method; and pH was measured using a standard pH meter at a 1:5 soil/water ratio (Thomas, 1996). Soil parameters were measured in triplicate, and the results were averaged.

**Scoring of Soil Structure**

A visual assessment of the soil structure was conducted in the field using the VESS method (Guimarães et al., 2011) at each sampling point as described above. To perform the VESS method, a soil block sized approximately 20 by 20 by 20 cm was extracted by a spade and transferred onto a tray. The soil block was then opened in the middle like opening a book by hand to obtain a natural soil profile. Soil color, roots, and size, shape, and appearance of aggregates and porosity were carefully observed and recorded for each soil layer, if there was layering. A score for each item was assigned for each layer according to the standard description card given by Guimarães et al. (2011), and a sub-final score for each layer was determined by the scoring of each item. At the end, a final score for each soil block was calculated by multiplying the score of each layer by its thickness and dividing the product by its overall depth (see https://www.sruc.ac.uk/info/120625/visual_evaluation_of_soil_structure). The final score of the soil structure is the Sq score. The scoring of each item follows a principle of “the smaller the score is, the better the soil structure.”

**Aggregate Size Distribution and Mass Fractal Dimension**

To explore soil aggregation and its stability, the dry aggregate size distribution was determined and is as the weight percentage
(\% w/w) by placing 100 g of loose air-dried sample in a set of sieves (10, 5, 3, 2, 1, 0.5, and 0.25 mm) and shaking with a reciprocating shaker (Retsch VS. 1000) for 10 min (Nimmo and Perkins, 2002). Sizes of six aggregates were read by a Vernier caliper for each size class after sieving, and their mean value was regarded as the mean diameter of aggregates at this size class. For size classes < 1 mm (0.5–1, 0.25–0.5, and <0.25 mm), the mean particle size was determined as the arithmetic mean of the upper and lower sieve sizes. Thus, the MWD was calculated as

\[
\text{MWD} = \sum_{i=0}^{n} \pi_i W_i
\]

where \( \pi_i \) is the mean diameter (mm) of aggregates in the \( i \)th size class and \( W_i \) is the fraction (\% w/w) of aggregates in the \( i \)th size class. A higher MWD value represents better soil aggregation and higher soil aggregate stability.

A fractal dimension of mass, \( D_m \), quantifies the space-filling characteristics of the solid in a space of radius \( r \). For a mass fractal, the scaling of mass, \( M \), follows a relationship of the form (Giménez et al., 1997)

\[
M \propto r^{D_m}, \quad D_m \leq d
\]

where \( d \) is the embedding dimension, defined as the minimum number of coordinates needed to enclose an object (i.e., \( d = 2 \) and \( d = 3 \) correspond to two- and a three-dimensional spaces, respectively). The value of \( D_m \) can be obtained from measurements of mass of aggregates of different sizes. It can be estimated based on the Tyler and Wheatcraft (1992) model, which can be expressed as

\[
D_m = 3 - \frac{\log(W_i/W_0)}{\log(d_i/d_{\max})}
\]

where \( W_i \) is the mass of aggregates with size \( < d_i \); \( W_0 \) is the total mass of aggregates; \( d_i \) is the mean aggregate diameter at a size class between \( d_i \) and \( d_{i+1} \); and, in this study, \( d_i \) shared the same data with \( \pi_i \) in Eq. [1]; \( d_{\max} \) is the mean diameter of aggregates at the top sieve (>10-mm class in this study).

**Soil Water Retention Curve Determination and Characterization of Pore Structure Based on the Measured Curve**

Soil cores were saturated with distilled water from the bottom. The hanging water column method was applied for pressure heads of \( -1, -2.5, -10, -31.1, -63.1, \) and \(-100 \) cm H\(_2\)O by a sandbox apparatus, while, subsequently, pressure plates (Soilmoisture Equipment Corp.) were used for \(-33, -51, -100, -500, \) and \(-1500 \) kPa. After equilibrium was reached at \(-1500 \) kPa at the end of experiment, the soil cores were oven dried at 105 ± 5°C for 24 h. The dry bulk density (\( \rho_d \)) was then calculated from the oven-dried mass and the volume of the undisturbed soil sample (Lal and Kimble, 2001), and the total porosity (\( \phi \)) was estimated from \( \rho_d \) by assuming a particle density (\( \rho_p \)) of 2.65 g cm\(^{-3}\).

The water retention data were fitted by the single-porosity van Genuchten (1980) model using the RETC fitting program (RETC Version 6.02, University of California). The model can be written as

\[
\theta(b) = \theta_s + \frac{\theta_r - \theta_s}{(1 + |b|^n)^m}
\]

where \( \theta \) is the volumetric water content (m\(^3\) m\(^{-3}\)), \( b \) is the pressure head (cm); \( \theta_s \) and \( \theta_r \) are the residual and saturated water contents (m\(^3\) m\(^{-3}\)), respectively; and \( \alpha \) (cm\(^{-1}\)), \( n \), and \( m \) (= 1 − 1/\( n \)) are empirical parameters.

Water content at the inflection point (\( \theta_{inf} \)) of the fitted van Genuchten (1980) model and the inflection slope (\( S_{inf} \)) were calculated from these model parameters using the equations from Dexter (2004):

\[
\theta_{inf} = \theta_s + (\theta_r - \theta_s) \left( \frac{2n - 1}{n - 1} \right)^{1/n - 1}
\]

\[
S_{inf} = -n(\theta_r - \theta_s) \left( \frac{2n - 1}{n - 1} \right)^{1/n - 2}
\]

Several parameters were calculated to characterize the pore structure of the soil from estimated parameters by methods proposed by van Genuchten (1980) and Reynolds et al. (2007). Effective porosity is the difference between \( \theta_r \) and \( \theta_{inf} \); it is the portion of the total porosity that contributes the most to saturated flow, which typically corresponds to meso- or macropores in soil (Han et al., 2008). Soil air capacity (AC) and plant-available water capacity (PAWC) were derived from the SWRC as

\[
\text{AC} = \theta_s - \theta_{FC}
\]

\[
\text{PAWC} = \theta_{FC} - \theta_{WP}
\]

where \( \theta_{FC} \) and \( \theta_{WP} \) are the volumetric water contents at field capacity (\( b = -337 \) cm) and at the permanent wilting point (\( b = -15,300 \) cm), respectively.

To express the pore size distribution, \( r \) (\( \mu m \)), which is the maximum equivalent radius of pores that remain full of water at a given pressure head \( b \) (cm), can be calculated from the absolute value of \( b \) by the Young–Laplace equation (Vomocil and Flocker, 1965):

\[
r = \frac{1490}{|b|}
\]

In this study, the soil pore system fitted by the SWRC was classified into three main categories according to the drainage capacity of the pores (Wang et al., 2015): (i) non-drainable micropores (\( r < 0.1 \mu m \) or \( |b| > 14,900 \) cm, residual water); (ii) drainable pores (0.1 < \( r < 125 \mu m \) or 12 cm < \( |b| < 14,900 \) cm); and (iii) gravitationally drainable macropores (\( r > 125 \mu m \) or \( |b| < 12 \) cm).

**Computed Microtomography Image Processing and Pore Structure by Computed Tomography Image**

To further understand the effect of inundation in the TGR zone, we compared the pore structure of soils in the non-WLF
zone (as the reference soil) and soils with the maximum intensity of inundation. Therefore, micro-CT scanning and imaging was conducted on soils from the upper land and lower land. Two soil cores (5 cm in height and 4 cm in inner diameter) at 0- to 5- and 35- to 40-cm depths from the upper land and another two from the lower land were stored in polyvinyl chloride (PVC) cylinders and were scanned by a Phoenix Nanotom S micro-CT scanner (GE Sensing and Inspection Technologies). The settings for scanning were 100 kV, 100 μA, and 1250-ms timing. The detector type was ham-c 7942 with a size of 2304 by 2304 pixels. For each CT scanning session, a stack of at least 2000 two-dimensional slices in 16-bit depth was obtained. The 16-bit images were later converted into 8-bit depth. Isotropic voxels had a resolution of 25 μm in all three directions.

Image processing was performed by three-dimensional rock images analysis software (Sichuan University). The identical regions of interest (same position and same volume) were selected such that the same solid phase was probably analyzed for each core. In this case, a circular area of 3.7 cm in diameter in the middle of each core image was extracted. To avoid edge effects, only 1000 contiguous slices from each stack were used for analysis. The reconstructed volume produced a three-dimensional visualization of about 1.85 by 1.85 by 2.5 cm. Segmentation was performed using a unique threshold level throughout the whole volume data. Manual thresholding was applied because the grayscale level of each soil sample was slightly different. Pores smaller than three voxels in volume were removed as noise during the post-segmentation procedure. In binary images, the object was valued to 255 (the pore) and the background was valued to 0. We colored the soil pore space blue and the soil matrix black.

The targeted binary images were imported into the software module for three-dimensional morphological analysis to reconstruct the three-dimensional model. The soil pore number, pore surface area, pore volume, and shape factor were calculated from the three-dimensional pore network model (Gong et al., 2016):

\[
\text{shape factor} = \frac{36\pi \times D \times V \times V}{S \times S \times S} \tag{10}
\]

where \(D\) is the diameter of the pore, \(V\) is the pore volume, an \(S\) is the surface area of the pore. Soil pores were classified into five groups based on pore size in diameter: 25–125, 125–250, 250–500, 500–1000, and >1000 μm.

**Statistical Analysis**

Data collection and collation were performed using Microsoft Excel 2010 software. Statistical analysis was performed using SPSS software (IBM SPSS, Version 22). Differences in basic soil properties or hydraulic properties were analyzed using an analysis of variance (one-way ANOVA analysis) and least significant difference (LSD) at the significant level of \(P < 0.05\). Origin software (Origin Lab 9.0) was used to obtain the figures.

### Results

#### Soil Basic Properties

X-ray diffraction analysis showed that quartz (31.9–37.8%) and plagioclase (24.3–32.0%) were the dominant primary minerals, accounting for as much as 60% (Supplemental Table S1). No significant changes in soil mineral composition were found among the study sites. Clay content ranges from 13.3 to 21.4%, silt from 35.8 to 45.1%, and sand from 38.2 to 49.7%. Soil pH shows a significant decrease from upper land (8.0) and middle land (8.1) to the lower land (6.8), which might reflect some change in the soil micro-environment due to inundation within the WLF zone. Soil in the lower land had a significantly higher CEC than the other two soils (\(P < 0.05\)). Normally, a high CEC is associated with fine soil texture and high soil pH (Bigorre et al., 2000); however, no relationships between CEC and clay content or soil pH were found in this study. The possible reason is that the number of soil samples is not large enough to show a relationship. Another possible reason is that the clay contents in the sampled soils have too narrow variance to show a relationship. Soil total porosity was significantly (\(P < 0.05\)) higher in the upper land than the other areas. Soil organic matter ranged from 4.99 to 15.63 g kg\(^{-1}\). No significant difference in average SOM was found among the soils. However, by soil layer, the lower land showed a much higher (not significant) SOM content (15.63 g kg\(^{-1}\)) at a depth of 0 to 10 cm than the other two soils, indicating a hint of an accumulation of SOM in the surface soil of the lower land. The accumulation of SOM in the surface soil might be a result of soil erosion from the surface soil of the upper lands, with enhanced flow movement during the wet season (Tang et al., 2016b). The redistributed soil from the upper land to the lower land was rich in SOM, as the upper lands were tillage fields with enriched organic matter inputs. For each elevation, SOM decreased significantly with depth, which is reasonable because more organic matter from plants (aboveground litter, root decay, and rhizo-deposition) and their breakdown products are present in the surface soil (Kögel-Knabner, 2017).

#### Soil Structure by Visual Examination and Soil Aggregate Fractal Dimension

During the application of VESS, all soils required an effort to extract and to break up. Soil in the upper land had relatively good porosity, with rounded aggregates with small size (most <6 mm) (represented by a lower Sq score) (Table 1). Soil in the middle land had a similar structure to the soil of the upper land, but more effort was required to break up the soil block. Soil in the lower land was more difficult to break up (two hands required). Macropores were present, and most soil aggregates were angular. Soil aggregates with size >2 cm in the lower land accounted for approximately 40% of the total number. The greater Sq scores showed a worse soil structure quality in the lower land. This was also supported by the lower soil porosity and higher soil \(\rho_b\) observed in the lower land. Tang et al. (2016a) also described the appearance of soil cracks in land submerged in water, whereby they concluded that inundation created cracks in the soil.
The lower MWD in the top two layers (0–10 and 10–20 cm) in the lower land possibly illustrates a decrease of soil aggregation and aggregate stability, which might be caused by inundation and washing by water during water-level fluctuation. The average $D_m$ in the lower land at 0 to 40 cm is significantly different compared with the other soils. Significant differences in $D_m$ with depth were found ($P < 0.05$) for each elevation. At the upper land, $D_m$ increased with depth ($P < 0.05$), and in both the middle land and lower land, $D_m$ decreased with depth ($P < 0.05$).

Table 2 shows the results of the MWD and $D_m$. Both the middle land and the lower land showed a significantly smaller MWD than that of the upper land, indicating worse aggregation or aggregate stability. Six et al. (2004) discussed the mechanism of reduced MWD by submergence with respect to the possible changes in main biotic or abiotic binding agents for the formation of aggregates. In the upper land and middle land, there was no significant change in MWD observed with depth. However, in the lower land, the MWD increased significantly with depth.

<table>
<thead>
<tr>
<th>Depth</th>
<th>pH</th>
<th>Bulk density</th>
<th>Porosity</th>
<th>CEC</th>
<th>SOM</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>VESS Sq score</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td></td>
<td>g cm$^{-3}$</td>
<td>m$^3$ m$^{-3}$</td>
<td>cmol kg$^{-1}$</td>
<td>g kg$^{-1}$</td>
<td>%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–5</td>
<td>7.66 ± 0.15a</td>
<td>1.47 ± 0.05c</td>
<td>0.45 ± 0.02a</td>
<td>22.05 ± 0.99b</td>
<td>9.35 ± 0.99b</td>
<td>38.83</td>
<td>44.33</td>
<td>16.84</td>
<td>2.0 ± 0.2A</td>
</tr>
<tr>
<td>10–15</td>
<td>7.99 ± 0.24ab</td>
<td>1.36 ± 0.03ab</td>
<td>0.49 ± 0.01bc</td>
<td>21.69 ± 0.39a</td>
<td>7.21 ± 0.95a</td>
<td>38.75</td>
<td>44.41</td>
<td>16.84</td>
<td></td>
</tr>
<tr>
<td>20–25</td>
<td>8.14 ± 0.25b</td>
<td>1.28 ± 0.08a</td>
<td>0.52 ± 0.03c</td>
<td>21.99 ± 0.90ab</td>
<td>6.84 ± 1.75a</td>
<td>38.84</td>
<td>36.66</td>
<td>14.50</td>
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</tr>
<tr>
<td>35–40</td>
<td>8.10 ± 0.14b</td>
<td>1.43 ± 0.03bc</td>
<td>0.48 ± 0.03ab</td>
<td>23.27 ± 1.43b</td>
<td>6.27 ± 1.29a</td>
<td>36.41</td>
<td>42.71</td>
<td>20.88</td>
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</tr>
<tr>
<td>Avg.</td>
<td>7.97 ± 0.26b</td>
<td>1.39 ± 0.14A</td>
<td>0.48 ± 0.03B</td>
<td>22.25 ± 1.11A</td>
<td>7.42 ± 1.68A</td>
<td>38.21</td>
<td>44.45</td>
<td>17.34</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depth</th>
<th>Upper land</th>
<th>Middle land</th>
<th>Lower land</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWD</td>
<td>g cm$^{-3}$</td>
<td>m$^3$ m$^{-3}$</td>
<td>cmol kg$^{-1}$</td>
</tr>
<tr>
<td>0–5</td>
<td>11.13 ± 1.89a†</td>
<td>5.81 ± 0.98a</td>
<td>6.14 ± 1.10a</td>
</tr>
<tr>
<td>10–20</td>
<td>8.70 ± 1.10a</td>
<td>5.31 ± 1.02a</td>
<td>6.54 ± 1.54a</td>
</tr>
<tr>
<td>20–30</td>
<td>8.78 ± 1.52a</td>
<td>6.04 ± 1.25a</td>
<td>8.24 ± 1.05ab</td>
</tr>
<tr>
<td>30–40</td>
<td>7.74 ± 2.05a</td>
<td>7.65 ± 1.54a</td>
<td>9.12 ± 0.85b</td>
</tr>
<tr>
<td>Avg.</td>
<td>9.12 ± 1.58B</td>
<td>6.23 ± 1.45A</td>
<td>7.89 ± 1.24A</td>
</tr>
</tbody>
</table>

† Mean ± standard deviation; means for the same depth followed by different lowercase letters are significantly different at the 0.05 level within the same elevation based on one-way ANOVA; means within an elevation followed by different uppercase letters are significantly different at the 0.05 level based on one-way ANOVA.
Soil Hydraulic Parameters and Pore Size Distribution
Estimated by Soil Water Retention Curve

The SWRC fitted by the van Genuchten model (Fig. 2) and Table 3 show the soil hydraulic parameters and pore size distribution estimated by the SWRC. Soils of the upper land and lower land showed a relatively higher estimated $\theta_s$, ranging from 0.45 to 0.49 and 0.41 to 0.46 m$^3$ m$^{-3}$, respectively, than the values obtained in the middle land (0.35–0.41 m$^3$ m$^{-3}$). It was proposed that $\theta_{\text{inf}}$ could be used as the boundary of soil textural pore space and structural meso- and macropores (Dexter et al., 2012; Han et al., 2008), thus the observed higher $\theta_{\text{inf}}$ for upper land and lower land indicate a larger proportion of water-filled textural porosity in the soils than that of the middle land. The soil effective porosity ($P_{\text{eff}}$) represents the portion of the total porosity that contributes to saturated flow, and the lower $P_{\text{eff}}$ observed in the lower land indicates poorer permeability of water, especially at deeper layers (AC = 0.15 and 0.14 m$^3$ m$^{-3}$ at depths of 20–25 and 35–40 cm, respectively).

The volumetric proportion of three soil pore size classes ($r < 0.1$ μm, $0.1 < r < 125$ μm, and $r > 125$ μm) was estimated by the SWRC and is shown in Fig. 3. All soils showed similar proportions of gravitationally drainable macropores ($r > 125$ μm). Soil in the lower land contained a significantly greater volume of non-drainable micropores ($r < 0.1$ μm, $P < 0.05$) and a smaller volume of slowly drainable pores (0.1 < $r < 125$ μm, $P < 0.05$) compared with the soil in the upper land and middle land, illustrating a possible shift of slowly drainable pores to non-drainable micropores in the lower land. It might be the clogging of slowly drainable pores due to the deposition of fine colloidal particles in the lower position of a slope (Tang et al., 2014).

Soil Pore Structure by Computed Tomography

Obvious differences in soil pores between the investigated elevations and depths can be seen from the micro-CT images (Fig. 4 and Supplemental Fig. S2). Compared with the upper land, the total number of detectable pores with a diameter >25 μm is much less in the lower land at both 0 to 5 and 35 to 40 cm (Table 4). The pore diameter (equivalent spherical diameter) has no distinct difference, neither between the upper land and lower land nor between 0- to 5- and 35- to 40-cm depths. The total pore surface

![Fig. 2. Soil water retention curves obtained by fitting the measured pressure head ($h$) vs. water content ($\theta$) data to the single-porosity van Genuchten model for soil core samples collected at depths of 0 to 5, 10 to 15, 20 to 25, and 35 to 40 cm, respectively.](image-url)
area of the upper land soil was lower than that of the lower land by 28.33 and 17.20% at 0 to 5 and 35 to 40 cm, respectively, while no marked differences in total pore volume were observed. Both macroporosity estimated from micro-CT images and the ratio of macropore volume determined from the images to total pore volume by oven drying and weighing saturated cores were markedly smaller in the lower land (Tables 1 and 4), which was subject to the longest duration of submergence among the three elevations. The number of pores was lower in the lower land for each pore size class than in upper land (Supplemental Table S2; Supplemental Fig. S2). Compared with the upper land, the total pore volume of each pore size class in the lower land was smaller than in the upper land by 6.98, 38.35, 24.96, 24.71, and 55.16% at a depth of 0 to 5 cm and by 54.79, 49.80, 28.28, 9.29, and 51.17% at a depth of 35 to 40 cm for pore size classes of 25 to 125, 125 to 250, 250 to 50, 500 to 1000, and >1000 μm, respectively. Assuming that all three elevations had similar soil pore structures before construction of the TGR, as expected from their similar soil textures and tillage practices, the differences in pore structure between upper land and lower land indicate that the effect of the timing of inundation within the WLF zone led to a marked loss in the number of pores in the 125- to 250- and >1000-μm size classes at a depth of 0 to 5 cm and the number of pores in the 25- to 125, 125- to 250-, and >1000-μm size classes at a depth of 35 to 40 cm.

### Discussion

We discuss the effects of the timing of inundation on soil physical quality from two aspects: soil structure quality and the soil pore system.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>θ_s m^3 m^{-3}</th>
<th>θ_r m^3 m^{-3}</th>
<th>α cm^{-1}</th>
<th>n</th>
<th>θ_p m^3 m^{-3}</th>
<th>S_{sw} m^3 m^{-3}</th>
<th>P_{eff}</th>
<th>MacPor</th>
<th>AC m^3 m^{-3}</th>
<th>PAWC m^3 m^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>0.46 (0.09)†</td>
<td>0.15 (0.03)</td>
<td>0.11 (0.02)</td>
<td>1.33 (0.05)</td>
<td>0.36 (0.06)</td>
<td>0.05 (0.01)</td>
<td>0.10 (0.02)</td>
<td>0.22 (0.02)</td>
<td>0.21 (0.05)</td>
<td>0.08 (0.01)</td>
</tr>
<tr>
<td>10–15</td>
<td>0.49 (0.08)</td>
<td>0.12 (0.05)</td>
<td>0.15 (0.03)</td>
<td>1.37 (0.03)</td>
<td>0.36 (0.10)</td>
<td>0.07 (0.02)</td>
<td>0.13 (0.02)</td>
<td>0.26 (0.03)</td>
<td>0.28 (0.06)</td>
<td>0.07 (0.00)</td>
</tr>
<tr>
<td>20–25</td>
<td>0.48 (0.10)</td>
<td>0.11 (0.03)</td>
<td>0.23 (0.05)</td>
<td>1.31 (0.02)</td>
<td>0.36 (0.09)</td>
<td>0.06 (0.01)</td>
<td>0.12 (0.01)</td>
<td>0.25 (0.10)</td>
<td>0.28 (0.03)</td>
<td>0.06 (0.01)</td>
</tr>
<tr>
<td>35–40</td>
<td>0.45 (0.05)</td>
<td>0.11 (0.01)</td>
<td>0.13 (0.05)</td>
<td>1.34 (0.03)</td>
<td>0.34 (0.04)</td>
<td>0.06 (0.02)</td>
<td>0.11 (0.01)</td>
<td>0.25 (0.11)</td>
<td>0.23 (0.02)</td>
<td>0.08 (0.01)</td>
</tr>
</tbody>
</table>

† Macroporosity is a dimensionless parameter (= 1 – θ_p/θ_s).
‡ Average, with standard deviation in parentheses.

Fig. 3. Volumetric proportions of soil non-drainable micropores (radii r < 0.1 μm), slowly drainable pores (0.1 < r < 125 μm), and gravitationally drainable macropores (r > 125 μm) estimated from the soil water retention curve SWRC at each soil depth in the upper land, middle land, and lower land. The error bar represents the standard deviation from triplicate measurements.

Table 3. Fitted soil water retention parameters for the van Genuchten (1980) model (saturated θ_s and residual water content θ_r, α and n), the water content (θ_p) and slope (S_{sw}) at the inflection point of the fitted soil water retention curve (SWRC), and soil effective porosity (P_{eff}), macroporosity (MacPor), air capacity (AC), and plant-available water capacity (PAWC) calculated from the fitted van Genuchten parameters.
Changes in Soil Structure Quality

In the sloping land, soil erosion and mass movement are two dominant geomorphological processes (Guerra et al., 2017) and both cause changes in soil structure quality. Since studies found that different geomorphological processes occurred with various intensities depending on slope position (Rodrigo Comino et al., 2017), soil structure quality responds differently. Our case study in the TGR illustrates some of these changes. First, the lower land seemed to have experienced a deterioration of soil structure quality, as we described above. At this position, the deposition of eroded soil transported via the surface runoff from the upper land could regularly occur. Normally, surface soil is rich in organic matter; thus, the transport of the eroded upper land surface soil downslope could have resulted in elevated organic matter content in the surface soil at the lower land. This spatial redistribution of soil could explain the observed highest SOM content of surface soil in the lower land. Normally, in the winter season, the lower land is completely submerged in water. During this time, the soil structure undergoes substantial changes where soil pores are full of water and some might deform, and soil aggregates might collapse due to swelling. The shrinkage and swelling processes during the wet–dry cycle can result in the breaking of soil aggregates (Ma et al., 2015) and the collapse or deformation of soil macro- and micropores. The observed higher proportion of micropores at all four soil layers and lower \( P_{\text{eff}} \) at deep soil layers (20–25 and 35–40 cm) in the lower land imply a shift of pore size distribution from macropores toward micropores, which occurs as a result of inundation. Coupled with pore size distributions estimated from the SWRC (Fig. 2), we can conclude that it was the slowly drainable pores \((0.1 < r < 125 \, \mu m)\) that diminished in association with the formation of more non-drainable micropores \((r < 0.1 \, \mu m)\). This shift also compressed the air capacity with the loss of the macropores, leading to limited air permeability at deep soil layers in the lower land (represented by lower AC at 20–25 and 35–40 cm). Andrade and Stone (2009) reported that the threshold of \( S_{\text{inf}} = 0.045 \) could be used to separate soils with good structural status from degraded soils, and \( S_{\text{inf}} \leq 0.025 \) illustrates soil with complete physical degradation. The \( S_{\text{inf}} \) values we obtained indicated that soil below the 10-cm depth in the lower land might be immersed in a degraded condition, as \( S_{\text{inf}} \) values are lower than the threshold of 0.045.

Changes in the Soil Pore System

Theoretically, the shrinkage and swelling processes during the wet–dry cycle can result in the breaking of soil aggregates (Ma et al., 2015) and the collapse or deformation of soil macro- and micropores. The observed higher proportion of micropores at all four soil layers and lower \( P_{\text{eff}} \) at deep soil layers (20–25 and 35–40 cm) in the lower land imply a shift of pore size distribution from macropores toward micropores, which occurs as a result of inundation. Coupled with pore size distributions estimated from the SWRC (Fig. 2), we can conclude that it was the slowly drainable pores \((0.1 < r < 125 \, \mu m)\) that diminished in association with the formation of more non-drainable micropores \((r < 0.1 \, \mu m)\). This shift also compressed the air capacity with the loss of the macropores, leading to limited air permeability at deep soil layers in the lower land (represented by lower AC at 20–25 and 35–40 cm). Andrade and Stone (2009) reported that the threshold of \( S_{\text{inf}} = 0.045 \) could be used to separate soils with good structural status from degraded soils, and \( S_{\text{inf}} \leq 0.025 \) illustrates soil with complete physical degradation. The \( S_{\text{inf}} \) values we obtained indicated that soil below the 10-cm depth in the lower land might be immersed in a degraded condition, as \( S_{\text{inf}} \) values are lower than the threshold of 0.045.
CT image draws a picture of the macropore system (r>micropores. Nevertheless, the definitions of pore size to total porosity (determined by the core method) in the lower micro- and macropore systems in the soil column, the micro-classes used for estimation of the pore size distribution based land soil implies the transformation of macropores, at least partially, to micropores. Therefore, the definitions of pore size classes should be made clear for all methods before further discussion.

Here, we categorized pores into size classes, including non-drainable micropores (r<0.1 \( \mu m \)), slowly drainable micropores (25 \( \mu m > r > 0.1 \mu m \)), fine macropores (125 \( \mu m > r > 25 \mu m \)), and coarse macropores (r>125 \( \mu m \)). Our data obtained from the micro-CT images showed that the timing of inundation caused a shift in the pore size distribution from macropores (r>25 \( \mu m \)) to micropores (25 \( \mu m > r > 0.1 \mu m \)). Bottinelli et al. (2016), in an incubation experiment, found an increase of macropores (225–1215 \( \mu m \)) during shrinkage due to the formation of cracks and the enlargement of preexisting macropores. In this study, observed decreases in the total volume of macropores and each of their size classes in the lower land can be attributed to the long duration of inundation, clay swelling, and sedimentation of fine particles in the soil pore system. However, for the complex hydrological and transport processes under such topography as a mixture of terrace and sloping land, like the TGR area, it is recommended to conduct seasonal and yearly field investigations on temporal and spatial variations of soil macropore structure to discover the possible mechanisms across multiple spatial scales.

### Conclusions

In this study, soil properties above and within the WLF zone of the TGR, which experience very different timing and intensity of inundation, were analyzed by adopting multiple methods including traditional laboratory measurements, soil structure assessment (VESS), and micro-CT imaging technology. The results show a deterioration of soil structure quality in the lower land within the WLF zone by virtue of the maximum intensity of inundation associated with the operation of the Three Gorges Dam. This deterioration involves increased bulk density, decreased porosity, and worsened overall quality (indicated by Sq scores in VESS). This research found the collapse of macropores and the formation of more micropores by inundation. Our finding of the changes in the soil pore system by inundation might be helpful to further understand the transport of nutrients and pollutants in the TGR area. Due to the deterioration of soil structural quality in the lower land in the WLF zone, any type of land use should be avoided; and there is a potential of soil surface erosion occurring in the lower land that should influence water body quality, too. This study also identified micro-CT imaging technology as useful to quantitatively examine the soil macropore structure, while more intact soil core samples are required to represent the inherent high heterogeneity of macropores in the field sites.

### Table 4. Parameters of soil pores estimated from computed microtomography images.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Upper land</th>
<th>Lower land</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore number</td>
<td>21,255</td>
<td>34,233</td>
</tr>
<tr>
<td>Total surface area, ( m^2 )</td>
<td>9.38 x 10^8</td>
<td>1.45 x 10^9</td>
</tr>
<tr>
<td>Total volume, ( m^3 )</td>
<td>1.72 x 10^10</td>
<td>2.61 x 10^10</td>
</tr>
<tr>
<td>Shape factor</td>
<td>0.86</td>
<td>0.86</td>
</tr>
<tr>
<td>Macroporosity, ( m^3 \ m^{-3} )</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>Pore number</td>
<td>11,290</td>
<td>15,154</td>
</tr>
<tr>
<td>Total surface area, ( m^2 )</td>
<td>1.34 x 10^9</td>
<td>1.67 x 10^9</td>
</tr>
<tr>
<td>Total volume, ( m^3 )</td>
<td>4.12 x 10^10</td>
<td>5.00 x 10^10</td>
</tr>
<tr>
<td>Shape factor</td>
<td>0.92</td>
<td>0.87</td>
</tr>
<tr>
<td>Pore number</td>
<td>5199</td>
<td>6372</td>
</tr>
<tr>
<td>Total surface area, ( m^2 )</td>
<td>2.76 x 10^9</td>
<td>3.32 x 10^9</td>
</tr>
<tr>
<td>Total volume, ( m^3 )</td>
<td>1.21 x 10^11</td>
<td>1.45 x 10^11</td>
</tr>
<tr>
<td>Shape factor</td>
<td>0.45</td>
<td>0.44</td>
</tr>
<tr>
<td>Pore number</td>
<td>1103</td>
<td>1292</td>
</tr>
<tr>
<td>Total surface area, ( m^2 )</td>
<td>2.91 x 10^9</td>
<td>3.34 x 10^9</td>
</tr>
<tr>
<td>Total volume, ( m^3 )</td>
<td>1.70 x 10^11</td>
<td>1.94 x 10^11</td>
</tr>
<tr>
<td>Shape factor</td>
<td>0.20</td>
<td>0.17</td>
</tr>
<tr>
<td>Pore number</td>
<td>244</td>
<td>263</td>
</tr>
<tr>
<td>Total surface area, ( m^2 )</td>
<td>4.60 x 10^10</td>
<td>5.12 x 10^10</td>
</tr>
<tr>
<td>Total volume, ( m^3 )</td>
<td>3.10 x 10^12</td>
<td>5.98 x 10^12</td>
</tr>
<tr>
<td>Shape factor</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Compared with the SWRC, which reflects both the micro- and macropore systems in the soil column, the micro-CT image draws a picture of the macropore system (r>75 \( \mu m \) in this study) in the soil column. Pronounced decreases in both the number of macropores and the ratio of macropore volume to total porosity (determined by the core method) in the lower land implies the transformation of macropores, at least partially, to micropores. Nevertheless, the definitions of pore size classes used for estimation of the pore size distribution based on SWRC are different. Consistent definitions of pore size classes should be made clear for all methods before further discussion.
Acknowledgments

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