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Modelling the performance of bunds and ditch dams in the hydrological restoration of tropical peatlands

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Abstract

Many tropical peatlands are subjected to artificial drainage that leads to degradation. Hence, hydrological restoration has recently been prioritized. Nevertheless, as field monitoring data are limited, little is known about how restoration measures, such as ditch dams and bunds, can regulate tropical peatland water tables. We used a hydrodynamic model —DigiBog_Hydro— to simulate the effectiveness of ditch dams and bunds across three El Niño–Southern Oscillation (ENSO) scenarios, which are El Niño, La Niña and Neutral, in three typical sites. The sites were moderately degraded (Mod-Dgr) and severely degraded (Sev-Dgr) peatland plots (each 0.2 km^2), representing typical peatland conditions in Sebangau National Park, Kalimantan, Indonesia. Our fine-scale (1 m $\times$ 1 m spatial resolution) modelling revealed that in the dry season of any ENSO scenario, the significant effects of ditch-dams alone on peatland water-level were limited to lateral distances of 26 m (in Mod-Dgr) and 12 m (in Sev-Dgr) from the ditch. In the dry season of an El Niño year, the combination of ditch dams and bunds helped maintain water levels up to 72 cm (in Mod-Dgr) and 69 cm (in Sev-Dgr) higher than in the no-restoration condition. During the extreme-dry period of an El Niño year, the bunds reduced the number of days when the water table was deeper than 40 cm in Mod-Dgr and in Sev-Dgr by 50% and 73%, respectively. We suggest that bunds used in combination with ditch dams are a practical restoration measure for tropical peatlands, providing critical extra water storage and helping maintain water tables near the peatland surface in dry periods. We also demonstrate how fine-scale hydrodynamic modelling is beneficial for planning and assessment of restoration measures in tropical peatlands.

KEYWORDS
El Niño, Kalimantan, rainfall, simulation, water table, wetland

1 | INTRODUCTION

Tropical peatlands are important globally as carbon stores and for hosting distinctive and biodiverse ecosystems (Agus et al., 2019; Girkin et al., 2020; Hapsari et al., 2017; Page & Baird, 2016; Wijedasa et al., 2020). Xu et al. (2018) estimated that tropical peatlands cover at least 3.38 $\times$ 10^5 km^2, representing 8% of global peatland coverage. The main tropical peatland areas are found in Southeast Asia (2.48 $\times$ 10^5 km^2), Peruvian Amazonia (0.22 $\times$ 10^5 km^2) and the Congo Basin (1.45 $\times$ 10^5 km^2), accounting for an estimated carbon storage of 68.5 Pg C, 3.14 Pg C and 30.6 Pg C, respectively (Dargie et al., 2017; Draper et al., 2014; Honorio Coronado et al., 2021; Page et al., 2011; Warren et al., 2017).

Since the 1980s, many tropical peatlands have been converted to agricultural land and plantation forestry, and these conversions have been associated with widespread drainage (Dohong, Aziz, & Dargusch, 2017; Farmer et al., 2014; Graham et al., 2017; Könönen et al., 2018). As an example, in 1995, the Indonesian Government implemented the Mega Rice Project (MRP) that resulted in the drainage of 3 million hectares of tropical peatland before the scheme was stopped in 1999 (Dohong et al., 2018b; Dohong, Aziz, & Dargusch, 2017). Drainage involved the construction of canals and ditches to lower water tables (Boehm & Siegert, 2001; Limin et al., 2007; Medrilzam et al., 2017; Ward et al., 2021). Canals are up to 25 m wide, 4.5 m deep, can extend for tens of km, and receive drainage water from neighbouring ditch networks (Page et al., 2009; Sinclair et al., 2020). Secondary canals divided peatland into compartments of roughly 6.25 km^2 each (Blackham et al., 2014; Mawdsley et al., 2009), in particular those in Mantangai (Block A of the Ex-MRP). Meanwhile, ditches tend to be between 2–4 m wide and 1.5–3 m deep, generally designed in a grid pattern, bounding small peat plots typically of 0.15–0.25 km^2. The depth of canals and ditches may vary over time due to subsidence.

Drainage causes rapid decay (oxidative loss) and an increase in the bulk density of peat, both leading to subsidence (Carlson et al., 2015; Hooijer et al., 2012; Sinclair et al., 2020). Couwenberg et al. (2010) suggested that each additional water-table lowering of 10 cm will trigger an approximate 0.25×10^{-6} Pg of C loss per year per km^2 of tropical peatland, and 0.9 cm of annual peat subsidence. Subsidence can be extreme, as in an abandoned area of the Ex-MRP, the peat surface subsided by 25 cm between 9 July 2007 and 1 September 2010 (Hoyt et al., 2020; Zhou et al., 2019). Drained peatlands are also susceptible to fire, and fire is used to clear natural forests as part of land conversions (Cooper et al., 2019; Dadap et al., 2019; Roucoux et al., 2017). Studies of fire distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 showed that there was less fire in areas without artificial drainage than in drained areas (Miettinen et al., 2017). Peatland fires can last many weeks and lead to extremely high rates of C loss (as CO_2 and CH_4) (Ballhorn et al., 2009; Page et al., 2002). Accordingly, predictions suggest that drainage and peatland conversions for agriculture in Southeast Asia will cause CO_2 emissions of 4.43–11.45 Pg between 2010 and 2130 if restoration is not carried out (Hergoualc'h & Verchot, 2011; Roucoux et al., 2017; Wijedasa et al., 2018).

Because of the environmental damage caused by drainage, there have been recent government initiatives to restore or rehabilitate tropical peatlands. These initiatives formed a part of the 'Brazzaville Declaration', 21–23 March 2018, attended by representatives of Democratic Republic of the Congo, Republic of the Congo, Republic of Peru and Republic of Indonesia (Desai, 2018; International Climate Initiative, 2021). The Indonesian Government, for example, aims to maintain peatland water tables at depths shallower than 40 cm from the surface (the 40-cm limit) (The Regulation of The Republic of Indonesia No. 57 Year 2016 about Peatland Ecosystem Protection and Management, 2016). Measures being implemented to keep within this limit include restoring native peatland vegetation, banning new peatland drainage operations, installing canal dams and ditch dams and infilling of ditches (Dohong et al., 2018a; Dohong, Cassiophea, et al., 2017; Harrison et al., 2020). Little is known as to whether these restoration measures, specifically ditch damming, are sufficient to ensure peatland water tables stay within the 40-cm limit. However, a study by Putra et al. (2021) in Sebangau peatland, Kalimantan, indicated that dams alone could not keep water tables within the 40-cm limit, especially during the dry season. In summary, Putra et al. (2021) provided empirical evidence that the ditch dams do not maintain the ditch and peatland water levels in the dry period, because not enough water was retained in the peatland at the beginning of the dry season. Therefore, if the 40 cm water-table policy is to be achieved, extra water needs to be retained in the peatland at the end of a wet period, to act as buffer to maintain the water table of the peatland during subsequent dry periods.

Based on some initial studies in temperate peatlands, some researchers have proposed supplementing dams with bunds to keep a peatland wet (Glenk et al., 2020; Land & Brock, 2017; Payne et al., 2018; Shantz & Price, 2006). Bunds tend to be impermeable or very low permeability linear barriers installed on the peatland surface (not in canals or ditches). They are designed to store rainfall or surface water in the area behind the bunds. In temperate peatland studies, researchers have promoted two types of bund: (i) cell design (for relatively flat peatland applications) and (ii) contour bunds (for sloping peatland applications). The cell bunds might be suitable for application in Sebangau peatland, given the relatively flat terrain of the peatland.

Before bunds can be promoted and used more widely in tropical settings, it is important to appraise their effectiveness. However, undertaking field trials can be costly and time-consuming (Kasih et al., 2016; Novitasari et al., 2018; Ritzema et al., 2014). An alternative approach is to use a physically based hydrodynamic model to simulate the effect of bunds in combination with other restoration measures. Models based on the Boussinesq groundwater equation have been applied to simulate water-table response to peatland drainage and variations in meteorological conditions (e.g. see Baird et al. (2017)), and also to model restoration scenarios (e.g. see Urzainki et al. (2020)). In this study, we evaluated the combined and separate effects of dams and bunds on water tables in a typical Indonesian tropical peatland under different climate scenarios. The climate scenarios covered three El Niño–Southern Oscillation (ENSO) conditions, which are ENSO neutral (medium rainfall), El Niño (limited rainfall) and La Niña (abundant rainfall) conditions (more detailed explanation is available in the methods section). We focused on two research questions: how do different ditch dam and bunding arrangements affect seasonal and spatial water-level dynamics in tropical peatlands and how does the degree to which the peat has been degraded influence the effectiveness of restoration measures?

2 | DATA AND METHODS

2.1 | Typical drained sites

We simulated drained peatlands, typical of those found in Sebangau, Kalimantan, Indonesia (see Putra et al. (2021)), using a hydrodynamic model —DigiBog_Hydro (Baird et al., 2012). In Sebangau, drained peatland areas are commonly divided into plots by a grid of ditches. There are typically two to four ditch dams installed for a peat plot in restored areas, but no ditch dams in other drained plots. In Sebangau, ditches are 2–3 m wide and 2–4 m depth (although ditch depths can change over time due to peat surface subsidence following drainage, see Hooijer et al. (2012)). The thickness of the ditch dams installed in ditches is approximately 1–2 m. The main body of ditch dams is designed as a single block of sand or compacted peat enclosed by plastics, whereas the outer shell of the ditch dam is created with a layer of wood slabs or poles (Dohong et al., 2018a; Suryadiputra et al., 2005). The ditch dam has wings, which are extensions of the main body that are about 2–3 m long, anchored sideways into the ditch banks. The ditch dams aim to be water deflectors (Dohong et al., 2018a; Dohong, Cassiophea, et al., 2017), diverting some water in ditches to the peatland, slowing channel flow. Restoration bunds have not been trialled yet in the Sebangau area.

In temperate peatlands, restoration bunds are sometimes built to enhance surface water storage, to help 'buffer' water tables during dry periods. These restoration bunds are made of poorly permeable material (plastic, clay or compacted peat), arranged in such a way to allow 30–50 cm of temporary surface inundation (Payne et al., 2018; Price et al., 2003; Wichmann et al., 2017). In the Sebangau area, local farmers create ridges to produce an elevated surface above a peatland so that crops can be planted on it, but not in a configuration to trap water on site (Figure 1). Thus, bunding for restoration might be acceptable to local communities as ridge structures are familiar. Here, we modelled a bund system that seeks to reduce drying of the peatland during the early phase of a dry season by retaining surface water on the peatland.

2.2 | Modelling scenarios

In this study, the scenarios that were modelled included several components: degree of peatland degradation, climate, presence or absence of ditch dams and bunds, and bund depth (Figure 2). First, two peatland degradation conditions were modelled: moderately degraded (Mod-Dgr, assumed to be a drained peatland with a dense vegetation cover and with no fire record in the last 20 years) and severely degraded (Sev-Dgr, interpreted as a drained ex-agricultural peatland that has been burnt and that has bare peat or a sparse vegetation cover). Second, three climate scenarios were implemented: El Niño, Neutral and La Niña. Third, four drainage and restoration

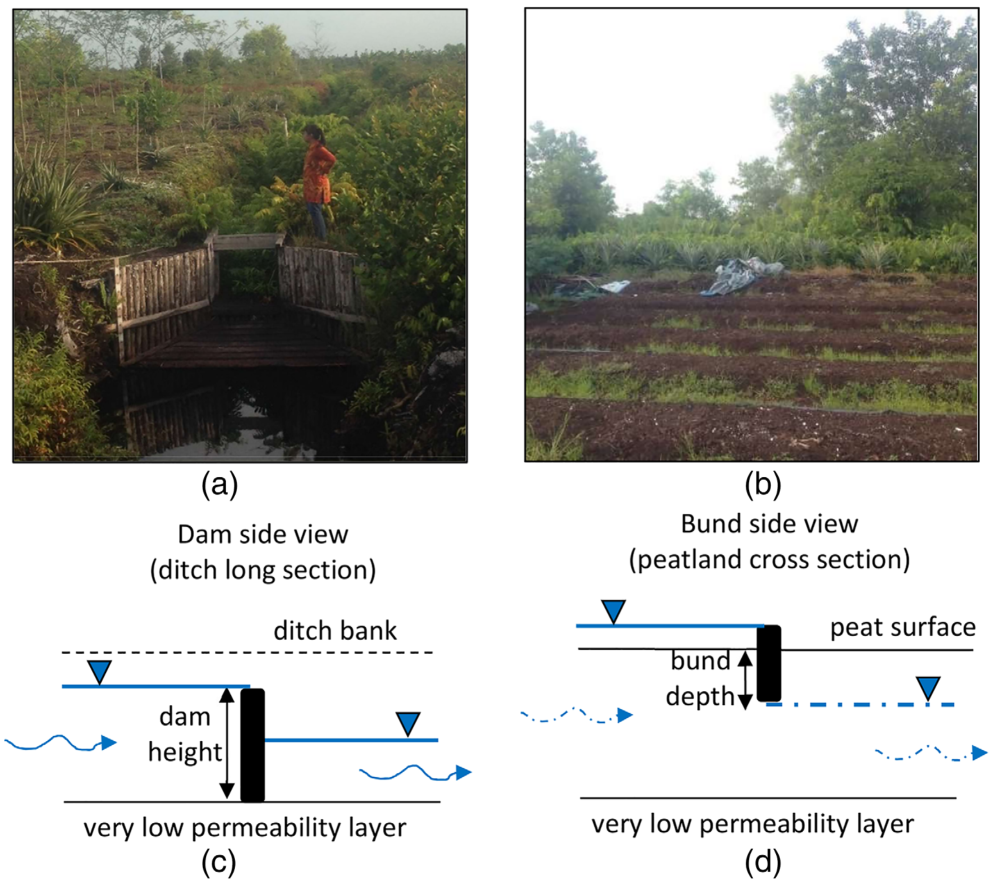

FIGURE 1 The ditch dam and agricultural bunds in the Sebangau area, Indonesia. The ditch dam (a) has been used to restore peatland water level in the studied area. Agricultural bunds (b) are commonly created in the area, but water-level restoration bunds have not been trialled (see Payne et al. (2018) and Wichmann et al. (2017) for the application of restoration bunds in temperate peatlands). The sectional water-level schematization in (c) is for a ditch dam and the one in (d) is for a restoration bund. The cross-section scheme for an agricultural bund is not shown. The lines with triangles represent water levels, in which the light blue lines are ditch/surface water levels, and the dash-dotted lines are the sub-surface water level. Wavey arrows show water flow direction

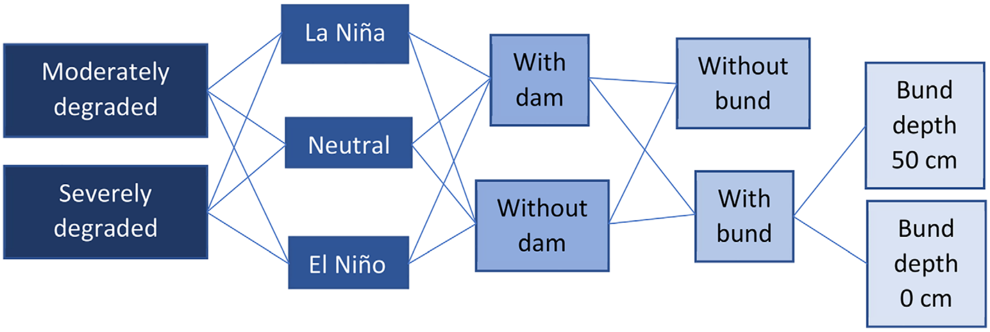

FIGURE 2 Schematic diagram of modelling scenarios

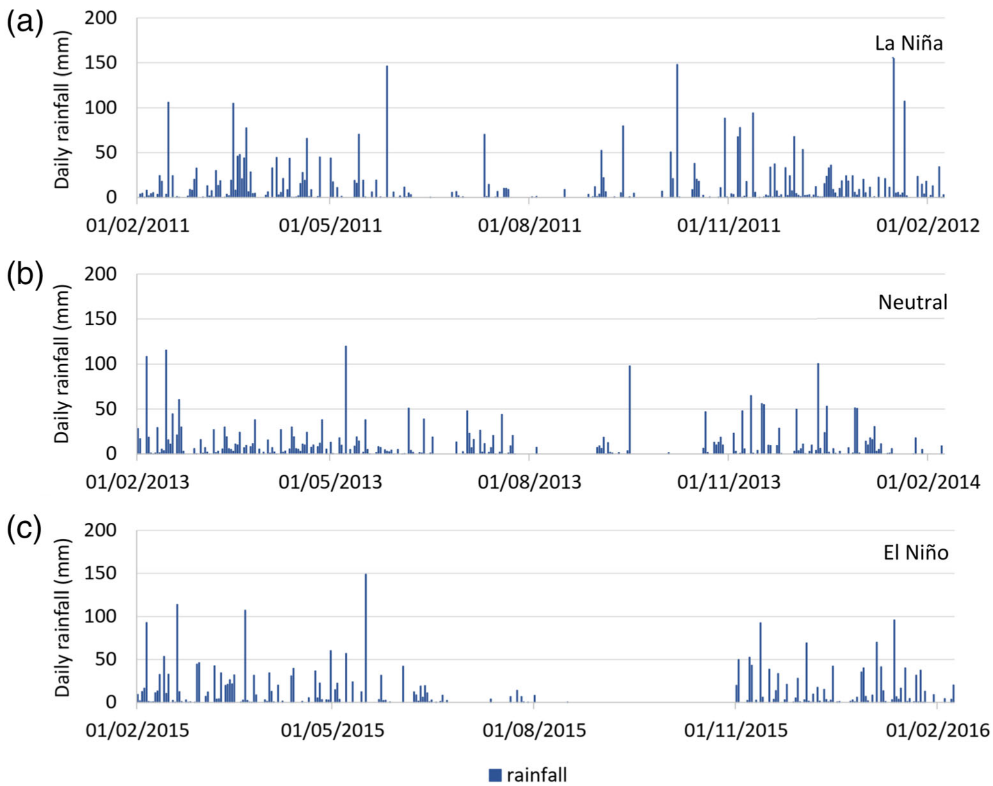

FIGURE 3 The time series of daily rainfall of a La Niña, a Neutral and an El Niño year that are used in the modelling scenarios

scenarios were used: a drained peatland restored with dams and bunds (Combined), a peatland restored with bunds but without dams (Bunded), a peatland restored with dams but without bunds (Dammed) and finally a peatland without dams and without bunds (Control). These scenarios were chosen to compare restoration strategies with each other and with the unrestored control condition. Fourth, in the Bunded scenario, two bund types were considered: On-Surface (bund depth 0 cm) and Extended (bund depth 50 cm), in which the bund depth values are the extent to which the bund penetrates below the peat surface. The height of the bund above ground in this modelling study was set to 30 cm.

In total, 32 model setups were used to represent all scenarios across the targeted modelling variables (see Figure 2), which were four dam/bund arrangements, two peat types, and three ENSO conditions, plus eight scenarios of bund type variation ($[4 \times 2 \times 3] + 8 = 32$ setups). For the model simulations, we assumed a rectangular tropical peat plot of 500 m × 400 m bounded by ditches. The selected typical peat plot dimensions mimicked the conditions of a drained peatland with ditch dams studied by Putra et al. (2021).

Weather data for the model runs were obtained from the BMKG (Indonesian Meteorology, Climatology and Geophysics Agency) weather station in Palangka Raya City (2.2279°S, 113.9462°E, 10 m.a.s.l.) —WMO Weather Station ID: 96655, located 13 km from the northernmost tributary of the main canal in Block C MRP (near Kalampangan village). The weather station has long rainfall records (1978–2021) for the Sebangau area. The total daily rainfall records were collected from a ground-sited rain gauge. Three meteorological scenarios were chosen based on inter-annual ENSO variations: a La Niña year (1 February 2011 to 8 February 2012), a 'Neutral' year (1 February 2013 to 8 February 2014), and an El Niño year (1 February 2015 to 8 February 2016) (Figure 3). The rainfall totals for those years were 3594 mm (La Niña), 2844 mm (Neutral) and 2778 mm (El Niño).

The particular years were selected based on recent meteorological studies and reports (Supari et al., 2018; Susilo, Yamamoto, Imai, Inoue, et al., 2013; WMO, 2012, 2014a, 2014b, 2016), but also considering the BMKG rainfall data availability and reliability. Years in the BMKG database with greater than 5% of days with no data during the associated wet period (November to April), or a total of yearly rainfall higher than 4000 mm, were not used in this study.

The weather data inputted to DigiBog_Hydro are in the form of daily net rainfall (rainfall minus evapotranspiration). Hirano et al. (2015) determined that the values of yearly evapotranspiration (ET) in tropical peatland were 1374 ± 75 mm in a Sev-Dgr site (site with peat fire records) and 1636 ± 53 mm in a Mod-Dgr site (less disturbed site). Hirano et al. (2015) also suggested that daily ET values were in the range 3.27–3.35 mm in a Sev-Dgr site, but 4.09–4.60 mm in a Mod-Dgr site. Therefore, in this study, it is assumed that there are differences in ET between typical moderately and Sev-Dgr sites under the implementation of hydrological restoration management. However, given we had no actual daily ET measurements for the studied periods, the daily ET data of each typical site were assumed to be uniform for the whole year and across ENSO scenarios (Figure 3). The chosen daily ET values were 3.76 mm for Sev-Dgr and 4.48 mm for Mod-Dgr. In Sev-Dgr, the calculated yearly net rainfalls were 2190 mm (La Niña), 1440 mm (Neutral) and 1373 mm (El Niño). Accordingly, in Mod-Dgr, the calculated yearly net rainfalls were 1922 mm (La Niña), 1172 mm (Neutral) and 1106 mm (El Niño).

The model was implemented with different peat properties across layers and peat degradation conditions (Table 1). Generally, there were four different layers set above the model base (a very low permeability layer), but five layers for the area behind the bund. The additional uppermost layer (the fifth layer) was used to simulate surface inundation on the area behind the bunds, as described in the DigiBog_Hydro User Manual (Baird et al., 2020). The layers varied in thickness and the peat properties were assumed to be homogeneous within a layer (Table 1). Some of the peat properties values were adopted from the literature (Kobayashi, 2016; Kurnianto et al., 2019) and others were estimated based on the assumption that hydraulic conductivity decreases with depth (Baird et al., 2017; Cobb et al., 2017; Kelly et al., 2014). Drainable porosity has not been measured in many tropical peatlands. Cobb and Harvey (2019) provided a drainable porosity profile for a pristine tropical peatland, based on the response of the water table to rainfall, which is similar to the Mod-Dgr peatland profile in Table 1. Wösten et al. (2008) estimated drainable porosity values from measurements, which showed 50% drainage of total pore spaces in the top peat layer with a drop of peatland water table by 40 cm from the surface. The same estimation was used by Mezbahuddin et al. (2015). Baird et al. (2017) set drainable porosity values at 0.6 (upper), 0.45 (middle) and 0.35 (lower) for each peat layer based upon expert judgement but their values were not based on field measurements. We chose drainable porosity values based on the values reported in the above studies. In scenarios involving bunds (Combined and Bunded), the additional layer was set to have high drainable porosity and high hydraulic conductivity to represent surface flow through dense vegetation.

2.3 | DigiBog_Hydro model

The DigiBog_Hydro model simulates subsurface flow and water-table dynamics in the *x*–*y* plane. It also allows for variation in hydraulic conductivity and drainable porosity laterally and with depth below the surface. Therefore, despite not simulating vertical water flow, it can be described as a 2.5-dimensional model. It is based on a numerical solution to the following version of the Boussinesq equation (Baird et al., 2012):

$$\frac{\partial h}{\partial t}=\frac{\partial}{\partial x}\left(\frac{\kappa(d)}{s(d)}d\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\kappa(d)}{s(d)}d\frac{\partial h}{\partial y}\right)+\frac{P(t)-E(t)}{s(x,y,d)}$$

in which:

h is water-table elevation above a datum (set below the peat) [L];

d is the thickness of flow (i.e. the local height of the water table above an underlying assumed impermeable layer [mineral soil, sediment or rock]) [L];

t is time [T];

x is horizontal distance in the x coordinate direction [L];

y is horizontal distance in the y coordinate direction [L];

TABLE 1 Peat properties used in the DigiBog_Hydro model scenarios

Layer depth	Severely degraded site		Moderately degraded site		Bund-d-50 cm		Bund-d-0 cm	
(cm)	K (cm.s^{-1})	s	K (cm.s^{-1})	s	K (cm.s^{-1})	s	K (cm.s^{-1})	s
−30 to 0	5	0.9	3	0.9	1×10^{-6}	0.11	1×10^{-6}	0.11
0 to 20§	2.4769×10^{-3}§	0.45	1.1631×10^{-2}§	0.6	1×10^{-6}	0.11	–	–
20 to 50	6.2847×10^{-4}§	0.42	4.3287×10^{-3}‡	0.55	1×10^{-6}	0.11	–	–
50 to 80†	1.0995×10^{-4}†	0.37	2.3148×10^{-4}†	0.45	–	–	–	–
80 to 200†	3.4722×10^{-5}†	0.3	4.9769×10^{-5}†	0.3	–	–	–	–

Note: K is hydraulic conductivity and s is drainable porosity. There are bund depth 50 cm and 0 cm (on surface only) scenarios. A part of the presented K data († & ‡) are median values taken from Kurnianto et al. (2019) (†) and Kobayashi (2016) (‡). The other K data (§) were estimated, considering that K decreases with depth (Baird et al., 2017; Cobb et al., 2017; Kelly et al., 2014). The s data were chosen based on values presented in previous studies (Baird et al., 2017; Mezbahuddin et al., 2015; Wösten et al., 2008).

s is drainable porosity [dimensionless];

κ is depth-averaged hydraulic conductivity below the water table [$L\ T^{-1}$];

P is the rate of rainfall addition to the water table [$L\ T^{-1}$];

E is the rate of evapotranspiration from the water table [$L\ T^{-1}$].

In this study, the DigiBog_Hydro model was set up using cells and layers to represent the modelled domain. The setup of the model is shown in Figure 4. The model domain represents a typical rectangular peat plot surrounded by ditches, in which ditch dam and bund presence varies across scenarios. The typical peat plot was represented by a set of active cells in the model domain. The grid cell size used was 1 m × 1 m in plan dimensions and was not varied across scenarios. The water level for the active cells was calculated based on the full Boussinesq equation during the simulation period. Fixed head (water level) —Dirichlet — boundary cells were used to represent ditches. The dams were represented by two different water levels in a ditch segment. The set water levels behind the dam (upstream) were higher than the levels set in front (downstream) of the dam. The bunds were represented using active cells containing peat layers with a low hydraulic conductivity (1×10^{-6} cm.s^{-1}) and a low drainable porosity (0.11) (Table 1). As the bund depth was not assumed to reach the impermeable layer, the peat layers below the bunds were set to have the same hydraulic properties as the surrounding peat at that depth. The overall thickness of the model was 2 m, below which an impermeable layer was assumed.

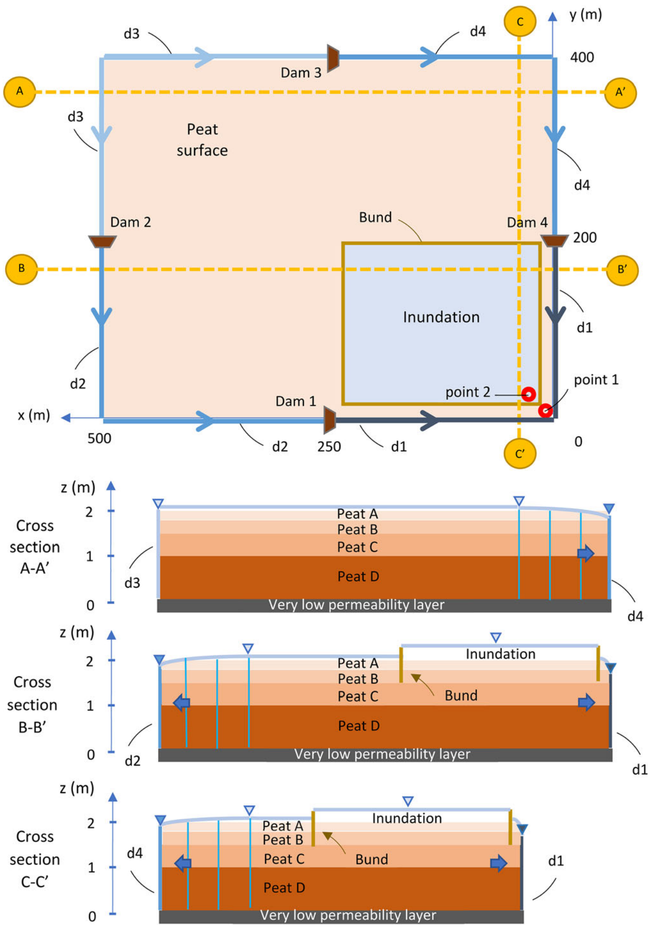

FIGURE 4 Plan and cross-sectional view of the DigiBog_Hydro modelling domain used in this study. The three cross-sections show the layers used in the simulations, considering the ditch water levels of Early Wet period. The triangles and light-blue curves show example water-table positions. The vertical light-blue lines and dark-blue arrows show the possible flow directions. There are four implemented types of Dirichlet boundary (d1 to d4). The red doughnut symbols are monitoring point 1 (in front of the bund, $x = 10$ m and $y = 8$ m) and monitoring point 2 (behind the bund, $x = 40$ m and $y = 32$ m). The main outlet of the modelled peat plot is located at $x = 0$ m and $y = 0$ m

In this study, we simulated a 0.2 km^2 (500 m × 400 m) area of drained peatland. For the Combined and Bunded scenarios, the area that was enclosed by the bunds (220 m × 180 m) was one fifth of the surface area of the selected typical plot (3.96×10^{-2} km^2). The restoration bunds were 30 cm in height above the peat surface. The thickness of the bunds was 100 cm. We considered such a partial bunded option for our simulations because if it is applied in the field, it would require less budget and would be less radical to local people than constructing the bund around the whole peat plot. The bunded area was located near to the lowest outlet of the peat plot (Figure 4), in which the closest bund corner was 28.2 m from the outlet of the peat plot. The bunded area was placed in the downstream corner of the model domain because it is the driest zone of the peat plot, inferred from the water-level data of a ditch-dam-blocked area studied in the field by Putra et al. (2021). Time-series model output data were obtained for two model 'monitoring points' shown in Figure 4. Point 1 is near the drainage outlet and in front of the bund in those scenarios where the bund is present. Point 2 is located within the main block of peat and occurs within the bund enclosure in the bunding scenarios.

We represented surface water storage and movement in the model using virtual layers. In the un-bunded area, water was allowed to pond to a depth of 5 cm so that a virtual layer was used. This water could escape to the margin only by entering the peat below and moving laterally via subsurface flow. The 5-cm virtual layer (the uppermost layer) functioned to limit the ponding depth in the area, acting as a 'tank' that temporarily stored excess water from rainfall. No hydraulic conductivity value was applied to this layer and no surface runoff modelling was implemented for the virtual layer. Any rainfall causing the 5-cm ponding limit to be exceeded was assumed to be immediately lost to the model boundaries. In effect, this loss is the equivalent of rapid overland flow. In the area enclosed by the bunds, two layers were used to represent surface water storage and flow. To the top of the peat was added a 30-cm layer with a high hydraulic conductivity and drainable porosity (Table 1). Water could flow laterally 'through' this layer and through the lower-permeability bunds. It could also escape downwards and thence laterally through the deeper peat. On top of the 30-cm layer was a 5-cm layer the same as in the un-bunded area.

The total simulation time for each scenario was 364 days. In the Dammed and Combined scenarios, the effect of the dams on the ditch water levels was assumed to vary between dry and wet periods. Each yearly simulation was divided into four different 100-day periods, with 12 days overlap between periods (Table 2). The water-level output resulting from the preceding period was used as an initial condition for the next period. The results for periods of overlap were similar (fewer than 2 cm in difference), providing assurance that the model spin-up time was sufficient and indicating that the initial condition did not introduce artefacts to the results. Those periods were Late Wet (1 February to 11 May), Early Dry (1 May to 8 August), Late Dry (1 August to 8 November) and Early Wet (1 November to 1 February of the following year). The ditch water levels were set to different Dirichlet boundary water levels for each of the modelled periods and were kept constant during each period. The ditch water levels were based on data collected by Putra et al. (2021) and discussions with local forest rangers. The values that were used are given in Table 2, which were implemented across different climatic years.

3 | RESULTS

Our simulations show that, in the dry season, water levels in the Combined scenario (with ditch dams and bunds) were higher compared with water levels in the Control scenario. The effect of bunds in storing 'excess' water for the bunded area and its surroundings was distinct in the dry season. By contrast, in the dry season, the ditch-dam effects on water-level dynamics were limited around the ditches. The bund depth (in the On-surface and Extended scenarios) leads to different responses in terms of the amount of water stored behind the bunds, which depend on the state of peat degradation. Table 3 contains basic statistics from the modelling results (seasonal water-table depths and day counts of deep water-table condition) to support the graphical outputs in the figures.

3.1 | Seasonal water-level dynamics

Figure 5 shows how water levels vary in relation to seasons, ENSO conditions, peatland degradation and restoration measures. In the Late Wet period, the water levels across different scenarios ranged from being above the peat surface to 10 cm below the peat surface. In the Early Dry period, water levels started to decrease, although inundation still occurred, depending on rainfall and water levels in the preceeding Late Wet period. Water levels continued to fall in the Late Dry period to reach the lowest level of the year (levels varied across scenarios). Water levels rose again in the Early Wet period with the increase in net rainfall. Water levels in Sev-Dgr were normally higher than in Mod-Dgr (in all scenarios), especially in the dry period. In the wet period, water levels in both Sev-Dgr and Mod-Dgr at monitoring point 2 were mostly above the peat surface (>95% of the time).

The scenarios with bunds had higher dry season water levels than the scenarios without bunds. The water-level responses to bunding were different behind and in front of the bund. Behind the bund (monitoring point 2), in the scenarios involving bunds, water levels were above the peatland surface in the dry periods of the La Niña and Neutral years. At point 2, the Combined and Bunded scenarios resulted in higher dry season water levels than the Control scenario, in which the largest differences were 72 cm (in Mod-Dgr) and 69 cm (in Sev-Dgr), for day 272 of the simulated El Niño period. In the wet period, at point 2, the water levels in the Combined and Bunded scenarios were 30–35 cm higher than in the Control scenario. At point 2, there was no difference in the water-level pattern between the Dammed and Control scenarios across seasons. In front of the bund (monitoring point 1), the water levels in the Dammed and Bunded scenarios were similar to those for the Control scenario (fewer than 5 cm difference, see Figure 5a,c), but the water level for the Combined scenario was unique. In the dry periods of the La Niña and Neutral years, peatland water-table depths at point 1 in the Control scenario were deep (up to 74 cm in Mod-Dgr and 59 cm in Sev-Dgr), but those in the Combined scenario were shallower (up to 45 cm in Mod-Dgr and 50 cm in Sev-Dgr). In the Early Wet period, at point 1, the water level in the Dammed scenario rose for 20 days in Sev-Dgr and 30 days in Mod-Dgr, faster than in the Control scenario, and also the green dashed lines were not overlayed on the red dotted lines during this period (see Figure 5a,c).

There were different water-level patterns across the three ENSO conditions. In the modelled La Niña year of 2011, all water tables were shallower than the 40-cm depth limit, except around the ditches (e.g. monitoring point 1) for a part of the Late Dry period (for 50 days in Sev-Dgr and 70 days in Mod-Dgr). The La Niña water-level profiles show clearly that the supplied rainfall maintained water levels above

TABLE 2 DigiBog_Hydro model boundary conditions for different scenarios

	Modelling periods			
Scenarios	**Late Wet**	**Early Dry**	**Late Dry**	**Early Wet**
With ditch-dams				
WL at all d1 cells (outlet segment)	189	132	101	165
WL at all d2 and d4 cells (upstream of Dam 1 and Dam 4)	195	137	110	187
WL at all d3 cells (upstream of Dam 2 and Dam 3)	198	141	116	198
Without ditch-dams				
All ditches WL	128	96	49	118

Note: All boundaries are Dirichlet cells, and the boundary water levels (WL) are measured in cm above the impermeable base of the 200-cm peat profile. The ditch locations are shown in Figure 4.

TABLE 3 Basic statistics of the modelled scenario outputs

Results	Modelling periods			
	Late Wet	Early Dry	Late Dry	Early Wet
Average WL (with SD) in an El Niño year (cm)				
In moderately degraded scenarios (cm)				
Combined at Point 1	−4.0 (1.4)	6.1 (10.4)	74.1 (31.1)	19.0 (26.7)
Combined at Point 2	−35.2 (1.0)	−30.4 (5.5)	6.5 (18.2)	−22.9 (13.6)
Dammed at Point 1	−4.0 (1.4)	14.2 (16.1)	96.1 (32.2)	28.4 (33.7)
Dammed at Point 2	−4.4 (0.8)	2.0 (8.1)	62.5 (26.5)	12.4 (22.2)
Bunded at Point 1	−2.5 (3.4)	14.2 (16.2)	97.9 (33.3)	34.5 (34.4)
Bunded at Point 2	−35.2 (1.0)	−30.4 (5.5)	6.6 (18.2)	−22.9 (13.6)
Control at Point 1	−2.5 (3.4)	15.2 (16.9)	102.3 (33.9)	37.7 (35.6)
Control at Point 2	−4.4 (0.8)	2.0 (8.1)	62.6 (26.5)	12.5 (22.2)
In severely degraded scenarios (cm)				
Combined at Point 1	0.5 (4.6)	9.4 (6.2)	76.8 (33.3)	32.1 (25.3)
Combined at Point 2	−34.9 (1.2)	−28.4 (7.2)	19.8 (21.6)	−8.4 (20.2)
Dammed at Point 1	0.5 (4.6)	27.9 (16.3)	116.5 (37.5)	48.7 (37.7)
Dammed at Point 2	−4.2 (1.0)	4.4 (10.2)	69.6 (28.5)	28.7 (25.3)
Bunded at Point 1	8.3 (7.6)	27.4 (15.2)	115.7 (38.8)	59.1 (37.4)
Bunded at Point 2	−34.9 (1.3)	−28.4 (7.3)	20.9 (22.0)	−7.6 (20.6)
Control at Point 1	8.4 (7.7)	28.6 (17.0)	124.7 (39.9)	67.0 (38.3)
Control at Point 2	−4.2 (1.0)	4.3 (10.1)	69.5 (28.4)	28.7 (25.2)
Average deep water-table days (with SD) during the dry periods (total 183 days) in an El Niño year				
In the area in front of bunds in moderately degraded scenarios (days)				
Combined	—		97.0 (6.6)	
Dammed	—		106.3 (9.8)	
Bunded	—		109.8 (22.2)	
Control	—		112.5 (21.5)	
In the area behind the bunds in moderately degraded scenarios (days)				
Combined	—		72.4 (4.3)	
Dammed	—		102.7 (5.2)	
Bunded	—		73.2 (5.6)	
Control	—		102.6 (5.2)	
In the area in front of bunds in severely degraded scenarios (days)				
Combined	—		88.1 (10.2)	
Dammed	—		92.6 (7.0)	
Bunded	—		93.1 (19.9)	
Control	—		96.0 (17.7)	
In the area behind the bunds in severely degraded scenarios (days)				
Combined	—		20.1 (2.5)	
Dammed	—		90.0 (0.0)	
Bunded	—		20.7 (2.6)	
Control	—		90.0 (0.0)	

Note: The water levels (WL) are measured in cm from the peat surface, in which negative values indicate those above the peat surface. The standard deviation (SD) is included for each mean value.

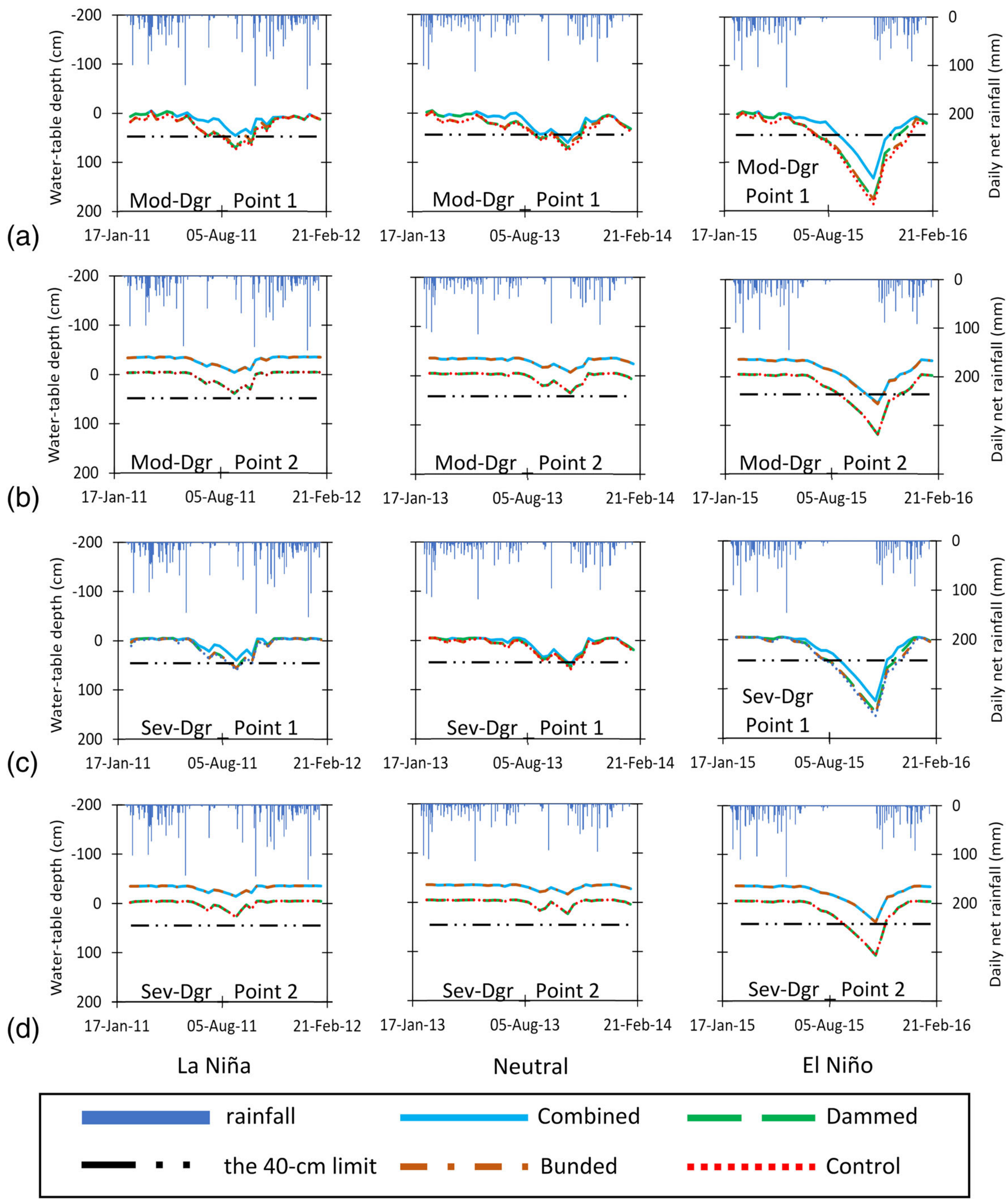

FIGURE 5 Water-table depth time series for different modelled scenarios

the 40-cm limit, despite the drainage effect of the ditches. The Neutral year of 2013 resulted in similar water-level profiles to the La Niña year, but with fewer fluctuations during the dry periods. There was also a decrease in water level at the end of the Neutral year, which was not found in the La Niña year. The El Niño year of 2015 resulted in the steepest water-level decrease in the Late Dry period. The water-level fluctuation in the period without rain (1 August to 30 October 2015) was not distinct. The El Niño year resulted in large water-level recoveries after rainfall events in the Early Wet period, such as at monitoring point 1 (up to 150 cm in Sev-Dgr and 185 cm in Mod-Dgr compared with the condition at the beginning of the Early Dry period).

3.2 | Spatial water-level profiles

Figure 6 presents the performance of the different restoration measures during the Late Dry and Early Wet periods. The performance is based on the accumulated number of deep water-table days during those periods, defined as days when the water table is deeper than

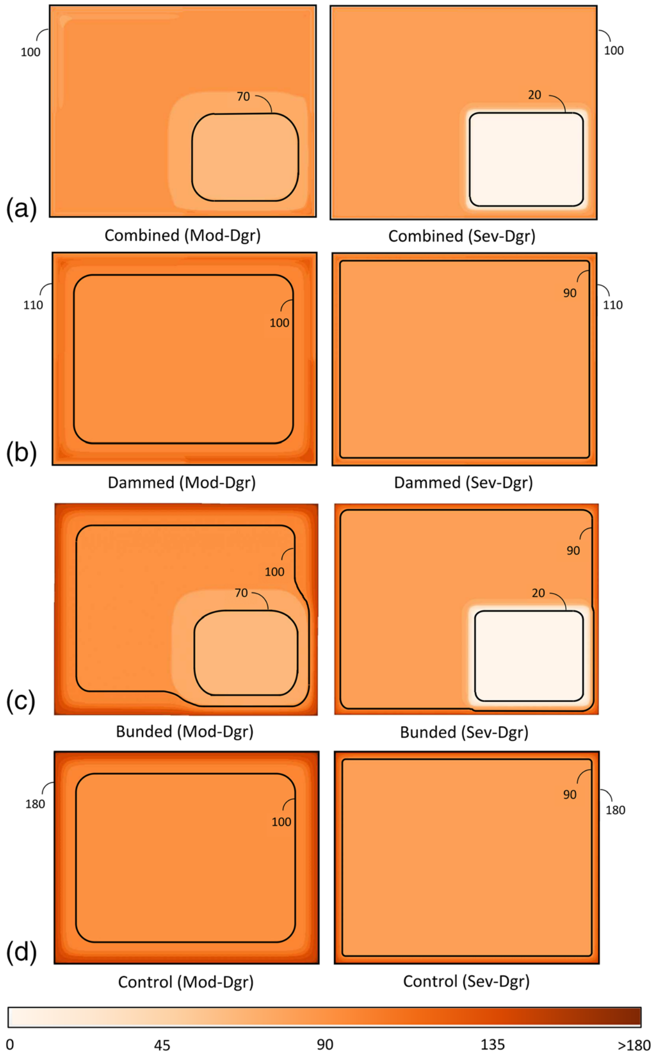

FIGURE 6 Spatial variations in the accumulated number of deep water-table days during the Late Dry and Early Wet periods (total 183 days) in an El Niño year. The spectral scale bar and contours represent the number of days in which the water table at a certain point in the peatland is deeper than 40 cm from the surface

40 cm from the ground surface. The spatial variations of deep water-table days presented in Figure 6 are only for the Late Dry and Early Wet periods, as the water levels were above the 40-cm depth policy limit in the Late Wet and Early Dry periods. Figure 7 shows a typical water-level surface profile from each restoration scenario for day 232 of the simulation, an ordinary no-rain day within the Late Dry period.

The ditch drainage effect in lowering peatland water levels was more intense in Mod-Dgr than in Sev-Dgr. In Mod-Dgr, the zone with the intense drainage effect (>90 deep water-table days) was within 26 m of the ditch (see Figure 6). The intensely drained zone was just within 12 m of the ditch in Sev-Dgr. The number of days with deep water tables in Mod-Dgr was more than for Sev-Dgr (see Table 3). The water-table profile for a modelled dry day shows that the slope of the water-level in the area near the ditches was steeper in Sev-Dgr than in Mod-Dgr (see Figure 7). The water level at points distant from dams, bunds and ditches, had a relatively flat profile (fewer than 5 cm water-level difference).

The number of days with a deep water table in the Dammed scenario was fewer than for the Control scenario; this was true for all model cells. For both the Dammed and Control scenarios, there were more deep water-table days near ditches than elsewhere in the peat plot (Figure 6). In the Dammed scenario, there were slightly more deep-water table days around ditches near the peat plot outlet (d1) than around ditches farther from the outlet (d3) (the differences were up to 10 days in Sev-Dgr and 20 days in Mod-Dgr). By contrast, in the Control scenario, deep water-table days were similar within the area around all ditches, which were around 130 days in Mod-Dgr and 160 days in Sev-Dgr. On day 232, a typical dry day of the El Niño Year (Figure 7), the water level within 26 m of the ditches in the Dammed scenario was higher than that in the Control scenario (e.g. it was 40 cm higher at point $x = 50$ m and $y = 1$ m). However, on that example dry day, the water levels at points farther than 26 m from ditches in both the Dammed and Control scenarios were almost the same (approximately 60 cm below peat surface at the centre of the peat plot).

In the Bunded scenario, the bund reduced deep water-table days in the area behind the bund by 70 days in Sev-Dgr and 30 days in Mod-Dgr compared with the Control scenario (see Table 3). The bunded area also supplied water to the surrounding zone, in which the supplied area was wider in Mod-Dgr than in Sev-Dgr (29% compared with 24% of the total area during the dry period of an El Niño year, see Figure 6a,c). However, the bund did not reduce deep water-table days in the area near the ditches, as the number of days were similar for the Bunded and Control scenarios. The slope of the water table near bunds in Sev-Dgr was sharper than the one in Mod-Dgr (Figure 7c). The Combined scenario had the fewest deep water-table days among the scenarios (see Table 3). Locations with deep water-level days did not exist during the Late Wet and Early Dry periods of the El Niño year in the Combined scenario, either in Mod-Dgr or in Sev-Dgr, except in areas near ditches. In the Combined scenario, deep water-table days for the non-bunded area were more than for the bunded area (between 88 and 97 days compared with between 20 and 72 days), during the Late Dry and Early Wet periods (total 183 days) of the 2015 El Niño year.

3.3 | The performance of the different bund types

Figure 8 shows that bund types perform differently in maintaining water level on drained tropical peatland. The subtraction of the water-table depths of the Extended bund scenario from the Surface bund scenario is referred to here as *wt-diff*. As is to be expected, the *wt-diff* values were higher in the bunded area (monitoring point 2) than for any points outside the bunded area (e.g. monitoring point 1). Overall, the time series graphs of *wt-diff* were similar between the Bunded and Combined scenarios. The *wt-diff* in the El Niño year was greater than in the La Niña or Neutral years, which was up to 20 cm in Mod-Dgr or 10 cm in Sev-Dgr during the dry period.

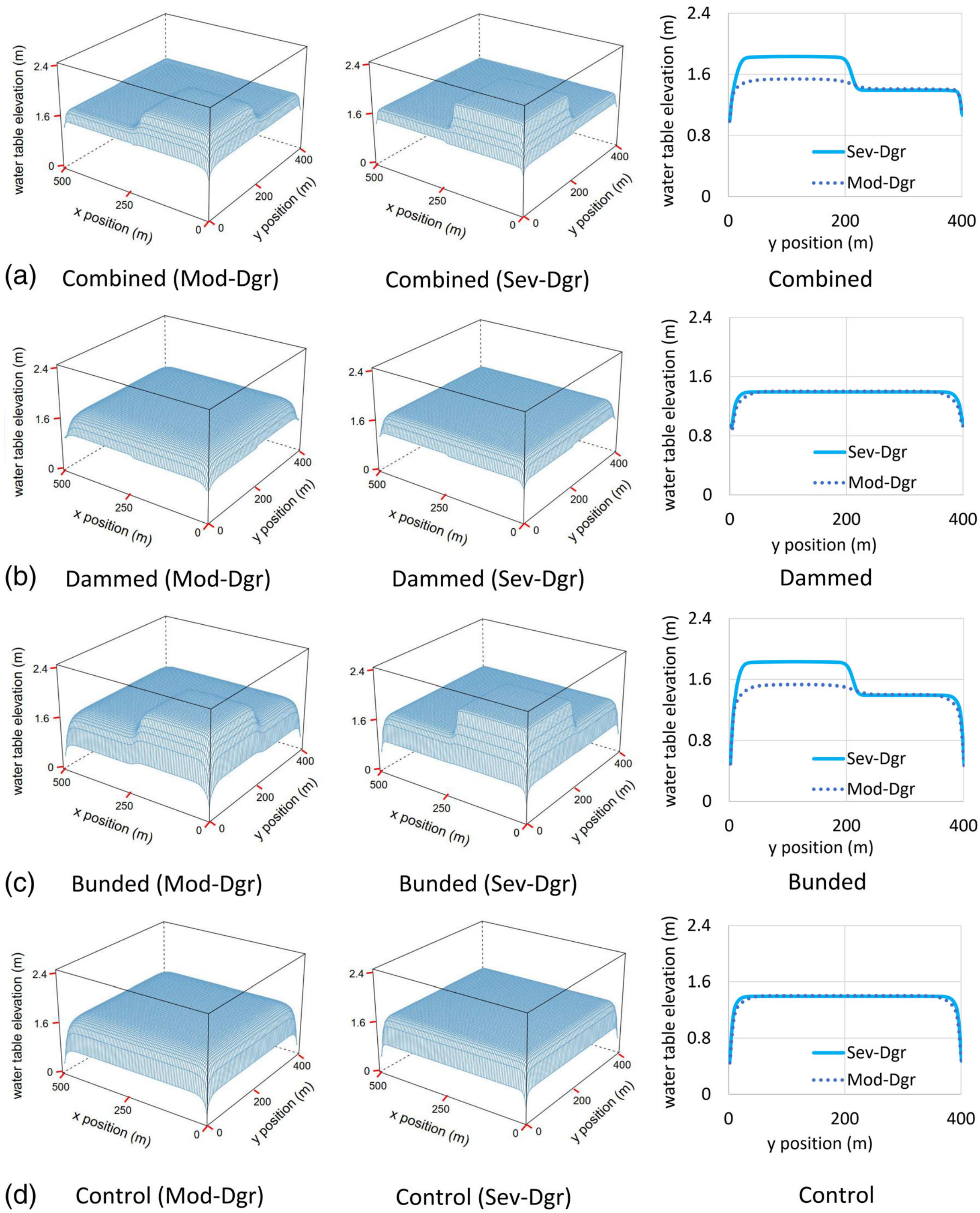

FIGURE 7 Three and two-dimensional spatial water-table profiles on different peatland conditions during the Late Dry period of the El Niño year (day 232 of the simulation). The two-dimensional profiles are taken at cross section C–C′, which is along the line of $x = 50$ m

In Sev-Dgr, at monitoring point 2, the *wt-diff* values were fewer than 20 cm across seasons. The *wt-diff* became larger towards the end of the Late Dry period, before it receded towards zero when more rainfall occurred during the Early Wet period. Nevertheless, in Sev-Dgr, the *wt-diff* fluctuations were not simply related to rainfall patterns. The maximum *wt-diff* values decreased by about 9 cm in 10–15 days after a series of rainfall events occurred in the Early Wet period (see Figure 8c). In Sev-Dgr, during the La Niña or Neutral years, the *wt-diff* recession occurred only during the final phase of the Late Dry period. By contrast, during the El Niño year, the *wt-diff* recession lasted from the Late Dry period to almost the end of the Early Wet period.

In Mod-Dgr, in the bunded area, the first and third quartiles of *wt-diff* were around 10 to 25 cm in the La Niña year, 15 to 30 cm in the Neutral year, and 5 to 35 cm in the El Niño year. The maximum *wt-diff* value was 45 cm, occurring during the Late Dry period of the

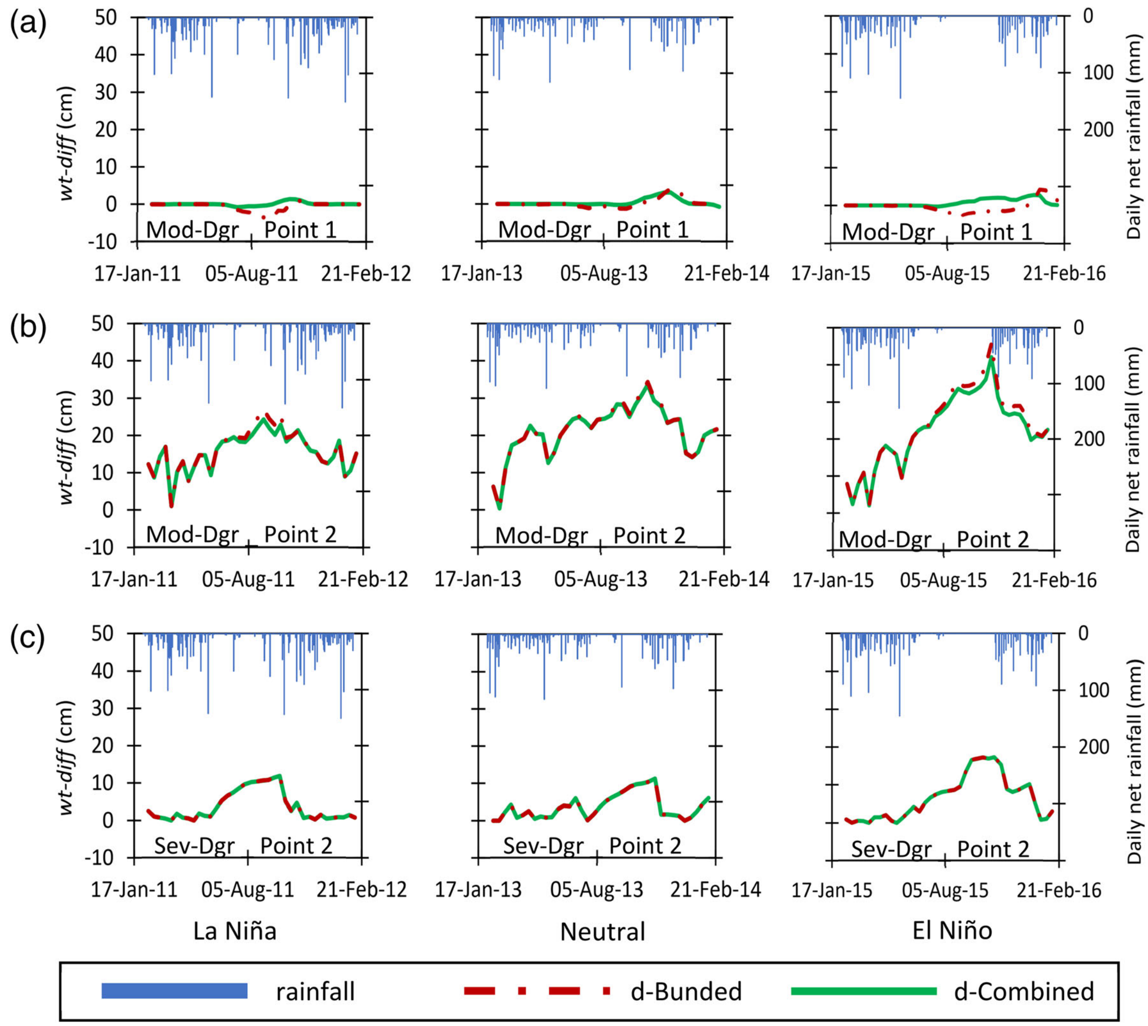

FIGURE 8 Differences in water-table depths between the Extended bund and the Surface bund scenarios (*wt-diff*). The negative values indicate that the water table of the Extended bunds scenario was deeper than that of the Surface bunds scenario. The red dashed lines (d-Bunded) are results from the Bunded scenario. The green lines (d-Combined) are results from the Combined scenario

El Niño year. In Mod-Dgr, the low *wt-diff* values (near to zero) were found in the Late Wet period of all different climatic years, usually when the bunded area was inundated. In Mod-Dgr, the *wt-diff* increased during periods with fewer rainfall events (dry periods — Figure 8), but deceased when there were days with a daily net rainfall of at least 50 mm. In Mod-Dgr, the *wt-diff* values outside of the bunded area were close to zero (fewer than 5 cm) (see Figure 8a).

4 | DISCUSSION

4.1 | The effects of bunds and ditch dams on water levels

Bunds increase the amount of water that can be stored in a peatland during the wet season. They store surface water that would otherwise be lost as overland flow to the ditches. The stored water in the bunded area can then 'subsidize' the ET demand and replenish subsurface seepage losses to the ditches during the dry season.

Our modelling results suggest that bunds can be used as a promising restoration solution for maintaining higher water levels in formerly drained tropical peatlands during El Niño years. Considering the moderate to high permeability of peat in tropical peatlands (as reported by Baird et al. (2017), Cobb and Harvey (2019), and Kelly et al. (2014)), extra water storage is necessary in dry periods. Bunds would be best placed in the areas that have the most deep-water-table days, for example near the lowest outlet of the model peat plot. Bunds could be placed at another adjacent location, but the stored water would need to be channelled from the bunded areas to unbunded parts of a peatland if the latter become too dry (valved pipes could be fitted across the bunds for this purpose).

Choice of bund design (depth) must be related to peat degradation conditions. In Sev-Dgr, there is no need for extended bunds as the performance of both bund types was nearly the same. The similar performance was expected because the lower hydraulic conductivity of peat in Sev-Dgr reproduces the flow dampening effect of the extended bund. Several studies have confirmed that low hydraulic conductivity peat tends to trigger surface runoff and/or inundation rather than subsurface flow (Crockett et al., 2016; Holden et al., 2014; Rezanezhad et al., 2016). However, in Mod-Dgr, during the dry period in an El Niño year, the maximum *wt-diff* was nearly 50 cm, which suggests extended bunds should be used. The extended bunds also set longer paths for the water to flow from the bunded area to its surroundings, creating a longer water retention time (e.g. the sheet piling effect in peatland; Armstrong et al., 2009; Huth et al., 2020; Schimelpfenig et al., 2014).

Our findings show that ditch dams may boost bund performance, as the Combined scenario have the lowest number of deep water-table days in the non-bunded areas of the model peat plot. First, the ditch dams reduce water-level variations in the areas near the ditches (Kasih et al., 2016; Putra et al., 2021; Urzainki et al., 2020). Second, the dams minimize the hydraulic gradient between ditches and the peatland, as also indicated by several comparable studies in tropical (Planas-Clarke et al., 2020; Ritzema et al., 2014; Susilo, Yamamoto, Imai, Ishii, et al., 2013) or temperate peatlands (Evans et al., 2018; Holden et al., 2017; Peacock et al., 2015). Third, in the Early Wet period, the ditch dams raised the ditch water levels, reduced flow to the margin of the peat, and accelerated water refilling in the model plot. However, ditch dams by themselves will not be of great help in reducing the number of deep water-table days during an El Niño year, as the Dammed and the Control scenarios show (both had a similar low-water-level pattern).

The results indicate that bunds, when combined with ditch dams, perform well for the La Niña and Neutral years, but not so well during part of the dry period of the El Niño year. Enlarging the area which is bunded and perhaps increasing the bund height may enhance water storage and maintain water table during the dry period. For the Mod-Dgr peatland, the extension of the bund depth is an alternative to reduce water-table drawdowns in the bunded area, given that the Extended scenario performed better in maintaining water than the On-Surface one.

4.2 | Benefits of modelling water-table restoration

Hydrodynamic models, such as DigiBog_Hydro, can be used in advancing our understanding of tropical peatland water-level dynamics for different peat degradation and climatic conditions. We have shown how different ENSO conditions resulted in different water-level dynamics in a typical tropical peatland, a finding that was previously suggested by multi-year field studies from a few dipwells (Ishikura et al., 2017, 2018; Tsuji et al., 2019). Deep water-level conditions in a drained tropical peatland depend strongly on the dry season net rainfall rather than the total yearly net rainfall, in line with findings from other studies (Deshmukh et al., 2021; Mezbahuddin et al., 2015; Putra & Hayasaka, 2011; Ritzema et al., 2014). Our modelling approach could allow assessment of restoration plans under more extreme meteorological conditions, which are expected within future climate-change scenarios (see IPCC (2021)).

DigiBog_Hydro is similar to the model used by Urzainki et al. (2020), who investigated how canal dams affect peat water tables across larger scales than considered here. However, Urzainki et al. (2020) did not consider surface water storage and the role of bunds or dams within a peat-plot domain. Models such as Modflow may also be used to investigate peatland water-table behaviour (see Reeve et al. (2006) and Painter et al. (2008)), but can be difficult to apply to systems with fine-scale variations in near-surface peat properties and where the water-table is highly dynamic.

Our study provides a site-based water-level modelling approach for tropical peatland restoration planning and assessment, as an alternative to the water-level optimization approach (Urzainki et al., 2020) or the canal-slope based approach (Jaenicke et al., 2010). Unlike coarser-scale studies (Cobb & Harvey, 2019; Ishii et al., 2016; Jaenicke et al., 2010; Urzainki et al., 2020), our fine-scale study (1 m $\times$ 1 m cell resolution) allows investigation of water-level variations in areas near ditches and bunds, which is important when bunds are usually only 1–2 m in thickness. Our fine-scale approach can accommodate different ditch-dam and bund placements in a typical small peat plot (0.2 km^2) that cannot be set in coarse-scale studies. Our approach can also include variation of microtopography in typical small restoration plots, as demonstrated by the difference in the modelled surface elevation in the area behind and in front of the bunds. Thus, our modelling approach could be adopted by local agencies for tropical peatland restoration to support practical design of restoration features. In doing so, peatland managers would reduce the risk of putting in place ineffective restoration measures, an important concern when trying to maximize benefits from resources allocated to peatland restoration (Hansson & Dargusch, 2018; Ota et al., 2020; Parish et al., 2021; Sari et al., 2021). Nevertheless, our fine-scale study requires shorter modelling time steps (e.g. less than a minute), meaning more computational resources (e.g. for a comparable modelling area) compared with coarse-scale studies. In addition, empirical peat physical properties data, meteorological data and ditch/peatland water-level data are still limited in tropical peatland settings and would add value to fine-scale modelling studies (Deshmukh et al., 2021; Hoyt et al., 2019; Nguyen-Thi et al., 2021; Tsuji et al., 2021).

4.3 | Modelling limitations and further study

This research has not explored the overall effects of bunding on the ecosystem. The inundation on the bunded area may affect vegetation survival or recruitment of vegetation inside the bund (Jans et al., 2012; Lampela et al., 2016). This ecological constraint needs to be considered when determining the coverage of the bunded area in the peat plot. Inundation may also enhance methane release, and further research is required into such effects. In a place where more than 3 months of inundation on the bunded area is unacceptable, it is suggested to drain the storage of the bunded area in the wet period but allow it to fill fully at the beginning of the Early Dry period. Keeping the peatland sufficiently wet (Evers et al., 2017; Ismail et al., 2021) and maintaining peatland water tables near to the surface should reduce fire risk (Page et al., 2009; Wösten et al., 2006).

Given that the ET is strongly dependent on the water-table depth (Deshmukh et al., 2021; Hirano et al., 2015), the approximation of using fixed ET values for moderately and severely degraded peatlands in this study may not reflect the real condition. The scarcity of onsite ET measurements from the Sebangau tropical peatlands did not allow daily ET data to be included in the simulations for the associated ENSO years. Considering common seasonal ET variations in tropical peatlands (Ohkubo et al., 2021a, 2021b; Putra et al., 2021), our results may slightly overestimate water levels in the wet periods and underestimate them in the dry periods. We expect that daily ET will be higher in the bunded area when inundation occurred, which is perhaps similar to the wet period daily ET determined by Ohkubo et al. (2021a, 2021b).

DigiBog_Hydro model is sensitive to the value of the hydraulic conductivity and drainable porosity parameters (Baird et al., 2017; Young et al., 2017), and more field-based data from tropical peatlands are required on these properties to improve the robustness of hydrodynamic modelling experiments like those conducted in this study. Homogeneous peat layers and the assumption of a flat peat surface may not reflect real site conditions. Lateral variability of peat properties as a result of drainage and disturbances (e.g. fire) (Dhandapani et al., 2021; Sinclair et al., 2020) is to be expected and zones of bypassing flow (perhaps due to soil pipes) may occur in field conditions. Those factors should be evaluated in field studies and accounted for in model simulations.

While our study provides an insight into the potential benefits of bunding on drained tropical peatlands, it is important to understand whether local communities can implement such practices. In Sebangau, the arrangement of agricultural ridges (acting as bunds) could be converted from parallel rows (e.g. with 2 m intervals) to rectangular grids (e.g. with 10 m intervals), while still allowing agricultural practice. In order to minimize disturbances to farming activities on the ridges by higher water levels, ridge height could be increased or plants that are more resilient to high water-table conditions could be planted (Budiman et al., 2020; Tan et al., 2021; Uda et al., 2020). In temperate agricultural peatlands, the same problem exists and trials with waterlogging-tolerant crops and cost-effective paludiculture practices are ongoing (e.g. see Tanneberger et al. (2020)). Thus, further work is required on the physical arrangement of bunding solutions and the related socio-economic requirements for agricultural production.

5 | CONCLUSIONS

This article demonstrates the use of a hydrodynamic model (DigiBog_Hydro) depicting tropical peatland water-level dynamics over fine spatial scales. By incorporating information on peat properties, net rainfall and ditch water levels, DigiBog_Hydro can be used to plan restoration infrastructure before it is installed in the field, or to assess existing restoration arrangements. The installation of bunds and ditch dams allowed more water storage in a typical drained tropical peat plot during dry periods compared with conditions without restoration. Ditch dams alone reduced hydraulic gradients in the zone up to 26 m from the ditches but had a limited effect on peatland water levels during the dry season. In such dry periods, bunds were not only able to maintain a higher water level for the area enclosed by the bund, but also supplied water to surrounding un-bunded parts of the peatland. The existence of ditch dams and bunds, as well as the type of bunds used, influenced how long water tables took to recover during the early part of the wet season. However, the performance of either ditch dams or bunds depends on the degree of peat degradation (peat hydrological properties) and seasonal weather patterns (net rainfall supply). Our results strongly suggest that the construction of bunds in combination with ditch dams would be beneficial when restoring drained tropical peatlands under different ENSO conditions.

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DATA AVAILABILITY STATEMENT

The inputs, settings, and outputs of the model that are presented in this study are available via the University of Leeds data repository under Creative Commons BY-NC 4.0 Licence (https://doi.org/10.5518/1053).

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SUPPORTING INFORMATION

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