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First Measurements of Saturated Hydraulic Conductivity From Peats of the Central Congo Basin

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ABSTRACT

The peat swamp forests of the central Congo Basin represent the largest, most carbon-rich peatland complex in the tropics. The maintenance of peat carbon stocks and accumulation relies on persistent soil saturation, yet the hydrological functions of tropical peatlands remain poorly understood, particularly in the central Congo Basin. We report the first measurements of saturated hydraulic conductivity (K_{sat}) from Congolese peats. We used Mini Disk tension infiltrometers to estimate K_{sat} at depths of 0 and 10 cm across three study areas in the Democratic Republic of the Congo. K_{sat} ranged from 1.55×10^{-5} to 5.75×10^{-4} m s^{-1}, with a mean of 1.78×10^{-4} m s^{-1}. A general linear model revealed significantly higher K_{sat} at the surface than at 10 cm depth, while K_{sat} is negatively related to degree of peat humification. However, K_{sat} did not vary between palm, hardwood and mixed forest types, or with proximity to rivers (a proxy for flooding regime). Although our linear model is not sufficiently skilful to predict K_{sat} reliably, our findings suggest that a generalisable model for tropical peat K_{sat} may be attainable with larger datasets that span greater ranges of depths and levels of decomposition. Notably, our surface K_{sat} values are lower than those from deeper layers in Southeast Asia and the Americas, implying lower depth-integrated permeability in peats of the central Congo Basin. This may reflect low rainfall and deeper water tables in the region, which would enhance decomposition and reduce pore space more rapidly.

1 | Introduction

The peat swamp forests of the central Congo Basin (CCB), only recently mapped in detail, comprise the largest and most carbon-rich tropical peat complex in the world (Dargie et al. 2017; Crezee et al. 2022). They are thought to cover ~167 000 km^2 and store ~29 billion tonnes of peat carbon, equivalent to 28% of the total tropical peat carbon store (Crezee et al. 2022). Peatlands are characterised by waterlogged, anoxic soil conditions, which allow carbon-rich peat to accumulate. Peatland ecosystem functions and services are tightly coupled to water availability, such that even modest reductions in surface wetness and/or length of inundation during wet seasons can lead to large increases in peat decomposition and CO_2 efflux (Couwenberg et al. 2010). Congolese peatlands exist in a drier climate than those in Southeast Asia and Central and South America (Garcin et al. 2022) and are thus particularly sensitive to drought. Two recent studies showed how an extended period of climatic drying that culminated approximately 2000 years ago led to large losses of carbon through peat oxidation (Garcin et al. 2022;

Young et al. 2023). As such, Congolese peatlands appear to be close to the edge of the hydroclimatic envelope that can support peat accumulation (Garcin et al. 2022). Aside from soil carbon storage, tropical peatlands are biodiverse habitats (e.g., Posa et al. 2011; Beekman et al. 2024). Congolese peatlands also support the livelihoods of local communities, acting as sources of timber and as important hunting, fishing and foraging grounds (Campbell 2005; Biddulph et al. 2021). Compared to northern peatlands, relatively little is known about hydrological processes and structures in tropical peatlands, particularly in the CCB, hindering their meaningful representation in Earth system and ecosystem models and thus projections of their likely future fate under changing climates.

Saturated hydraulic conductivity, K_{sat}, is one of the most important properties in determining the hydrological behaviour of peatlands. Where hydraulic gradients are steep, such as close to riverbanks, low K_{sat} in deep peat plays a potentially important role in limiting lateral drainage, thereby allowing a domed peat surface to form (cf. Davenport et al. 2020), and thick, carbon-rich peat to accumulate. Saturated hydraulic conductivity also defines the upper limit of unsaturated hydraulic conductivity and therefore plays an important role in determining surface-atmosphere evaporative exchanges and transport of water to roots for transpiration. Although studies remain limited, existing research on tropical peatlands in Southeast Asia and Central and South America suggests that K_{sat} values fall within a similar, albeit somewhat narrower, range (10^{-8} to 10^{-2} m s^{-1}; Dommain et al. 2010) compared to those observed in northern peatlands (10^{-10} to 10^{-1} m s^{-1}; Morris et al. 2022).

In some tropical peatlands, K_{sat} is thought to decrease with increasing depth, meaning that the greatest flows are concentrated in upper peat layers (Takahashi and Yonetani 1997; Kelly et al. 2014; Kurnianto et al. 2016, 2019; Ghimire et al. 2018). However, in some sites this depth trend in K_{sat} is less clear, or is absent entirely (e.g., Kelly et al. 2014; Kurnianto et al. 2019). Cobb et al. (2017) and Cobb and Harvey (2019) hypothesised that K_{sat} increases exponentially with proximity to the surface and that surficial values as high as 1.5×10^{-2} m s^{-1} are required to explain the morphometry and water-table behaviour of a domed tropical peatland in Brunei. Their hypothesis is currently untested with surficial or near-surface measurements; the shallowest reported measurements of K_{sat} in tropical peatlands are from 50 cm depth (e.g., Kelly et al. 2014; Ghimire et al. 2018). Peat K_{sat} also declines with increasing degree of humification (Wösten et al. 2008; Kurnianto et al. 2019), as decomposition weakens peat fibres, causing pores to collapse, reducing total porosity and breaking interconnections between pores (e.g., McCarter et al. 2020). There is a limited amount of evidence that tropical peat K_{sat} also varies with peat floristic composition (Baird et al. 2017; Kurnianto et al. 2019). To our knowledge, no previous study has reported hydraulic properties of CCB peatlands.

Our aim was to quantify K_{sat} in shallow peat layers of the central Congo Basin. We also sought to investigate potential relationships between K_{sat} and other, more readily measurable peat properties. To this end, we collected surficial and near-surface K_{sat} measurements from a range of peatland sites across the central Congo Basin during a field campaign conducted as part of the broader CongoPeat project (see https://congopeat.net/). We then assessed the feasibility of developing predictive equations for K_{sat} using independent variables such as depth, degree of peat humification and forest type.

2 | Methods

2.1 | Study Sites and Sampling Design

We conducted fieldwork between June and August 2019, at three peatland sites in Équateur Province, Democratic Republic of the Congo (DRC). We refer to the three sites informally as Mpeka, Bolengo and Bondamba after nearby settlements. The Mpeka site is alongside the Ruki River, a blackwater, left-bank tributary of the Congo River, while the Bolengo and Bondamba sites are on opposing banks of the Busira River, a blackwater tributary of the Ruki (Figure 1) (see also Drake et al. 2023). All three peatland sites are river-influenced according to the classification of Crezee et al. (2022) (in the case of Mpeka, see also Georgiou et al. 2023). At Mpeka and Bondamba, we established transects running perpendicularly from the riverbank through peat swamp and seasonally flooded forest, along which we took regularly spaced measurements. Where our sampling locations fall within non-peat forming forest, we omit the K_{sat} data from our analysis since our research questions concern peat and not mineral soils. At the third site, Bolengo, we took measurements at a single sampling site rather than along a transect.

The Mpeka transect (start: 0.19051° S, 18.85268° E; end: 0.13482° S, 18.92314° E) is located on the right bank of the Ruki, approximately 85 km upstream of Mbandaka, the provincial capital of Équateur. The transect starts at the riverbank in non-peat-forming, seasonally flooded forest and extends 10 km inland in an approximately north-easterly direction. Peat begins at 1.25 km along the transect, beyond which the forest alternates between palm swamp and hardwood swamp. The palm swamp is initially dominated by the *Raphia sese* palm, but after 2.25 km *Raphia laurentii* becomes the dominant palm and remains common even in the hardwood swamp. No single taxon dominates the hardwood swamp, but the most common species are *Cryptosepalum congolanum*, *Baphia* sp., *Entandrophragma palustre*, *Uapaca corbisieri*, *Carapa procera*, *Guibourtia demeusei* and *Prioria oxyphylla*. Peat depth along the transect reaches a maximum of 6.0 m at 9.75 km (see Figure S1). At the time of our visit, at the height of the dry season, the peat in this transect was relatively dry, with water tables as deep as 50 cm below the surface in some locations.

The Bondamba transect (start: 0.23537° S, 19.68548° E; end: 0.17344° S, 19.69599° E) is located on the right bank of the Busira River, approximately 210 km upstream of Mbandaka. The transect starts close to what appears to be an old, slowly infilling meander of the Busira River, in an area of non-peat-forming, seasonally flooded forest and extends 7 km in an approximately north-by-northeasterly direction. After 500 m, the transect enters the peatland, briefly traversing an area of hardwood swamp forest, before transitioning after 1 km into a monodominant *Raphia laurentii* palm swamp forest. This monodominance persists for most of the rest of the transect, although by 7 km the forest becomes more mixed with hardwood species such as *Cryptosepalum congolanum* starting to appear.

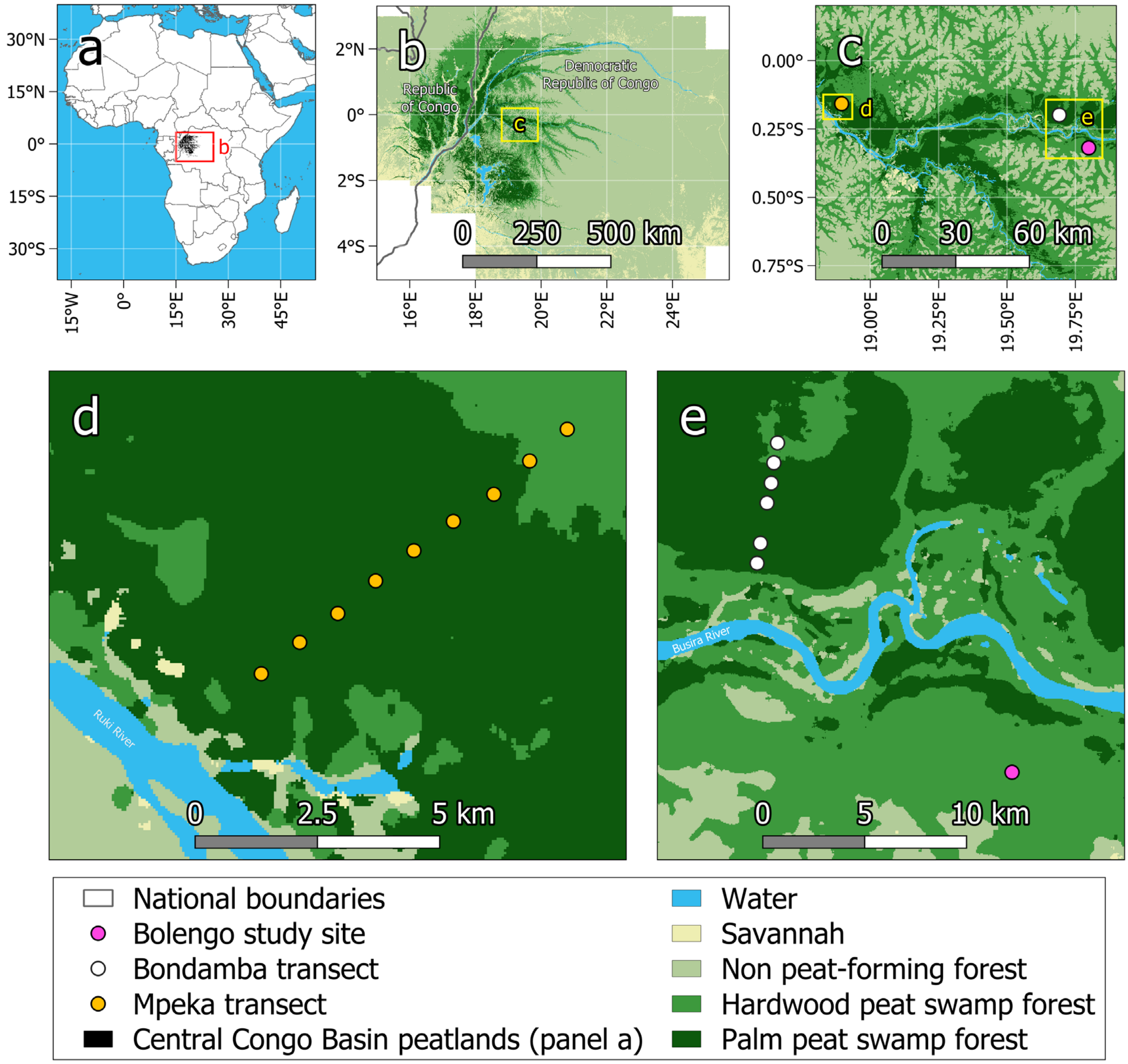

FIGURE 1 | Sampling locations. Land cover classes in all panels are the most likely classifications determined by Crezee et al. (2022) at 50 m resolution, smoothed with a 7 × 7 window; peat extent in (a) is the combined extent of the hardwood and palm peat swamp forest classes. Red and yellow bounding boxes indicate spatial extents of smaller-scale panels.

Maximum peat depth is 6.4 m at 6.5 km along the transect (see Figure S1). Like Mpeka, we visited Bondamba during the height of the dry season and found the palm-dominated swamp there to be particularly dry, with water tables as deep as 40 cm below the surface.

The Bolengo study site (0.31869° S, 19.79940° E) is located 4 km south-west from the left bank of the Busira River, approximately 220 km upstream of Mbandaka and 10 km upstream from the start of the Bondamba transect. The study location is in hardwood swamp forest dominated by *Coelocaryon botryoides*. At the time of our visit, conditions underfoot were less dry than in the Mpeka and Bondamba transects, with water tables typically no more than 20 cm below the ground surface.

At every 1 km along the Mpeka and Bondamba transects we conducted four replicate K_{sat} measurements at the peat surface within a few metres of one another, using tension infiltrometers; we also measured K_{sat} at 10 cm depth every 2 km. At the Bolengo site we conducted three replicate K_{sat} measurements at the surface, again within a few metres of one another. In some sampling locations, high water levels precluded subsurface—and occasionally surface—measurements. Locations with usable K_{sat} data are shown in Figure 1. For both depths, we selected sampling locations with minimal understory vegetation and away from major tree roots. Prior to surficial K_{sat} determinations we cleared surface litter to create a level platform and ensure a wetted contact between the infiltrometer and the peat. For subsurface measurements at 10 cm depth, we used a hand trowel to carefully excavate a flat sill of peat to seat the instrument upon.

2.2 | Hydraulic Conductivity Determinations

We measured K_{sat} using METER Group (formerly Decagon) Mini Disk tension infiltrometers configured as shown in

Figure S2. The tension at which infiltration takes place is set by adjusting the position of the suction control tube. Typically, we used five water-supply pressure heads (φ) for each infiltrometer position: −6 cm, −3 cm, −1.5 cm, −0.5 cm and 0 cm of water. The manufacturer's manual (https://metergroup.com/products/mini-disk-infiltrometer/) suggests that the smallest tension that can be set using the tube is 0.5 cm (i.e., a pressure head of −0.5 cm). However, by pulling the suction control tube free of the water in the bubble chamber, a pressure head of 0 cm is applied. Doing so is standard practice in other designs of tension infiltrometer (e.g., Baird 1997). At each supply head we ran the test until the flow rate from the water reservoir was steady. We used the heads in ascending order (i.e., starting at −6 cm), which eliminated possible hysteresis effects caused by drainage occurring close to the disk, while wetting continued near and at the infiltration front. An ascending order also meant that steady-state conditions were established more quickly for each head. We used the method of Reynolds and Elrick (1991) (see also Baird 1997) to analyse the data and obtain values of both unsaturated hydraulic conductivity (K_{unsat}) and K_{sat}, although only the latter are considered here. Specifically, we made the calculations in Steps 1–4 given at the end of the section entitled 'Steady Tension Infiltration from a Surface Disk' in Reynolds and Elrick (1991) (see also Baird 1997). The method assumes that the relationship between hydraulic conductivity (K) and φ is piece-wise exponential but makes no assumptions about the overall shape of the K(φ) relationship. Infiltration rates should increase as ever-greater supply heads are used. If infiltration rates remained the same or decreased between supply heads, we took this to indicate a problem with the test and discarded those measurements. This led to 16 measurements being discarded, out of 89 that we attempted. It is unclear why discharge did not increase monotonically in these 16 tests, but possibilities include a poor contact between the instrument and the peat surface and invertebrate activity in the peat.

The footprint of the Mini Disk tension infiltrometer is relatively small. The disk has a diameter of 4.4 cm, so the volume of soil being sampled in each test is also quite small—like that of a laboratory permeameter—and may be below the representative elementary volume (see discussion in Beckwith et al. 2003). To some extent this problem can be mitigated by making numerous measurements, which we did. Nevertheless, it should be borne in mind when interpreting the results. We did not, however, observe obvious surface heterogeneity or possible zones of enhanced macropore flow at scales of 10 s cm, away from the major tree roots that we avoided (see above, Section 2.1).

2.3 | Peat Humification

At each sampling location, we conducted the von Post hand-squeeze test (Ekono Inc 1981) to estimate the degree of peat humification. The von Post scale assigns a humification score (H-score) ranging from H1 (fresh, undecomposed plant material) to H10 (black, amorphous peat with no visible plant remains). Following each K_{sat} measurement, we collected approximately 5 cm^3 of peat from the surface beneath the infiltrometer and used this for the humification assessment. To minimise observer drift, we referred to a printed copy of the scale before and after each test.

2.4 | Data Analysis

We analysed our data using linear models, fitted with the *lm* function in R (R Core Team 2024) and the *lmer* function from the R package *lme4* (Bates et al. 2015). Because K_{sat} was highly positively skewed, we applied a $\log_{10}$ transformation prior to modelling. We tested various combinations of independent variables, including continuous covariates such as von Post H-score and distance from the river and categorical predictors such as depth and forest type. Although the von Post H-score is strictly ordinal, we treated it as continuous, following the rationale of Morris et al. (2019). Conversely, although depth is measured on a continuous scale, our depth measurements are highly bounded, with only two possible values (0 and 10 cm), so we treated depth as a categorical predictor. We classified the forest type at each measurement location into one of three categories—hardwood, palm or mixed—based on field observations. We experimented with random intercepts to account for pseudoreplication within our sampling design. We tried random intercepts with study site (Bolengo, Bondamba, Mpeka) as the subject; and with sampling location as the subject, nested within study site. To assess the suitability of each variable for inclusion in our model, we used the *aictab* function from the R package *AICcmodavg* (Mazerolle 2023) to compare corrected Akaike Information Criterion (AICc) (Hurvich and Tsai 1989) values between models with and without each variable. We interpreted the change in AICc as a Chi-squared statistic, with degrees of freedom equal to the change in the number of model parameters. We considered variables that increased AICc or produced non-significant reductions to represent overfitting and so omitted them. We also calculated variance inflation factors (VIFs) using the *vif* function from the R package *DescTools* (Signorell 2023); we interpret VIF values exceeding $\sqrt{5}$ as indicators of problematic multicollinearity (cf. Morris et al. 2022). Once we had decided on the final model specification, we analysed it with the *Anova* function from the R package *car* (Fox and Weisberg 2019) using Type-III sum of squares.

3 | Results

Our dataset comprises 73 measurements of K_{sat}, which range between 1.55×10^{-5} and 5.75×10^{-4} m s^{-1} (Figure 2). Measured marginal mean K_{sat} at the surface (2.05×10^{-4} m s^{-1}) is nearly double that at 10 cm depth (1.13×10^{-4} m s^{-1}), while the median at the surface (2.03×10^{-4} m s^{-1}) is more than four times that at 10 cm (4.64×10^{-5} m s^{-1}) (Figure 2a). Von Post H-scores range between H2 and H6 and are significantly greater at 10 cm depth than at the surface (two-sample, unpaired t-test, $p < 0.001$; Figure 3). K_{sat} generally declines with increasing von Post H-score, albeit not monotonically: H2 has slightly lower measured marginal mean K_{sat} than H3 (Figure 2b). K_{sat} differs little between palm and hardwood swamp forest types and is slightly higher for mixed swamp forest (Figure 4a). No clear trend is evident in K_{sat} with distance from the river (Figure 4b). Our samples come mainly from peat beneath palm swamp forest (47/73 measurements), with relatively few from hardwood (15/73) or

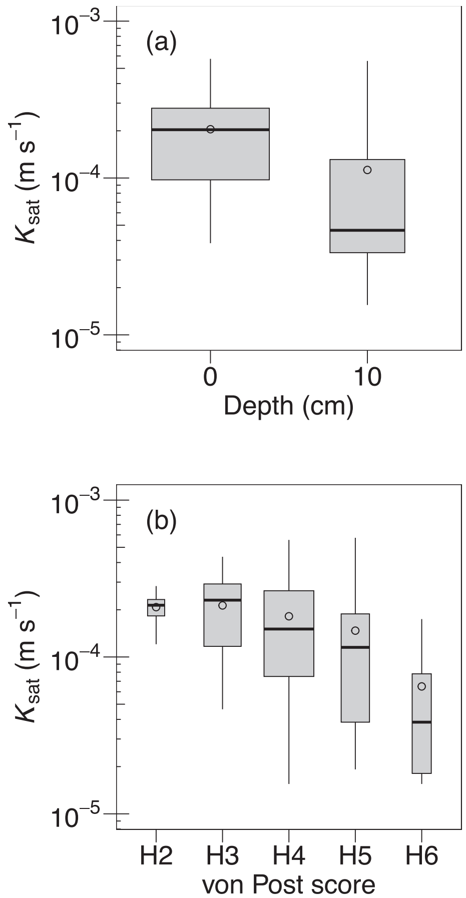

FIGURE 2 | Boxplots showing K_{sat} against (a) depth and (b) von Post H-score. Note log-scale on vertical axes. Box hinges indicate upper and lower quartiles; heavy lines indicate medians; open circles indicate arithmetic means; whiskers extend to sample maxima and minima. Box widths are proportional to the square root of sample size. In our linear model, the effect of depth upon $\log_{10}(K_{sat})$ is highly significant ($p<0.001$); while von Post H-score, which is treated as a continuous variable, is marginally significant ($p=0.040$).

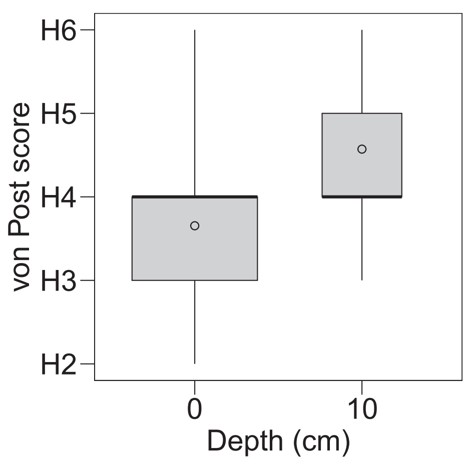

FIGURE 3 | Boxplot showing von Post H-scores against depth. Box hinges indicate upper and lower quartiles; heavy lines indicate medians; open circles indicate arithmetic means; whiskers extend to sample maxima and minima. Box widths are proportional to the square root of sample size.

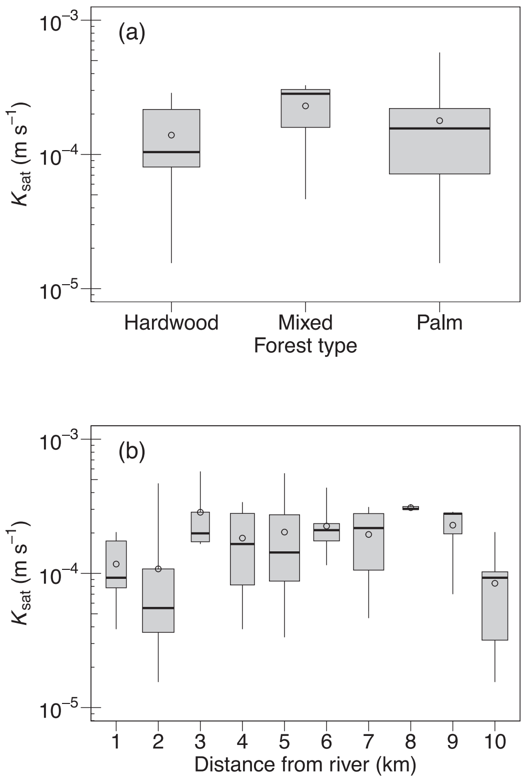

FIGURE 4 | Boxplot showing K_{sat} against (a) forest type and (b) distance from river. Note log-scale on vertical axes. Box hinges indicate upper and lower quartiles; heavy lines indicate medians; open circles indicate arithmetic means; whiskers extend to sample maxima and minima. Box widths are proportional to the square root of sample size. Neither variable improved the performance of our linear model, so they are omitted from the final model specification.

mixed (11/73) forest types (Table 1). Furthermore, most samples are from 0 cm depth (52/73), while relatively few are from 10 cm (21/73) (Table 1). There is a more even spread of distances from river and of von Post scores, although H3 and H4 are the most common categories (Table 1).

After experimenting with various model specifications, our best linear model to describe $\log_{10}(K_{sat})$ includes two independent variables: a categorical representation of depth and a continuous representation of von Post H-score. Our model indicates a significant, negative, approximately linear relationship between $\log_{10}(K_{sat})$ and von Post H; and a strong, significant difference in $\log_{10}(K_{sat})$ between 0 and 10 cm depth. The model exhibits a low-to-moderate r^2 of 0.291. Lin's concordance correlation coefficient indicates high levels of bias ($\rho_c=0.451$), which is manifest as an overestimation of low observed K_{sat} values and an underestimation of high values (see also Figure S3). Depth is the strongest predictor of $\log_{10}(K_{sat})$. In a model that omits depth, r^2 drops to 0.166, while AICc indicates significantly poorer performance ($p=0.008$). Analysis of variance indicates that the fitted parameter for depth is highly significantly different from zero ($p<0.001$). Von Post H-score has a less important effect on the model and the argument to include this variable contains some equivocacy. Omitting von Post H-score from the model only causes r^2 to fall to 0.247. On the other hand, AICc indicates a drop in model performance, analysis of variance indicates that the fitted parameter for von Post H is significantly different from zero, albeit marginally so ($p = 0.040$) and variance inflation is low (VIF = 1.24), indicating that parameter estimates are meaningful. Full details of model parameters are shown in Table 2. Residuals for our best model, which includes both depth and von Post, are approximately normally distributed and unstructured.

Our model does not include forest type or distance from river as independent variables, nor does it include any random effects. Although the inclusion of forest type caused a small increase in r^2 to 0.342, it also increased variance in other parameter estimates, causing the effect of von Post to become non-significant. Although AICc is slightly reduced by inclusion of forest type, this is highly non-significant ($p = 0.677$), indicating overfitting. Similarly, including distance from river failed to improve the model, causing hardly any increase in r^2 to 0.295 and no improvement in model performance according to AICc. Importantly, analysis of variance indicates that the parameter estimate for distance from river is not significantly different from zero ($p = 0.537$). All combinations of random effects for study sites and sampling locations produced singular model solutions, indicating overfitting, so we omitted those. Further details of the model-fitting procedure can be found in Table S1.

TABLE 1 | Summary of sample sizes and grouping of measurements under independent variables used in our linear modelling.

Variable	Level	Number of observations
Depth	0 cm	52
	10 cm	21
Von Post H-score	H2	4
	H3	19
	H4	34
	H5	11
	H6	5
Forest type	Hardwood	15
	Mixed	11
	Palm	47
Distance from river	1 km	5
	2 km	12
	3 km	4
	4 km	7
	5 km	11
	6 km	8
	7 km	11
	8 km	3
	9 km	4
	10 km	8

4 | Discussion

Comparison of our data to deeper measurements from peatlands in other tropical regions suggests that depth-integrated K_{sat} is relatively low in CCB peatlands. We are not aware of any previous studies of tropical peatlands having measured K_{sat} at the surface in the way that we have, but our measurements are approximately two to three orders of magnitude lower than those hypothesised by Cobb et al. (2017) and Cobb and Harvey (2019) for surficial peats in Brunei. Previous studies have measured K_{sat} at depths of at least 50 cm, often using piezometer slug tests that require the piezometer screen to be below the water table. Surficial K_{sat} at our sites is comparable to that at depths of 50 to 100 cm, or deeper, reported in SE Asia (Kurnianto et al. 2016; Ghimire et al. 2018) and South America (Kelly et al. 2014). Our measurements are also approximately two orders of magnitude lower than those from depths of 55 to 65 cm in a Panamanian peatland (Baird et al. 2017), although K_{sat} seems to be unusually high at that site compared to other tropical peatlands. Since K_{sat} is usually highest at the surface of a peat profile, as seen both in our data for the shallowest part of the profile and in previous studies for greater depth ranges (Takahashi and Yonetani 1997; Kelly et al. 2014; Kurnianto et al. 2016; Ghimire et al. 2018), we suspect that depth-integrated K_{sat} in CCB peatlands may well be lower than in other tropical peatland regions. If this is the case, low K_{sat} in CCB peats may be a response to low precipitation compared to other tropical peatland regions (Garcin et al. 2022). Drier dry seasons and lower total annual precipitation in the CCB may cause deeper water tables, leading to a prevalence of oxic soil conditions, rapid decomposition and so reduced

TABLE 2 | Details of fitted parameters from the final model.

Variable	Scale	Units	Level	Parameter	Standard error	Sum of squares	Degrees of freedom	F	Significance
Intercept	Continuous	—	—	−3.420	0.172	43.069	1	394.627	< 0.001
Depth	Ordinal	cm	0	—	—	1.352	1	12.384	< 0.001
			10	−0.334	0.095				
von Post	Continuous	—	—	−0.095	0.045	0.479	1	4.386	0.040

Note: Depth is treated as an ordinal variable; no parameter is assigned to depths of 0 cm, which represents a reference category in the model. Sum of squares, degrees of freedom, F-values and significance relate to Type-III sum-of-squares analysis of fitted model. Dependent variable is $\log_{10}(K_{sat})$. Residual sum of squares is 7.640 (70 degrees of freedom).

permeability, compared to peatlands in wetter climates. This hypothesis is consistent with the moderate levels of humification (up to H6) in many of our surficial samples, where one would expect to find the freshest, least humified peat. On the other hand, we cannot rule out the possibility of methodological artefacts. In a large meta-analysis of K_{sat} in northern peatlands, Morris et al. (2022) found that measurements taken using tension disk infiltrometers were lower than other methods. However, Morris et al. (2022) did not make a direct intercomparison of methods on the same samples and tension disk infiltrometer measurements in that study are predominantly from blanket peatlands, where K_{sat} is inherently low. A comprehensive intercomparison of K_{sat} measurement techniques on the same samples would be a valuable future goal for peatland hydrology, to quantify any such artefacts and to allow more confident comparison of datasets.

Our measurements are also towards the lower end of what would be expected at similar depths in northern peatlands (cf. Liu and Lennartz 2019; Morris et al. 2022). Hydraulic conductivity measurements from woody northern peats arguably provide a more meaningful comparison to our tropical wood peats than those from mossy and herbaceous northern peats. When present at depth in a profile, wood has sometimes been observed to form a low-permeability barrier in northern peatlands, with K_{sat} as low as $10^{-10}\,\mathrm{m\,s^{-1}}$ (Paat et al. 2022; see also Glaser et al. 2021). However, Crockett et al. (2016) found woody peat at the surface of a mountain fen in Colorado, USA, to have K_{sat} of approximately 10^{-5} to $10^{-4}\,\mathrm{m\,s^{-1}}$, comparable to our surficial samples from equatorial Africa. Whittington and Koiter (2025) also found similar K_{sat} of $10^{-4}\,\mathrm{m\,s^{-1}}$ at a depth of 75 cm in woody peats in a boreal bog in Manitoba, Canada.

Even though our measurements are confined to the uppermost 10 cm of the peat profile, depth is the most important control on K_{sat} in our dataset. Depth has been shown to be an important control over K_{sat} in studies of both tropical and northern peatlands, across depth ranges of several metres (e.g., Cobb et al. 2017; Cobb and Harvey 2019; Morris et al. 2022). When back-transformed, our log-linear model indicates an exponential relationship between K_{sat} and depth, as hypothesised by Cobb et al. (2017) and Cobb and Harvey (2019) at their study site in Brunei. However, caution must be adopted because our dataset only has two depths, 0 and 10 cm and more depth intervals across a greater depth range would be required to test the exponential hypothesis in CCB peatlands. It is unclear whether the effect of depth reflects depth-related changes in peat dry bulk density, which we did not measure, changing humification, or some independent influence of depth, as previously suggested for northern peats (Morris et al. 2019, 2022). Our measured K_{sat}-depth relationship is steep in the upper 10 cm and this gradient seems unlikely to apply to the entire peat column. Extrapolating our fitted slope parameter beyond 10 cm implies a decline in K_{sat} of more than three orders of magnitude per metre, which would lead to implausibly low permeability beyond a few metres' depth. Dargie et al. (2017) and Crezee (2022) found that peat dry bulk density across the CCB increases with increasing depth in the uppermost 1 m or so of the peat profile but stabilises below this. The relationship between K_{sat} and dry bulk density in tropical peats is somewhat ambiguous, as the few studies that have investigated it reached contrasting conclusions. Kurnianto et al. (2016) found that K_{sat} in degraded Kalimantan peats was well predicted by dry bulk density, amongst other variables; while Kolay and Shafiee (Kolay and Shaifee 2007) also found that K_{sat} was negatively related to dry bulk density in Sarawak peats. In contrast, Ghimire et al. (2018) found no such relationship when comparing intact peat swamp forests with acacia plantations on drained peat in Sumatra. If K_{sat} in our sites is related to dry bulk density in a manner similar to that observed by Kurnianto et al. (2016) and in northern peats (e.g., Liu and Lennartz 2019; Morris et al. 2022), then we might reasonably expect the K_{sat}-depth relationship in the CCB to flatten in deeper peat layers. Indeed, Ghimire et al. (2018) found that K_{sat} declined exponentially with depth in the upper 1.25 m of the peat profile but remained low and relatively constant at greater depths.

Depth and humification are positively correlated with one another and therefore exhibit some redundancy as predictors when both are included in our model. In the model, depth is a stronger control than von Post, although the two are clearly interlinked when it comes to determining peat hydraulic properties (cf. McCarter et al. 2020). Decomposition proceeds as peat ages, meaning that older, deeper peats are generally more humified than younger, shallower peats (e.g., Morris et al. 2022). Additionally, a deeper position in a peat profile means greater overburden and thus compression of pores; while higher levels of decomposition weaken the structural integrity of a peat matrix, leaving pore structures more susceptible to collapse (Clymo 1984). It is challenging to separate the independent effects of depth and humification upon K_{sat}, as process-based understanding of their interaction is incomplete. The relationship between K_{sat} and humification seems to be weaker in tropical peats than in northern peats (Liu and Lennartz 2019; Morris et al. 2019, 2022). There are several examples in the literature of the relationships between humification and K_{sat}, and between humification and depth, breaking down in tropical peats, which we might expect to hold based on more extensive studies of northern peats. For example, Wösten et al. (2008) found a negative relationship between humification and K_{sat} in peats in central Kalimantan; while in Sumatra, Nugroho et al. (1997) found higher K_{sat} in peats with von Post scores of H6 than in those with H4 or H5, albeit over a narrow range of humification. Bragg (1997) described an inverted depth profile of humification at a site in Sarawak, with von Post scores of H8–H10 within 1 m of surface, overlying H5–H7 peat in the middle part of the peat profile and H1–H4 peat at the base. The high wood and root content of tropical peats, including in our samples, may weaken the relationships between humification and hydrophysical properties such as K_{sat} compared to those seen in northern peats. For example, it may be possible to obtain a high von Post H-score for a peat that has a well-decomposed matrix, but which retains some roots and root channels, leading to relatively high bulk K_{sat} despite a high H-score.

The lack of difference in peat K_{sat} between palm and hardwood swamp forests, and the lack of influence of distance from the riverbank upon K_{sat}, may make K_{sat} harder to predict in tropical peats than in northern peats, where factors such as plant community and trophic status are meaningful predictors (Morris et al. 2022). Kurnianto et al. (2019) found strong differences in peat K_{sat} between locations with intact peat swamp forest cover, those that had been recently burnt, those in the early stages of forest re-establishment after clearance and those that had been converted to oil palm plantations. The more subtle distinction between intact hardwood and intact palm swamp forests in our dataset appears to be insufficient to generate identifiable differences in surficial K_{sat}. Dargie et al. (2017) found no difference in peat dry bulk density between palm- and hardwood-swamp peats, which is consistent with the lack of difference in K_{sat}.

In its current form, our linear model cannot be used to make reliable predictions about K_{sat} in central Congo Basin peats because its performance is too low, as indicated by low explanatory power (r^2) and high bias (low ρ_c). Indeed, Kurnianto et al. (2019) recommended that K_{sat} in tropical peat should not be estimated from other peat properties and that it must instead be measured directly. However, their conclusion seems due in part to a small range of measured peat dry bulk density, which led to a low ratio of between:within sample variance in their own statistical modelling and so low-confidence parameter estimates. Similarly, the limited performance of our model likely stems from the narrow depth range of our samples (0–10 cm), a constraint imposed by the logistical and financial challenges of conducting fieldwork in this remote forest. Samples across a greater range of predictor variables—for instance, covering several metres' depth, and/or larger ranges of humification and dry bulk density—would likely yield more confident, reliable models, with greater explanatory power. The significant effects of depth and von Post H-score in our model suggest that a generalisable model might be attainable in future, particularly from datasets that include deeper measurements. Incorporating peat dry bulk density as a predictor would also likely improve model performance. Although hydraulic measurements from tropical peats remain comparatively sparse, recent meta-analyses of northern peats have shown that powerful pedotransfer functions can be developed when suitably large datasets are available (e.g., Lennartz and Liu 2019; Liu and Lennartz 2019; Morris et al. 2022; Wang et al. 2021). We propose that comparable models for tropical peats and the datasets that would underpin them remain valuable and achievable goals for future research.

Our data and findings can support improved representation of hydrological processes in Congolese peatlands in simulation models at a range of spatial scales. Doing so is particularly important given the uncertainty in future climates that are projected by climate models for equatorial Africa, with some combinations of models and emissions scenarios projecting wetter future climates and others much drier (Lee et al. 2021). Our measurements broadly validate the K_{sat}-decomposition relationship represented in DigiBog_Congo (Young et al. 2023), an ecosystem-scale, cohort-based model of peatland development in the CCB in which peat K_{sat} declines logarithmically with increasing decomposition. Additionally, our data recently informed the improved parameterisation of a new version of the model (Young et al. in press). Our findings will also help to inform ongoing efforts to improve the representation of tropical peatlands in larger scale models, such as land surface schemes in general circulation models. A version of the Joint UK Land Environmental Simulator (JULES) has recently been developed to represent peatland-specific processes in northern and temperate peatlands (Chadburn et al. 2022) and it is currently being extended and adapted to represent tropical peatlands, specifically those in the CCB (e.g., Cook et al. 2023). As with DigiBog, our measurements will help to constrain the parameterisations of JULES's soil hydraulic routines.

5 | Conclusions

To our knowledge, ours are the first measurements of saturated hydraulic conductivity in peats from the central Congo Basin. They provide constraints on hydrological processes in a poorly studied, carbon-rich environment in which ecosystem functions and services are highly sensitive to seasonal water budgets. Our surficial and near-surface measurements suggest that depth-integrated K_{sat} is lower in the CCB than in other tropical peatlands, which may reflect the CCB's drier climate. However, deeper measurements of K_{sat} in the CCB would be needed to confirm this. Depth is the strongest control over K_{sat} in our database and the degree of peat humification is also significant. We found no difference in peat K_{sat} between hardwood, palm and mixed swamp forest types, nor any relationship with proximity to rivers. Although the predictive power of our linear model is limited, our results suggest that with more comprehensive data, generalisable models of K_{sat} in the CCB, and potentially the wider tropics, might be attainable in future, similarly to recent advances in northern peats. Our measurements will help inform the ongoing development of representations of CCB peatlands in terrestrial ecosystem models at a range of scales, including in large-scale Earth-system models.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Peat depths (top) and saturated hydraulic conductivity (bottom) along the Bondamba (left) and Mpeka (right) transects. **Figure S2:** Cross-sectional diagrammatic representation of the alternative configurations we used to take measurements of both unsaturated and saturated hydraulic conductivity with the METER Group Mini Disk tension infiltrometers. On the left, the instrument is shown with the bottom end of the suction control tube positioned below the water surface in the bubble chamber, which exerts a tension on water passing through the sintered steel disk into the soil below. The instrument is used this mode to take unsaturated hydraulic conductivity readings. On the right, the suction control tube is lifted so that its lower end is above the water surface in the bubble chamber, meaning that water passing through the sintered steel disk into the soil below is not subject to any suction. The instrument is used in this mode to take measurements of saturated hydraulic conductivity. **Figure S3:** Model performance plot showing modelled values of K_{sat} against the observed measurements. Broken black line indicates the loci of perfect concordance between measured and modelled values; solid black line represents linear best-fit relationship between measured and modelled K_{sat}; and ρ_c is Lin's concordance correlation coefficient, used to assess model bias. **Table S1:** Details of variable selection during model-building process. The final model reported in the main article is referred to here as Model 1; Models 2 to 5 contain different combinations of candidate variables and are shown in comparison Model 1. Lower AICc indicates improved model performance. Change in AICc compared to Model 1 is interpreted as a Chi-Square statistic, with degrees of freedom equal to the change in the number of parameters. Significance is the *p*-value from the Chi-square test for each model. In the cases of Models 2 and 3, where variables have been removed compared to Model 1, the Chi-square test is used to determine whether any reduction in model performance, as indicated by an increase in AICc, is significant. Conversely, in the cases of Models 4 and 5, variables have been added compared to Model 1 and the Chi-Square test is used to determine whether any increase in performance, as indicated by a decrease in AICc, is significant.