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Geomorphic Factors Impact Groundwater Levels More Than Harvesting in a Coast Redwood Forest

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ABSTRACT

Groundwater is a major source of stream baseflow during the summer and can supply additional water to plant transpiration, which may be particularly important in Mediterranean environments where the growing season is decoupled from wet season precipitation. However, little is known about how forest management may affect groundwater level. We used a paired watershed design in a northern California coast redwood forest to study how intrinsic and extrinsic factors as well as harvesting affect groundwater level and the connectivity between soils, groundwater, and streams. Geomorphic variables such as soil depth, well depth (or depth to the confining layer), and slope were influential factors in our random forest model on groundwater level, and basal area was of moderate importance. However, harvesting did not have a significant effect on either wet or dry season groundwater level, which may be due to the large drought that occurred post-harvest. In this coast redwood forest, it appears that factors that affect vertical infiltration and lateral flow of rainfall, such as slope, soil depth, and well depth, may be more important than vegetative characteristics like stand density.

1 | Introduction

Groundwater is a critical water supply in many forested ecosystems that provides stream baseflow and subsidises plant available water between precipitation events (Barbeta and Peñuelas 2017; Orlova and Branfireun 2014). In Mediterranean environments where the growing season is decoupled from wet season precipitation, groundwater may be a particularly important water source for both dry season streamflow and plant water use (Klos et al. 2018; Link et al. 2014; McCormick et al. 2021). Despite the vital role of groundwater in the forest water balance, subsurface storage remains understudied, representing a critical gap in our understanding of forested watershed resilience in the face of climate change and other perturbations (Green et al. 2011). Given the significance of groundwater, it is imperative to discern the factors that influence groundwater processes.

Groundwater level can vary temporally and spatially within catchments and across topographic positions (Detty and McGuire 2010; Haught and van Meerveld 2011; Lana-Renault et al. 2014; Seibert et al. 2003). Groundwater recharge and groundwater level may be impacted by precipitation (including total precipitation, extreme precipitation, seasonality of rainfall, and rainfall intensity), soil texture, soil moisture, slope, and vegetation cover (Bachmair and Weiler 2012; Detty and McGuire 2010; Fu et al. 2019; Lee et al. 2014; Zhang et al. 2016; Zomlot et al. 2015). Slope, vegetation, and soil texture and moisture all vary throughout catchments, which may explain some of the spatial variability observed in groundwater level. The temporal variation in groundwater level may be related to seasonal cycles in precipitation and evapotranspiration, which in turn impact groundwater recharge and/or storage (Gribovszki et al. 2010; Lana-Renault et al. 2014; Minea et al. 2022; Taylor et al. 2013). If seasonal variations in groundwater recharge and/or storage are extreme enough, hazards like floods and droughts may develop, which may impact groundwater-dependent ecosystems and downstream communities (Jyväsjärvi et al. 2015; Taylor et al. 2013). By studying seasonal and spatial trends of groundwater, we can better understand what factors affect groundwater level.

Groundwater levels can also be affected by anthropogenic activities such as forest management. For instance, forest harvesting has been consistently shown to alter hydrologic dynamics in forests across a wide variety of ecosystems and regions; however, few studies have investigated the effects of harvesting on groundwater (del Campo et al. 2022; Schenk et al. 2020), though there are notable exceptions (see Brown 1995; Jutras et al. 2006; Keppeler and Brown 1998; Ruprecht et al. 1991; Stoneman 1993). These past studies generally showed harvesting increases water table elevation (Jutras et al. 2006; Ruprecht et al. 1991; Stoneman 1993) and the water available for deep percolation (del Campo et al. 2014; Garcia-Prats et al. 2018). However, little is known about the seasonal timing of harvest-related impacts on groundwater. For example, if harvesting increases groundwater in the wet season but not the dry season, there may be minimal benefits for vegetation and streamflow. Since harvesting effects on streamflow have been found to differ between the summer and winter seasons (e.g., Burton 1997; Callegari et al. 2003), it is possible that groundwater level increases may only occur seasonally. One of the few studies on harvesting and groundwater found that in a Florida flatwoods landscape water tables were drier during the growing season and higher during the non-growing season compared with the predicted uncut condition (Bliss and Comerford 2002), suggesting higher evapotranspiration rates post-harvest. If plant water use of groundwater increases post-harvest during the growing season, this could lessen the amount of baseflow in streams during the growing season, which could have ramifications for aquatic organisms and other riparian vegetation.

We explored the broad theme of forest management interactions and controls on subsurface water storage and movement at an experimental watershed in northern California. This paper addressed the following objectives: (1) how do groundwater levels vary seasonally among different sub-watersheds and hillslope positions, (2) what intrinsic (basal area, well depth, soil depth, slope, etc.) and extrinsic (annual precipitation) factors may affect groundwater levels, and (3) the extent to which forest harvesting affects groundwater levels.

2 | Methods

2.1 | Site Description

We conducted our study in the South Fork Caspar Creek Experimental Watershed in Jackson Demonstration State Forest in northern California, USA (Figure 1; 39°21′ N, 123°44′ W). Caspar Creek experiences a Mediterranean climate (Köppen-Geiger Csbn) with cool, dry summers characterised by frequent coastal summer fog events and mild, moist winters with rare snowfall. Caspar Creek has a 30-year mean monthly temperature of 10.6°C that ranges from 6.8°C in December to 14.5°C in August (1992–2021; Dymond, Richardson, et al. 2021; Dymond, Wagenbrenner, et al. 2021). The 30-year mean annual precipitation from 1993 to 2022 was 1167 mm, with more than 90% of annual rainfall occurring between October and April. Annual rainfall pre-harvest averaged 1497.5 mm (1358–1637 mm; WY 2016–2018) and

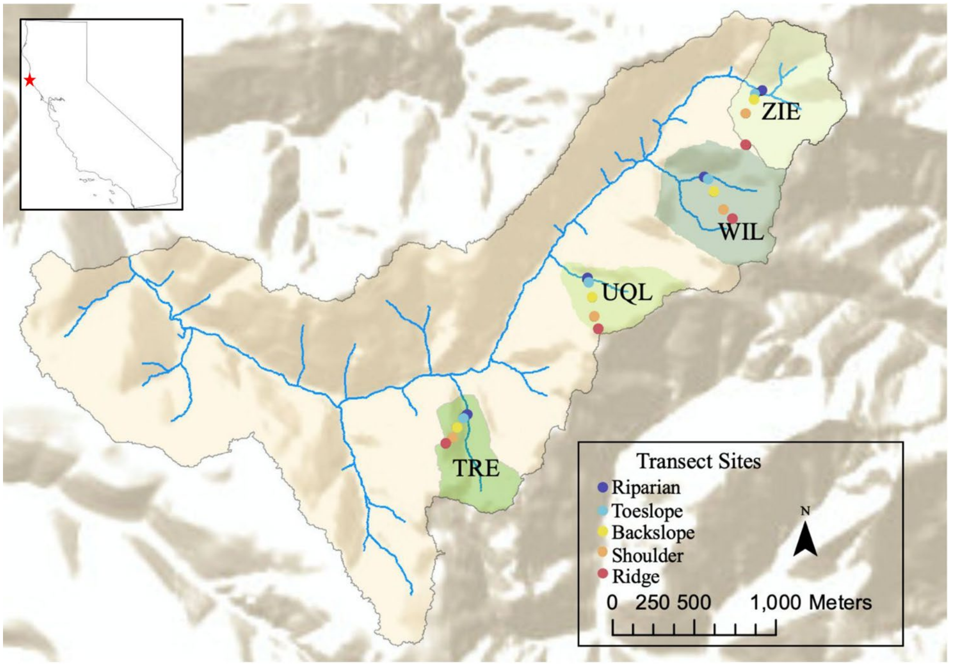

FIGURE 1 | The South Fork Caspar Creek and four experimental sub-watersheds are located near Fort Bragg, CA, USA (see inset).

post-harvest 902 mm (564–1390 mm; WY2019–2022). Rainfall routes to stream channels via subsurface flow, including preferential flow paths in both the soil and saprolite (Keppeler and Brown 1998). Soil depths range from 100 to 300 cm (Dymond, Richardson, et al. 2021; Dymond, Wagenbrenner, et al. 2021) and primarily consist of well-drained clay loam Ultisols and Alfisols derived from Franciscan sandstones and shales (Rittiman and Thorson 2006).

The overstory vegetation in the South Fork consists of primarily third-growth coast redwood, (*Sequoia sempervirens* (D. Don) Endl.), Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), grand fir (*Abies grandies* (Doug ex. D. Don), Lindl.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and a few tanoaks (*Lithocarpus densiflorus* (Fook. and Arn. (Rohn.))). Stand composition at the onset of this study (2015) was about two-thirds 45-year-old third growth (last harvested in 1973) and one-third approximately 120-year-old residual second growth dating back to the late-1800s.

2.2 | BACI Design

To assess the effects of harvesting on groundwater, a before-after-control-impact (BACI) design, also known as a paired watershed design, was implemented in the South Fork Caspar Creek (Dymond, Richardson, et al. 2021). A BACI design is a commonly used ecological design (Richardson et al. 2023) where at least two watersheds are chosen based on similar characteristics such as vegetation, overall size, aspect, elevation, soils, geology, and climate (Dymond, Richardson, et al. 2021). These watersheds are then instrumented, and a response variable of interest is measured. One of the variables is the ‘control’ watershed while the other is the ‘impacted’ watershed where some type of treatment (i.e., harvesting, controlled burn, etc.) is implemented. The response variable is measured during a calibration period known as the ‘before’ period. After the calibration period, some type of treatment is applied and then the response variable is measured in the ‘after’ period. A calibration relationship is developed between the control and impacted watershed for the ‘before’ period and then we determine if the relationship is different in the ‘after’ period.

The control and treatment sub-watersheds were chosen carefully in the South Fork Caspar Creek based on the relationship between peak flows in the control versus treatment sub-watersheds (Dymond, Richardson, et al. 2021). The treatment sub-watersheds were thinned. We define harvesting as the selective removal of vegetation throughout the study plots to observe the impacts of forestry management on hydrology. Four sub-watersheds were instrumented with north-facing hillslope transects in 2015–2016. These transects represented similar slope, aspect, elevation, and soil types. Along each 200–250 m transect, five hillslope positions (riparian, toeslope, backslope, shoulder, and ridge) were chosen as 1/20th ha circular plots (Dymond, Richardson, et al. 2021; Miller and Schaetzl 2015; Ruhe and Walker 1968).

Three of the sub-watersheds (TRE, UQL, and ZIE) were incrementally harvested in 2018 (Impact), while the fourth sub-watershed (WIL) served as the reference sub-watershed (Control; Dymond, Richardson, et al. 2021; Dymond, Wagenbrenner, et al. 2021; Table 1). Basal area reductions in the four study sub-watersheds were 0% in the control sub-watershed (WIL), 40% (TRE), 47% (UQL), and 76% (ZIE). While actual basal area reductions varied across each sub-watershed and did not precisely meet the overall targets (0%, 35%, 55%, and 75%, respectively), these target reductions were closely adhered to within the 1/20th ha circular transect plots used in this study (Table 1). There were exceptions for the riparian and toeslope positions, where California Forest Practice Rules restricted harvesting within the riparian buffer zone (Figure 1, Table 1; California Forest Practice Rules 2017). Cable-yarding on steep slopes and ground-based skidding on less-steep ground were used to remove felled timber. Data were collected pre-harvest in water years (1 October–30 September) 2016–2017 (before), in the harvest water year of 2018, and post-harvest water years 2019–2022 (after). Because of potential effects related to disturbances during the harvest process, we do not include data from 2018 in any of our forest harvest analyses.

2.3 | Hydrologic Instrumentation and Variables

To monitor groundwater levels at each of the transect plots ($n = 20$), piezometers were installed in Fall 2015 (except UQL wells, which were augured in the summer of 2016). Bore holes were hand-augured to bedrock depth, although this was often within the zone of fractured regolith. HOBO U20 water level loggers (ONSET; MA, USA; resolutions: < 0.02 kPA water; accuracy: 1.0 cm) were deployed to measure and record groundwater levels at 10-min intervals. Groundwater level was considered to be the water level in the piezometers above the bottom of the wells. Screen depth was 15 cm for all but the riparian positions, which had thick wet clay in the boreholes. The screen depth is the depth across which the pipe was slotted diagonally using a hack saw at around 5 cm intervals.

We aggregated the 10-min data to 30-min and daily averages for each site. Using the 30-min groundwater level averages, we calculated the average, minimum, and maximum groundwater levels for the wet season (December–March) and the dry season (June–September) for each site (Dymond, Wagenbrenner, et al. 2021).

Similarly, we installed EC5 soil moisture sensors (METER Group Inc.; WA, USA; resolutions: 0.001 $m^3 m^{-3}$; accuracy ± 0.03 $m^3 m^{-3}$) at each of the transect sites to measure soil moisture. Sensors were placed vertically into the soil at 15, 30, and 100 cm depths and connected to EM60 data loggers (Onset Computer Corp; MA, USA). Volumetric water content (VWC, θ, $m^3 m^{-3}$) measurements were recorded every 10 min and averaged for each depth and day (VWC_{15}, VWC_{30}, and VWC_{100}). Soil water content measurements during the pre-harvest period were available for WIL, TRE, and ZIE commencing October 2015 and for UQL commencing December 2016 (Dymond, Wagenbrenner, et al. 2021).

2.4 | Analyses

All analyses were conducted in the R version 4.3.2 environment (R Core Team 2024). To determine how sub-watershed

TABLE 1 | ID, sub-watershed name, topographic position, soil depth, well depth, screen depth, slope, aspect, elevation, pre- and post-harvest basal area (BA), and plot-level basal area reduction.

ID	Sub-watershed name	Topographic position	Soil depth (cm)	Well depth (cm)	Screen depth (cm)	Slope (%)	Aspect (°)	Elevation (m)	Pre-harvest BA ($m^2 ha^{-1}$)	Post-harvest BA ($m^2 ha^{-1}$)	BA reduction (%)[a]
WIL	Williams	Riparian	221	432	100	46	300	166	264	266	−1
		Toeslope	193	363	15	50	320	173	68	72	−6
		Backslope	107	183	15	80	350	204	68	79	−16
		Shoulder	152	754	15	55	357	252	141	154	−10
		Ridge	155	760	15	25	288	274	94	105	−11
TRE	Treat	Riparian	111	150	50	60	86	89	147	152	−3
		Toeslope	282	550	15	55	77	101	136	122	11
		Backslope	222	500	15	45	38	130	48	35	27
		Shoulder	145	608	15	70	105	149	48	36	25
		Ridge	254	682	15	36	91	165	124	45	63
UQL	Uqlidisi	Riparian	205	355	50	19	305	135	203	204	0
		Toeslope	242	416	50	53	355	142	19	19	−2
		Backslope	170	503	15	57	357	180	53	28	47
		Shoulder	387	426	15	32	21	217	84	43	49
		Ridge	110	803	15	8	3	233	115	56	51
ZIE	Ziemer	Riparian	107	158	50	15	10	196	436	441	−1
		Toeslope	234	292	15	55	0	202	18	24	−32
		Backslope	184	258	15	85	18	224	147	57	61
		Shoulder	136	429	15	28	351	248	59	22	62
		Ridge	196	406	15	19	294	270	108	34	69

[a]Negative BA reductions reflect growth between 2017 and 2019 measurements. The Ziemer toeslope anomaly is likely due to a variation in pre- and post-harvest sampling boundary.

and hillslope position affected seasonal groundwater levels (Objective 1), we used a Kruskal–Wallis test (R Core Team 2024) and Dunn's non-parametric test (Dinno 2024) for a pairwise comparison due to the non-parametric nature of the data (Dunn 1964; Kruskal and Wallis 1952). We used an alpha level of 0.01 to determine significance. We also ran a Spearman's correlation to examine the correlation between annual precipitation and groundwater level (Spearman 1904; stats-package: The R Stats Package n.d.).

We used a random forest model to examine what factors affected groundwater level at Caspar Creek during the wet (December–March) and dry seasons (June–September; Objective 2). Random forest models are robust, multivariate, and appropriate for non-parametric data (Breiman 2001). For each random forest model, we used seasonal groundwater level (30-min intervals) as the dependent variable and depth to bedrock (m), slope (°), accumulated water year precipitation (cm of precipitation from 1 October), basal area ($m^2 ha^{-1}$), VWC_{15}, VWC_{30}, and VWC_{100} ($cm^3 cm^{-3}$) as our independent variables.

We used the package randomForest (Cutler and Wiener 2022) to train the data and conduct cross-validation on each random forest model. A random forest model is a machine-learning algorithm that creates many decision trees based upon the best splits to subset the data to make improved predictions. The random forest models were trained on 80% of the data, and 20% of the data were used for testing. Cross-validation found that for the dry season model, $n_{tree} = 500$ (number of trees to grow) and $m_{try} = 3$ (number of variables randomly sampled as candidates at each split) were the best parameters, and $n_{tree} = 500$ and $m_{try} = 4$ for the wet season model. We used a maxnodes (the maximum number of terminal nodes trees can have) of 100 and a nodesize (minimum size of terminal nodes) of 20 for both models based on the lowest mean squared of residuals. To understand the explanatory power of the independent variables, we calculated the percentage of variance explained using Gini Impurity, which is the probability of misclassifying a randomly chosen element in the dataset (Cutler and Wiener 2022).

We used a generalised linear mixed effects model to test if harvesting impacted groundwater level metrics and to test for the presence of hypothetically important random effects (Bolker et al. 2009). The model determined the proportion of variance in groundwater level explained by the fixed effects of period (pre- or post-harvest), treatment (reference or harvested), and their interaction (the treatment effect). We used a tweedie distribution with a log link because of the mix of zero and positive values. We tested the fit of these models using the package DHARMA and residuals, histograms, and Q–Q plots. The best fit of the model was determined using Akaike's information criterion (AIC; Akaike 1974). We found that including the random effects of site significantly improved the model. Analyses were performed using the glmmTMB function in the glmmTMB package (Brooks et al. 2024).

Eight of the 20 wells were dry more than 96% of their available time series. These dry wells occurred in the toeslope (TRE, ZIE), the backslope (TRE, UQL, ZIE, WIL), and the shoulder (TRE, ZIE). Since these wells rarely had any measurable groundwater (> 0.01 m) in them, we did not include them in the majority of our final analyses (Table S1) and considered these to be more indicative of a piezometric response than actual groundwater level variations.

3 | Results

3.1 | Hillslope Position and Groundwater Level

When looking at all 20 sites, we found that groundwater level varied widely across the five hillslope positions at all four sub-watersheds (Figure 2). Across all sub-watersheds, the riparian position contained groundwater throughout most of the study period (98.4% of the time, averaged across all sub-watersheds). This was followed by the ridge position, which contained groundwater 64.7% of the time. The toeslope, backslope, and shoulder positions only had measurable groundwater in them 33%–40% of the time across all sub-watersheds ($n = 20$). For the sites with consistent

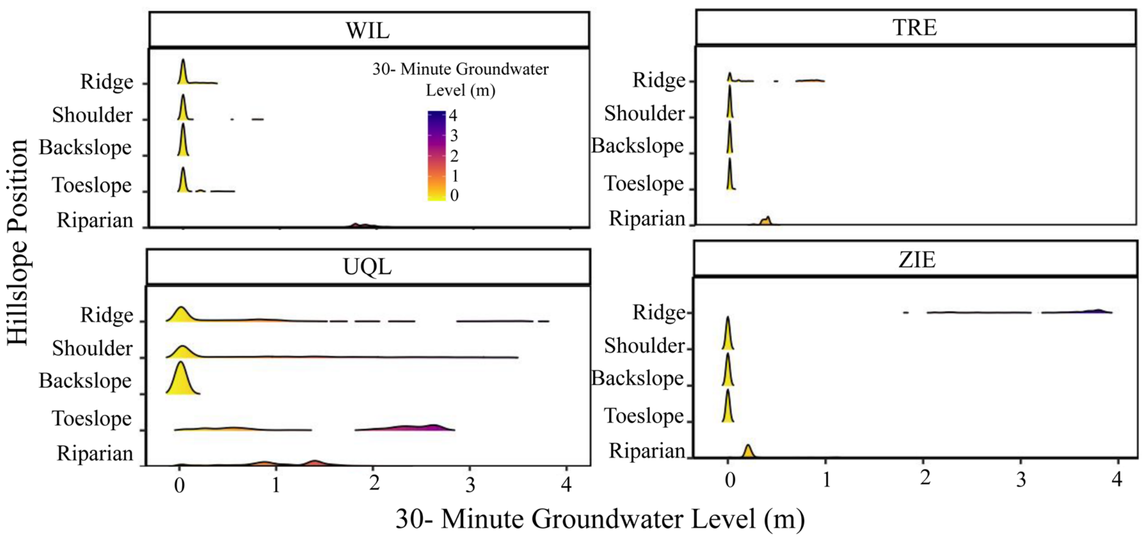

FIGURE 2 | Ridgeline plots showing the density distribution (i.e., the distribution of groundwater level) of 30-min groundwater level at the four sub-watersheds and the five hillslope positions. All wells were included in this figure ($n = 20$).

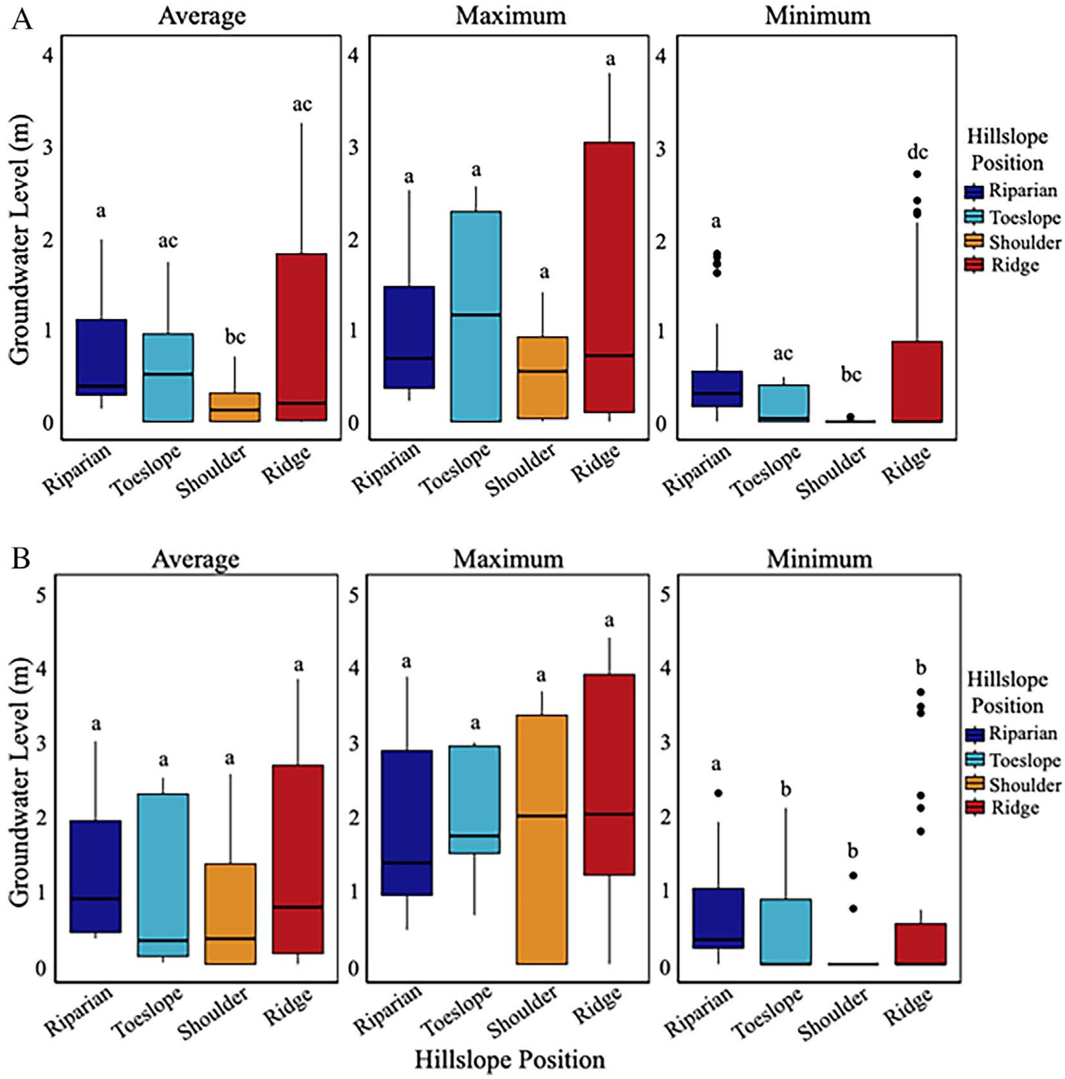

FIGURE 3 | Seasonal comparison of 30-min groundwater level data for the five hillslope positions for the average, maxima, and minima groundwater levels for the dry (A) and wet (B) seasons. Different letters indicate significant differences among hillslope positions according to Dunn's test (alpha = 0.01). Twelve dry wells (wells with groundwater < 0.01 m for at least 95% of the time), including all backslope wells, were not included in this analysis.

groundwater (levels above 0 m), there were seasonal differences across the hillslope positions ($n = 12$; Figure 3). For both the dry and wet seasons, we found that the shoulder position was generally the driest position. Wet season maximum groundwater levels, however, were lower in the riparian and toeslope positions than in the shoulders. The toeslope and riparian positions often had the most groundwater in them, but the ridge positions also remained relatively wet. Groundwater level was more variable across hillslope positions during the dry season than during the wet season. However, many of these differences in groundwater level between the hillslope positions were not significantly different ($p > 0.01$). Generally, groundwater level in the riparian position was most often significantly different from the other hillslope positions, especially from the shoulder and ridge positions.

3.2 | Factors That Affect Groundwater Levels

We found a similar pattern for both the wet and dry seasons for the factors that were most influential for determining groundwater level in our random forest models (Figure 4). The random forest models explained between 97.9% with a 0.018 mean of squared residuals (dry season groundwater level) and 92.3% with a mean of squared residuals of 0.118 (wet season groundwater level) of the variation in groundwater level (Table S2). For the dry season random forest model, we found that soil depth was the most influential variable, followed by well depth and basal area. Slope had moderate importance, and annual precipitation and soil moisture (VWC_{15}, VWC_{30}, VWC_{100}) were minimally important. Similarly, the wet season random forest model had soil depth as the most influential variable followed by well depth. However, we found that basal area was a slightly less influential variable in the wet season model than the dry season model. All three soil moisture depths and annual precipitation were minimally important in the models. For both wet and dry season groundwater levels, soil moisture at the 30 cm depth was the least influential variable included in the models, while 100 cm soil moisture was the most influential of the soil moisture depths included.

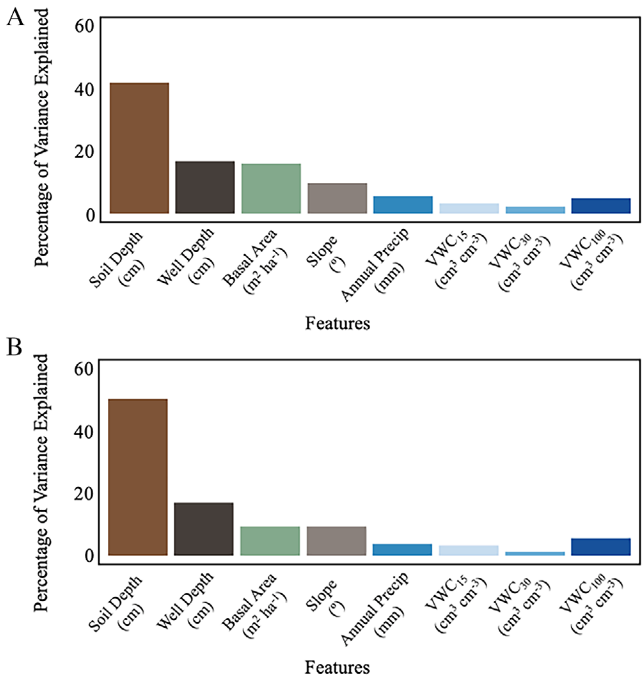

FIGURE 4 | Percentage of variance explained for the dry season groundwater level (A) and wet season groundwater level (B). Data do not include the 12 wells that had water levels < 0.01 m more than 95% of the time. For each random forest model, we included the seasonal groundwater level as the dependent variable and soil depth (cm), well depth (cm), basal area ($m^2 ha^{-1}$), slope (°), annual water year precipitation (cm water from 1 October to 30 September), average daily VWC15, average daily VWC30, and average daily VWC100 ($cm^3 cm^{-3}$) as independent variables.

3.3 | Groundwater Levels and Harvesting

Our generalised linear mixed effects models found no significant effect of period (pre- versus post-harvest), treatment (reference versus harvested), or their interaction on average, minimum, or maximum groundwater level for either dry or wet season ($p > 0.01$; Figure 5; Tables S3 and S4). Rather, it appears that both the reference and harvested sites had slightly higher groundwater levels during the post-harvest dry season compared to the pre-harvest dry season, whereas during the post-harvest wet season the reference and thinned sites had lower groundwater levels than the pre-harvest wet season period. We also found no significant effect of period, treatment, or their interaction when comparing the proportion of days during each water year where groundwater level was greater than 0 for either the wet or dry season ($p > 0.01$; Tables S5 and S6). Rather, it appears that groundwater levels appeared to follow the annual precipitation patterns, though the strength of this correlation varied among sub-watersheds (Table S7).

4 | Discussion

4.1 | Groundwater Level Varied Widely Across Sub-Watersheds and Topographic Positions

Like other studies, we found a wide range of groundwater levels across the four sub-watersheds and five hillslope positions (Guyo et al. 2024; Seibert et al. 2003). The volume of water that vertically infiltrates below the soil-bedrock interface versus the water that flows down the slope has been reported to depend on bedrock permeability, soil depth and permeability, and slope angle (Appels et al. 2015; Ebel and Loague 2008; Hopp and McDonnell 2009). The ridges, which had unexpectedly high groundwater levels, also have some of the deepest soils and some of the shallowest slopes. Thus, sub-watersheds and hillslope positions with deeper soils and bedrock as well as shallower slopes may have more vertical infiltration and/or less lateral flow (Figure 6). Though our sub-watersheds were carefully chosen for their similarities in characteristics such as geology, vegetation, size, slopes, and soils, there were intrinsic differences between the sub-watersheds as there are in every paired watershed design. These differences between the sub-watersheds may have also led to some of the differences observed in groundwater levels.

4.2 | Geomorphic Characteristics and Basal Area Play Important Roles in the Wet and Dry Season Groundwater Level

Geomorphic characteristics at our field sites were found to be influential factors in our random forest model. Other studies have found that soil depth and other soil characteristics may be important variables for groundwater recharge and subsurface flow (Appels et al. 2015; Bachmair and Weiler 2012; Buttle and McDonald 2002; Hopp and McDonnell 2009). We found that soil depth was the most influential factor for predicting groundwater level in the wet and dry seasons in our study. Soil depth is an important factor for storing and re-distributing rainfall as well as the generation of rainfall into lateral flow (Appels et al. 2015; Rai et al. 2017). Deeper soils may lead to higher groundwater levels because of better drainage (Rai et al. 2017) and a higher available storage capacity of water and control on the size of the vertical flux of water (Appels et al. 2015). Thus, deeper soils may have allowed for less runoff or lateral flow and increased groundwater recharge, which in turn could lead to higher groundwater levels.

Alternatively, historic tractor-logging in the South Fork of Caspar Creek disrupted subsurface flow paths and altered connectivity along the hillslope profile, which may explain some of the variability in groundwater level and groundwater connectivity along the hillslope profile. Skid trails from previous harvesting in the South Fork of Caspar Creek entailed cut and fill construction with large cut slopes and significant compaction resulting in daylighting previously subsurface macropore and pipe flow. Where depth of disturbance exceeds soil depth, the flowpaths may have been impacted or even intercepted, in turn impeding infiltration and percolation similar to the role of roads intercepting and rerouting subsurface stormflow.

Slope was of moderate importance in our random forest models. Higher slope can lead to a decrease in vertical infiltration (Essig et al. 2009; Morbidelli et al. 2015) and an increase in deep flow (Morbidelli et al. 2015), which has been found to be true in Alfisols and Ultisols (Patin et al. 2012). Sites with steeper slopes on our hillslopes may have had lower groundwater levels because of lower infiltration and increased lateral flow.

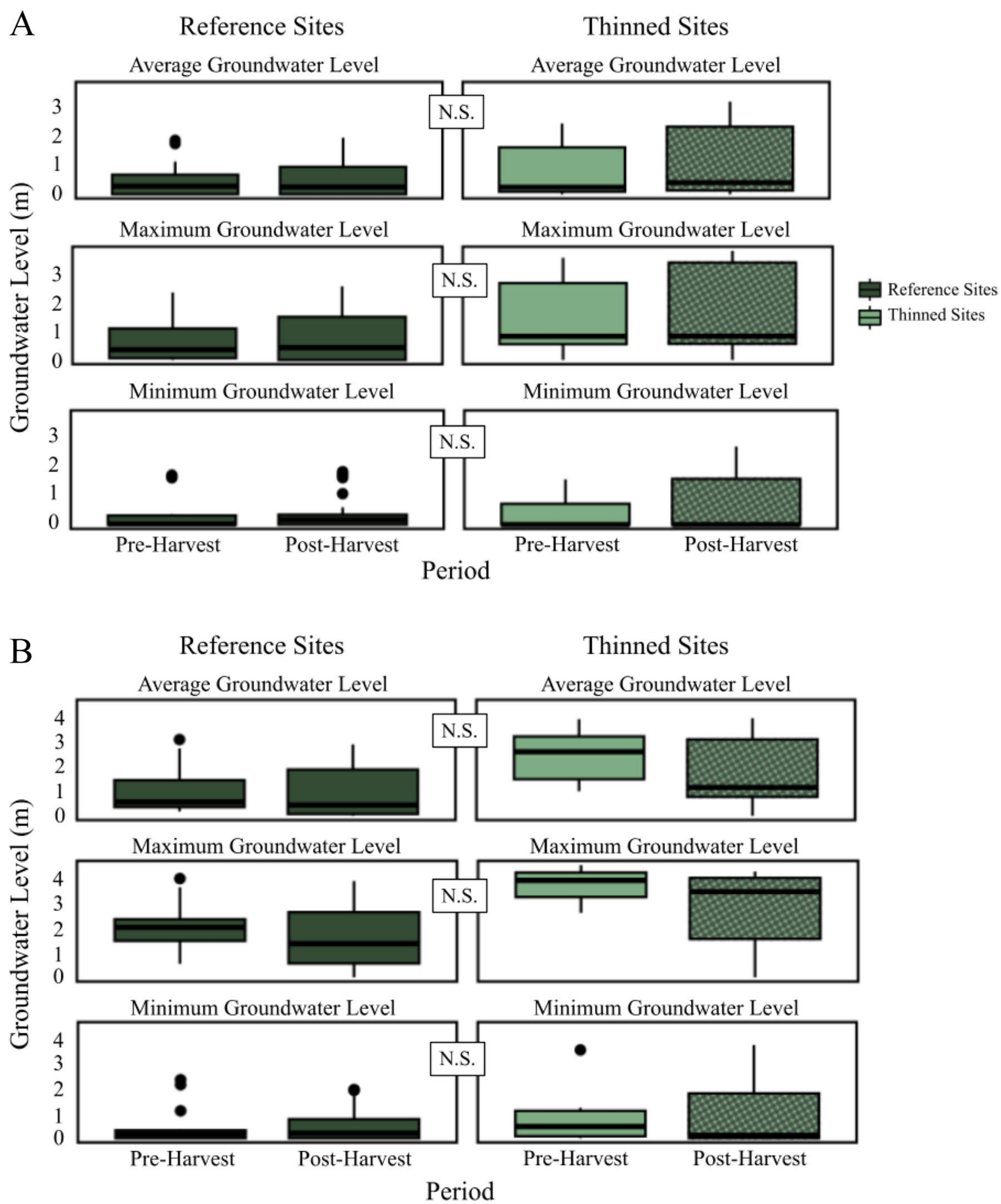

FIGURE 5 | Boxplots representing the average, maximum, and minimum dry (A) and wet (B) season groundwater levels between the reference sites ($n = 7$) and harvested sites ($n = 4$) during the pre- and post-harvest periods, not including the dry wells ($n = 8$). The cross-hatched bars represent the sites that had been harvested. N.S. represents no significant interaction ($p > 0.01$) between treatment (reference vs. harvest) and period (pre- vs. post-harvest).

A main difference between the wet and dry season random forest models was that basal area was slightly less influential on groundwater levels during the wet season. Since the growing season coincides with the dry season at Caspar Creek, evapotranspiration and plant water use may be important drivers of groundwater level at Caspar Creek. Douglas-fir, a co-dominant species at our field site, has been shown to shift towards using more groundwater as shallow soil moisture declines during the growing season, which could be one potential explanatory factor for the moderate relationship between groundwater level and basal area at our site (Andrews et al. 2012; Meinzer et al. 2007; Warren et al. 2005).

The fact that accumulated precipitation was not influential on groundwater level during either the wet or dry season was unexpected. A study in Illinois, USA found that the strongest temporal relationship between precipitation and groundwater occurred after a lag of one month, with lags of up to 2 months in Alfisol soils (Changnon et al. 1988). Alfisols are forest soils with generally thick forest floors and potentially large soil storage.

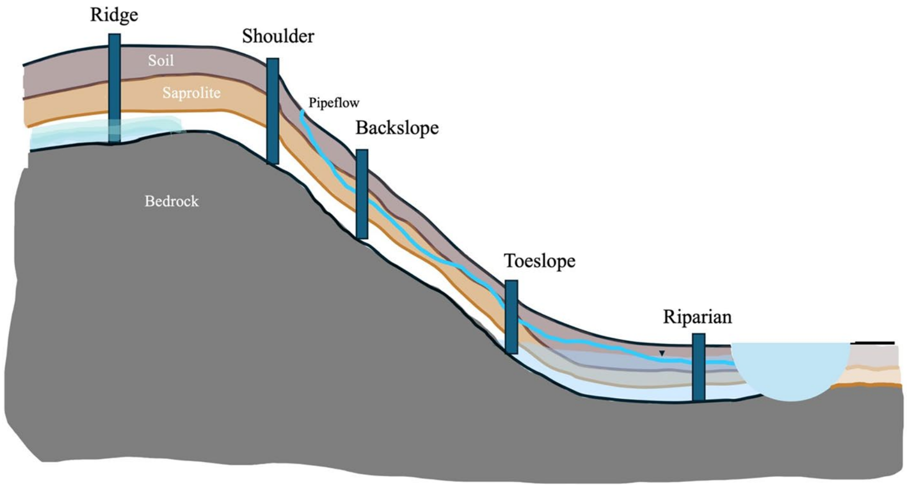

FIGURE 6 | A conceptual figure of the presence of groundwater at different hillslope positions and potential soil depths during wet conditions. Brown indicates soil, orange represents clay, grey represents saprolite/bedrock, and light blue represents groundwater. The darker blue line represents pipeflow, which occurs in these watersheds when the soil near the pipe inlet is at or near saturation.

Deeper soils also have a higher storage capacity as well. At Caspar Creek, where Alfisols are one of the main soil orders, a temporal lag may have hidden the relationship between groundwater and precipitation or reduced its importance in our random forest model either because of high storage or high interflow. Daily soil moisture at Caspar Creek has been found to respond quickly to rainfall and then drain quickly in the 15-, 30-, and 100-cm depths (Dymond, Wagenbrenner, et al. 2021). Another study at Caspar Creek found a lag of up to 100 h in some of the piezometers between rainfall start and groundwater response (McKeever 2025). Since soil depth was the most influential variable in our random forest models along with basal area, well depth, and slope, it is likely that soil water storage and interflow are highly important hydrologic drivers at Caspar Creek, which has been shown previously in pipeflow studies at the site (Albright 1992). Groundwater response may be concentrated along flow paths, and we may have captured more of these pathways in sub-watersheds WIL and TRE, which is why the correlation between annual precipitation may have been significant. Thus, the amount of rainfall may be less important at our site than how much of that rainfall percolates through the soil column to the groundwater and how much flows down the hillslope laterally.

4.3 | Harvesting and Groundwater Level

Though other studies have found increases in water table elevation after harvesting (Jutras et al. 2006; Ruprecht et al. 1991; Stoneman 1993) and our random forest model found basal area to be of moderate importance to groundwater level, we found no effect of harvesting on groundwater level. Unlike other studies that may have had too small a basal area reduction (2.8 $m^2 ha^{-1}$) to induce changes in groundwater level (Surfleet et al. 2020), the minimum basal area reduction in our study was around 14 $m^2 ha^{-1}$. Since net precipitation increased post-harvest in harvested sites at Caspar Creek (Keppeler unpublished data; Reid and Lewis 2009), this reinforces our findings that accumulated rainfall, and even the amount of rainfall reaching the soil was not an important factor for groundwater level in this study. Rather, geomorphic factors, like soil depth and slope, may be more important controls on groundwater level at Caspar Creek. Bachmair and Weiler (2012) found that at three adjacent hillslopes in Germany, soil properties and topography had the highest single explanatory factor when looking at shallow water table dynamics, and vegetative characteristics had a minor role. Again, this potentially means that vertical infiltration and lateral flow might be important factors at Caspar Creek for groundwater level. Alternatively, the two extremes of high amounts of precipitation in 2019 and below-average precipitation in 2021 (both post-harvest) may have masked the effects of the harvest on groundwater level. There may be a recovery period needed to make up for the deficit in groundwater storage (Whiting et al. 2023).

All sites had slightly higher groundwater during the post-harvest dry seasons, though the increase was not significant. One potential explanation is that the large amount of precipitation that fell in 2019 refilled the groundwater storage deficit at all sites; thus, when the post-harvest drought had less of an effect on all sites. Based on this, Caspar Creek may have relatively shallow subsurface storage pools, which means that if the storage is completely refilled each year, short-term droughts may have a less severe effect on groundwater and streamflow. Indeed, a study on why some areas in California survived a mega-drought found that sites limited by storage capacity did not experience significant tree mortality during the 2011–2016 drought compared to sites that were precipitation limited (Hahm et al. 2019). These storage-capacity limited sites are typical of much of the northern California coast (Hahm et al. 2019), which would include Caspar Creek.

Pipeflow also occurs at Caspar Creek and can be higher post-harvest (Ziemer and Albright 1987; Ziemer 1992). Pipeflow may begin when saturation reaches the pipe (Tsukamoto et al. 1982). The depth of soil pipes at Caspar Creek varies from 0.5 to 2 m (Ziemer and Albright 1987; Ziemer 1992). Since groundwater can be an important component in pipeflow (Vannoppen et al. 2017), some areas of hillslope groundwater level may be regulated by pipeflow. Thus, when groundwater reaches some threshold, pipeflow may activate, draining water towards the stream and preventing further groundwater rise (Sun et al. 2012). Anecdotal evidence suggests that the isotopic composition of stream discharge is decoupled from groundwater and is more closely related to the isotopic composition of precipitation, which may illustrate that pipeflow could impact groundwater levels at Caspar Creek.

5 | Conclusion

Seasonal groundwater level metrics (average, minimum, and maximum) varied spatially across the South Fork Caspar Creek, both among sub-watersheds and hillslope positions due to soil depth, slope, and well depth. We found that in both the wet and dry seasons, geomorphic characteristics, specifically soil depth, were the most influential factor for groundwater level. Though basal area was of moderate importance for the dry season groundwater level in particular, harvesting did not have a significant effect on either wet or dry season groundwater levels, which may be due to the large drought that occurred post-harvest. In a coast redwood forest, it appears that factors that affect vertical infiltration and lateral flow of rainfall, such as soil depth, depth to the confining layer, and slope, may be more important to groundwater than vegetative characteristics.

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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. **Table S1:** Wells that were dry greater than 95% and their sub-watershed, hillslope position, percentage of time the well was dry during their time-series (does not include NAs), and the maximum groundwater level (m) observed during the time series. **Table S2:** Random forest model variances explained: ntree = the number of trees, mtry = the number of variables tried at each split, maxnodes =, nodedepth = mean squared error (average of squared residuals), and the percentage of variance explained without the dry wells ($n = 12$). **Table S3:** Generalised linear mixed model outputs from using the average, minimum, and maximum groundwater level during the dry season as the dependent variables. **Table S4:** Generalised linear mixed model outputs from using the average, minimum, and maximum groundwater levels during the wet season as the dependent variables and site as a random effect. **Table S5:** Generalised linear mixed model outputs from applying a beta family distribution and logit link function with the proportion of days that groundwater was greater than 0 as the dependent variable during the dry season. **Table S6:** Generalised linear mixed model outputs from applying a beta family distribution and logit link function with the proportion of days that groundwater was greater than 0 as the dependent variable during the wet season. **Table S7:** Spearman's correlation examining the correlation between average groundwater level (m) and annual precipitation (mm) for all years (except the 2018 harvest period) excluding the eight dry wells ($n = 12$).