

## Article

# Mapping Inundation Dynamics and Hydrologic Ecosystem Service Indicators Across U.S. Conservation Sites Using Sentinel-2 and Machine Learning

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## Abstract

Conserved land represents an important mechanism for protecting ecologically sensitive lands while maintaining working landscapes. Despite their significance, nationwide tools for continuous hydrological monitoring of conservation easement lands remain limited. This study conceptualizes surface-water inundation as an indicator of hydrologic connectivity and ecosystem function, reflecting how water dynamics influence the resilience and ecological performance of conservation easement landscapes. We present a scalable framework to assess inundation dynamics across more than 340,000 conservation sites between 2018 and 2024 by integrating Sentinel-2 satellite imagery, Dynamic World land-cover data, and machine-learning classifiers (Support Vector Machine, Random Forest, and CART) within the Google Earth Engine platform. Spectral water indices (NDWI, MNDWI, and NDMI) were combined with Dynamic World classifications to generate quarterly inundation maps at 10 m spatial resolution, enabling consistent detection of surface-water presence across space and time. Among the evaluated classifiers, the Support Vector Machine (SVM) model achieved the highest performance in surface-water detection. Results reveal strong regional and seasonal variability in inundation patterns across conservation land. Higher inundation frequencies were observed in the Midwest, Gulf Coast, and Pacific Northwest, where wetland-associated easements showed persistent inundation (>50%) during spring and early summer, highlighting their role in supporting biodiversity, groundwater recharge, and flood mitigation. Overlay analysis with the National Wetlands Inventory (NWI) and SSURGO hydric soils confirmed a strong spatial correspondence between inundation occurrence and wetland-prone landscapes, extending the same Sentinel-2 and machine-learning framework to conservation land and enabling the first systematic cross-program comparison of hydrological dynamics across two major U.S. conservation mechanisms. This work highlights the critical role of conservation lands including Conservation Reserve Program (CRP) areas and conservation easements in supporting inundation dynamics and hydrological connectivity. These functions are essential for sustaining wetland habitats, maintaining water quality, and enhancing flood mitigation at the national scale.



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## 1. Introduction

Protected areas represent one of the most widely adopted strategies for conserving biodiversity and maintaining ecological integrity across landscapes. By limiting land conversion and protecting critical habitats, protected areas help reduce biodiversity loss, slow the extinction of threatened species, and preserve ecosystem services that support environmental stability [1–3]. Many studies have demonstrated that protected lands can significantly reduce habitat degradation and fragmentation compared with surrounding unprotected regions [1,4]. Protected areas also contribute to climate regulation, water resource protection, and landscape resilience under changing environmental conditions [5].

In the United States, the Protected Areas Database of the United States (PAD-US) serves as the official national inventory of protected terrestrial and marine lands, developed and maintained by the U.S. Geological Survey (USGS) in collaboration with federal, state, tribal, and non-governmental partners [6,7]. The database encompasses national parks, wildlife refuges, wilderness areas, land trust preserves, and conservation easements, forming a nationwide conservation network that supports biodiversity conservation, ecosystem management, and land-use planning [8–10]. Today, PAD-US includes more than three billion acres of terrestrial and marine areas classified according to ownership, designation, and conservation management objectives, with Version 4.0 released in 2024 representing the most comprehensive inventory to date [10–15].

A growing body of research has examined the environmental and ecological impacts of PAD-US lands. Studies have shown that terrestrial protected areas can help maintain vegetation extent and ecosystem condition across large landscapes [16]. Biodiversity declines have been associated with protected area downgrading, downsizing, and degazettement, highlighting growing conservation risks within protected land networks [16,17]. Efforts have also been made to expand the usability of PAD-US for recreation and accessibility planning through modified datasets such as PAD-US-AR, which identifies protected areas suitable for public outdoor activities [18]. Protected areas continue to face increasing human pressures such as land development and infrastructure expansion, which can undermine their ecological integrity [19]. Connectivity analyses are therefore used to identify ecological corridors and prioritize conservation efforts to maintain landscape connectivity and reduce fragmentation [12,20].

PAD-US lands also play an increasingly important role in climate mitigation and ecosystem resilience. Protected landscapes can contribute to national conservation targets such as the “30 × 30” initiative, which aims to conserve 30% of U.S. lands and waters by 2030 [21]. While some newly designated protected areas have shown limited improvements in ecological conditions or development pressures [22], biodiversity levels within protected lands are generally higher than those in surrounding landscapes [23]. Consequently, PAD-US functions as a critical national framework for conservation planning, biodiversity protection, and environmental policy development [24].

Beyond biodiversity conservation, protected lands play an increasingly recognized role in regulating hydrological processes and reducing flood risks, contributing directly to climate adaptation and landscape resilience [25,26]. Community-level flood exposure studies across the United States have further demonstrated how protected landscapes and surrounding land-use patterns interact with floodplain dynamics [27]. In the western United States alone, approximately 18.9% of land falls within PAD-US designations,

providing significant benefits for drinking-water protection, carbon storage, biodiversity conservation, and future carbon accumulation [28]. Protected lands also play an important role in climate mitigation through carbon sequestration [29]; forest losses between 1992 and 2001 were substantially lower in protected areas compared with unprotected landscapes, preventing nearly 7 Tg of carbon emissions annually [5].

Recent advances in remote sensing and machine learning have substantially improved the ability to monitor inundation dynamics and wetland hydrology across large conservation landscapes [30,31]. High-resolution satellite imagery, particularly from sensors such as Sentinel-2 and Landsat, has been widely used to map surface-water extent and seasonal flooding patterns in wetlands and floodplain environments [32–34]. Spectral indices such as the MNDWI and NDWI are commonly applied to enhance water detection and distinguish inundated areas from surrounding vegetation and built surfaces [32,35]. More recently, cloud-based platforms such as Google Earth Engine have enabled large-scale analysis of satellite time series to assess hydrologic variability and wetland dynamics over long periods [31,36]. Machine-learning approaches including SVM, RF, and decision-tree models have further improved classification accuracy for water and wetland mapping by integrating spectral, spatial, and temporal features from multisource datasets [37–40]. Global and regional studies using these techniques have successfully quantified inundation frequency, floodplain dynamics, and wetland persistence across large landscapes [33,41–43]. Despite these advances, applications specifically focused on conservation easement lands remain limited, highlighting the need for scalable remote-sensing frameworks capable of continuously monitoring hydrologic conditions within protected landscapes.

Despite the ecological importance of protected lands, large-scale assessments of hydrological dynamics within PAD-US conservation easement sites remain critically limited. Most previous studies have focused on biodiversity, connectivity, or land management [8,12,14], while the spatiotemporal behavior of surface-water inundation across easement landscapes has received comparatively little attention. Nationwide tools for continuous hydrological monitoring of conservation easements are largely absent, and no study to date has systematically quantified inundation dynamics across the full portfolio of PAD-US easement sites at high spatial resolution. This gap is particularly significant given that many conservation easements are specifically established to protect and restore wetland ecosystems, where hydrologic function is the primary determinant of ecological performance. In this study, we develop a scalable remote-sensing framework that integrates Sentinel-2 imagery, Dynamic World land-cover data, and machine-learning classification to quantify inundation dynamics across more than 340,000 PAD-US conservation easement sites from 2018 to 2024. By combining satellite-derived water indices with ecological reference datasets including the National Wetlands Inventory (NWI) and Soil Survey Geographic Database (SSURGO) hydric soils, the analysis provides a spatially explicit evaluation of how hydrologic variability influences the ecological functioning of conservation easements. The study addresses three key questions: (1) How effectively can satellite-derived indicators represent the spatial and temporal inundation dynamics of PAD-US conservation lands? (2) How do seasonal and interannual inundation patterns vary across conservation sites landscapes between 2018 and 2024, particularly in relation to wetland inventories and hydric soils? (3) How can remote sensing-based inundation mapping support strategic conservation planning and prioritization of hydrologically valuable conservation lands?

## 2. Methodology and Data Collection

### 2.1. Study Area

The study area consists exclusively of conservation easement sites contained within the PAD-US database. Easements represent conservation lands specifically established to

restore and protect wetland ecosystems, and they typically include hydrologically sensitive landscapes such as floodplains, depressional wetlands, and riparian zones (Figure 1). These areas are particularly suitable for inundation analysis because surface water presence within sites is inherently dynamic, varying seasonally and in response to climatic variability and extreme events. Many conservation easements parcels are in low-lying terrain with strong surface water groundwater interactions, making them effective indicators of hydrologic change and wetland functioning. By focusing on conservation easements, this study targets landscapes where inundation patterns directly influence habitat quality, ecosystem processes, and restoration outcomes, thereby providing a focused framework for evaluating wetland hydrology and informing conservation and management strategies.

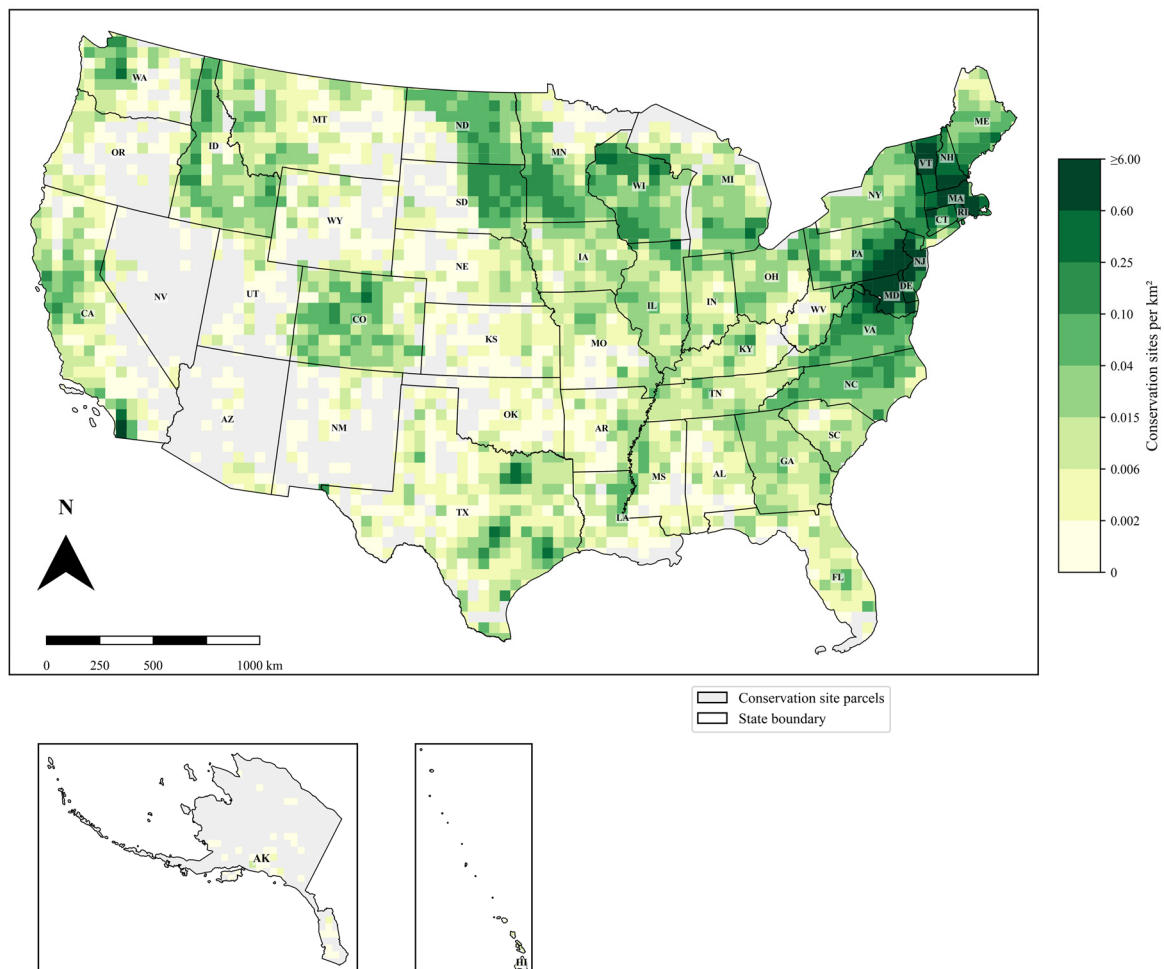


**Figure 1.** Spatial distribution of conservation easement sites across the United States (subset of the PAD-US database).

A total of 341,826 conservation easement sites were extracted from the PAD-US database, representing a nationwide network of lands dedicated to wetland restoration and conservation. Easement sites sizes vary substantially, ranging from very small parcels to large landscape-scale units exceeding 307,000 hectares, reflecting differences in restoration scope, ownership patterns, and hydrologic settings. This pronounced variability in site area underscores the importance of assessing inundation dynamics across multiple spatial scales, as water persistence and hydrologic responses can differ markedly between smaller tracts and extensive wetland complexes. Focusing on this extensive portfolio of conservation easements provides a strong basis for evaluating national-scale patterns of wetland inundation and their implications for ecosystem functioning and conservation outcomes.

The state-level summary of conservation easement sites reveals substantial geographic variability in both the number and size of protected areas across the United States (Table S1). States such as Maryland, Massachusetts, Vermont, and Pennsylvania contain exceptionally large numbers of small-sized protected parcels, reflected in low minimum areas and small standard deviations. In contrast, states like Alaska, New Mexico, Montana, Texas, and Maine include fewer but significantly larger protected areas, with maximum site sizes exceeding tens of thousands of hectares and correspondingly high variability. This diversity highlights the heterogeneity of the national conservation landscape, where some states are dominated by extensive wilderness units and others by numerous small community-managed or municipal parcels. Understanding this state-wise variation is critical for interpreting inundation dynamics, as hydrologic behavior and exposure to flooding may differ substantially between states dominated by small, fragmented parcels versus those containing large contiguous conservation areas. Such variability underscores the importance of evaluating inundation patterns at both national and state scales to capture landscape-specific flood responses, conservation priorities, and management needs.

## 2.2. Data Collection and Processing

Accurate characterization of surface-water inundation requires the integration of multi-temporal and multi-source satellite observations capable of capturing seasonal hydrologic variability across large landscapes. In this study, open-access Earth observation datasets were used to quantify inundation dynamics across conservation easement lands in the USA. Surface water conditions were derived using a combination of the Dynamic World land-cover dataset [44] and Sentinel-2 multispectral imagery for the period 2018–2024. This temporal window corresponds to the operational availability of both datasets and enables consistent generation of cloud-free image composites suitable for multi-seasonal hydrologic analysis. Although the seven-year study period represents a relatively recent timeframe, it captures substantial climatic variability across wet and dry years, providing a robust baseline for evaluating short-term inundation dynamics and supporting future monitoring efforts.

Dynamic World land-cover data, available through Google Earth Engine (GEE) [45] as `ee.ImageCollection("GOOGLE/DYNAMICWORLD/V1")`, provide near-real-time global land-cover classifications at a spatial resolution of 10 m. These data were integrated with Sentinel-2 Harmonized imagery (`ee.ImageCollection("COPERNICUS/S2_HARMONIZED")`) to improve the spatial and temporal detection of surface-water inundation [46]. Easement sites boundaries were obtained PAD-US database [11].

Spectral indices derived from Sentinel-2 optical bands were used to enhance the identification of inundated surfaces. The Modified Normalized Difference Water Index (MNDWI), calculated using the green and shortwave infrared (SWIR) bands, was used as the primary feature for detecting surface-water presence [32,47]. MNDWI improves the detection of open water by suppressing signals from vegetation and built-up areas, thereby enhancing water land contrast [32]. MNDWI is expressed as a normalized ratio of green and shortwave infrared (SWIR) reflectance.

Additional indices were incorporated to capture complementary hydrologic and vegetation signals. The Normalized Difference Moisture Index (NDMI) [48], derived from near-infrared and SWIR bands, was used to characterize vegetation moisture conditions, while the Normalized Difference Water Index (NDWI), calculated using green and near-infrared bands, supported the detection of surface wetness and shallow water features. Together, these indices provide a robust spectral framework for identifying inundation patterns across heterogeneous landscapes, with NDMI also helping to capture moisture conditions in vegetated and transitional wetland areas where surface water may not be fully visible [49].

To place the satellite-derived inundation patterns within an ecological context, additional geospatial datasets describing wetland distribution were incorporated. The NWI layer was used as a baseline reference to identify potential wetland areas across the study region [50,51]. NWI wetland delineations are derived from aerial imagery interpretation supported by field verification and are periodically updated as new imagery becomes available [51]. However, the timing of these updates varies geographically, with some regions mapped using imagery from earlier decades and others updated more recently. Consequently, the NWI dataset was used primarily as a reference layer to indicate potential wetland zones rather than as a representation of current wetland conditions during the 2018–2024 study period.

To further examine the relationship between inundation patterns and underlying landscape characteristics, surface-water inundation frequency was compared with the hydric soil layer from the SSURGO. SSURGO provides detailed soil attribute information including drainage class, texture, and hydric soil designation, with many surveys updated through 2024 [52]. Because these soil properties generally remain stable over long time periods, SSURGO provides a reliable baseline for evaluating hydrologic potential during the study period. Hydric soils characterized by prolonged saturation and anaerobic conditions during the growing season are widely recognized indicators of areas naturally conducive to wetland formation. By integrating remotely sensed inundation patterns with soil-based hydrologic indicators, the analysis enables a more comprehensive assessment of how conservation easement lands correspond with landscapes possessing inherent wetland potential.

### 2.3. Research Framework

This study evaluates surface-water inundation dynamics across conservation easement lands using an integrated workflow that combines remote sensing, machine learning, and geospatial analysis, as illustrated in Figure 2. Surface water conditions were derived from Sentinel-2 multispectral imagery (10 m spatial resolution) and the Dynamic World land-cover dataset, both accessed through the GEE platform. Sentinel-2 imagery was first preprocessed to remove cloud and shadow contamination using the s2cloudless algorithm, after which seasonal composite images were generated for the period 2018–2024 to capture multi-seasonal hydrologic variability. To improve the identification of inundated areas, spectral indices including the MNDWI, NDWI, and NDMI were derived from Sentinel-2 green, near-infrared, and shortwave infrared bands [32,47]. These indices were combined with Dynamic World probabilistic land-cover outputs, particularly water and flooded vegetation classes, to enhance the discrimination of open water and mixed inundated conditions. In addition, ecological context was incorporated using the NWI and SSURGO hydric soil datasets, which provide baseline information on wetland distribution and soil-based hydrologic potential [50–52].

Following preprocessing, a feature stack was constructed using Sentinel-2 spectral bands, derived indices, and Dynamic World probabilities, which served as inputs for model development. A labeled dataset of approximately 50,000 samples was generated from manually delineated polygons representing five land-cover classes: water, vegetation, bare soil, built surfaces, and snow. The dataset was randomly divided into 75% for model training and 25% for validation to ensure reliable performance assessment. Supervised classification was then implemented within GEE using three machine learning algorithms SVM, RF, and CART. The SVM model was applied to capture non-linear relationships between spectral features and land-cover classes, while RF and CART model parameters were selected based on previously published studies to optimize classification performance and minimize overfitting [53–55]. To better represent mixed land–water conditions, a

sub-pixel water fraction approach was implemented by integrating spectral indices with Dynamic World probabilities for water and flooded vegetation classes, enabling estimation of partial inundation within each 10 m pixel.

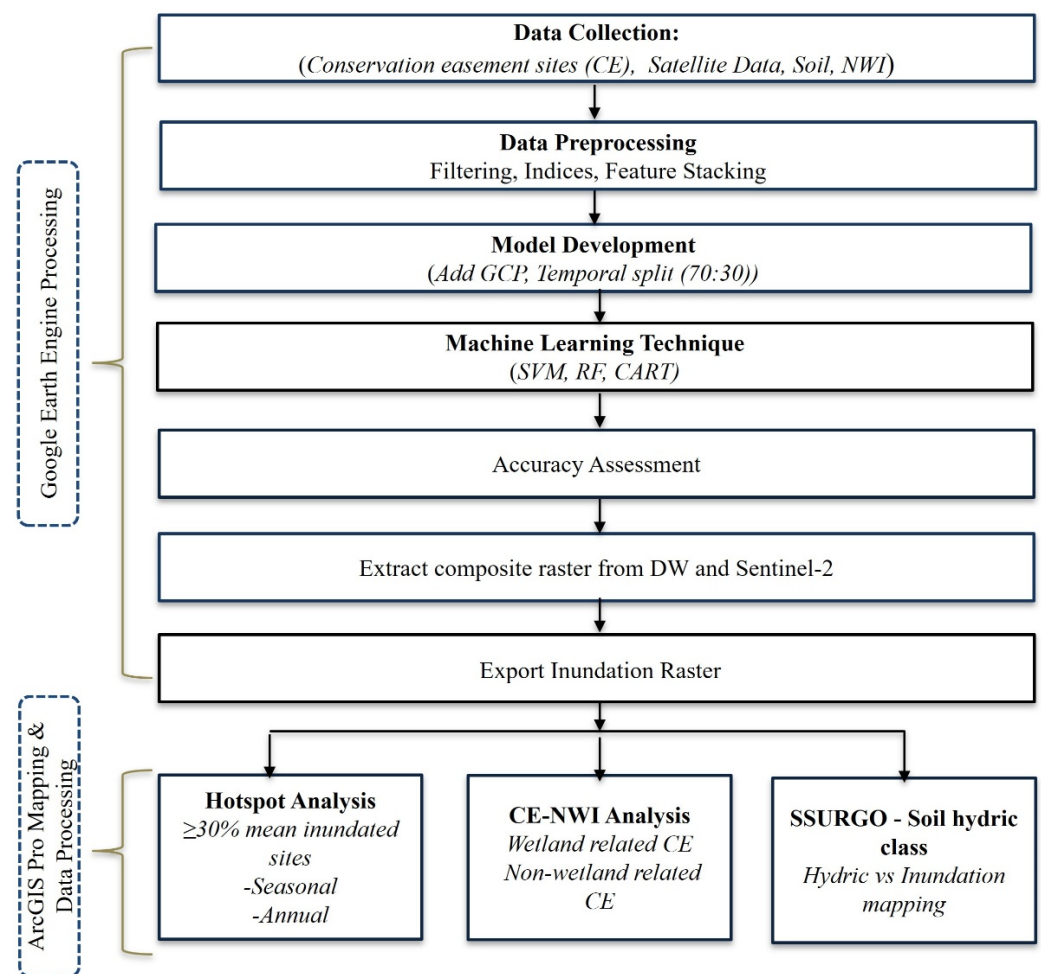


**Figure 2.** Integrated Workflow for Inundation Mapping and Multi-Scale Spatial Analysis of Conservation Easement sites.

Model performance was evaluated using both training and independent validation datasets. The confusion matrix from the training phase (Figure 3a) shows strong separability among the five land-cover classes water, vegetation, bare soil, built-up areas, and snow, demonstrating the effectiveness of Sentinel-2 spectral features and water indices in distinguishing inundated surfaces. The validation error matrix (Figure 3b) further confirms the robustness of the models, with high classification accuracy and limited misclassification across validation samples. Among the evaluated algorithms, SVM and RF exhibited consistent and stable performance, while CART showed comparatively higher training accuracy than validation accuracy, indicating potential overfitting. Based on these results, SVM was selected for generating the final inundation outputs. The resulting classified layers were used to extract composite inundation rasters from Sentinel-2 and Dynamic World data, which were then exported for further geospatial analysis. Given the 10 m spatial resolution of Sentinel-2, the derived surface-water extent is considered sufficiently accurate for regional- and national-scale hydrological assessments, particularly for identifying seasonal inundation patterns and hotspot regions, although very fine-scale variations may not be fully captured. The final inundation datasets were subsequently used to quantify spatial and temporal patterns of surface water across conservation easement sites and to support

downstream analyses, including hotspot identification, conservation easements–NWI comparisons, and hydric soil–inundation relationships, thereby providing a comprehensive assessment of hydrologic dynamics across protected landscapes.

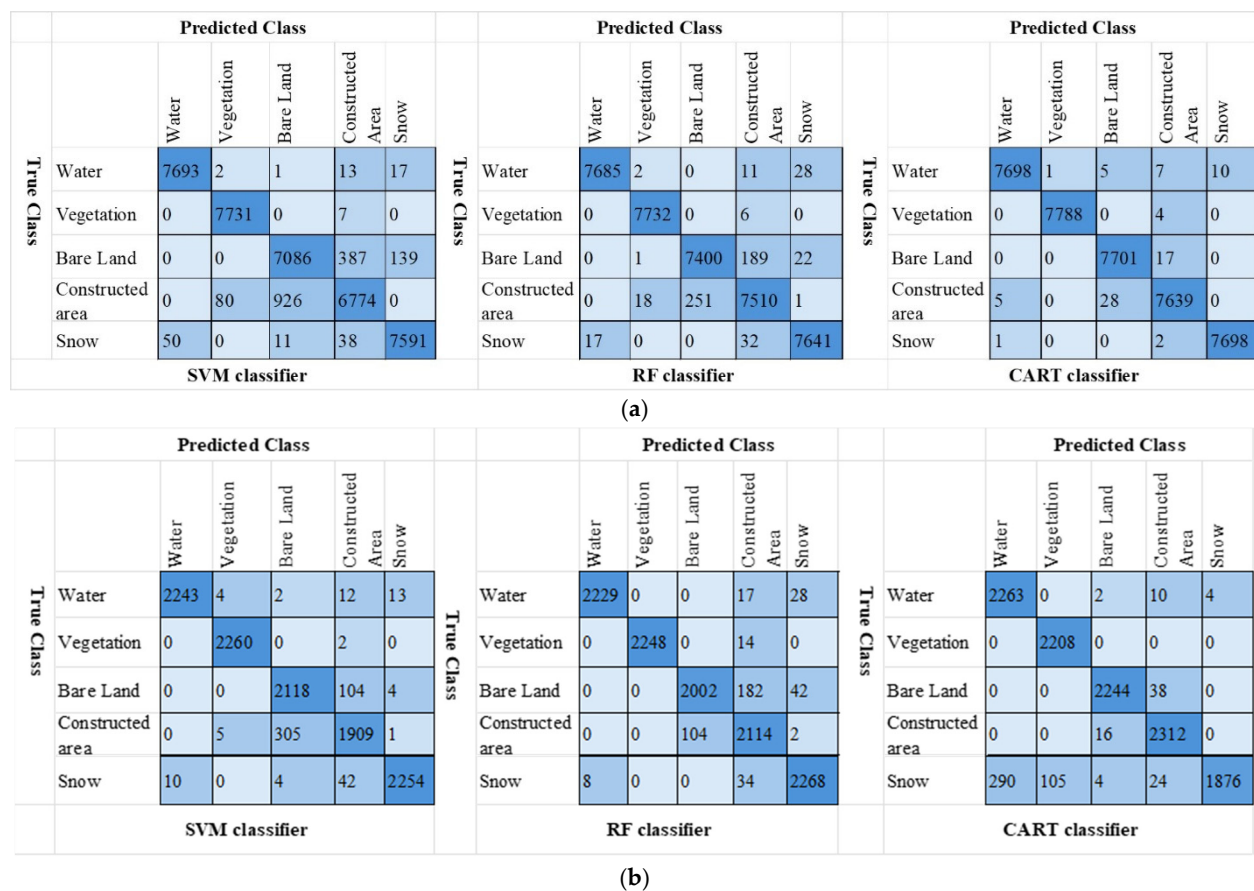


**Figure 3.** (a) Heatmaps of confusion matrices showing training performance of SVM, RF, and CART classifiers. Diagonal values indicate correct classifications across water, vegetation, bare land, constructed areas, and snow, while off-diagonal values represent misclassifications. (b) Heatmaps of validation confusion matrices for SVM, RF, and CART classifiers. Diagonal values show correct classifications, while off-diagonal values indicate errors. The blue color gradient represents the number of samples in each confusion matrix cell; darker blue indicates higher counts, and lighter blue indicates lower counts.

A comparative assessment of classifier performance (Figure 4) shows that both SVM and RF achieved high and stable training and validation accuracies, indicating strong generalization capability. In contrast, the CART model exhibited substantially higher training accuracy relative to validation accuracy, suggesting potential overfitting during model training. Finally, the relative importance of predictor variables derived from Random Forest and CART models (Figure 5) highlights the dominant role of spectral water indices and key Sentinel-2 bands in identifying inundated surfaces. Indices such as MNDWI, NDWI, and NDMI, along with shortwave infrared and visible bands, contributed strongly to classification performance, confirming their effectiveness for detecting open water and flooded vegetation in conservation landscapes. The gap between CART's training and validation accuracy reflects its inherent susceptibility to overfitting compared to SVM and RF [37,39]. Additionally, spectral overlap between snow, water, and constructed surfaces in the NDWI feature space contributes to CART's higher misclassification rate during validation, an ambiguity that MNDWI's SWIR-based formulation helps mitigate in the more generalizable SVM and RF classifiers [32,54].

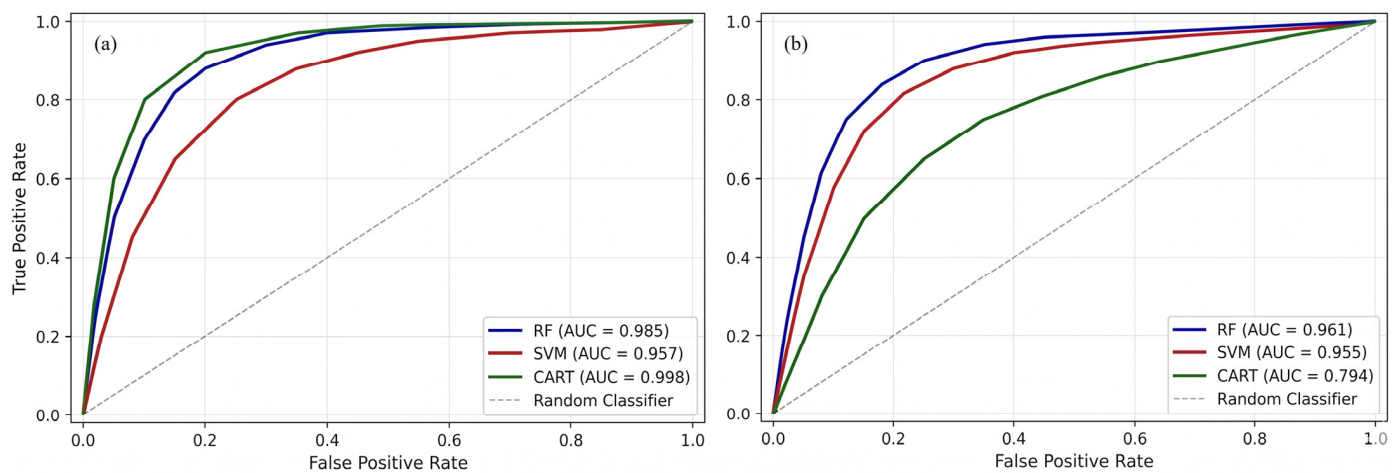


**Figure 4.** Comparative analysis of training (a) and validation (b) accuracies across SVM, RF, and CART classifiers.

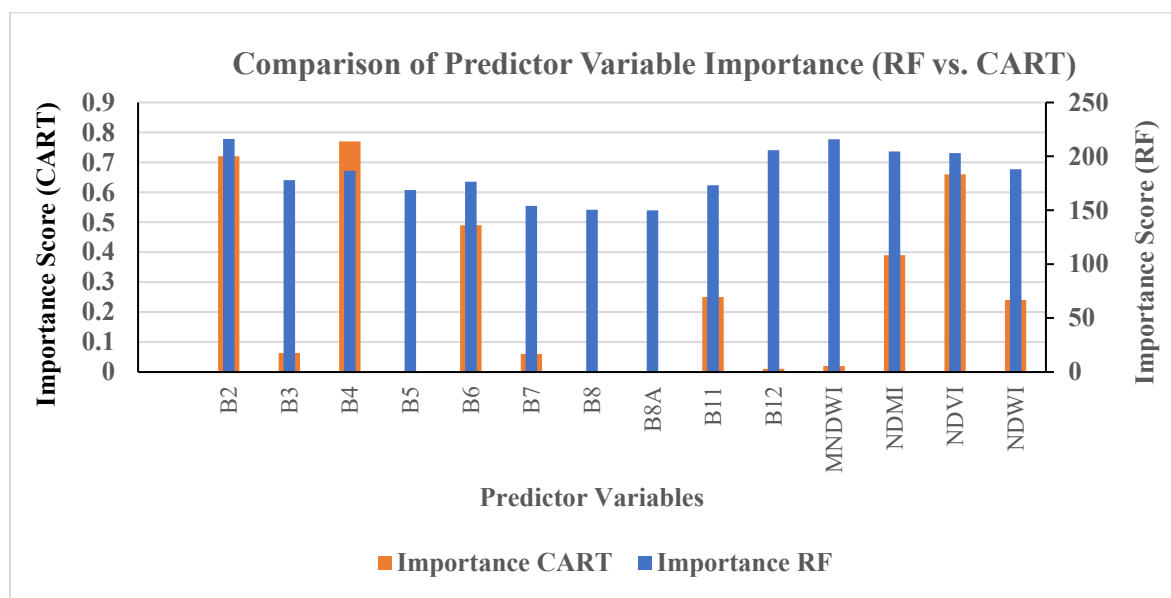


**Figure 5.** Relative importance of predictor variables (Sentinel-2 bands and spectral indices) derived from Random Forest (RF) and CART classifiers.

Given its consistent performance, SVM classifier was selected for subsequent analyses. Quarterly composites (2018–2024) were used to compute long-term inundation frequency at 10 m resolution, expressed as percentage inundation. To ensure consistency, inundation metrics were defined at the conservation easement site level using seasonal composites. The study period (2018–2024) was divided into four seasons as Season 1 (March–May), Season 2 (June–August), Season 3 (September–November), and Season 4 (December–February), and seasonal composites were generated for each year. Inundation frequency was calculated as the proportion of seasonal observations in which surface water was detected at a given site relative to the total number of seasonal observations across the study period. Inundation percentage represents the mean proportion of inundated pixels within each site for a given season or across all years. A combined inundation map (2018–2024) was generated by averaging seasonal inundation values across all years. For hotspot analysis, conservation easement sites with mean inundation  $\geq 30\%$  were classified as hydrologically active hotspots, representing areas with relatively high and persistent surface water presence. All data and code used in this study are publicly available at <https://doi.org/10.5281/zenodo.19891607> [56].

Furthermore, to examine the climatic controls on surface-water inundation across conservation easement lands, seasonal precipitation patterns were derived from the NOAA nClimGrid monthly precipitation archive, a 5 km gridded climate dataset produced by the National Centers for Environmental Information (NCEI) [57,58]. Monthly precipitation data (2018–2024) were processed in Python using xarray, geopandas, and rioxarray to generate spatially consistent gridded precipitation fields across the United States. The 2025 TIGER/Line state boundary dataset was reprojected to the WGS84 coordinate system and used as a spatial mask to exclude non-terrestrial grid cells beyond the U.S. boundary [59–62]. Monthly precipitation grids were grouped into the four standard climatological seasons March–May (MAM), June–August (JJA), September–November (SON), and December–February (DJF) and precipitation totals were aggregated across the seven-year study period to produce mean seasonal precipitation surfaces. Final precipitation maps were generated using Cartopy with a Plate Carrée projection, enabling spatially explicit visualization of hydro-climatic patterns and supporting interpretation of inundation dynamics across conservation easement sites [63,64].

### 3. Results

Inundation dynamics across conservation easement sites exhibit strong and predictable spatiotemporal structure driven by the interaction of regional hydroclimatic regimes, physiographic setting, and seasonal precipitation patterns (Figure 6). This structure is not uniform across the country rather; it reflects fundamental contrasts between hydrologically connected landscapes in the east and climatically arid environments in the west. Hotspots, defined as sites exhibiting  $\geq 30\%$  inundation frequency, are widely distributed but show pronounced regional clustering that varies by season. Inundation hotspots are most extensive in the Upper Midwest and Mississippi River Basin during spring (Season1), reflecting snowmelt-driven hydrologic inputs and seasonal precipitation peaks. In Season 2, the spatial extent of hotspots contracts slightly in northern regions but intensifies in parts of the Gulf Coast and central plains, consistent with convective storm activity and summer hydrologic variability. Season 3 shows a redistribution of hotspots, with notable concentrations along major river corridors and coastal areas, likely influenced by late-season rainfall and tropical systems. In Season 4, hotspots persist primarily in southern and coastal regions, while northern areas exhibit reduced inundation frequency due to frozen conditions and lower surface runoff. The combined analysis for 2018–2024 highlights persistent multi-year hotspots concentrated along major hydrologic systems, including the Mississippi Alluvial Valley, Great Lakes region, Gulf Coast, and Atlantic coastal plains. These patterns indicate that inundation within conservation easements is strongly controlled by regional hydroclimatic regimes and physiographic settings. Overall, the results demonstrate that while seasonal variability is evident, certain landscapes consistently experience higher water persistence, underscoring their importance for wetland function, floodwater storage, and habitat provisioning. This spatiotemporal consistency suggests that long-term inundation monitoring can effectively identify priority areas for wetland management, restoration evaluation, and climate resilience planning.

Critically, the contrast between the persistently inundated easements of the Mississippi Alluvial Valley and Gulf Coast where spring precipitation and snowmelt drive sustained surface water presence and the episodically inundated sites of the Great Plains and western United States where limited precipitation and high evapotranspiration restrict water persistence illustrates how regional hydroclimatic gradients fundamentally control the hydrologic performance of conservation easements across the national network.

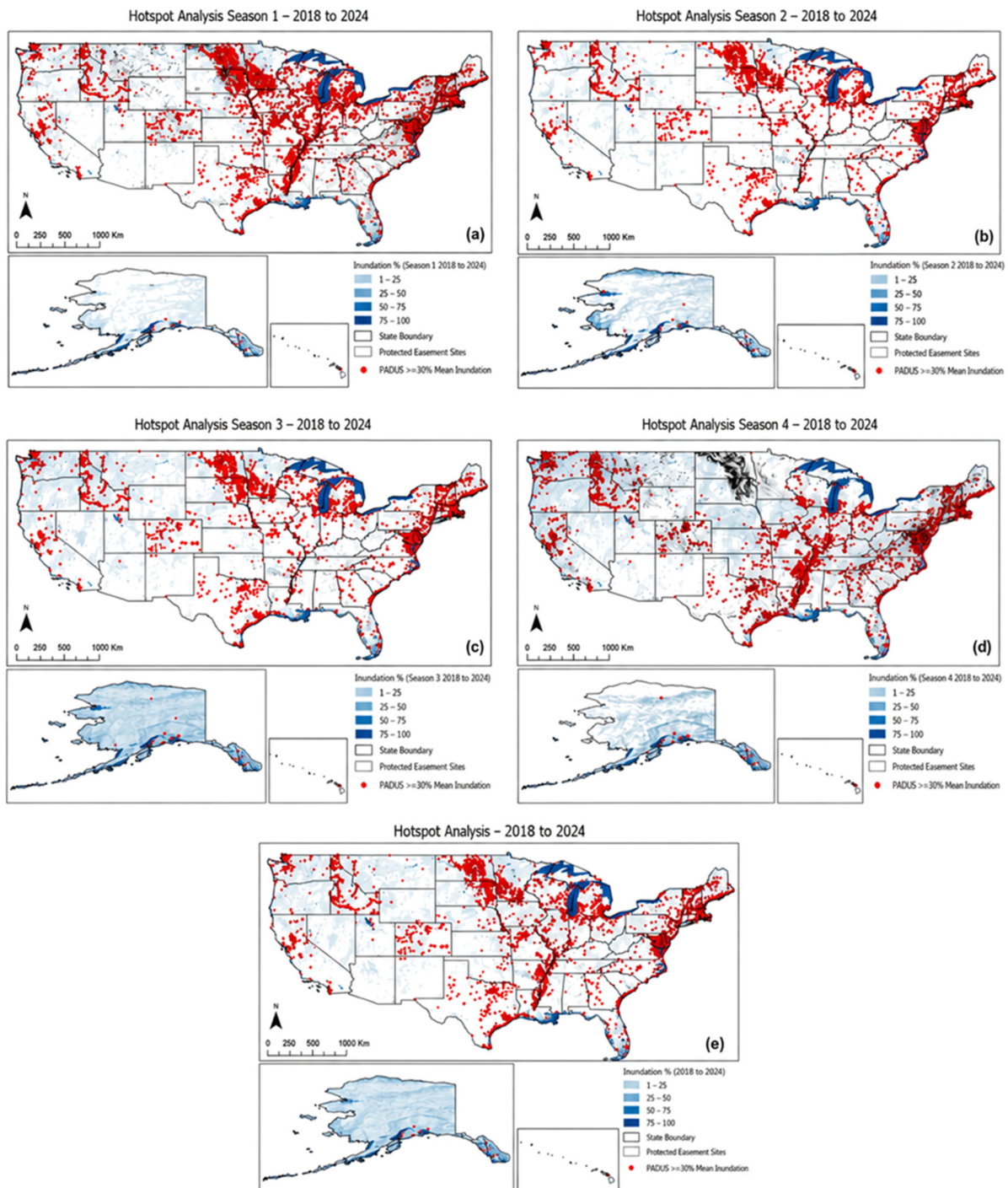


**Figure 6.** Seasonal and multi-year inundation hotspot distribution across conservation easement sites in the United States (2018–2024). Panels (a–d) show seasonal hotspot locations for Season 1 (March–May), Season 2 (June–August), Season 3 (September–November), and Season 4 (December–February), respectively, while panel (e) presents the combined multi-year hotspot pattern. Red points represent conservation easement sites exhibiting  $\geq 30\%$  inundation frequency, overlaid on mean inundation intensity, illustrating spatiotemporal variability and persistent hydrologic concentration zones across major river basins and coastal regions.

Hydrologic connectivity to surface waterbodies emerges as a primary mechanistic control on inundation behavior across conservation easement sites, with sites intersecting rivers, lakes, or other surface water features showing consistently and significantly higher inundation than non-intersected sites across nearly all states (Figure 7). This pattern is mechanistically expected; direct floodplain and riparian connectivity provides lateral water

inputs during high-flow periods that sustain inundation well beyond what local precipitation alone could maintain. Across most states, sites intersecting rivers, lakes, or other surface water features exhibit higher mean inundation percentages and greater variability, reflecting stronger and more direct hydrologic connectivity. In contrast, non-intersected sites generally show lower mean inundation levels, with more moderate dispersion, suggesting that water presence at these locations is driven primarily by local precipitation, topography, or shallow groundwater rather than direct surface water influence. Notably, several states display pronounced increases and wider error ranges for intersected sites, highlighting the role of adjacent waterbodies in amplifying both the magnitude and variability of inundation. Overall, these results demonstrate that proximity to surface water is an important control on conservation easement hydrology, reinforcing the significance of hydrologic connectivity in shaping wetland water persistence and functional performance across diverse geographic settings.

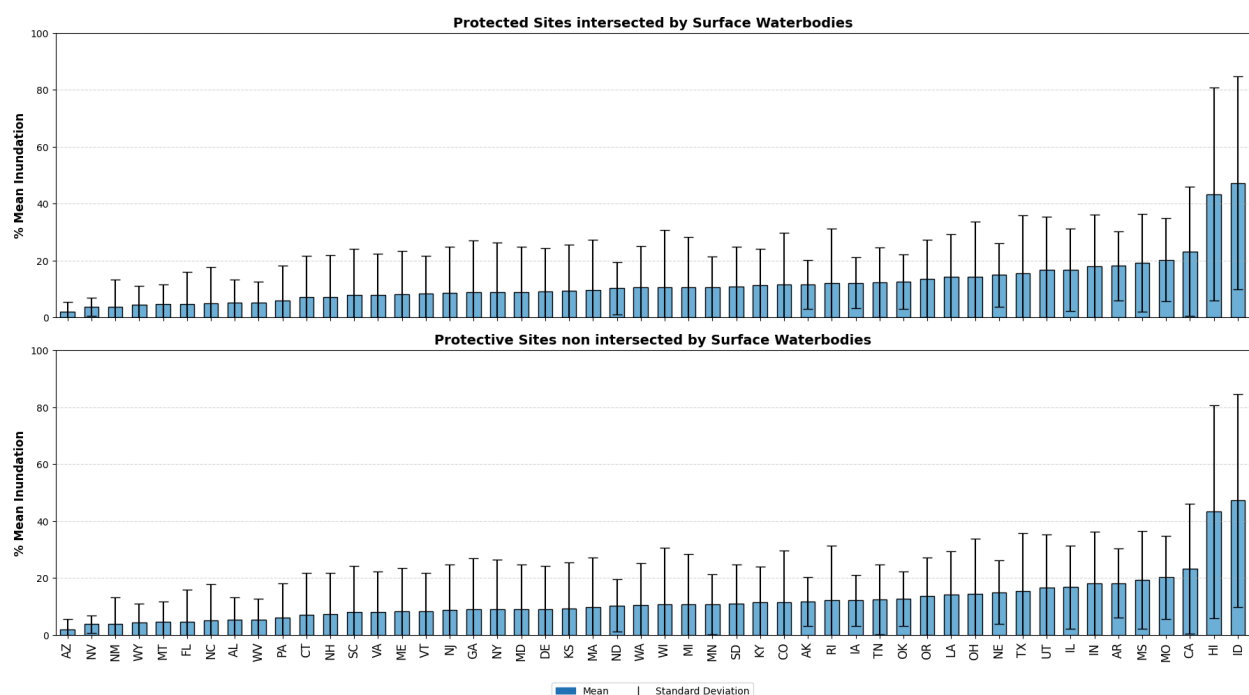


**Figure 7.** State-level comparison of mean inundation across conservation easement sites intersecting and not intersecting mapped surface waterbodies. The upper panel shows the mean inundation percentage ( $\pm$ standard deviation) for sites with direct spatial intersection with surface water features, while the lower panel presents the same metric for sites without such intersection. The comparison highlights the influence of hydrologic connectivity on inundation magnitude and variability across states.

The influence of pre-existing wetland landscape context on inundation behavior is clearly demonstrated by the systematic difference in inundation frequency between NWI-designated and non-NWI easement sites across all 50 states (Figure 8). This finding has an important mechanistic implication on conservation easements placed within historically mapped wetland environments that inherit the hydrologic infrastructure of those landscapes, including depressional topography, hydric soils, and shallow water tables, all of which collectively sustain inundation independently of short-term precipitation variability. Sites within the NWI layer exhibit notably higher mean inundation percentages and broader variability, indicating stronger and more persistent surface water presence associated with mapped wetland environments. In contrast, easement sites outside the NWI footprint generally display lower inundation levels and reduced dispersion, suggesting more intermittent or localized hydrologic conditions. The magnitude of this contrast

varies regionally but remains evident across most states, highlighting the role of existing wetland landscapes in enhancing water retention and hydrologic connectivity. Overall, these findings demonstrate that alignment with NWI-designated wetlands is a significant determinant of inundation behavior, reinforcing the importance of wetland context in shaping restoration performance and hydrologic function within conservation easements.

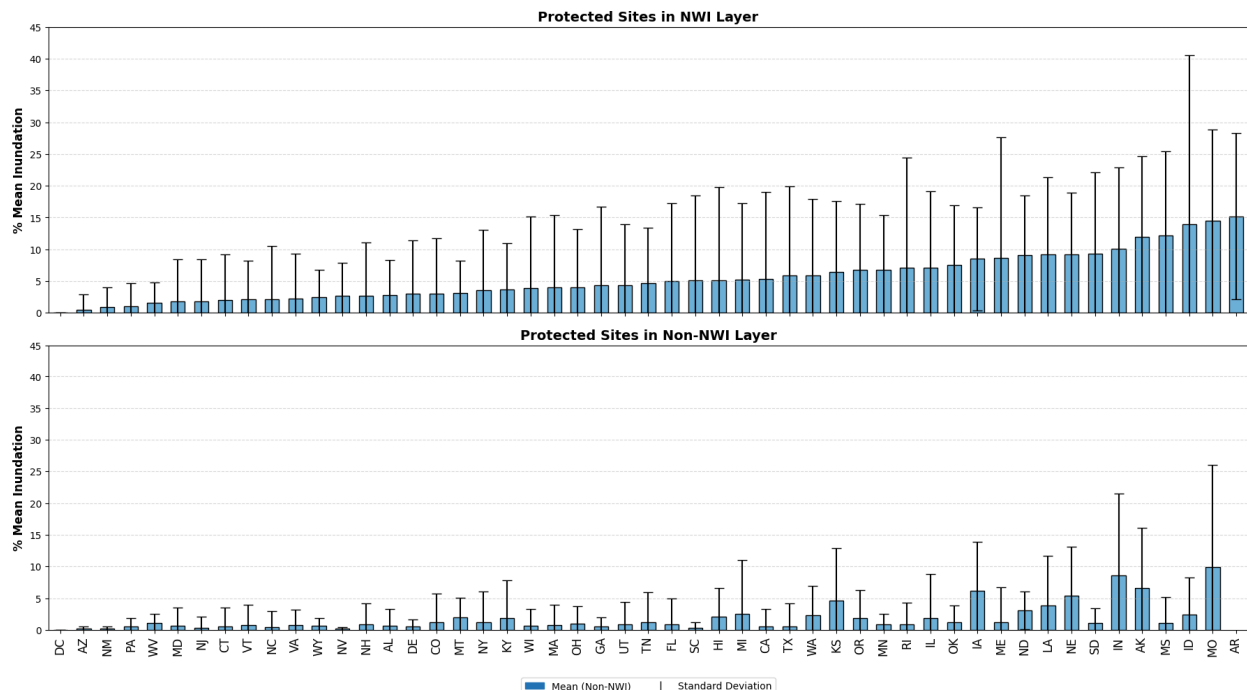


**Figure 8.** Comparison of mean inundation across conservation easement sites within and outside NWI mapped wetlands. The upper panel shows state-level mean inundation percentages ( $\pm$  standard deviation) for conservation sites intersecting the NWI layer, while the lower panel presents the same metric for sites outside NWI polygons. The figure illustrates the influence of mapped wetland context on inundation magnitude and variability across the United States.

Paired-sample *t*-test is used to compare mean inundation frequency between waterbodies and non-waterbodies at the state level [65]. This test evaluates whether the average difference between paired observations (i.e., within the same state) is significantly different from zero. Wilcoxon signed-rank test was also conducted as a robustness check [66]. The paired sample *t*-test indicate that inundation frequency was significantly higher in waterbodies compared to non-waterbodies within states ( $t(49) = 7.23$ ,  $p < 0.005$ ) (Table 1). The mean paired difference was 8.23 (95% CI [5.94, 10.51]).

Across the 50 states, paired comparisons showed consistently higher inundation frequencies in both water-related and protected site categories. Inundation was significantly greater in mapped waterbodies than in non-waterbodies ( $t(49) = 7.23$ ,  $p < 0.005$ ), with a mean paired difference of 8.23 and a 95% confidence interval (CI) of 5.94–10.51, confirming a clear hydrologic distinction between these land-cover classes. Similarly, NWI-easement sites exhibited markedly higher inundation than non-NWI easement sites (mean = 5.3 vs. 1.8), yielding a significant paired difference of 3.5 ( $t(49) = 9.8$ ,  $p < 0.001$ ; 95% CI: 2.8–4.3). The consistency of these results across parametric and non-parametric tests indicates robust evidence that both designated waterbodies and protected wetland areas experience substantially greater inundation relative to their counterparts. These statistical findings directly address the second research question of this study, demonstrating that inundation patterns across conservation easement lands vary systematically and significantly in relation to both mapped wetland inventories and surface water proximity with

wetland-designated and waterbody-intersecting sites consistently exhibiting stronger and more persistent hydrologic behavior across all 50 states.

**Table 1.** *T*-test comparison of mean inundation between conservation easement sites located within and outside mapped water bodies, and between sites overlapping the NWI and non-NWI areas.

| Measure                                       | N (States) | Mean | SD   | SE   | Test/Statistics | <i>p</i> Value         | 95% CI for Mean Difference |
|-----------------------------------------------|------------|------|------|------|-----------------|------------------------|----------------------------|
| Waterbodies                                   | 50         | 12   | 8.3  | 1.12 |                 |                        |                            |
| Non-Waterbodies                               | 50         | 4    | 3.2  | 0.5  |                 |                        |                            |
| Paired Difference                             | 50         | 8.2  | 8    | 1.14 | $t(49) = 7.2$   | $2.88 \times 10^{-9}$  | [5.9, 10.5]                |
| Overlay with National Wetland Inventory layer |            |      |      |      |                 |                        |                            |
| NWI-Easements                                 | 50         | 5.3  | 3.5  | 0.5  |                 |                        |                            |
| Non-NWI-Easements                             | 50         | 1.8  | 2.14 | 0.3  |                 |                        |                            |
| Paired Difference                             | 50         | 3.5  | 2.5  | 0.4  | $t(49) = 9.8$   | $3.92 \times 10^{-13}$ | [2.8, 4.3]                 |

Out of a total of 341,826 conservation sites evaluated, 112,398 sites (32.9%) experienced surface water inundation at least once during the seven-year analysis period. A substantial proportion of sites exhibited low-frequency inundation, with 28,880 sites (25.7%) showing water presence in only one year, indicating predominantly episodic or transient inundation. The number of sites decreases for two years (15,858; 14.1%) and three years (12,342; 11.0%), suggesting that persistent multi-year inundation is less common across PADUS lands. Notably, a secondary peak is observed for four years (19,826; 17.6%) and six years (19,103; 17.0%) of inundation, reflecting a subset of sites with moderate to high inundation recurrence, likely associated with hydrologically connected wetlands, floodplain systems, or managed conservation areas. Sites inundated in five years account for 12,488 (11.1%), while only 3901 sites (3.5%) exhibited water presence in all seven years, representing the most persistently inundated easement locations. Overall, these results indicate strong heterogeneity in hydrologic behavior across easement sites, with most inundated areas experiencing intermittent rather than permanent water presence, and a smaller fraction functioning as consistently wet or semi-permanent aquatic systems. This stratification of inundation frequency provides a robust basis for distinguishing episodic, seasonal, and persistent water-dependent conservation lands in subsequent ecological and management analyses.

The results reveal a coherent national pattern in which inundation frequency across conservation easement lands is governed by three interacting controls, regional hydro-climatic forcing, landscape hydrologic connectivity, and inherent wetland soil properties. Sites in the humid eastern United States, particularly those intersecting waterbodies and overlapping NWI-designated wetlands, consistently show the highest and most persistent inundation, reflecting both greater precipitation inputs and stronger landscape-level hydrologic memory. In contrast, sites in arid and semi-arid regions, or those disconnected from surface water networks, exhibit episodic and climatically driven inundation with limited persistence. This tripartite control structure explains the strong heterogeneity in inundation behavior observed across the 341,826 easement sites evaluated and provides a mechanistic foundation for interpreting regional and seasonal differences throughout the analysis.

### 3.1. Overlay Analysis of Hydric Soil Distribution and Inundation Patterns in Conservation Easement Sites

Figure 9 illustrates the spatial distribution of conservation easement sites across the United States based on the combined classification of hydric soil occurrence and satellite-

derived surface-water inundation levels. The SSURGO hydric soil dataset was harmonized with the inundation layer to enable a consistent spatial comparison between soil hydrologic properties and observed water dynamics. Conservation easement sites were grouped into five categories representing different combinations of hydric soil presence and inundation percentage. A substantial number of sites fall within the Non-Hydric and Non-Inundated class, particularly across the western and southwestern United States where arid climatic conditions limit persistent surface water. In contrast, areas classified as 76–100% Hydric and Inundated are concentrated primarily in the eastern United States, the Upper Midwest, and portions of the Lower Mississippi River Basin, indicating landscapes with strong wetland potential and sustained hydrologic connectivity. Intermediate classes, including 51–75% Hydric and Inundated, are common across parts of the Northern Great Plains and Midwestern states such as South Dakota, Nebraska, and Iowa, reflecting regions where hydric soils support seasonal or intermittent inundation. Lower overlap categories (1–25% and 26–50% Hydric and Inundated) are more broadly distributed across the central and southeastern United States, suggesting transitional environments where soil conditions and seasonal hydrology jointly influence wetland formation. Overall, the strong spatial correspondence between hydric soil distribution and inundation frequency highlights the ecological significance of conservation easement lands located within hydric landscapes, as these areas demonstrate greater potential to sustain wetland functions and associated ecosystem services such as water retention, habitat provision, and flood mitigation.

### Analysis of Hydric Soil and Inundation in Protected Area Sites

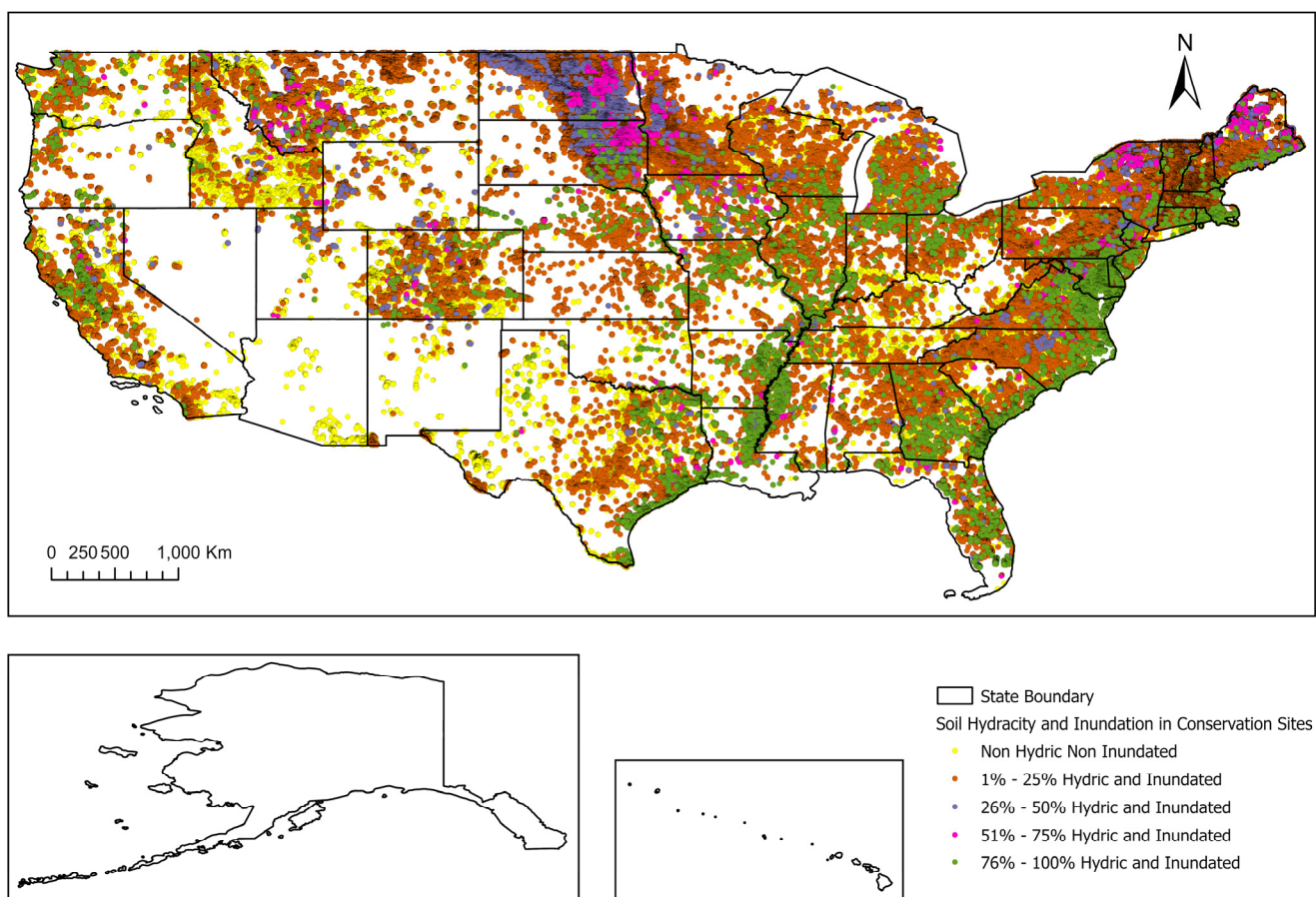


**Figure 9.** Spatial distribution of conservation easement sites showing the relationship between SSURGO-derived hydric soils and satellite-derived inundation frequency across the United States. Sites are classified into five categories representing combinations of hydric soil presence and percentage of surface-water inundation.

### 3.2. Influence of Seasonal Precipitation Patterns on Inundation Dynamics in Conservation Easement Sites

A comparison between the seasonal precipitation patterns (Figure 10a–e) and the spatial distribution of inundation hotspots across conservation easement sites (Figure 6a–e) reveals a clear hydro–climatic relationship between precipitation regimes and surface-water persistence. Seasonal analysis shows moderate precipitation–inundation relationships, with Pearson’s  $r$  ranging from 0.3 to 0.7 and corresponding  $R^2$  values between 0.09 and 0.49. These results indicate that precipitation explains a moderate portion of inundation variability, with strength varying across seasons. Regions receiving higher precipitation totals particularly the Lower Mississippi River Basin, Gulf Coast, Great Lakes region, and much of the eastern United States correspond closely with dense clusters of inundation hotspots where mean inundation exceeds 30%. The precipitation maps (Figure 10a,b) indicate that these regions experience elevated rainfall during spring (MAM) and summer (JJA), which aligns with the higher concentration of inundated easement sites observed in the seasonal hotspot analyses (Figure 6a,b). In contrast, the western and southwestern United States, characterized by comparatively low precipitation levels in Figure 10, exhibit sparse inundation hotspots across all seasons in Figure 6, reflecting limited hydrologic inputs. Transitional patterns are visible across the central United States and Great Plains, where moderate precipitation corresponds to scattered inundation sites, indicating seasonal hydrologic variability. The combined precipitation pattern (Figure 10e) further supports this relationship, as regions with sustained multi-year precipitation accumulation coincide with areas showing persistent inundation hotspots in the overall analysis (Figure 6e). Together, these patterns suggest that regional precipitation gradients play a fundamental role in shaping the spatial distribution and seasonal persistence of inundation across conservation easement landscapes.

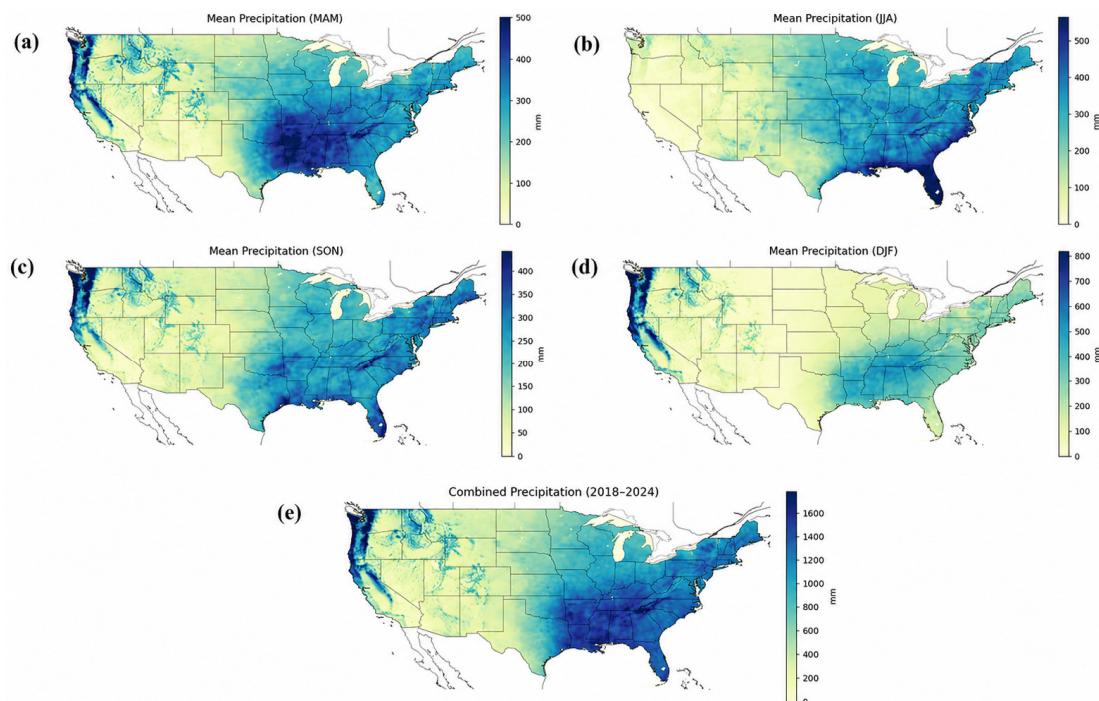


**Figure 10.** Mean seasonal precipitation across the United States derived from the NOAA nClimGrid dataset for the period 2018–2024: (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), (d) winter (DJF), and (e) multi-year combined precipitation. The maps illustrate regional hydro–climatic gradients used to interpret spatial patterns of inundation across conservation easement sites.

## 4. Discussions

### 4.1. Advancing Hydrological Understanding of Conservation Lands

This study provides the first nationwide, spatially explicit assessment of surface-water inundation dynamics across conservation easement lands contained within the PAD-US database. While previous research has primarily evaluated PAD-US in terms of biodiversity representation, landscape connectivity, or conservation planning [8,12,14], relatively little attention has been given to understanding the hydrological functioning of conservation easements. By integrating Sentinel-2 imagery, Dynamic World land-cover data, and machine-learning classification within a cloud-based framework, this study advances existing monitoring approaches by enabling continuous, high-resolution tracking of inundation dynamics across more than 340,000 conservation easement sites nationwide. Unlike earlier studies that focused mainly on mapping surface water extent, this work moves a step further by explicitly linking inundation patterns to conservation landscapes, allowing for a functional interpretation of how these lands contribute to hydrologic processes. In this sense, the novelty of the study lies not only in scale, but also in framing inundation as an indicator of ecosystem performance within protected easement systems.

### 4.2. Methodological Contribution and Machine Learning Performance

The classification results demonstrate that machine-learning methods provide robust tools for detecting surface water in heterogeneous landscapes. Among the tested algorithms, the SVM model produced the most consistent classification performance, supporting findings from previous studies that highlight the effectiveness of SVM and ensemble classifiers for land-cover and water-mapping applications [37–40]. The strong predictive contribution of spectral water indices such as MNDWI and NDWI further confirms their suitability for identifying inundated surfaces across diverse environments [32,35].

While similar approaches have been used in flood mapping, the integration of Dynamic World probabilistic outputs with spectral indices in this study provides a more refined representation of mixed land–water conditions. This becomes particularly important in wetland and easement landscapes, where inundations are often partial and temporally variable rather than fully saturated. Recent studies using machine learning for flood mapping and wetland monitoring have also emphasized the importance of combining multispectral imagery with advanced classification techniques to improve detection accuracy and scalability [43,67,68], and this study extends those approaches to a national conservation context.

To directly address the first research question, the classification framework was evaluated through both internal and ecological validation. Internal validation on an independent holdout dataset of 15,000 samples yielded SVM validation AUC of 0.955 and RF validation AUC of 0.961, confirming strong classifier generalization across spectrally diverse land-cover conditions. Ecological validation was carried out by comparing satellite-derived inundation outputs against two nationally authoritative independent datasets the NWI and SSURGO hydric soils, neither of which was used in model development. The statistically significant spatial correspondence between inundation frequency and NWI-designated wetlands ( $t(49) = 9.8, p < 0.001$ ) and hydric soil presence confirms that the satellite indicators are capturing real and ecologically meaningful hydrologic signals. Together, this evidence supports the reliability of the inundation framework at national scale. Future work incorporating field-based validation, cross-comparison with very high-resolution airborne imagery, or benchmarking against established global surface water products would further strengthen and extend these findings.

#### 4.3. Interpreting Inundation Hotspots: Beyond Expected Patterns

The inundation hotspot analysis reveals strong spatial clustering across major U.S. hydrologic regions, particularly the Mississippi River Basin, Great Lakes region, Gulf Coast, and Atlantic coastal plains. These patterns are broadly consistent with known floodplain and wetland distributions reported in previous studies [33,34,43]. However, the contribution of this study goes beyond simply confirming these patterns. By focusing specifically on conservation easement lands, the results show how these protected areas are not randomly distributed within the hydrologic landscape but are strongly aligned with regions of persistent water presence and hydrologic activity. This highlights the strategic placement and ecological significance of easements within flood-prone and wetland-dominated systems. The strong correspondence between inundation hotspots and hydric soil distributions further reinforces this interpretation [43,51], suggesting that conservation easements are often located in landscapes with inherent hydrologic potential. This provides new insight into how easement placement contributes to maintaining wetland functionality and long-term ecosystem resilience.

#### 4.4. Role of Hydrologic Connectivity in Conservation Function

The results clearly demonstrate that hydrologic connectivity plays a central role in shaping inundation dynamics across conservation easements. Sites intersecting mapped waterbodies exhibit significantly higher inundation frequencies than non-intersected sites, indicating that proximity to rivers, lakes, and floodplains strongly influences water persistence. These findings align with previous hydrological studies emphasizing the importance of floodplain connectivity and surface-water exchange in sustaining wetland ecosystems [69,70]. What this study adds is a large-scale, empirical confirmation of this relationship across thousands of protected sites, showing that conservation easements function as active components of hydrologic networks rather than isolated land parcels. This has important implications for conservation planning, particularly in identifying areas where maintaining or restoring connectivity could enhance ecosystem services such as flood attenuation and groundwater recharge.

While this study does not directly quantify hydrologic ecosystem services in volumetric terms, the inundation frequency and persistence data generated here serve as meaningful, quantitative proxies for key services including floodwater storage, groundwater recharge, and wetland habitat support, all of which are well-recognized functions of inundated landscapes [71–73]. In practical terms, the 32.9% of easement sites that experienced inundation at least once over the seven-year study period represent landscapes actively contributing to surface water retention, while sites with persistent inundation exceeding 50% concentrated in the Mississippi Alluvial Valley, Gulf Coast, and Great Lakes regions indicate the strongest potential for flood attenuation and groundwater recharge. The statistically significant difference in inundation between NWI-overlapping and non-NWI easements (mean = 5.3% vs. 1.8%;  $t(49) = 9.8$ ,  $p < 0.001$ ) further provides a quantitative basis for distinguishing sites with high versus low ecosystem service potential across the national easement network. Together, these metrics move beyond simple water mapping to offer a spatially explicit, data-driven picture of where conservation easements are most actively delivering hydrologic benefits, providing conservation planners and water resource managers with actionable information to prioritize hydrologically valuable sites and guide restoration efforts at the national scale.

#### 4.5. Hydro–Climatic Controls on Inundation Dynamics and Conservation Strategy Perspective

Climatic drivers also play a fundamental role in controlling the spatial distribution of inundation across conservation easement landscapes. The comparison between

seasonal precipitation patterns and inundation hotspots reveals a clear hydro–climatic linkage, with higher concentrations of inundated sites occurring in regions receiving greater precipitation [34,74]. Regions such as the Gulf Coast and Lower Mississippi River Basin, which experience frequent precipitation and strong groundwater connectivity, show sustained inundation across multiple seasons. While this relationship is expected, the study provides a spatially explicit, nationwide confirmation of how precipitation gradients translate into hydrologic behavior within protected lands. This is particularly relevant under changing climate conditions, where shifts in precipitation regimes may directly alter inundation dynamics and wetland functionality. The moderate strength of precipitation–inundation relationships suggests that while precipitation is a key driver, it does not solely control inundation dynamics across conservation lands. The remaining unexplained variability is likely governed by interacting environmental and landscape factors, including topography, slope, soil properties, drainage connectivity, and land management practices, which influence water retention, runoff, and storage [43,70]. Seasonal differences in correlation further indicate that hydrological responses are context-dependent, reflecting variations in antecedent moisture conditions and landscape characteristics. These findings highlight the need for integrated, multivariate, and spatially explicit modeling approaches to better capture the complex controls on inundation and improve predictive capability.

These findings complement our recently published nationwide assessment of CRP lands [75], which applied the same remote sensing and machine-learning framework across approximately 1.3 million CRP sites. While CRP lands showed relatively lower mean inundation (1.54%) and demonstrated a positive relationship between conservation enrollment duration and hydrologic performance, conservation easements examined here exhibit stronger and more persistent inundation patterns, reflecting their placement within inherently water-rich environments such as floodplains and riparian corridors. Together, these two studies provide a unified, comparative perspective on how different conservation mechanisms contribute complementary hydrological ecosystem services across the national conservation landscape. CRP lands primarily enhance water retention within agricultural systems, whereas conservation easements protect landscapes that already sustain natural hydrologic processes. This distinction provides a more nuanced understanding of how conservation programs collectively contribute to flood mitigation, wetland restoration, and climate resilience [33,76–78].

#### *4.6. Implications for Management and Future Monitoring*

To address the third research question of this study, the inundation frequency maps, seasonal hotspot analysis, and hydric soil overlays generated in this research provide a spatially explicit, data-driven foundation for conservation prioritization and water resource management. Continuous monitoring of inundation dynamics can help identify conservation easement sites that consistently support wetland functions such as floodwater storage, habitat provision, and groundwater recharge. Sites exhibiting persistent inundations exceeding 50%, concentrated in the Mississippi Alluvial Valley, Gulf Coast, and Great Lakes regions, represent the highest priority areas for long-term wetland conservation investment and flood resilience planning. Sites with moderate inundation frequencies (25–50%) and hydric soil presence are strong candidates for targeted hydrologic restoration to enhance water retention and connectivity, while sites showing minimal inundation despite hydric soil presence may indicate disrupted hydrologic connectivity requiring management intervention. Combined with NWI and hydric soil overlays, this evidence-based spatial information offers conservation agencies and water resource managers a practical framework for allocating resources efficiently and aligning site-level decisions with national

wetland protection goals, including the 30 × 30 target, by prioritizing areas that maximize ecosystem service benefits [21].

Overall, this study demonstrates that integrating high-resolution satellite imagery with machine-learning classification provides a scalable and effective framework for monitoring hydrological dynamics across protected landscapes. Beyond mapping inundation, the study advances understanding by linking hydrologic patterns with conservation function, ecosystem services, and landscape context. As climate change continues to influence precipitation patterns and flood regimes, such approaches will be critical for supporting adaptive management and ensuring the long-term resilience of conservation easement lands.

## 5. Conclusions

This study presents the first nationwide, high-resolution assessment of surface-water inundation dynamics across more than 340,000 conservation easement sites within the PAD-US for the period 2018–2024. By integrating Sentinel-2 satellite imagery, Dynamic World land-cover data, and spectral water indices (MNDWI, NDWI, and NDMI) within a machine-learning framework implemented in Google Earth Engine, we developed a scalable approach to quantify seasonal and long-term inundation patterns at 10 m spatial resolution across conservation landscapes. Among the evaluated algorithms, the Support Vector Machine classifier demonstrated the most robust generalization performance, enabling consistent identification of inundated surfaces and supporting the generation of quarterly and multi-year inundation frequency maps.

The results reveal strong regional and seasonal variability in hydrologic behavior across conservation easements, shaped by an interplay of climatic, physiographic, and site-level factors. Higher inundation frequencies were observed in hydrologically active regions such as the Midwest, Lower Mississippi River Basin, Gulf Coast, and Pacific Northwest, where easement sites tend to be positioned within floodplains, riparian corridors, and lake margins that sustain persistent surface water connectivity. In contrast, conservation easements located in arid and semi-arid landscapes of the western United States, particularly smaller parcels situated away from perennial water sources or exposed to seasonal drought conditions, exhibited markedly lower inundation frequencies across all seasons. This distinction is important as the observed variability in inundation is not simply a reflection of regional precipitation gradients alone, but also of site-level characteristics including parcel size, topographic position, proximity to rivers and lakes, and the degree to which local hydrology is buffered against drought. Smaller easements in drought-prone regions naturally experience more episodic and less persistent inundation, while larger sites embedded within well-connected hydrologic systems maintain more consistent water presence even during drier periods. Recognizing this multi-scale control on inundation behavior is essential for interpreting conservation outcomes and setting realistic hydrological benchmarks for different easement types across diverse landscape settings.

Overlay analysis with National Wetlands Inventory wetlands and SSURGO hydric soil datasets confirmed a strong spatial correspondence between areas with hydric soils and persistent surface-water presence, reinforcing the ecological validity of satellite-derived inundation indicators as proxies for wetland functionality. The analysis further demonstrates that many easement sites naturally retain water seasonally, supporting ecosystem services such as flood mitigation, groundwater recharge, habitat provision, and landscape-scale hydrologic connectivity, while others require targeted management interventions to restore hydrologic function.

Beyond mapping inundation patterns, this research advances conservation monitoring by establishing a replicable national framework for continuous hydrologic assessment of protected lands using remote sensing and machine learning. The generated inunda-

tion datasets provide actionable information for water resource managers, conservation agencies, and policymakers, enabling them to identify hydrologically active easements, prioritize restoration efforts, and tailor management strategies to site-specific hydrologic conditions. Sites along valley floors, lakeshores, and coastal margins may warrant monitoring for flood regulation and wetland persistence, while smaller or drought-exposed easements may benefit from targeted interventions to improve hydrologic connectivity and water retention capacity. As climate variability and extreme hydrologic events intensify across the United States, scalable monitoring approaches such as the one presented here will be essential for evaluating the effectiveness of conservation programs and guiding adaptive management of protected landscapes toward long-term ecological resilience.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/su18115533/s1>, Table S1. State-wise summary statistics of easement sites, including total number of sites, minimum and maximum site area, and the standard deviation of site size for each U.S. state and territory.

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