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Sentinel 1 Synthetic Aperture Radar Based Flood Mapping in Punjab Pakistan From 2015 to 2025 for Livestock Disaster Preparedness

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Abstract

Punjab, Pakistan, experiences recurrent monsoon flooding that threatens livestock health and welfare, rural livelihoods, food security, and animal production systems. This study developed a reproducible Google Earth Engine workflow using Sentinel-1 Synthetic Aperture Radar (SAR) imagery to map annual and recurrent flood-affected areas across Punjab from 2015 to 2025 and assess their relevance to livestock disaster preparedness. A fixed − 15 dB VV backscatter threshold, supported by published literature, was adopted after comparison with Sentinel-2 pre-flood and post-flood true-color imagery at flood-affected locations showed correspondence with visually identified inundated areas. A sensitivity analysis was conducted using alternative thresholds ranging from − 22 to − 10 dB to examine flood extent variability; however, all reported flood maps were generated using the selected − 15 dB threshold. Annual mapped flood extent ranged from 2,869 km² in 2017 to 7,044 km² in 2025, with recurrent inundation concentrated along riverine and low-lying floodplains of southern and southwestern Punjab. A contextual participatory assessment with representatives of 10 livestock-owning families from recurrently flood-affected Sutlej River floodplain villages explored strategies to enhance livestock keeper resilience to future flood events. Discussions focused on practical preparedness measures, including livestock evacuation planning, improved shelter, availability of feed and water resources, disease prevention, veterinary access, and approaches to reduce economic losses during and after floods. Flood-prone livestock systems may also represent important One Health priority areas due to increased risks of zoonotic and vector-borne diseases associated with environmental exposure, animal movement, displacement, and congregation during flood events, particularly under extensive grazing systems. The combined approach provides reproducible spatial evidence and context-specific insights to support livestock disaster preparedness and resilience planning. Province-wide quantitative accuracy assessment and integration with current livestock exposure datasets would further strengthen operational applications.

1. Introduction

Pakistan lies within the South Asian monsoon region and is highly vulnerable to recurrent and severe flooding. This vulnerability results from the interaction of intense seasonal rainfall, river overflow, climatic extremes, land-use change, settlement expansion, and other anthropogenic modifications of natural drainage and floodplain systems. The country’s geography and topography further influence flood generation and movement: runoff from relatively steep upstream catchments enters the extensive, low-gradient alluvial plains of the Indus River system, where water may spread over large areas and remain for prolonged periods. Recent flood disasters have caused widespread damage to agriculture, settlements, infrastructure, and rural livelihoods, demonstrating the need for stronger disaster-risk assessment, preparedness, response, and recovery systems [1–3].

Punjab Province is particularly important in this context because it contains major river systems, extensive floodplains, densely populated rural settlements, a large irrigation network, and a substantial proportion of Pakistan’s agricultural and livestock production. Floodplain communities commonly

practice mixed crop–livestock farming, in which crops, fodder production, livestock ownership, milk marketing, and household income are closely interconnected. Smallholders often depend on relatively limited landholdings and a small number of animals for food, savings, income, and livelihood security. Consequently, the simultaneous loss of crops, fodder, livestock, shelters, and market access can severely reduce their capacity to recover after a flood [4–6]. Flooding in Punjab is therefore not only a hydrological or agricultural hazard but also a major veterinary, animal-welfare, food-security, livelihood, fisheries, and environmental concern.

The need to address these interconnected risks is consistent with the Sendai Framework for Disaster Risk Reduction 2015–2030, which emphasizes understanding disaster risk, strengthening disaster-risk governance, investing in resilience, and enhancing preparedness for effective response and recovery[7]. Within this framework, livestock should not be viewed solely as agricultural commodities. Animals provide food, regular income, household savings, social security, and livelihood continuity, particularly for smallholder and resource-limited communities. Their loss may therefore prolong poverty and food insecurity well beyond the immediate flood emergency [6, 8, 9].

Riverine floodplain zones, locally known as *kacha* areas, are especially relevant to veterinary disaster epidemiology. These landscapes commonly support extensive and free-ranging livestock-production systems, communal grazing, seasonal animal movement, open-access feeding practices, and close interaction between animals belonging to different households. During floods, livestock may drown, become injured or missing, or be displaced from their usual grazing and housing areas. Farmers frequently move animals toward nearby roads, bridges, embankments, elevated corridors, and other available high-ground locations. Although these sites provide immediate temporary refuge, they may become highly sensitive points of livestock concentration because of crowding, stress, inadequate shade, limited feed, insufficient drinking water, poor sanitation, and increased contact among animals from different herds [10–13].

Flood-related livestock problems extend beyond immediate mortality and physical displacement. Farmers may face shortages of fodder and clean water, destruction of stored feed, damage to grazing land and livestock sheds, interruption of milk production and marketing, difficulties in animal evacuation and transportation, and restricted access to veterinary treatment. Following severe losses, households may be compelled to sell surviving animals under distress conditions, often at depressed prices or under unfavorable bargaining arrangements, further reducing their ability to rebuild their livelihoods. Rehabilitation is particularly difficult when affected households return home without sufficient financial resources, feed reserves, safe water, functioning shelters, or access to formal livestock insurance.

Flooding is also a major animal-welfare issue. Affected animals may experience hunger, thirst, heat stress, lameness, injuries, exhaustion, prolonged standing in contaminated water, and confinement under unsuitable temporary shelter conditions. Crowding, animal movement, standing water, increased vector abundance, poor sanitation, and disruption of routine vaccination and veterinary services may increase the risk of infectious, parasitic, vector-borne, waterborne, and zoonotic diseases. These conditions can

contribute to skin and hoof disorders, parasitic infections, vector-borne disease transmission, and outbreaks involving displaced and immunologically vulnerable animals [14–17]. Animal carcasses may create additional environmental and public-health risks when retrieval and safe disposal are delayed. Flood impacts may also extend to commercial fishponds, aquatic animal production, wetlands, riparian habitats, biodiversity, and ecosystem services [18] .

Veterinary services therefore have a central role before, during, and after floods. Their responsibilities may include contingency planning, staff training, simulation exercises, resource inventories, early-warning communication, vaccination planning, disease surveillance, farmer awareness, evacuation support, emergency treatment, animal field triage, carcass management, and post-flood rehabilitation. International guidance, including the Livestock Emergency Guidelines and Standards, provides an important foundation for protecting animal health, welfare, and livestock-dependent livelihoods during disasters [19, 20]. Other studies have emphasized the importance of veterinary preparedness, coordinated institutional response, animal evacuation protocols, emergency field triage, and continuity of animal-health services [13, 21–23].

Government institutions, veterinary departments, humanitarian organizations, non-governmental organizations, community volunteers, livestock farmers, and local leaders may all participate in flood response. However, early-warning systems, livestock evacuation arrangements, shelter planning, insurance coverage, command structures, and institutional coordination may remain insufficient in many flood-prone settings. International organizations provide substantial guidance on the actions required to protect animals during emergencies, but veterinary services often lack readily adoptable geospatial tools for independently identifying where floods occur, which locations are repeatedly inundated, where livestock and infrastructure are exposed, and where interventions should be prioritized. This represents an important implementation gap between disaster-management guidance and operational, location-specific decision-making.

Spatially explicit historical flood mapping can help address this gap. Multi-year maps can show where inundation occurs, how floodwater spreads, how frequently particular landscapes are affected, and which livestock systems, settlements, fisheries, habitats, veterinary facilities, and transport routes are repeatedly exposed. Longitudinal analyses can also distinguish areas affected by isolated extreme events from locations experiencing recurrent inundation, thereby providing stronger evidence for preparedness and resilience planning than a single-event flood map [24–26]. Flood maps can further support flood-exposure assessment and preliminary risk planning by estimating the spatial extent and possible severity of impacts and by identifying locations requiring rapid field verification and emergency assistance.

One potential application of recurrent flood mapping is its integration with road and elevation data to identify candidate high-ground corridors for field assessment. During flood emergencies, livestock farmers may use roads, embankments, bridges, or other elevated locations as temporary refuge. Flood layers that have been locally corroborated against independent reference information can be overlaid

with transport and terrain data to identify locations for subsequent assessment of access, elevation, carrying capacity, drinking-water availability, shade, sanitation, veterinary coverage, and suitability for temporary livestock shelter. Such decision-support applications should still be verified locally before operational use.

Remote sensing provides an effective means of mapping floods across large, inaccessible, and rapidly changing landscapes. Synthetic Aperture Radar is particularly suitable for monsoon flood monitoring because it can acquire data during both daytime and nighttime and can operate through the persistent cloud cover that often prevents the use of optical satellite imagery during flood events. Smooth open-water surfaces generally produce low radar backscatter, allowing inundated areas to be differentiated from many surrounding land surfaces [27]. Sentinel-1 SAR imagery has consequently become an important source of data for rapid flood delineation and multi-temporal flood-frequency analysis, and its usefulness has been demonstrated in vulnerable areas of Punjab, including Dera Ghazi Khan and Rajanpur [28].

Google Earth Engine provides a cloud-based platform for processing large volumes of multi-temporal satellite data without requiring extensive local computing infrastructure. Its integration with Sentinel-1 imagery makes it possible to develop reproducible workflows for annual flood mapping and historical inundation analysis [24]. Nevertheless, relatively few studies have translated remote-sensing flood-mapping approaches into practical decision-support tools designed specifically for veterinary services. This gap is not confined to Pakistan; globally, remote sensing remains underused within veterinary disaster epidemiology, despite its potential to strengthen livestock-risk assessment and climate-related emergency planning.

Remote sensing and cloud-based geospatial platforms can broaden the evidence available to veterinary and disaster-management services by allowing recurrent inundation to be examined alongside locally available exposure data. In the present study, Sentinel-2 pre-flood and wet/post-flood optical imagery provided independent cross-sensor corroboration of the 2025 Sentinel-1 flood classification at a known flood-affected site, while the publicly available Google Earth Engine interface permits threshold-sensitivity inspection. For operational livestock-risk applications, this geospatial evidence should additionally be integrated with current livestock, infrastructure, and field information.

Accordingly, this study aimed to map annual potential flood-affected areas, quantify flood frequency, and identify recurrent inundation zones across Punjab, Pakistan, from 2015 to 2025 using Sentinel-1 SAR imagery and Google Earth Engine. It also considered how recurrent flood maps could be integrated in future applications with road, elevation, livestock, and veterinary-service data. Because spatial flood information alone cannot capture locally perceived livestock challenges and operational constraints, a small participatory qualitative assessment was conducted to contextualize experiences and potential preparedness options before, during, and after floods. The participatory component was intended to provide context-specific qualitative information rather than to validate the flood maps or generate statistically representative intervention estimates.

The complete Google Earth Engine code is publicly available through the link provided in the Data and code availability statement to support reproducibility, transparent threshold inspection, and local adaptation of the flood-mapping workflow. The dates, study boundary, threshold, and supporting layers can be modified for other settings. The interface includes a display-only threshold-sensitivity control, allowing users to examine nearby VV thresholds while preserving the fixed − 15 dB threshold used for the reported results. When the workflow is transferred to other locations or flood regimes, local cross-sensor or field-based corroboration is recommended before operational application. The resulting inundation layers can then be combined with locally updated livestock populations, veterinary facilities, roads, shelters, and disease-surveillance information to develop more complete exposure and preparedness assessments.

2. Materials and Methods

2.1 Study area and satellite data

The study was conducted in Punjab Province, Pakistan, using the provincial administrative boundary as the area of interest (AOI). Punjab is highly exposed to seasonal flooding due to monsoon rainfall, river overflow, and extensive low-lying floodplain environments. All satellite processing, classification, and area calculations were performed in the Google Earth Engine cloud-computing environment.

Sentinel-1 Ground Range Detected (GRD) Synthetic Aperture Radar (SAR) imagery from the Copernicus Sentinel-1 mission was used as the primary dataset. Sentinel-1 SAR provides observations independent of daylight and cloud conditions, making it suitable for flood monitoring during the monsoon season. The analysis used Interferometric Wide Swath (IW) mode imagery with 10 m spatial resolution and VV polarization. Both ascending and descending orbit acquisitions were included to maximize image availability during the 2015–2025 analysis period.

Additional datasets were incorporated for flood-mask refinement and optical interpretation. Permanent water bodies were identified using the Joint Research Centre (JRC) Global Surface Water dataset, where areas classified as water for ≥ 10 months were excluded from flood classification. Terrain information was derived from the Shuttle Radar Topography Mission (SRTM) digital elevation model, and areas with slopes ≥ 5° were excluded to reduce potential misclassification of radar-dark terrain. Sentinel-2 Surface Reflectance imagery and cloud-probability data were used only for visual comparison of the 2025 flood classification.

2.2 Seasonal Sentinel-1 image processing

Annual flood mapping was performed for each year from 2015 to 2025. For each year, two Sentinel-1 seasonal composites were generated: the dry-season reference composite (15 May–16 June) and the wet-season flood-period composite (1 August–1 October).

All available Sentinel-1 VV observations within each seasonal period were combined using the 10th percentile reducer. This approach selected relatively low backscatter observations while reducing dependence on individual acquisitions. A focal mean filter with a 50 m radius was subsequently applied to reduce SAR speckle effects and improve spatial continuity of detected water features.

2.3 Sentinel-1 flood classification and threshold sensitivity analysis

Potential inundated areas were identified using a fixed Sentinel-1 VV backscatter threshold of − 15 dB. The threshold was selected based on published SAR flood-mapping literature [29] and was retained as the operational threshold for all reported manuscript outputs.

Threshold sensitivity was examined using an interactive display tool that allowed testing of alternative thresholds ranging from − 22 to − 10 dB at 0.5 dB intervals. The initial interactive display threshold was − 20 dB; however, this sensitivity tool modified only the displayed flood layer and did not alter reported statistics, exported products, flood-frequency calculations, or recurrent-flood maps, which remained fixed at − 15 dB.

For annual flood identification, wet-season pixels with backscatter below the selected threshold were classified as potential water. These pixels were compared with the dry-season reference layer, and only locations classified as wet-season water but not dry-season water were considered potential flood areas. This approach was designed to distinguish temporary monsoon inundation from permanent or seasonal water bodies.

2.4 Sentinel-2 optical comparison

Sentinel-2 imagery was used for independent optical comparison of the 2025 Sentinel-1 flood classification and was not used directly in SAR flood detection. Sentinel-2 true-colour composites were generated from Level-2A surface reflectance imagery after cloud masking using cloud-probability and scene-classification layers. Removed pixels included cloud shadows, medium- and high-probability clouds, cirrus, snow/ice, invalid pixels, and incomplete image edges.

Pre-flood and wet/post-flood Sentinel-2 RGB composites were generated for 2025 using the corresponding dry and wet seasonal periods. These images were used to visually assess correspondence between SAR-derived flood patterns and optical flood signatures.

2.5 Flood-mask refinement

The initial flood layer was refined using three spatial filtering steps: permanent-water removal, in which pixels classified as persistent water by the JRC dataset were removed; slope filtering, in which areas with terrain slope ≥ 5° were excluded; and connectivity filtering, in which small isolated patches were removed by retaining connected flood areas containing at least 8 connected pixels within a 25-pixel neighbourhood. The resulting binary flood layer represented the final annual potential flood-affected area.

2.6 Flood area estimation and recurrent flood mapping

Annual flood extent was calculated by multiplying the final binary flood layer by pixel area and summing flood pixels within Punjab. Province-level area statistics were calculated using a 100 m analysis scale, while the original Sentinel-1 classification was generated from 10 m imagery.

Annual flood layers from 2015–2025 were combined to generate a flood-frequency product representing the number of years each pixel was classified as flooded. Locations classified as flooded in at least two years were identified as recurrent flood areas.

2.6 Participatory qualitative assessment and iterative co-author synthesis of livestock-resilience findings in the Sutlej River floodplain

A contextual participatory qualitative assessment was conducted in 10 recurrently flood-affected villages in the Sutlej River floodplain of Lodhran District. Informal, open-ended individual discussions were held with representatives of 10 flood-affected livestock-owning families. The villages occupy the same recurrent riverine floodplain and share broadly comparable flood exposure and mixed crop-livestock conditions; accordingly, the participatory component was designed to elicit recurring context-specific themes rather than to estimate population prevalence or produce statistically representative intervention effects. Discussions explored experiences before, during, and after floods, including animal evacuation and shelter, feed and water security, heat stress, disease prevention and treatment, access to veterinary services, economic losses, relief distribution, and recovery needs. Individual discussions were used rather than focus groups to reduce the influence of dominant participants and allow each family representative to describe experiences and priorities freely. Principal points were recorded as field notes and organized into preliminary thematic categories. These field-informed themes were then triangulated through multiple iterative meetings among the co-authors. Senior co-authors with more than 20 years of relevant experience in livestock services, flood management, rescue, emergency response, and disaster operations reviewed the themes, clarified veterinary and implementation details, grouped overlapping points, and developed consensus wording. The final outputs were treated as consolidated participatory findings grounded in family experiences and strengthened by experienced co-author synthesis. Their purpose is contextual interpretation of the Sutlej floodplain setting rather than statistical generalization to all flood-affected communities in Punjab.

3. Results

3.1 Annual flood-affected area in Punjab from 2015 to 2025

The annual flood-affected area showed clear variation across Punjab during the study period (Fig. 2). The mapped flood extent ranged from 2,869 km² in 2017 to 7,044 km² in 2025. Higher flood-affected areas were observed in 2015, 2016, 2023, and 2025, while comparatively lower flood extents were recorded in 2017, 2018, 2021, 2022, and 2024.

The largest flood extent was observed in 2025, when 7,044 km² was classified as flood-affected. This was followed by 2015 with 5,764 km² and 2016 with 5,737 km². The lowest flood extent was recorded in 2017, with 2,869 km² affected. A sharp decline was observed between 2016 and 2017, followed by moderate annual flood extents during 2018–2022. Flood extent increased again in 2023 to 5,002 km², declined in 2024, and then increased strongly in 2025. Overall, the results indicate that flooding in Punjab was episodic rather than uniform, with several high-flood years separated by years of moderate or lower inundation.

3.2 District-level variation in mapped flood-affected area based on Dorling cartogram

The Dorling cartogram shows district-level variation in mapped flood-affected area across Punjab (Fig. 3). In this figure, circle size represents district area, while color intensity represents the mapped flood-affected area. The cartogram indicates that mapped inundation was not evenly distributed across the province. The greatest mapped flood-affected areas were concentrated in southern and southwestern Punjab, especially in Rajanpur. Other districts with comparatively greater mapped flood-affected area included Dera Ghazi Khan, Muzaffargarh, Bahawalpur, Rahim Yar Khan, Bhakkar, and Mianwali.

Central districts such as Jhang, Khanewal, Multan, Vehari, Sahiwal, Pakpattan, and Okara showed moderate mapped flood-affected area. In contrast, several northern and northeastern districts, including Rawalpindi, Attock, Chakwal, Jhelum, Gujrat, Sialkot, Narowal, Lahore, and Sheikhupura, showed comparatively smaller mapped flood-affected areas. Because district size influences area-based comparisons, these results describe mapped inundation area rather than standardized district risk or livestock exposure.

3.3 Recurrent flood inundation areas

The recurrent flood map identifies areas that were classified as flooded in two or more years during the 2015–2025 period (Fig. 4). Recurrent inundation was mainly concentrated along riverine and low-lying zones rather than being evenly distributed across Punjab. The most prominent recurrent flood areas were observed in the southwestern part of the province, particularly around Rajanpur, Rahim Yar Khan, Dera Ghazi Khan, and Muzaffargarh. Additional recurrent flood patches were visible in central and eastern districts, including parts of Pakpattan, Okara, Bahawalnagar, Sahiwal, Jhang, Chiniot, Gujranwala, Sialkot, and Narowal.

The spatial pattern suggests that recurrent flooding was linked to persistent flood-prone corridors. These recurrently inundated areas represent candidate locations for subsequent field-based assessment of livestock exposure and veterinary preparedness needs. The scattered recurrent flood patches also indicate that localized repeated flooding occurred in several districts, even when the total annual flood extent was moderate.

3.4 Flood inundation frequency from 2015 to 2025

The flood frequency map shows the number of years in which each pixel was classified as flooded during the 2015–2025 period (Fig. 5). Areas with higher frequency values represent locations that experienced flooding repeatedly across multiple years. The highest frequency zones were concentrated in the southwestern riverine belt, especially near Rajanpur, Rahim Yar Khan, Dera Ghazi Khan, and Muzaffargarh. Moderate to high-frequency patches were also visible along central and eastern river systems, including areas near Pakpattan, Okara, Bahawalnagar, Sahiwal, Jhang, Gujranwala, Sialkot, and Narowal.

Most parts of the province showed low flood frequency, indicating that flooding was spatially selective and mainly restricted to river-adjacent, low-lying, or seasonally inundated zones. The frequency pattern supports the annual and recurrent flood results by showing that the same broad flood-prone corridors were repeatedly affected over time.

3.5 Participatory findings on livestock resilience in flood-prone areas

The participatory process produced 10 consolidated themes describing locally perceived livestock concerns and potential preparedness options in the recurrently flooded Sutlej River floodplain. The themes were grounded in experiences reported by representatives of 10 livestock-owning families from 10 villages situated within the same recurrent riverine floodplain, where flood exposure and livestock-management conditions are broadly comparable. This component was designed for contextual thematic exploration rather than statistical estimation. The field-derived themes were triangulated and refined through multiple co-author meetings, including senior co-authors with more than 20 years of relevant flood-management, livestock-service, rescue, and emergency-response experience. They are therefore presented as context-specific, field-informed findings supported by experienced operational interpretation, rather than as population prevalence estimates.

The themes covered animal evacuation and elevated shelter, fodder production and protected storage, emergency feed resources, heat-stress management, vaccination and parasite control, water security, mouza-level spatial preparedness, disease surveillance and risk communication, economic recovery, and delivery of subsidized support. Table 1 presents the reported concern associated with each theme and the corresponding context-specific preparedness option identified through participatory discussion and co-author synthesis.

Table 1
Context-specific livestock preparedness findings identified through participatory assessment and iterative co-authors triangulation in the Sutlej River floodplain

Theme	Field-informed concern	Consolidated participatory finding
Livestock evacuation and elevated shelter	Delayed evacuation, tied animals, drowning risk, and lack of safe high ground.	Use early warnings to move animals promptly; identify elevated refuge sites and raised, flood-resilient shelters.
Fodder production and protected storage	Flooding damages standing fodder, hay, and concentrates.	Promote locally suitable flood-tolerant fodder and store dry feed on raised platforms in waterproof containers.
Emergency feed resources	Prolonged inundation causes shortages of safe feed.	Pre-identify locally safe emergency feeds and arrange subsidized complete feed blocks through livestock centres.
Heat stress and animal welfare	Crowding, humidity, poor shade, and inadequate water increase heat stress.	Provide shade, ventilation, clean water, and veterinary guidance on appropriate supportive measures.
Pre-flood vaccination	Vector exposure may increase while vaccine access is disrupted.	Plan timely vaccination against locally important livestock diseases, including lumpy skin disease and bovine ephemeral fever.
Post-flood parasite control	Standing water and vector exposure increase ectoparasite and endoparasite concerns.	Undertake risk-based parasite control under veterinary supervision.
Safe water infrastructure	Floodwater contaminates drinking sources and temporary camps lack water.	Develop raised hand pumps, storage cisterns, and rainwater-harvesting facilities where feasible.
Mouza-level preparedness and surveillance	Responders may lack current maps, livestock-owner data, contacts, and disease intelligence.	Maintain local digital maps linking livestock, owners, flood-prone areas, veterinary contacts, and surveillance priorities, including evaluation of leptospirosis.
Awareness and early reporting	Informal messages may be inconsistent and disease signs may be reported late.	Use brief, approved, local-language materials and pre-monsoon sessions on disease recognition, prevention, and reporting.
Economic recovery and equitable support	Distress sales, rebuilding costs, and uneven relief reduce recovery.	Explore transparent subsidized feed and medicine delivery, fair valuation advice, and context-appropriate recovery finance.

Note: Findings reflect discussions with 10 livestock-owning families across 10 recurrently flood-affected Sutlej River floodplain villages and iterative triangulation through co-author synthesis

4. Discussion

This study mapped annual and recurrent flood-affected areas in Punjab, Pakistan, using Sentinel-1 SAR data in Google Earth Engine and considered their relevance to livestock disaster preparedness. Recurrent inundation was concentrated mainly along riverine and low-lying floodplain zones of southern and southwestern Punjab. This pattern is consistent with the known flood vulnerability of South Punjab, where monsoon rainfall, river overflow, low elevation, agricultural dependence, and livestock-based livelihoods contribute to flood impacts. Previous studies in Pakistan have reported persistent flood-management challenges and substantial effects on rural communities, agriculture, infrastructure, and livelihoods. The present study complements these observations by providing a multi-year spatial layer of recurrent inundation that may be useful in subsequent livestock-exposure assessment. Importantly, the 2025 Sentinel-1 classification was independently corroborated against cloud-masked Sentinel-2 pre-flood and wet/post-flood imagery at a known flood-affected site, and the publicly available code permits transparent inspection of nearby backscatter thresholds. This cross-sensor validation supports the spatial plausibility of the mapped flood pattern, although a province-wide quantitative accuracy matrix based on field ground truth was not available.

Previous research in Pakistan has mainly focused on flood hazard, flood susceptibility, agricultural damage, population exposure, community vulnerability, and infrastructure risk. [1] used remote and social sensing to assess exposure, damage, and population needs during the 2022 Pakistan floods. [2] examined the pre- and post-flood vulnerability of affected communities, while [28] developed a flood-susceptibility model for Punjab using remote sensing, GIS, and several flood-influencing factors, including elevation, slope, rainfall, distance from rivers and roads, drainage density, land use, NDVI, and topographic wetness index. Other recent studies from South Punjab have assessed flood risk management, livelihood vulnerability, resilience, and household adaptation in flood-prone farming communities [4–6]. Compared with these studies, the present work contributes a multi-year flood-frequency mapping workflow interpreted from the perspective of potential applications in livestock and veterinary disaster preparedness.

The potential veterinary relevance of recurrent flood mapping is supported by studies from flood-prone livestock systems in South Asia. Floods may affect livestock through drowning and injury, fodder scarcity, contaminated drinking water, animal displacement, shelter damage, distress sale, reduced access to veterinary services, and increased infectious or parasitic disease risks. These concerns are particularly relevant to kacha and other low-lying riverine communities; however, the present study did not quantify livestock populations, animal losses, disease occurrence, or veterinary-service disruption within the mapped flood zones. The recurrently inundated zones identified here should therefore be regarded as candidate areas for subsequent field verification and integration with livestock population, veterinary-infrastructure, road-access, and disease-surveillance data before specific interventions are prioritized.

The participatory assessment added a field-informed qualitative component to the satellite-derived flood patterns. Family discussions identified recurring concerns about delayed evacuation, unsafe shelter, feed and water shortages, heat stress, disease risk, restricted veterinary access, distress sales, and

inequitable assistance. The 10 participating families were drawn from 10 villages situated along the same recurrently flooded Sutlej River floodplain, where communities experience broadly comparable riverine flooding and mixed crop-livestock conditions. The purpose was therefore not statistical estimation, but contextual identification of recurring operational themes. Multiple co-author meetings then triangulated and refined these observations by combining reported family experience with practical veterinary and flood-management knowledge. Senior co-authors with more than 20 years of relevant operational experience contributed to this synthesis. Table 1 consequently presents context-specific, field-informed preparedness findings rather than prevalence estimates from a representative survey. Several themes were also consistent with reports from other flood-affected livestock systems, including pre-flood vaccination, post-flood parasite control, mouza-level digital preparedness information, standardized local-language awareness materials, subsidized feed and medicines, and transparent support mechanisms.

The participatory themes were broadly consistent with international disaster-management principles. Frameworks such as FAO Good Emergency Management Practice (GEMP), WOAH disaster-management guidance, and the Livestock Emergency Guidelines and Standards emphasize risk mapping, early warning, evacuation planning, veterinary preparedness, feed and water security, and post-disaster recovery. The present qualitative findings add locally generated perspectives on how these broad priorities may be interpreted in a recurrent Sutlej River floodplain setting. The geographic and livelihood similarity of the participating villages, together with iterative triangulation by experienced co-authors, strengthens the contextual credibility of the themes. Nevertheless, implementation feasibility, effectiveness, acceptability, and transferability beyond the study setting were not formally evaluated, and wider stakeholder assessment would be appropriate before extending specific measures to other flood-affected areas of Punjab.

Sentinel-1 SAR was suitable for this study because radar imagery can be acquired under cloudy and rainy monsoon conditions, when optical satellite data are often limited. The use of dry-season and wet-season composites provided a reproducible approach for detecting seasonal inundation. The fixed VV backscatter threshold of -15 dB enabled consistent comparison across years and was supported locally by independent Sentinel-2 optical corroboration for the 2025 flood. The threshold-sensitivity control further allows users and reviewers to inspect the spatial behavior of nearby thresholds without altering the reported results. Even with this validation step, the maps should be interpreted as remote-sensing flood delineations rather than exact hydrodynamic boundaries because SAR backscatter may vary with soil moisture, vegetation, crop stage, surface roughness, incidence angle, and built-up structures. Recent SAR flood-detection literature likewise recognizes threshold selection, vegetation cover, urban areas, reference-data quality, and accuracy assessment as continuing challenges in flood extraction [27].

Flood events are complex emergencies affecting animal welfare, livestock productivity, food security, and rural livelihoods. The present findings are consistent with international disaster-management frameworks that emphasize integrated preparedness, emergency response, recovery planning, stakeholder collaboration, and continuity of animal-health services. The participatory assessment

illustrates how locally grounded stakeholder input can identify preparedness priorities including risk communication, vaccination, feed and water security, shelter, evacuation, and veterinary access. These findings are best understood as context-specific planning options that require implementation assessment rather than as universally applicable interventions. Taken together, the cross-sensor-validated spatial analysis and triangulated participatory component provide a practical planning framework that can be further strengthened through broader quantitative accuracy assessment, current livestock-exposure data, and operational evaluation.

Several limitations should be acknowledged. First, the 2025 Sentinel-1 flood classification was validated through independent optical comparison with cloud-masked Sentinel-2 pre-flood and wet/post-flood imagery at a known flood-affected site, and the interactive interface permits sensitivity inspection across nearby VV thresholds. This provides cross-sensor corroboration of the selected − 15 dB threshold and mapped inundation pattern. However, a province-wide pixel-based field ground-truth dataset was not available, so formal confusion-matrix metrics such as producer's accuracy, user's accuracy, F1-score, omission error, and commission error could not be calculated for the full study area. Future work can extend the present validation using official flood inventories, high-resolution satellite imagery, Copernicus or UNOSAT flood products, field observations, or drone-based reference data. Second, fixed dry- and wet-season composite windows may miss short-duration flash floods, localized events, or peak inundation outside the selected periods. Third, despite the threshold-sensitivity facility, SAR backscatter can vary with incidence angle, vegetation cover, soil moisture, crop stage, surface roughness, and built-up structures. Permanent-water masking may also omit some genuine flood expansion near river margins, while floodwater beneath dense vegetation or built-up areas may be underestimated and wet agricultural surfaces may generate false positives. District-level comparisons based on mapped area may favor larger districts, and the spatial analysis did not directly integrate livestock population, animal mortality, disease incidence, veterinary-service disruption, economic loss, or household-vulnerability data.

The participatory component involved representatives of 10 livestock-owning families from 10 recurrently flood-affected villages. This number should be interpreted in relation to the purpose and setting of the qualitative inquiry: the component was not designed to estimate prevalence or generate statistically representative effect measures, and the villages lie within the same Sutlej River floodplain with broadly similar recurrent flood exposure and livestock-production conditions. The family-derived themes were additionally triangulated through iterative synthesis with senior co-authors having more than 20 years of relevant flood-management, livestock-service, rescue, and emergency-response experience. These features strengthen the contextual credibility and practical interpretation of the findings. They do not, however, establish statistical representativeness for all flood-affected communities in Punjab. The participatory findings should therefore be applied primarily to the study context and treated as a basis for wider stakeholder testing where transfer to other ecological, administrative, or livestock-production settings is intended.

Future research should broaden quantitative validation beyond the present Sentinel-2 cross-sensor corroboration and integrate locally updated livestock and veterinary-service exposure data. Additional reference information could include official flood inventories, independent satellite-derived flood products, high-resolution imagery, field observations, or drone surveys, with formal accuracy metrics reported where sufficient reference samples are available. Recurrent inundation layers can then be combined with livestock populations, veterinary facilities, roads, settlements, markets, water points, and other locally relevant variables to support more detailed exposure and preparedness assessments.

The FAO gridded livestock population data were not used in this study because their spatial resolution is relatively coarse for local planning, and some input information may be outdated for district- or village-level decision-making. Locally updated livestock data would allow more reliable estimation of animal exposure, particularly in kacha areas along riverbanks, where extensive livestock populations may be repeatedly exposed to seasonal flooding.

International lessons on livestock flood management should be adapted to local conditions rather than transferred directly to Punjab. Measures proposed in published literature and international guidelines should be evaluated through broader participatory approaches involving veterinary professionals, livestock farmers, flood-affected communities, local administration, disaster-management authorities, NGOs, and relief organizations. Such evaluation should examine feasibility, acceptability, resource requirements, and compatibility with local livestock-production systems before specific measures are recommended for implementation.

Overall, this study presents a reproducible Google Earth Engine-based approach for identifying annual and recurrent flood-affected areas in Punjab using Sentinel-1 SAR data. Recurrent inundation was concentrated mainly along riverine corridors and low-lying floodplains of southern and southwestern Punjab. The 2025 classification was independently corroborated with Sentinel-2 pre-flood and wet/post-flood optical imagery, while the publicly available code provides transparent threshold-sensitivity inspection and reproducibility. These spatial products can help prioritize locations for livestock-exposure assessment and preparedness planning when integrated with current livestock populations, veterinary facilities, roads, settlements, markets, water points, and disease-surveillance data. The main remaining geospatial limitations are the absence of province-wide quantitative accuracy metrics, sensitivity of SAR classification to surface conditions and seasonal timing, and the lack of direct livestock-exposure data. The participatory component contributes context-specific themes from 10 Sutlej floodplain villages that were triangulated through experienced co-author synthesis; its purpose was qualitative contextualization rather than statistical generalization. Wider stakeholder and operational evaluation would strengthen transfer of these findings beyond the study setting.

5. Conclusion

The Sentinel-1 and Google Earth Engine workflow identified substantial inter-annual variation in flood-affected areas across Punjab from 2015 to 2025, with recurrent and high-frequency inundation

concentrated mainly along riverine and low-lying floodplains of southern and southwestern Punjab. Independent comparison with cloud-masked Sentinel-2 pre-flood and wet/post-flood imagery provided cross-sensor validation of the 2025 Sentinel-1 flood classification, and the publicly available code enables transparent threshold-sensitivity inspection while preserving the fixed − 15 dB threshold used for reported results. The resulting maps provide a reproducible spatial basis for identifying recurrently inundated locations and can support livestock disaster preparedness when combined with current livestock populations, veterinary infrastructure, roads, settlements, markets, water sources, disease-surveillance information, and local field data. The participatory component identified locally perceived livestock concerns and preparedness options across 10 recurrently flood-affected Sutlej River floodplain villages; these findings were intended for contextual thematic interpretation and were triangulated through iterative synthesis with experienced co-authors. Their broader transfer should be assessed in additional settings, while future geospatial work should expand quantitative accuracy assessment and integrate direct livestock-exposure information.

Declarations

Ethics approval and consent to participate

Ethical approval was waived by the Institutional Ethical Review Board/Ethical Review Committee of the Cholistan University of Veterinary and Animal Sciences, Bahawalpur (Ref. No. ORIC/530, 21-08-2026). The research was conducted in accordance with the ethical guidelines and regulations of the Institutional Ethical Review Board/Ethical Review Committee. This study was based primarily on publicly available Sentinel-1 Synthetic Aperture Radar (SAR) imagery and open-access geospatial datasets. Verbal informed consent was obtained from participants involved in informal discussions, and no personally identifiable information was collected or disclosed.

Competing interests

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that could have influenced the objectivity of this research or the writing of this paper.

Data and code availability

All satellite and ancillary datasets used in this study are publicly available through Google Earth Engine and are identified in the Materials and Methods. The Google Earth Engine script used for image filtering, seasonal compositing, flood extraction, mask refinement, Sentinel-2 cross-sensor validation, threshold-sensitivity inspection, area calculation, and output generation is publicly available at https://code.earthengine.google.com/ebc3d6cbd01a1e50048e313565fde631.The consolidated participatory findings supporting the qualitative component are presented in Table 1.

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Figures

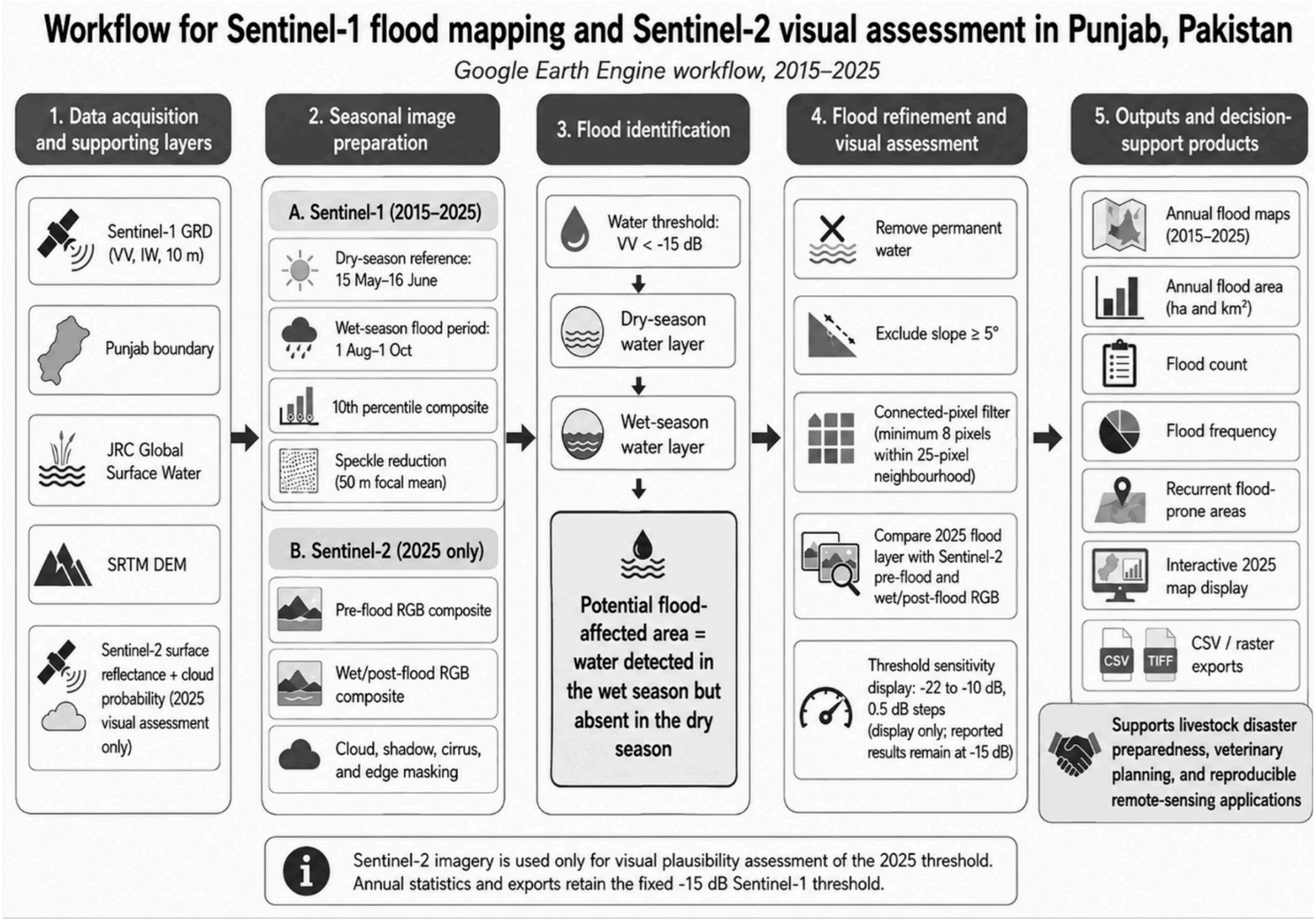


Figure 1

Workflow for Sentinel-1 flood mapping and Sentinel-2 cross-sensor validation in Punjab, Pakistan. The Google Earth Engine workflow combines Sentinel-1 dry- and wet-season composites, a fixed -15 dB VV threshold, permanent-water and slope masking, connected-pixel filtering, Sentinel-2 pre- and wet/post-flood optical comparison for 2025, threshold-sensitivity inspection, and annual and recurrent flood outputs

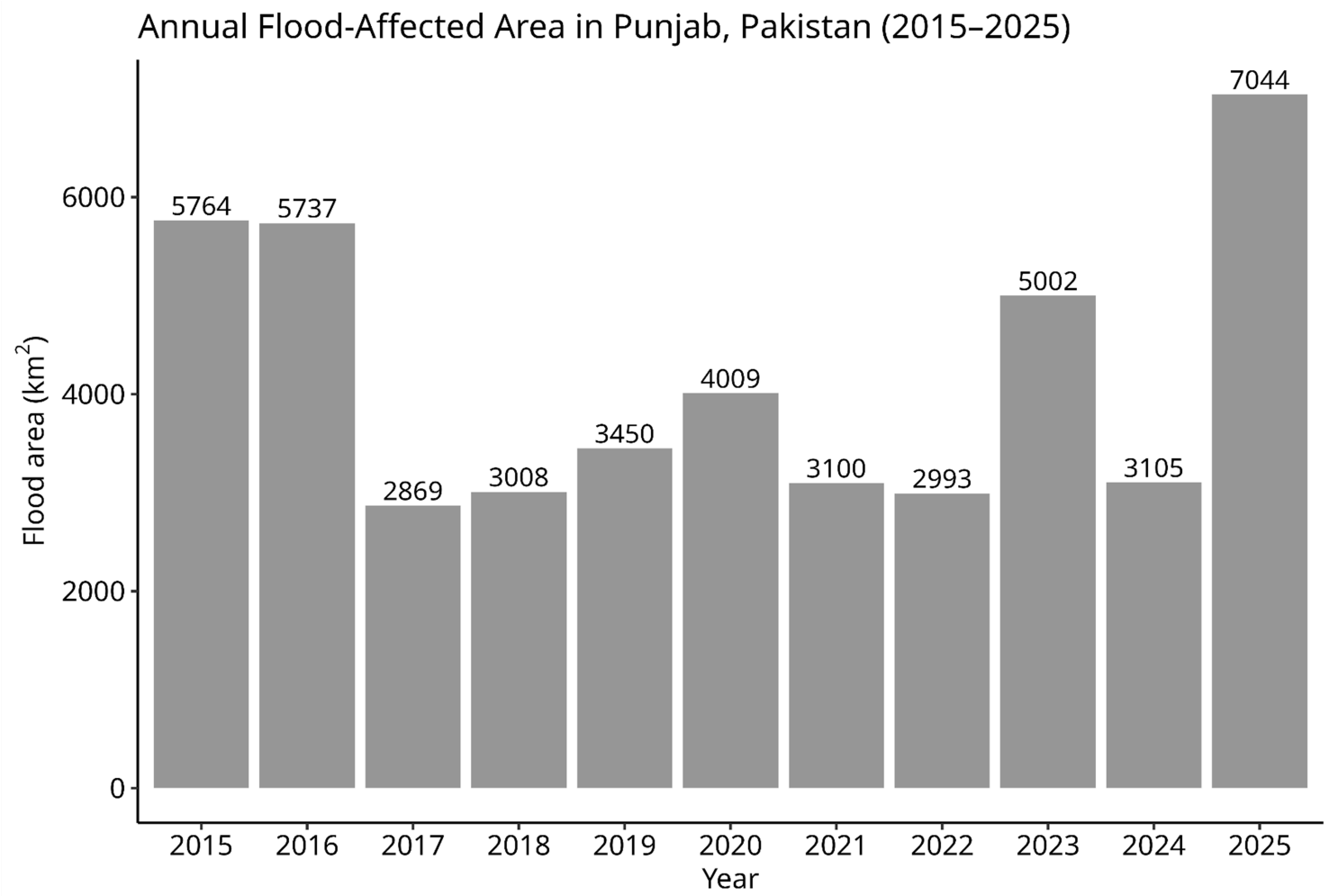


Figure 2

Annual mapped flood-affected area in Punjab, Pakistan, 2015-2025, derived from Sentinel-1 VV SAR imagery in Google Earth Engine. The highest mapped extent occurred in 2025 (7,044 km²) and the lowest in 2017 (2,869 km²)

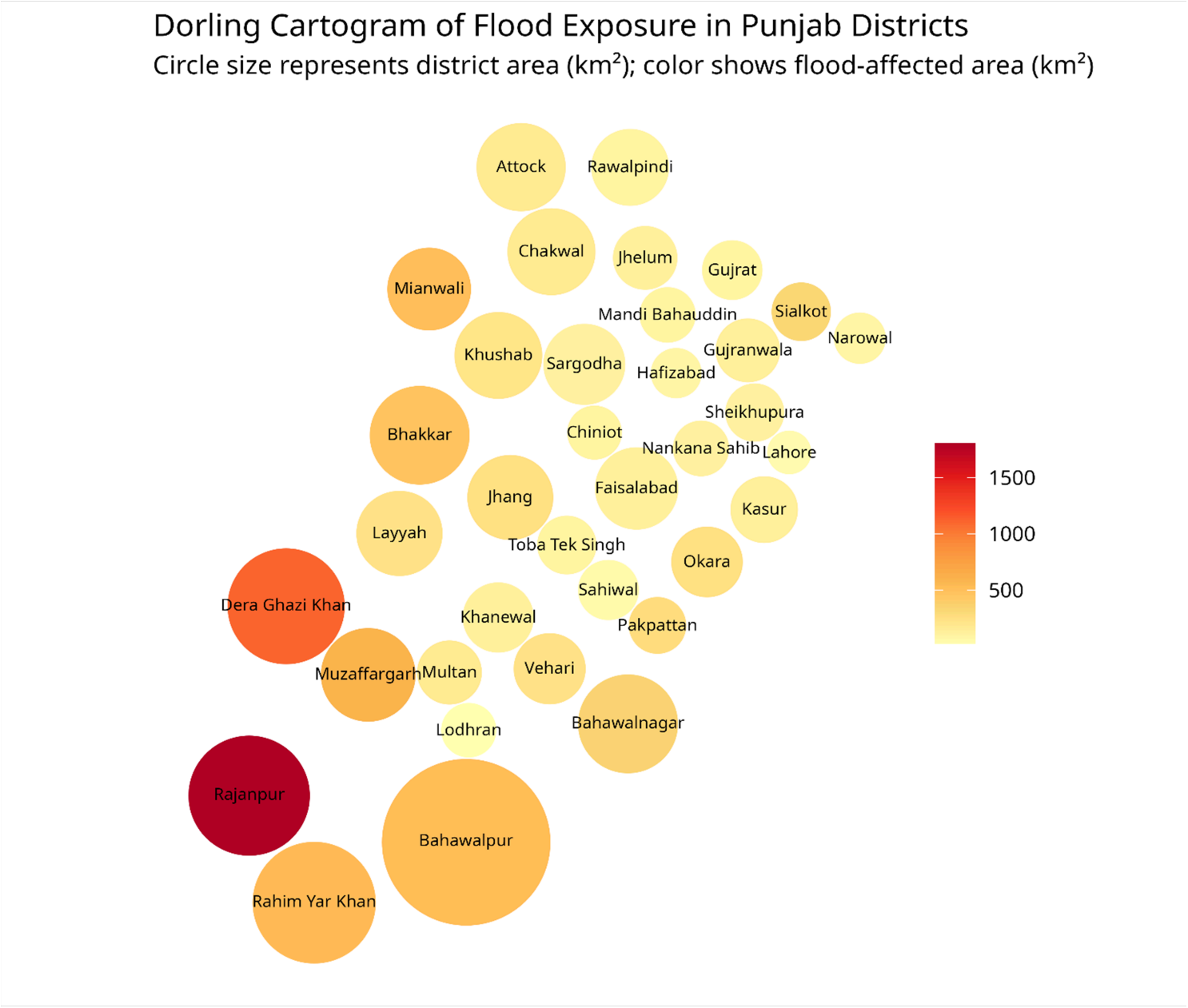


Figure 3

Dorling cartogram of mapped flood-affected area by Punjab district for year 2025. Circle size represents district area and color intensity represents mapped inundation; the graphic is descriptive and does not represent standardized district risk or livestock exposure

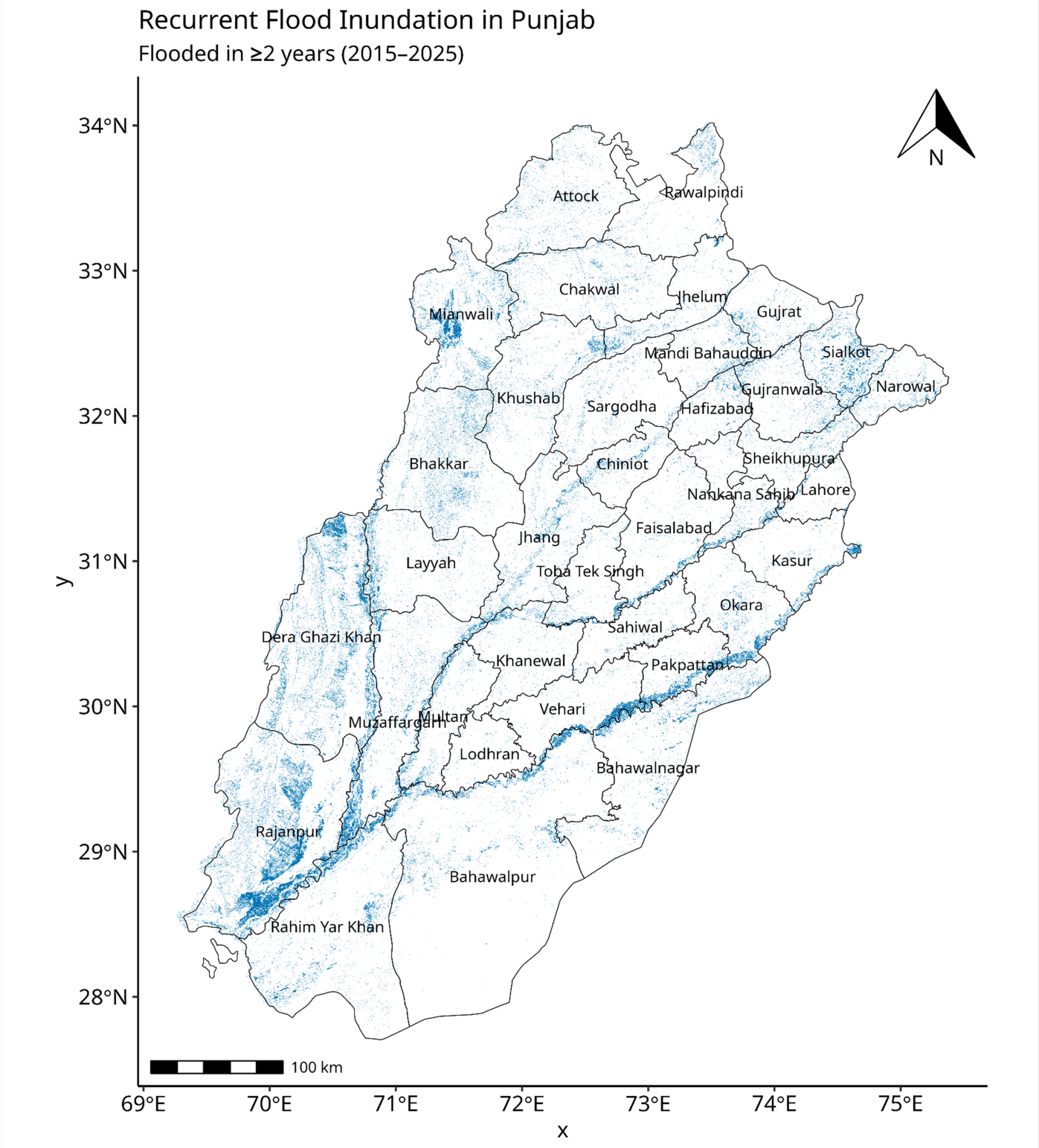


Figure 4

Recurrent flood inundation in Punjab, 2015-2025. Highlighted areas were classified as flooded in at least two study years, with the most extensive recurrent zones along riverine belts in southern and southwestern Punjab

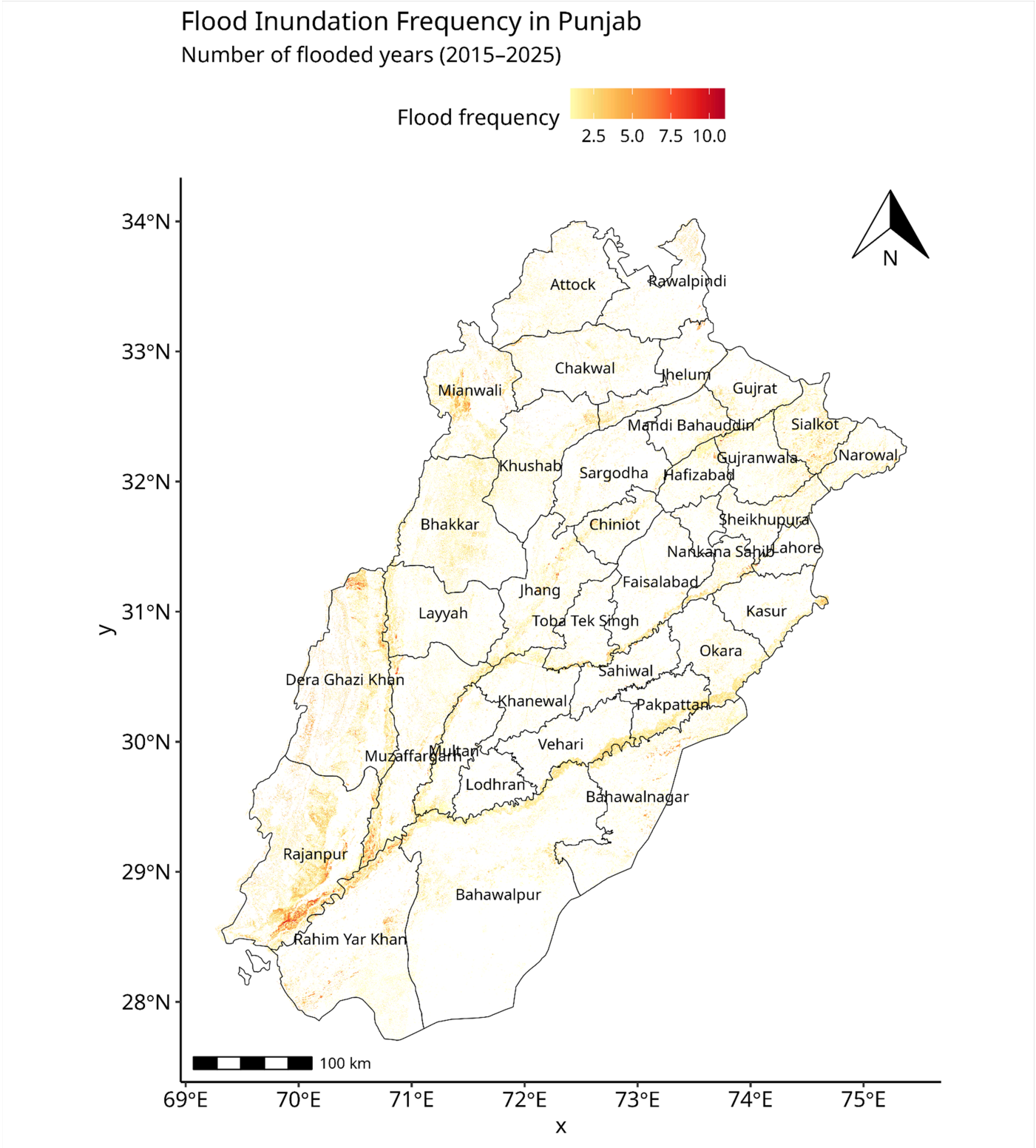


Figure 5

Flood inundation frequency in Punjab, 2015-2025. Values show the number of study years in which each location was classified as flooded; higher frequencies were concentrated mainly in southern and southwestern riverine districts