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Atmospheric Low-Level Disturbances, Rainfall, and Downstream Flood Risk in the Gal Oya River Basin, Sri Lanka: A Review

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Abstract - **The Gal Oya River basin is an important agricultural and water-resource system in eastern Sri Lanka, but its downstream low-lying areas remain exposed to rainfall-triggered flooding. Flood generation in the basin is controlled by seasonal rainfall as well as atmospheric low-level disturbances, including low-pressure systems, monsoon lows and troughs, easterly waves, convergence zones, and organized convective systems. These processes can modify moisture convergence and convection and thereby influence rainfall intensity, duration, and spatial distribution. This review synthesizes literature on tropical atmospheric processes, Sri Lankan rainfall systems, Gal Oya basin hydrology and morphometry, rainfall–runoff transformation, flood inundation, exposure, vulnerability, and reservoir operation. A structured narrative review identified three principal evidence gaps: limited event-based attribution of Gal Oya extreme rainfall to atmospheric disturbances; inadequate integration of atmospheric indicators with rainfall–runoff and inundation modelling; and limited basin-specific analysis of downstream hazard, exposure and vulnerability. The review also shows that satellite precipitation products should not be used as an unvalidated substitute for gauge observations during extreme events because upper-tail rainfall estimates can contain substantial bias [40]. A review-based analytical framework is therefore proposed in which disturbance identification, rainfall attribution, hydrological response, inundation modelling, and risk assessment are linked. The framework is intended for future empirical testing and is not presented as an already validated predictive model.**

Keywords: Gal Oya River, atmospheric low-level disturbances, northeast monsoon, rainfall, flood hazard, flood risk, Senanayake Samudraya, rainfall–runoff modelling.

I. Introduction

Flooding is a major hydro-meteorological hazard in tropical river basins because intense or persistent rainfall can exceed the capacity of river channels, drainage networks, reservoirs, and floodplains. Flood risk results from the interaction of hazard, exposure, and vulnerability rather than from rainfall alone [17, 35]. In South Asia, monsoon variability, tropical disturbances, land-use change, and increasing concentrations of people and infrastructure in flood-prone locations have increased the need for integrated flood-risk assessment [9, 26, 39].

Sri Lanka receives rainfall through the southwest monsoon, northeast monsoon (NEM), the two inter-monsoons, and weather systems embedded within these seasonal regimes. Rainfall is also influenced by atmospheric convergence, moisture transport, topography, and organized convection [31, 44]. Because the movement of the Intertropical Convergence Zone (ITCZ) is part of the seasonal transition, its influence is considered here as a background circulation process rather than as a separate disturbance category. Rainfall events with similar seasonal totals can produce different hydrological responses because their intensity, duration, spatial organization, antecedent rainfall, and basin-storage conditions differ [24, 42].

The Gal Oya River basin is located mainly in the eastern and southeastern dry zone of Sri Lanka. Its hydrological system is closely associated with irrigation development, reservoir storage, agricultural production, and downstream communities. GIS-based morphometric analysis classifies the basin as a sixth-order dendritic drainage system with moderate drainage texture [40]. The basin has a pronounced relief range, from about 1,341 m in the upper basin to about 5 m near the basin mouth [40]. This steep-to-flat elevation gradient can influence runoff concentration, flow velocity, flood-wave travel time, and the persistence of water in downstream low-lying areas.

Flood impacts in the basin are documented by the Irrigation Department. The February 2011 flood, for example, affected residential and agricultural areas, while rainfall records from several stations were reported at daily resolution [19]. More recent official flood warnings have also identified low-lying areas in several Gal Oya valley administrative divisions as potentially affected during high-rainfall conditions [19]. These observations show why basin-scale rainfall, river response, reservoir operation, topography, and downstream exposure need to be examined together rather than as separate processes.

Atmospheric low-level disturbances are important because they can organize moisture convergence and convection over Sri Lanka and surrounding seas. Low-pressure systems can strengthen low-level convergence and moisture transport, while easterly waves, monsoon troughs, and related circulation anomalies can provide favourable conditions for persistent rainfall [12, 15, 36, 37]. Their effects are not uniform: track, translation speed, moisture availability, rainfall organization, and interaction with topography can change the resulting basin response.

Although previous studies have addressed Gal Oya morphometry, rainfall variability, flood inundation, GIS-based susceptibility, and hydrological processes, the literature does not yet provide an integrated event-attribution framework linking atmospheric low-level disturbances to rainfall and downstream flood risk. This review therefore addresses three questions:

- Which atmospheric low-level disturbances and circulation conditions are associated with extreme rainfall in the Gal Oya basin?
- How can disturbance-related rainfall characteristics be linked to river discharge and downstream flood-wave development?
- Which downstream areas, communities, infrastructure, and agricultural lands are exposed and vulnerable to disturbance-associated flooding?

The objective is to synthesize the available evidence, identify methodological gaps, and formulate a research framework for future empirical investigation of atmospheric disturbances, rainfall, hydrological response, and downstream flood risk in the Gal Oya River basin.

II. Methodology

This paper uses a structured narrative literature-review approach rather than an empirical hydrological or hydraulic investigation. The review was organized around four evidence domains: (i) atmospheric low-level disturbances and tropical rainfall processes; (ii) rainfall and climate characteristics of Sri Lanka and the Gal Oya basin; (iii) rainfall–runoff, flood-frequency, GIS, remote-sensing, and inundation modelling; and (iv) flood hazard, exposure, vulnerability, reservoir operation, and early warning. The final synthesis contains 44 cited sources, comprising peer-reviewed studies, authoritative institutional reports, technical guidance, and established scientific references.

Search and selection were structured around combinations of the terms “Gal Oya”, “Gal Oya River Basin”, “Sri Lanka rainfall”, “northeast monsoon”, “low-level disturbance”, “easterly wave”, “MJO”, “rainfall–runoff”, “flood inundation”, “reservoir operation”, “flood risk”, “exposure”, and “vulnerability”. Sources were retained when they directly informed the atmospheric, hydrological, geomorphological, or risk dimensions of the research questions. Studies with relevance only to unrelated basins or unrelated hazards were not used to support Gal Oya-specific conclusions.

Findings were compared across atmospheric, rainfall, hydrological, inundation, and risk studies, with particular attention to temporal resolution, event attribution, reservoir representation, spatial scale, uncertainty, and validation. The proposed framework in Section VII is derived from these identified evidence gaps and should therefore be treated as a future research design rather than as a validated model.

III. Conceptual Definitions

A. Atmospheric low-level disturbances

In this review, atmospheric low-level disturbances refer to weather systems or circulation anomalies that modify pressure, low-level winds, moisture convergence, and vertical motion in the lower troposphere. The category includes low-pressure areas and weak tropical depressions; monsoon lows and troughs; easterly and other tropical waves; low-level convergence zones; organized convective systems; and rain-bearing disturbance remnants affecting Sri Lanka or the Bay of Bengal [12, 21, 36, 38].

The Madden–Julian Oscillation (MJO) is not treated as an individual low-level disturbance. It is a large-scale intraseasonal mode that describes an eastward-propagating convective envelope and associated changes in moisture and wind [23, 37, 43]. MJO phase and amplitude can therefore be used as background covariates when interpreting individual rainfall events, but an MJO phase alone should not be used to classify an event as a specific disturbance.

Events should be classified according to their atmospheric structure, intensity, duration, location, movement, and relationship with rainfall. Where the atmospheric evidence is insufficient, an event should remain “unclassified” rather than being forced into a disturbance category.

B. Rainfall hazard

Rainfall hazard is characterized by magnitude, duration, frequency, spatial extent, and temporal concentration. Relevant indicators include daily and sub-daily totals; maximum 1-, 3-, 6-, 12-, and 24-hour rainfall; antecedent rainfall over 3, 5, 7, and 15 days; spatial rainfall coverage; return periods; and intensity–duration–frequency characteristics. Short-duration rainfall may generate rapid runoff, whereas multi-day rainfall can increase soil saturation and basin-wide runoff.

C. Flood risk

For this review, flood risk is conceptually expressed as:

$$R = H \times E \times V$$

where R is flood risk, H is flood hazard, E is exposure, and V is vulnerability. Hazard represents the physical flood process, including flood depth, extent, velocity, duration, and probability. Exposure represents people, settlements, roads, bridges, irrigation infrastructure, schools, health facilities, paddy fields, and other assets located within the hazard area. Vulnerability represents the susceptibility of those exposed elements to harm and includes factors such as building

quality, livelihood dependence, warning access, elevation, and evacuation capacity [17, 35]. Response and coping capacity should be represented within the vulnerability assessment rather than treated as a substitute for hazard.

IV. Physical and Hydrological Setting of the Gal Oya Basin

The Gal Oya basin is a major river basin in eastern Sri Lanka. The basin rises in relatively elevated terrain and drains towards the eastern lowlands and coast. Morphometric analysis reports a sixth-order dendritic drainage network, a basin relief of approximately 1,336 m, and elevations ranging from about 1,341 m in the upper basin to about 5 m at the mouth [40]. The resulting steep-to-flat terrain transition is relevant to runoff concentration, channel routing, flood-wave travel time, and the conversion of upstream inflows into downstream inundation.

The basin also contains major engineered water infrastructure, particularly Senanayake Samudraya and associated irrigation systems. Reservoir storage can reduce or delay downstream peaks under some operating conditions, but storage levels, inflow conditions, rule curves, and releases become important during extreme rainfall. Flood analysis must therefore distinguish natural rainfall–runoff generation from regulated downstream discharge.

The basin's eastern and southeastern setting makes NEM and the second inter-monsoon particularly relevant to seasonal rainfall analysis [14, 31, 44]. However, individual flood events should not be attributed to the NEM alone. The analysis should determine whether low-level disturbances, organized convection, antecedent rainfall, reservoir conditions, or combinations of these factors were present during each event.

V. Literature Review

A. Atmospheric controls and Sri Lankan rainfall

Tropical rainfall depends on moisture supply, atmospheric instability, convergence, vertical motion, and convective organization [10, 16]. Monsoon rainfall varies between active and break periods and is modulated by low-pressure systems, monsoon depressions, equatorial waves, and intraseasonal variability [11, 36]. The MJO provides a useful large-scale background indicator, while Kelvin, Rossby–gravity, and easterly waves can interact with local convection [21, 23, 37, 38].

Sri Lanka has four principal rainfall seasons: first inter-monsoon, southwest monsoon, second inter-monsoon, and northeast monsoon [14]. Eastern and southeastern Sri Lanka receive substantial rainfall during the NEM and second inter-monsoon, making the Gal Oya basin sensitive to weather systems affecting the eastern side of the island [14]. Interannual variability is also associated with ENSO, the Indian Ocean Dipole, and monsoon circulation [3, 31, 44].

B. Rainfall–runoff and flood response

Rainfall is transformed into discharge through interception, infiltration, depression storage, evapotranspiration, surface runoff, subsurface flow, groundwater contribution, and channel routing [4, 7]. Soil moisture, land cover, slope, rainfall intensity, and antecedent rainfall influence the proportion of rainfall converted to direct runoff. HEC-HMS, SWAT, MIKE SHE, and hydraulic models provide established approaches, but model performance depends on input-data quality, parameter identifiability, reservoir representation, calibration, and independent validation [2, 5, 28, 34].

For Gal Oya, temporal resolution is particularly important. Daily rainfall may describe seasonal water balance but can miss short-duration intensities that determine peak runoff and lag time. Hourly or sub-hourly observations are preferable for event attribution where they exist. However, the official February 2011 Gal Oya flood documentation reports daily rainfall records for the stations used in that event [19]. Thus, the availability of hourly or sub-hourly observations should be established through a station-by-station data inventory before they are assumed in the research design.

C. Flood frequency, GIS, and inundation

Flood-frequency analysis commonly uses annual maximum series or peaks-over-threshold methods and distributions such as GEV, Generalized Pareto, Gumbel, and Log-Pearson Type III [8, 20]. Stationarity should be examined because rainfall, land use, reservoir operation, and climate conditions can change over time [25, 30]. For Gal Oya, event classification should precede frequency analysis so that disturbance-related multi-day events and isolated convective events are not automatically treated as physically identical populations.

GIS and remote sensing support flood-hazard and exposure mapping through digital elevation models, drainage analysis, land cover, and inundation observations. Synthetic Aperture Radar is useful under cloudy conditions, but flood classifications can be affected by vegetation, urban structures, wind-roughened water, and mixed pixels. Official Gal Oya inundation maps provide useful historical evidence but should be checked for event date, mapping method, spatial resolution, and whether the mapped area represents maximum or instantaneous inundation [19].

D. Satellite precipitation and gauge observations

Satellite precipitation products are valuable for spatial coverage, particularly where gauges are sparse, but they are indirect estimates and contain systematic and random errors. Studies of extreme rainfall have shown that satellite products can underestimate high-intensity rainfall and can differ substantially from gauge observations [46]. Therefore, satellite precipitation should be compared with available gauges before it is used to define event magnitude or model peak runoff. A practical approach is to evaluate bias, correlation, detection skill, and upper-tail performance and, where appropriate, apply gauge-based correction or merging [46].

VI. Results of the Literature Synthesis

The review does not produce new rainfall, discharge, inundation, or survey observations. Its results are therefore

literature-synthesis findings. Four consistent findings emerge.

A. Atmospheric attribution remains limited

The reviewed literature provides strong evidence that tropical rainfall is influenced by organized atmospheric processes, but Gal Oya flood studies have generally emphasized rainfall totals, basin morphometry, inundation, or hydrological response rather than event-by-event attribution to a specific atmospheric disturbance. This limits the ability to connect large-scale atmospheric information with basin-scale warning.

B. Temporal and spatial data limitations constrain peak-flood analysis

Daily rainfall records can conceal short-duration extreme intensities, while point gauges and gridded satellite estimates represent different spatial scales. Satellite products may also underestimate extreme rainfall. Consequently, peak-flow analysis should use gauge observations where available, satellite products as complementary spatial information, and explicit uncertainty or bias correction rather than treating any single rainfall product as definitive [19, 46].

C. Reservoir operation is a central Gal Oya control

Senanayake Samudraya and associated water-management infrastructure mean that downstream discharge cannot be interpreted solely as a direct function of rainfall. Storage conditions, inflows, operational releases, and emergency actions can modify the timing and magnitude of downstream flow. A future event-based model should therefore separate rainfall-generated inflow from regulated discharge.

D. Flood hazard and flood risk require separate assessment

The literature supports a clear distinction between physical flood hazard and risk. Flood depth, extent, velocity, and duration describe hazard, whereas risk requires information on who and what is exposed and how susceptible those elements are to damage [17, 35]. For Gal Oya, this includes downstream settlements, paddy lands, roads, bridges, irrigation infrastructure, schools, health facilities, and evacuation routes.

VII. Proposed Analytical Framework

Based on the literature synthesis, a four-stage framework is proposed for future empirical investigation. The framework is not presented as a validated predictive system.

A. Disturbance identification

Atmospheric events should be identified using reanalysis and satellite indicators including sea-level pressure, 850-hPa wind fields, relative vorticity, specific humidity, moisture flux and moisture-flux convergence, vertical velocity, outgoing longwave radiation (OLR), precipitation estimates, MJO phase and amplitude, and tropical-cyclone or depression tracks. These variables have different roles: sea-level pressure and 850-hPa winds describe circulation; relative vorticity helps identify rotational or cyclonic circulation; humidity and moisture flux describe moisture availability and transport; vertical velocity indicates large-scale ascent; and low OLR provides evidence of deep convective cloud activity. MJO phase and amplitude are used as background intraseasonal conditions rather than as an event label [23, 37, 43].

An event should be classified as disturbance-related only when atmospheric evidence shows a coherent circulation or convective anomaly that is spatially and temporally associated with unusual rainfall over or near the basin. Events that produce heavy rainfall without sufficient evidence of a defined disturbance should be retained as non-disturbance extreme events and analysed as a comparison group. If evidence is ambiguous, the event should be recorded as unclassified rather than forced into either category.

B. Rainfall attribution

Station observations should be combined with satellite precipitation products. Each event should be evaluated for total rainfall, maximum short-duration intensity, duration, spatial coverage, rainfall-centre movement, antecedent rainfall, and the percentage of the basin exceeding selected thresholds. Gauge–satellite differences should be quantified before satellite rainfall is used in hydrological modelling [40]. Disturbance-related and non-disturbance events should then be compared using consistent rainfall metrics.

C. Hydrological response

Rainfall should be converted into runoff using a calibrated hydrological model that represents major tributary inflows, reservoir inflow, downstream peak discharge, time to peak, flood-wave travel time, total runoff volume, and reservoir storage and releases. Calibration should include multiple events where data permit and should assess peak discharge, time to peak, runoff volume, and recession behaviour [5, 28].

D. Flood-risk assessment

Modelled discharge should be routed through a hydraulic or inundation model to estimate flood extent, depth, velocity, and duration. Hazard layers should then be overlaid with exposure and vulnerability data. The final outputs may include disturbance-specific flood-hazard maps, downstream exposure maps, critical-infrastructure risk maps, agricultural-loss zones, and locally calibrated rainfall and river-level warning thresholds.

VIII. Discussion

A. Atmospheric indicators and event attribution

The main methodological requirement is to avoid treating every heavy-rainfall event as evidence of a low-level disturbance. Atmospheric attribution should be based on multiple indicators and event chronology. Vorticity, pressure, winds, moisture flux, vertical motion, and OLR should be examined together rather than individually. This approach

also permits analysis of heavy events generated primarily by local or mesoscale convection without a coherent synoptic disturbance.

B. Data resolution and station availability

The review does not establish a verified basin-wide count of meteorological stations with hourly or sub-hourly rainfall records. The official Gal Oya flood documentation used for the February 2011 event explicitly notes daily rainfall records for the stations reported there [19]. Therefore, the next study should begin with a station inventory covering the Department of Meteorology, Irrigation Department, and other relevant networks, recording station location, period of record, temporal resolution, missingness, and data ownership. If no sufficiently dense hourly or sub-hourly network exists, the analysis should combine the available gauges with validated satellite/reanalysis products and explicitly quantify uncertainty.

C. Handling heavy rainfall without a detected disturbance

A non-disturbance event that produces extreme rainfall should not be discarded. It should be classified as a non-disturbance extreme event and included in the comparative analysis. Its rainfall intensity, duration, spatial organization, antecedent wetness, runoff response, and reservoir state should be analysed in the same way as disturbance-related events. This comparison is necessary to determine whether atmospheric disturbance information adds explanatory value beyond rainfall amount alone.

D. Hazard, exposure, vulnerability, and model validation

Flood hazard should be mapped before risk is assessed. The hazard component should describe water depth, extent, velocity, duration, and probability, while exposure and vulnerability should be evaluated separately. Modelled inundation should be validated against historical flood maps, river levels, satellite-derived inundation, and field observations where available [19, 35]. This separation reduces the risk of describing a physical inundation map as a complete flood-risk assessment.

IX. Conclusion

The literature indicates that flood risk in the Gal Oya River basin is produced by interacting atmospheric, rainfall, hydrological, geomorphological, reservoir, and social processes. The basin's strong elevation contrast—from approximately 1,341 m in the upper basin to about 5 m at the mouth—creates a marked transition from upstream terrain to downstream lowlands [40]. This physical setting interacts with the NEM and second inter-monsoon rainfall regime, atmospheric disturbances, antecedent wetness, channel routing, and reservoir operation.

Senanayake Samudraya is particularly important because downstream flood response cannot be interpreted from rainfall alone. Storage and release conditions need to be incorporated into future hydrological and hydraulic analyses. Historical flood documentation also shows that the basin has experienced substantial rainfall and downstream inundation, while some of the available station records are daily rather than sub-daily [19].

The review identifies three principal gaps: limited event-based attribution of extreme Gal Oya rainfall to atmospheric low-level disturbances; insufficient integration of atmospheric indicators with hydrological and inundation models; and limited basin-specific assessment of exposure and vulnerability. Satellite precipitation can extend spatial coverage, but its performance during extreme rainfall must be evaluated against gauges before it is used to characterize peak events [40].

The proposed framework therefore begins with atmospheric disturbance identification, quantifies rainfall characteristics, simulates rainfall–runoff and reservoir response, maps inundation, and then evaluates exposure and vulnerability. This framework is a research proposal derived from the reviewed evidence and has not yet been empirically validated. Future work should first establish the available rainfall and discharge data at hourly or sub-hourly resolution, classify both disturbance-related and non-disturbance extreme events, and then test whether atmospheric information improves flood prediction and risk assessment in the Gal Oya basin.

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