Research Article

From Rainfall Hazard to Adolescent Health Risk: A 124-Year Hydroclimatic and Pathway Analysis of the Banas Basin, India

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Abstract

Adolescents in semi-arid South Asia are exposed to rainfall hazards that are rarely quantified at basin scale, which limits the use of climate information in adolescent health planning. This study characterises long-term changes in rainfall extremes and monsoon dry spells in the Banas Basin of Rajasthan, India, and uses the published literature to map how these hazards can reach adolescent health. Hazard exposure was derived from IMD gridded daily rainfall for 1901–2024 with Mann–Kendall, Sen's slope and Pettitt analyses. Health pathways were mapped through a structured narrative review of epidemiological and public-health studies on floods, rainfall, drought, water scarcity and mental health in India and comparable settings. Annual and monsoon rainfall totals showed no significant trend, but annual maximum 1-day rainfall (Rx1day) increased by 0.815 mm/decade, with a significant shift around 1970 from 35.63 to 44.45 mm. Years with extreme Rx1day became about three times as frequent (6.7% to 20.8%, 1951–1980 vs 2001–2024), and the estimated 50-year return level of Rx1day rose from 60.8 to 93.0 mm. The longest monsoon dry spell shortened (−0.303 days/decade) and the frequency of wet and dry years changed little. These patterns point to heavy-rainfall and flood-related pathways (diarrhoeal disease, water contamination and psychological stress) as the more plausible near-term concern than a worsening monsoon dry-spell burden, while drought- and water-scarcity pathways (undernutrition, girls' water-collection burden, school absenteeism) remain relevant because annual rainfall variability persists. Adolescent-specific evidence is thin; most findings concern young children or the general population. No health outcome data from the Banas Basin were analysed, so the pathways are hypotheses for testing. We outline a surveillance and school-based adaptation agenda linking rainfall data with district health and education records.

Keywords: Adolescent health; Rainfall extremes; Monsoon dry spells; Climate and health; Semi-arid India; Banas Basin

1. Introduction

Adolescents (10–19 years) can be affected by climate-related hazards through infectious disease, nutrition, mental health, schooling and household work. Reviews of climate change and mental health in India indicate that children, women and rural populations are among the groups most affected by extreme weather (Basistha et al., 2025), and a recent review of child and adolescent mental health reports that those directly exposed to extreme events experience post-traumatic stress, anxiety, depression and grief (Giannakopoulos, 2025).

Rainfall is the hazard that most directly shapes the health environment in semi-arid regions that depend on the monsoon. Systematic evidence shows that diarrhoeal disease increases after heavy rainfall and flooding (Levy et al., 2016). In India, children exposed to repeated floods had a higher likelihood of diarrhoea in a study of under-five children (Saha et al., 2024), and excessive monsoon rainfall has been associated with childhood undernutrition across climate zones (Dimitrova and Bora, 2020). Vulnerability of agriculture to climate change has been linked to child malnutrition across India (Mahapatra et al., 2021), and a systematic review of drought in India documents effects on nutrition, sanitation, education and the workload of women and children (Algur et al., 2021).

The Banas Basin in eastern and south-eastern Rajasthan is a semi-arid, largely rainfed catchment where agriculture, groundwater and small surface storages support rural livelihoods. Earlier work on the basin has examined historical and projected rainfall variability and meteorological drought (Saini et al., 2025), and studies elsewhere in semi-arid Rajasthan have found that trends in annual and extreme rainfall are not significant at most stations (Biswas and Karmegam, 2023). Our companion analysis of 1901–2024 rainfall showed that the basin is experiencing more intense rainfall bursts without a significant change in rainfall totals. Whether and how such hydroclimatic change matters for adolescents has not been examined for this basin. The aim of this paper is therefore twofold: (i) to summarise the rainfall extreme and dry-spell hazard in the Banas Basin in terms relevant to health planning, and (ii) to map, using the published evidence, the pathways through which these hazards can affect adolescent health, stating clearly where evidence is strong, weak or absent.

2. Materials and Methods

2.1 Study design

The study combines two components. The first is a hydroclimatic hazard analysis of the Banas Basin, based on 124 years of gridded daily rainfall. The second is a structured narrative review of published evidence that is used to map how the observed rainfall hazards can reach adolescent health. The overall workflow is shown in Figure 1. The two components are linked through a conceptual framework (Figure 10) in which hazard indicators describe exposure and the reviewed literature describes pathways and outcomes. No health outcome data from the basin were analysed (Section 2.7).

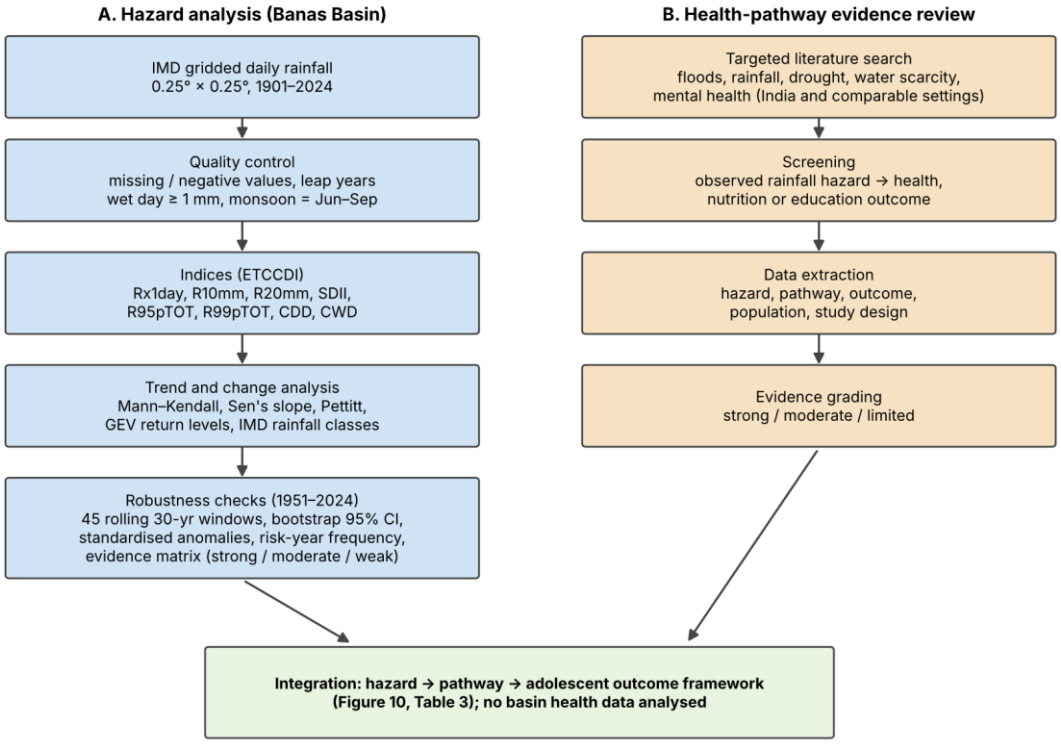
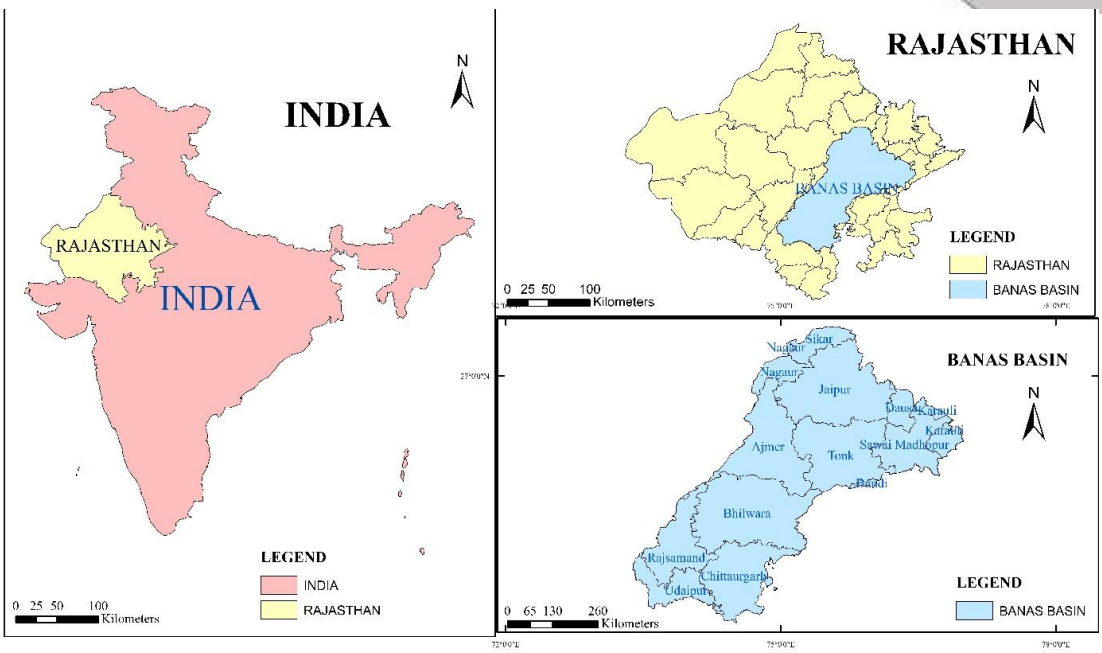


Figure 1. Methodological workflow: (A) rainfall hazard analysis and (B) health-pathway evidence review, integrated into a hazard–pathway–outcome framework.

2.2 Study area

The Banas Basin lies in the semi-arid zone of Rajasthan, India, between 24°17′–27°33′ N and 73°22′–76°60′ E, and covers about 51,652 km² (Figure 2). The river travels about 512 km before joining the Chambal River at Rameshwar in Sawai Madhopur district. The basin spans the districts of Ajmer, Bhilwara, Bundi, Chittorgarh, Dausa, Sikar, Jaipur, Karauli, Rajsamand, Sawai Madhopur, Tonk and Udaipur, and its elevation ranges from 176 to 1313 m (Figure 3). Rainfall is dominated by the June–September southwest monsoon, which contributes about 91.5% of annual rainfall. The mean annual rainfall for 1901–2024 is 617.76 mm, with a coefficient of variation of 27.9%.



STUDY AREA MAP OF BANAS RIVER BASIN

Figure 2. Location of the Banas Basin in India and Rajasthan.

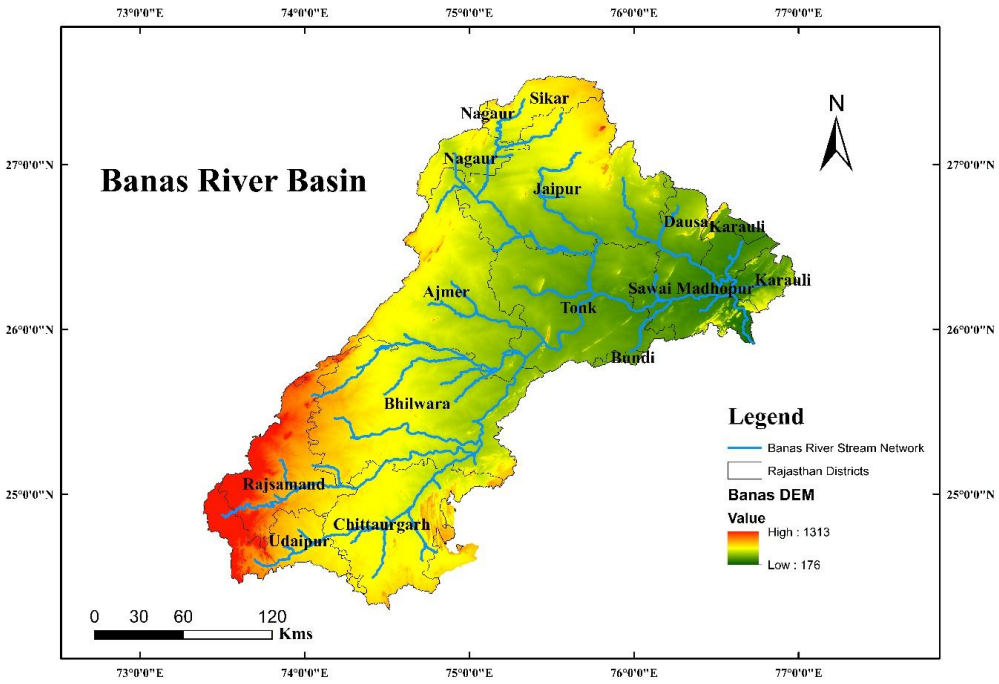


Figure 3. Banas Basin digital elevation model, stream network and district boundaries.

2.3 Rainfall data and quality control

Daily rainfall for 1901–2024 was extracted for the basin from the India Meteorological Department (IMD), Pune, gridded dataset at 0.25° × 0.25° resolution. The dataset is built from a dense rain-gauge network of 6955 stations (Pai et al., 2014). The daily data were first arranged into a continuous date-wise series and checked for missing values, unrealistic values and leap-year consistency; negative values, if any, were treated as missing. A wet day was defined as a day with at least 1 mm of rainfall and a dry day as a day with less than 1 mm. Analyses were carried out at annual and monsoon (June–September) scales, and robustness checks used the common period 1951–2024.

2.4 Rainfall extreme and dry-spell indices

Rainfall extremes and dry spells were quantified with standard daily indices of the Expert Team on Climate Change Detection and Indices (ETCCDI), calculated for each year and for the monsoon season (Table 1). Percentile thresholds for very wet and extremely wet days were estimated from all wet days in the complete 1901–2024 record. Dry-spell characteristics were derived from runs of consecutive dry days: the maximum run (CDD), the number of dry spells, mean dry-spell duration, the total number of dry days and the frequency of long dry spells. Monsoon dry spells were also examined by early, middle and late monsoon phases.

Table 1. Rainfall indices used to describe hazard exposure.

Index	Definition	Relevance to health pathways
Rx1day	Annual (or monsoon) maximum 1-day rainfall, mm	Single-day intensity; flooding and drainage stress
R10mm, R20mm	Number of days with rainfall ≥10 mm and ≥20 mm	Frequency of moderate and heavy rainfall days
SDII	Total wet-day rainfall divided by the number of wet days, mm/day	Average rainfall intensity on wet days
R95pTOT, R99pTOT	Rainfall on days above the 95th and 99th percentile of wet-day rainfall, mm	Contribution of very wet and extremely wet days
CDD	Maximum number of consecutive dry days (<1 mm)	Dry-spell length; water availability stress
CWD	Maximum number of consecutive wet days (≥1 mm)	Prolonged wet spells

2.5 Statistical analysis

Monotonic trends in each index were tested with the Mann–Kendall test and the rate of change was estimated with Sen's slope, with a 5% significance level. Serial correlation was checked with the lag-1 autocorrelation coefficient, which was not significant for the main series (Rx1day, monsoon CDD and rainfall totals; $|r| \leq 0.14$), and trend-free pre-whitening gave the same significance conclusions. Abrupt shifts were located with Pettitt's change-point test. To describe changes between climatological periods, indices were compared across the early historical (1901–1960), middle (1961–1990) and recent (1991–2024) periods.

Changes in the upper tail of daily rainfall were examined in two further ways. First, a generalised extreme value (GEV) distribution was fitted by maximum likelihood to annual Rx1day for 1901–1970 and 1971–2024 (split at the 1970 Pettitt change point), and return levels for 10-, 25-, 50- and 100-year return periods were estimated with 95% confidence intervals from 1000 bootstrap resamples. Because the split year was identified from the same data, the comparison describes the observed change and is not an independent test. Second, days at or above the India Meteorological Department (IMD) class thresholds for moderate (15.6–64.4 mm) and heavy (≥ 64.5 mm) rainfall were counted on the basin-average daily series, and the numbers of years with a heavy-rain day in the two periods were compared with Fisher's exact test.

Robustness of the detected signals was assessed over 1951–2024 in four ways. First, the Mann–Kendall test and Sen's slope were recomputed in 45 overlapping 30-year moving windows. Second, uncertainty in Sen's slope was

quantified by bootstrap resampling to obtain 95% confidence intervals, and trends were recomputed for alternative start years (1951, 1961, 1971, 1981 and 1991, all ending in 2024). Third, recent-period (2001–2024) anomalies were expressed as standardised anomalies relative to the 1951–1980 baseline, with 1961–1990 and 1971–2000 used to test baseline sensitivity. Fourth, risk years were identified from the 90th and 10th percentiles of 1951–2024 (wet years: annual rainfall above the 90th percentile; dry years: below the 10th percentile; extreme-Rx1day years: Rx1day above the 90th percentile, 63.3 mm; very wet-day years: R95pTOT above its 90th percentile), and their frequencies were compared between 1951–1980 and 2001–2024. Heavy-rain days (≥ 20 mm) were also counted by month for the same two periods. Finally, an evidence matrix combined the trend (scored 0–2), change-point (0–1), recent-anomaly (0–2) and rolling-window (0–2) results of each indicator, expressed as a percentage of the attainable score, to classify the evidence for change as strong (≥65%), moderate (40–65%) or weak (<40%).

2.6 Health-pathway evidence review

Health pathways were mapped through a structured narrative review rather than a systematic review. Adolescents were defined as people aged 10–19 years. The literature search targeted (i) flooding, heavy rainfall and diarrhoeal or waterborne disease, (ii) monsoon rainfall, drought, agricultural vulnerability and child undernutrition in India, (iii) climate extremes and mental health in India and in children and adolescents, and (iv) water scarcity and school attendance in semi-arid India. Studies were retained when they reported an observed association, or a synthesis of associations, between a rainfall hazard and a health, nutrition or education outcome. For each retained study the hazard, pathway, outcome, population and study design were recorded, and the findings were organised into hazard–pathway–outcome links (Figure 10, Table 3).

Each pathway was graded as strong (systematic review or multiple concordant studies), moderate (a single large study or a review with caveats) or limited (narrative or qualitative evidence, or evidence in younger children only). Studies were not formally appraised for risk of bias, and effect sizes from other settings are not transferred to the Banas Basin.

2.7 Scope and limits of inference

No health, nutrition, school-attendance or disease-surveillance data from the Banas Basin were analysed. The paper is therefore an exposure and pathway analysis. Statements about adolescent health describe what the literature suggests may occur under the observed hazard changes, not outcomes measured in the basin.

3. Results

3.1 Hazard exposure in the Banas Basin

Rainfall totals showed marginal and statistically insignificant increases (annual +6.26 mm/decade; monsoon +4.98 mm/decade). Short-duration extremes changed more clearly. Annual Rx1day increased significantly (+0.815 mm/decade, 1901–2024; Table 2), and monsoon Rx1day showed an equivalent increase (+0.826 mm/decade). Pettitt's test placed a significant shift in Rx1day around 1970, raising the mean from 35.63 mm to 44.45 mm (about +25%). Over 1951–2024 the Rx1day trend was +1.94 mm/decade (bootstrap 95% CI +0.60 to +3.41), although no individual 30-year window showed a significant trend, so the intensification is a long-period signal.

Figure 4 shows the Rx1day series with its 1970 shift and the monsoon dry-spell series, Figure 5 shows the rainfall totals and the monthly distribution of heavy-rain days, Figures 6 and 7 show return levels and heavy-rain days, and Figures 8 and 9 compare 1951–1980 with 2001–2024. The longest monsoon dry spell shortened significantly (−0.303 days/decade), with mean monsoon CDD falling from 17.15 days in 1901–1960 to 14.85 days in 1991–2024. The related change point (1992) was not significant, and the frequency of dry spells of at least 7 days showed no significant trend. Annual CDD did not change significantly. The highest annual Rx1day values were 91.9 mm in 1981, 88.4 mm in 2014 and 87.7 mm in 2012. The decadal mean of Rx1day was about 34 mm in the 1960s and 51.5 mm in 2010–2019. Heavy-rain days (≥ 20 mm) are concentrated in July and August; their mean number per year in August rose from 2.17 in 1951–1980 to 3.12 in 2001–2024, while the July and September values fell slightly (2.43 to 2.21 and 0.83 to 0.58). The monthly comparison is descriptive and was not tested for significance. Between 1951–1980

and 2001–2024, extreme-Rx1day years rose from 6.7% to 20.8% of years, while wet-year and dry-year frequencies changed little.

The change is clearest in the upper tail. The median of annual Rx1day was higher in 1971–2024 than in 1901–1970 (Figure 6b; Mann–Whitney U test p = 0.004, interpreted with the caveat given in Section 2.5). GEV fits indicate that the 10-year return level of Rx1day increased from 50.1 mm (95% CI 46.1–55.9) to 66.2 mm (57.4–75.1), the 25-year level from 56.5 mm (51.0–61.9) to 81.0 mm (66.5–97.2), and the 50-year level from 60.8 mm (53.7–68.6) to 93.0 mm (75.4–115.8). The 100-year level increased from 64.6 mm (55.7–74.9) to 105.7 mm (80.0–145.4), with wide intervals because the periods are short. In practical terms, the 50-year Rx1day of the earlier period (60.8 mm) lies below the 10-year level of the recent period (66.2 mm), so it is now expected more often than once in 10 years.

The number of moderate-rain days (15.6–64.4 mm) showed no trend (about 10.3 days per year in 1901–1970 and 10.6 in 1971–2024; Mann–Kendall p = 0.73; Figure 7a). Days at or above the IMD heavy-rain threshold of 64.5 mm were rare: nine were recorded in 124 years and none reached the very heavy class (≥ 115.6 mm). Only one such day occurred in 1901–1970 (1923), against eight in 1971–2024 (1971, 1979, 1981, 2001, 2012, 2014, 2019 and 2024), so heavy-rain days occurred in 8 of 54 recent years but in 1 of 70 earlier years (Fisher's exact test p = 0.010; Figure 7b). Because the series is a basin average over 51,652 km², local rainfall at individual villages is likely to have been higher.

Table 2. Rainfall hazard indicators for the Banas Basin relevant to health planning (from the companion analysis).

Indicator	Result	Significance
Annual rainfall trend, 1901–2024	+6.26 mm/decade	Not significant
Annual Rx1day trend, 1901–2024	+0.815 mm/decade	Significant
Monsoon Rx1day trend, 1901–2024	+0.826 mm/decade	Significant
Rx1day change point (1970)	35.63 → 44.45 mm (+24.75%)	Significant
Extreme-Rx1day years, 1951–1980 vs 2001–2024	6.7% → 20.8%	Small sample; indicative
Monsoon CDD trend, 1901–2024	−0.303 days/decade	Significant
Monsoon CDD, 1901–1960 vs 1991–2024	17.15 → 14.85 days	Change point (1992) not significant
Wet-year and dry-year frequency	Little change	Not significant
Rx1day 50-year return level, 1901–1970 vs 1971–2024	60.8 → 93.0 mm (95% CI 53.7–68.6 vs 75.4–115.8)	CIs do not overlap; split year data-driven
Days ≥ 64.5 mm (IMD heavy), years with one	1 of 70 years → 8 of 54 years	Fisher's exact p = 0.010

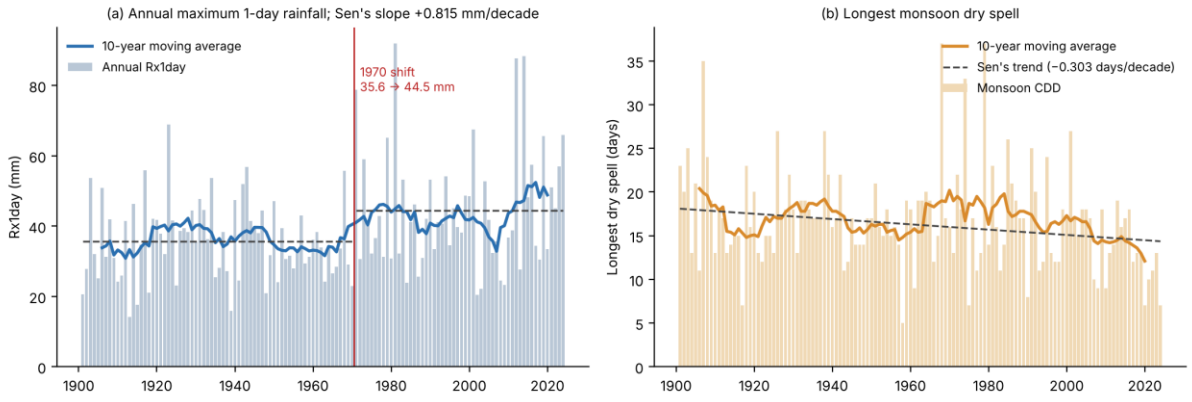


Figure 4. (a) Annual Rx1day with the 1970 Pettitt shift and 10-year moving average; (b) longest monsoon dry

spell (CDD) with 10-year moving average and Sen's trend, Banas Basin, 1901–2024.

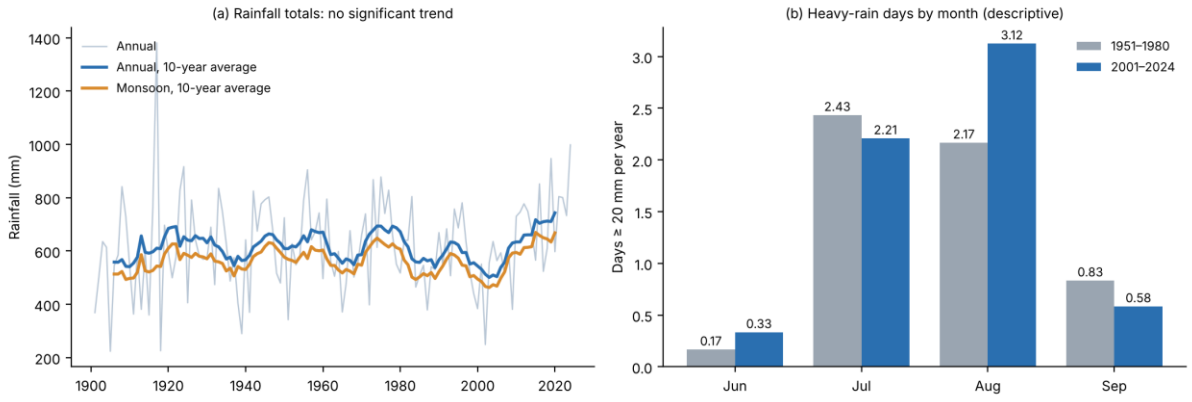


Figure 5. (a) Annual and monsoon rainfall totals with 10-year moving averages, 1901–2024; (b) mean number of days with rainfall ≥ 20 mm per year by month, 1951–1980 vs 2001–2024 (descriptive).

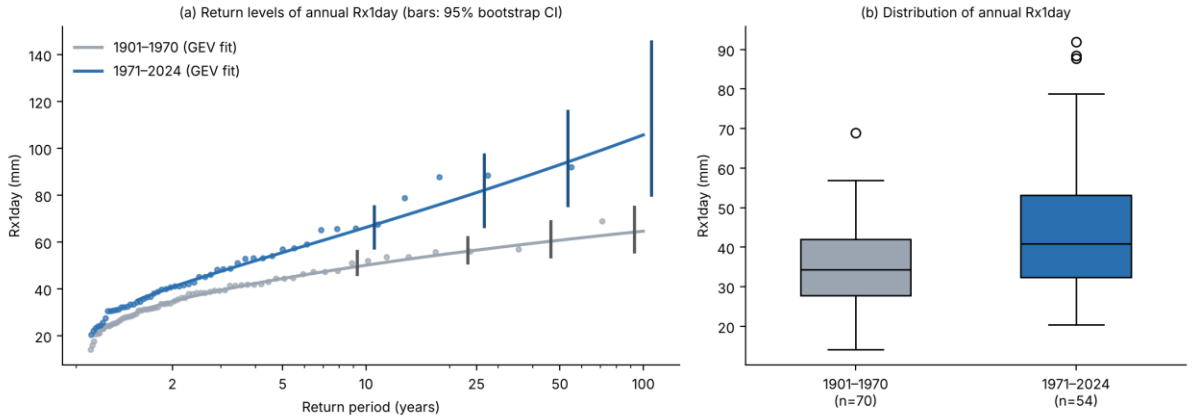


Figure 6. (a) Return levels of annual Rx1day for 1901–1970 and 1971–2024 from GEV fits with 95% bootstrap confidence intervals; (b) distribution of annual Rx1day in the two periods.

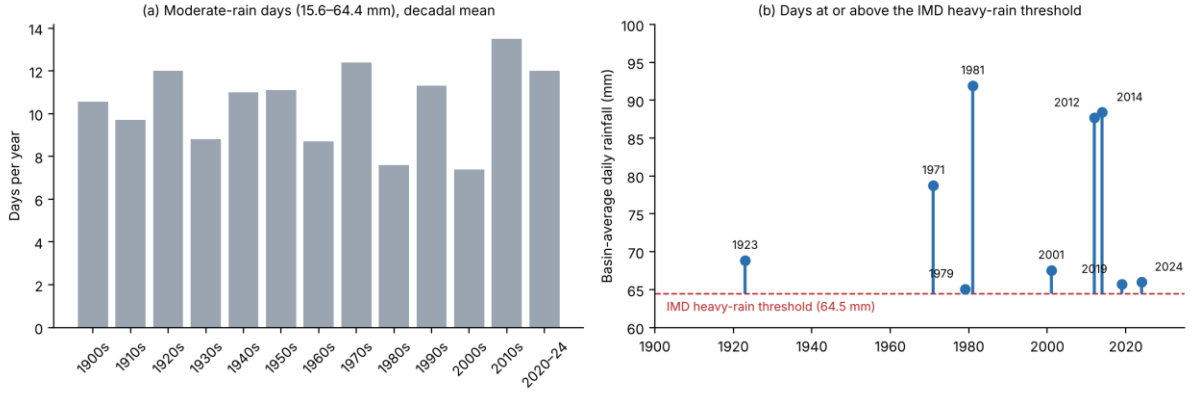


Figure 7. (a) Mean number of moderate-rain days per year by decade; (b) days at or above the IMD heavy-rain threshold (64.5 mm) on the basin-average daily series, 1901–2024.

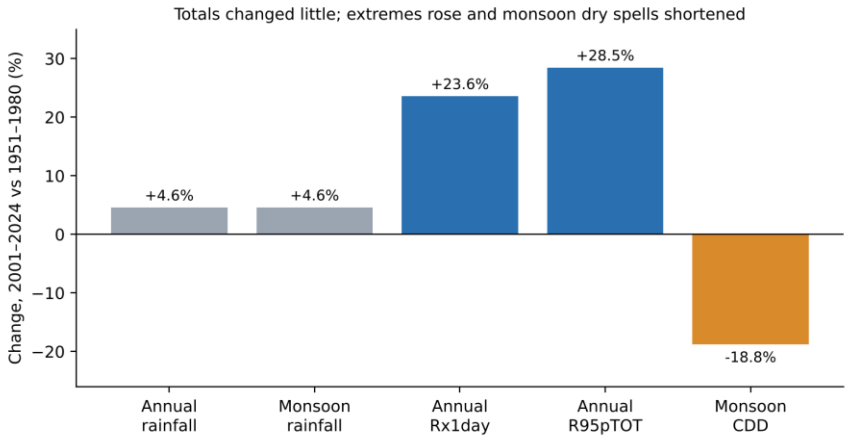


Figure 8. Percentage change in rainfall totals, extremes and monsoon dry spells between 1951–1980 and 2001–2024.

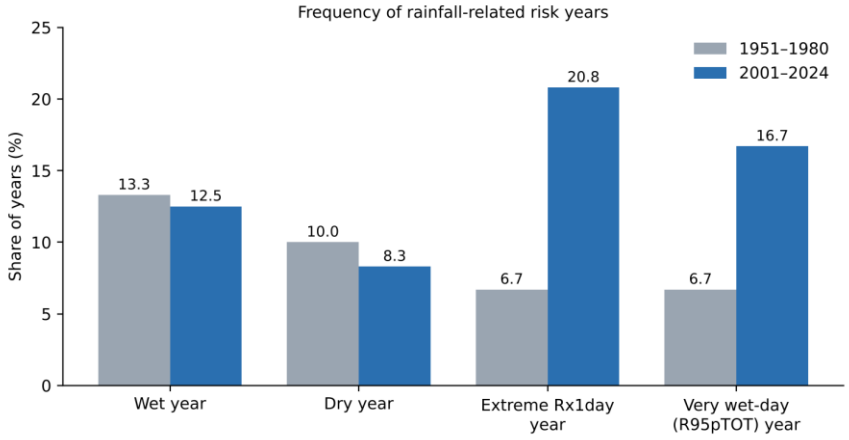


Figure 9. Share of wet, dry, extreme-Rx1day and very wet-day years, 1951–1980 vs 2001–2024.

3.2 Pathways from rainfall hazards to adolescent health

Figure 10 gives the conceptual framework and Table 3 summarises the pathways identified. Heavy rainfall and flooding have the most consistent evidence base, through diarrhoeal and other waterborne disease (Levy et al., 2016; Saha et al., 2024). Excessive monsoon rainfall has been associated with childhood undernutrition in India, with differences among climate zones; the same study found reduced risk in some drier mountainous areas (Dimitrova and Bora, 2020). Drought and water scarcity operate through food insecurity, income loss, migration, household water-collection work and school absenteeism (Algur et al., 2021; Kookana et al., 2016). Mental-health pathways are supported by reviews of climate extremes in India and by child and adolescent mental health reviews, but the evidence is largely narrative.

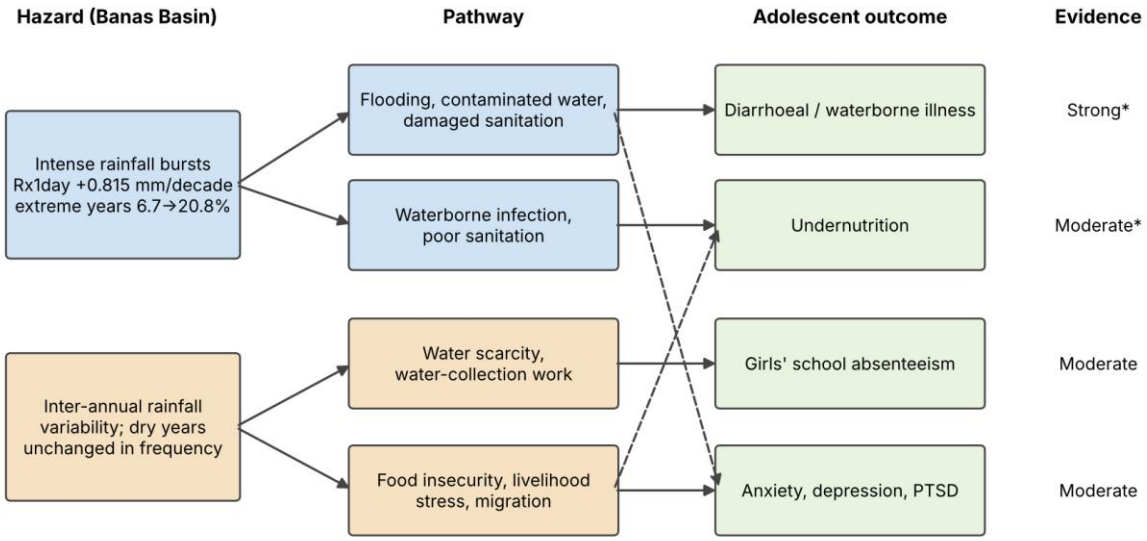


Figure 10. Conceptual framework linking Banas Basin rainfall hazards to adolescent health outcomes, with strength of published evidence.

Table 3. Hazard–health pathways, adolescent relevance and strength of evidence.

Hazard (Banas Basin signal)	Pathway	Health or education outcome	Evidence and source	Strength
Intense rainfall bursts (Rx1day ↑)	Flooding, contaminated water, damaged sanitation	Diarrhoeal and other waterborne illness	Diarrhoea increases after heavy rainfall and flooding (Levy et al., 2016); repeated floods and child diarrhoea in rural India (Saha et al., 2024). Under-five evidence mainly.	Strong for general population; limited for adolescents
Intense rainfall bursts (Rx1day ↑)	Waterborne infection and poor sanitation after heavy rain	Undernutrition	Excess monsoon rainfall linked to childhood undernutrition, with diarrhoea proposed as one channel (Dimitrova and Bora, 2020). Evidence for ages under 5.	Moderate; limited for adolescents
Extreme events (all)	Fear, loss, displacement, family stress	Anxiety, depression, post-traumatic stress	Reviews on climate and mental health in India and in children and adolescents (Basistha et al., 2025; Giannakopoulos, 2025).	Moderate (reviews; few Indian adolescent data)
Rainfall deficit or variability (annual totals)	Food insecurity, income loss, migration	Undernutrition, wasting, stunting	Agricultural vulnerability to climate change linked to child malnutrition in India (Mahapatra et al., 2021); effects of drought on women	Moderate

			and children reviewed in Algur et al. (2021).	
Rainfall deficit or variability (annual totals)	Water scarcity and household water collection	School absenteeism among girls	About 60–65% of students in semi-arid Rajasthan and Gujarat watersheds missed school for water-related work; girls' absenteeism in Rajasthan was much higher (Kookana et al., 2016).	Moderate (two watersheds)
Rainfall deficit or variability (annual totals)	Livelihood stress, care burden	Mental and physical health of women and children	Systematic review of drought in India (Algur et al., 2021).	Moderate (low-confidence synthesis)

3.3 Why adolescence needs separate attention

Most quantitative studies identified here concern children under five or the general population. The adolescent-specific evidence is concentrated in two areas: the school-attendance and water-collection burden on girls (Kookana et al., 2016) and mental health (Giannakopoulos, 2025). The absence of adolescent-specific effect estimates for flood, rainfall and drought exposure in India is the central evidence gap identified by this review.

4. Discussion

4.1 What the hazard signal suggests

The Banas Basin shows more intense short-duration rainfall but no significant change in rainfall totals, and its longest monsoon dry spell has become shorter. Read against the literature, this points first toward intense-rainfall pathways. A shift in mean Rx1day from about 36 to 44 mm and a tripling in the frequency of extreme-Rx1day years imply more frequent days on which drainage, wells, ponds and sanitation are overwhelmed, which is the setting in which diarrhoeal risk rises (Levy et al., 2016). The return-level result sharpens this point: rainfall depths that were rare before 1971 are now far more common, and since heavy-rain days (≥ 64.5 mm) rose from 1 to 8 while moderate-rain days did not change, the shift is in the tail and not in the everyday rainfall regime. Shorter monsoon dry spells, by themselves, do not suggest a worsening within-season drought burden. Drought-related pathways nevertheless remain relevant, because dry years did not become less frequent and because rainfed livelihoods remain exposed to inter-annual variability.

These readings carry limits. The return-level estimates rest on 54 to 70 annual values per period, their intervals are wide at long return periods, and the split year was chosen from the same data. The extreme-year frequency estimates rest on short windows, no single 30-year window showed a significant Rx1day trend, and the dry-spell change point was not significant. Basin-averaged gridded data may also smooth the point rainfall experienced by a village. Our drought analysis was based on dry-spell and wet/dry-year indicators, not on a formal drought index, so the drought tail may be understated.

4.2 Adolescent-specific considerations

Two findings in the literature are specific to adolescents and young people. First, girls often carry water and household labour in water-scarce households, which links rainfall deficit to missed school (Kookana et al., 2016). Second, children and adolescents directly affected by extreme events are reported to experience post-traumatic stress, anxiety, depression and grief (Giannakopoulos, 2025). We do not claim that these effects have been measured in the Banas Basin.

4.3 Implications for practice

Four actions follow from the hazard signal and the pathway evidence. (i) Link IMD rainfall and heavy-rainfall alerts with district disease surveillance so that diarrhoeal and other waterborne illness can be monitored after extreme rainfall events. (ii) Prioritise school water, sanitation and hygiene (WASH) facilities that remain functional during and after heavy rainfall. (iii) Where rainfall variability reduces water availability, support water access near households so that girls' time is not diverted from school, and include adolescents in school feeding and nutrition programmes. (iv) Include adolescent mental-health support in post-event response. These are plausible measures derived from the cited evidence; they should be evaluated locally.

4.4 Research agenda

A test of the pathways requires linking basin rainfall indices with outcome data at block or district level, for example monthly diarrhoea counts from the health information system, school attendance records, and adolescent nutrition indicators from national surveys, using time-series or case-crossover designs with rainfall lags. Adolescent-specific analyses and analyses stratified by sex are the priority.

4.5 Limitations

This is a narrative synthesis, not a systematic review, and its search was not exhaustive. No health data from the Banas Basin were analysed, and associations reported elsewhere may not transfer to the basin because they depend on sanitation, housing, health-care access and livelihoods. Several cited studies concern children under five rather than adolescents, and some use ecological designs. These limits mean that Table 3 should be read as a map of hypotheses.

5. Conclusion

Rainfall in the Banas Basin has become more intense over 1901–2024 without a significant change in totals, and the longest monsoon dry spell has shortened. Using published evidence, we identified heavy-rainfall and flood-related pathways (waterborne disease and psychological stress) as the more immediate concern for adolescent health, with drought and water-scarcity pathways (undernutrition, girls' school absenteeism) remaining relevant because of inter-annual variability. The evidence for adolescents specifically is limited, and measurement of basin-level health outcomes against these rainfall indices is the necessary next step.

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Conflict Of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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