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Heavy Rainfall Impact on Agriculture: Crop Risk Assessment with Farmer Participation in the Paravanar Coastal River Basin

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Abstract: Heavy rainfall significantly impacts agriculture by damaging crops and causing substantial economic losses. The Paravanar River Basin, a coastal river basin in India, experiences heavy rainfall during the monsoon season. This study analyzed both ground-level rainfall measurements and farmers' experiences to understand the effects of heavy rainfall on agriculture. Rainfall data from nine rain gauge locations were analyzed across three cropping seasons: Kharif 1 (June to August), Kharif 2 (September to November), and Rabi (December to May). To determine the frequency of heavy rainfall events, a detailed analysis was conducted based on the standards set by the India Meteorological Department (IMD). Villages near stations showing increasing rainfall trends and a higher frequency of heavy rainfall events were classified as vulnerable. The primary crops cultivated in these vulnerable areas were identified through a questionnaire survey with local farmers. A detailed analysis of these crops was conducted to determine the cropping season most affected by heavy rainfall events. The impacts of heavy rainfall on the primary crops were assessed using the Delphi technique, a score-based crop risk assessment method. These impacts were categorized into eight distinct types. Among them, yield reduction, waterlogging, crop damage, soil erosion, and crop failure emerged as the most significant challenges in the study area. Additional impacts included nutrient loss, disrupted microbial activity, and disease outbreaks. Based on this evaluation, risks were classified into five categories: low risk, moderate risk, high risk, very high risk, and extreme risk. This categorization offers a framework for understanding potential consequences and making informed decisions. To address these challenges, the study recommended mitigation measures such as crop management, soil management, and drainage management. Farmers were also encouraged to conduct a cause-and-effect analysis. This bottom-up approach raised awareness among farmers and provided practical solutions to reduce crop losses and mitigate the effects of heavy rainfall.

Keywords: heavy rainfall; crop risk assessment; Delphi technique; vulnerability; cause-and-effect analysis

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1. Introduction

The impacts of heavy rainfall on agricultural production have become a growing concern in recent years. According to the Indian Meteorological Department (IMD), heavy rainfall is defined as precipitation ranging from 64.5 to 115.5 mm per day. Changing rainfall patterns, influenced by climate change, are increasingly disrupting agricultural systems, particularly in developing countries where agriculture is a primary livelihood [1]. Climate change has amplified both the frequency and intensity of heavy rainfall events, creating significant challenges for the agricultural sector [2,3].

The causes and effects of these agricultural risks vary across geographic regions, reflecting the complex interplay of environmental and socio-economic factors [4]. The Intergovernmental Panel on Climate Change (IPCC) projects that monsoon rainfall intensity in India will increase substantially, with extreme and heavy rainfall events expected to rise by as much as 25% by the end of the century [5]. While the rainfall distribution from observations can vary depending on the sources [6], this anticipated shift not only heightens the immediate risk of crop damage but also exacerbates long-term vulnerabilities in agricultural systems, including hydrologic changes, soil degradation, loss of productivity, and disruptions in planting and harvesting cycles [7].

Rainfall variability has a profound impact on Indian agriculture, where extreme weather events, particularly heavy rainfall, result in significant economic losses. An estimated INR 50,000 crores are lost annually due to these events [8]. Heavy-rainfall-induced flooding is one of the primary drivers of crop failures, leading to reduced agricultural output and severe financial setbacks for farmers. For instance, studies suggest that extreme weather conditions can reduce farmer incomes by as much as 80% in affected regions [9]. This loss is particularly concerning in states like Uttar Pradesh, Bihar, and Assam, where approximately 40% of agricultural land is prone to flooding [10].

India's agricultural sector is further challenged by its vulnerability to natural disasters. Ranked 11th among 15 countries at "extreme risk" for natural disasters, India faces a compounding threat from climate change [11,12]. The intersection of these risks underscores the urgent need for adaptive measures to protect agricultural productivity and ensure food security.

Addressing the challenges posed by heavy rainfall requires a multifaceted approach, combining scientific insights with practical solutions tailored to local contexts. Investments in climate-resilient farming practices, improved water management systems, and policies that strengthen farmer support networks are critical in mitigating the adverse effects of heavy rainfall on agriculture.

The Paravanar River Basin in the Cuddalore District of Tamil Nadu is classified as a disaster-prone zone due to its unique geological characteristics and low-lying topography [13]. Agriculture in this region primarily depends on monsoon rainfall, making any changes in rainfall patterns highly consequential. Previous studies have observed an increasing trend in rainfall during November in Cuddalore [14]. Research has also highlighted the adoption of crop diversification and altered cropping patterns as adaptive strategies to mitigate the destructive impacts of recurrent cyclones in the district [15].

Amid the growing impacts of climate change, it is crucial to deepen our understanding of how heavy rainfall affects agricultural productivity and to develop effective adaptation strategies [16]. Risk assessment is a key component in minimizing the damage caused by extreme weather events [17]. Engaging farmers in research provides critical insights into crop-specific vulnerabilities and helps inform the development of resilient agricultural practices [18,19].

The Delphi technique, a participatory method widely used across industries such as engineering, finance, and healthcare, is a valuable tool for assessing the potential impacts of heavy rainfall on agriculture [20,21]. A comprehensive review of the literature underscores the urgent need for enhanced agricultural risk management, particularly in developing countries [22].

This study proposes the use of a multi-round Delphi technique to systematically evaluate the impacts of heavy rainfall on crops. This approach facilitates the collection of precise data, enables the classification of risks, and guides the development of tailored response strategies. By employing this method, the study aims to contribute to the creation of more resilient agricultural systems in disaster-prone regions like the Paravanar River Basin.

This study evaluates the risks associated with heavy rainfall on five major crops in the Paravanar River Basin: cashew nut, coriander, sugarcane, sweet potato, and turmeric. The impacts of heavy rainfall are classified into eight categories: yield reduction, waterlogging, crop damage, soil erosion, crop failure, nutrient loss, disrupted microbial activity, and disease outbreak. These risks are further categorized into five levels—low, moderate, high, very high, and extreme—based on their observed effects. This classification provides a foundation for developing targeted mitigation strategies aligned with crop-specific risk assessment scores and impact types.

The proposed mitigation strategies include crop management techniques to optimize growth and production, soil management practices to enhance fertility and structure, and drainage management to prevent waterlogging and maintain proper moisture levels. Implementing these strategies can strengthen crop resilience, minimize losses from heavy rainfall, and improve overall productivity in the region, thereby supporting more sustainable agricultural practices.

Quantitative risk assessment of climate and physiological controls is vital for sustainable agricultural resource management and achieving high crop yields [23,24]. To measure the study's impact on farmers, participants are encouraged to conduct a cause-and-effect analysis of heavy rainfall risk management. The identified risks and corresponding response strategies are presented within a cause-and-effect framework, enabling farmers to understand and address these challenges effectively.

This research plays a critical role in advancing comprehensive crop risk assessment and mitigation planning. By fostering sustainable agricultural practices and enhancing resilience to heavy rainfall, it contributes to ensuring the long-term viability of farming operations in regions vulnerable to extreme weather events.

This study's primary contribution is a thorough evaluation of the effects of excessive rainfall on agriculture in the Paravanar River Basin, India, through the integration of rainfall data and farmers' experiences. The study employs observed rainfall data (which are not normally used) and the Delphi technique for crop risk assessment to identify and categorize the major issues encountered by farmers (with local survey), such as yield decrease, waterlogging, crop damage, soil erosion, and crop failure. The study presents a risk classification framework that discusses the severity of these consequences and provides actionable mitigation options, including crop, soil, and drainage management, to diminish crop losses and enhance resistance to heavy rainfall. The study's bottom-up approach from field scale directly contributes to farmer awareness and promotes practical, regionally sustainable, and suitable solutions.

2. Study Area and Data Description

The Paravanar River Basin is located in the Cuddalore District of Tamil Nadu, India. It lies between latitudes 11°18′ and 11°45′ north and longitudes 79°18′ and 79°45′ east, covering a total geographical area of 872.34 square kilometers. It is the second-smallest river basin among the 17 river basins in Tamil Nadu. The Cuddalore District comprises six administrative blocks: Cuddalore, Panruti, Kurinjipadi, Kammapuram, Mel Bhuvanagiri, and Parangipettai. The Paravanar River Basin is bordered by the Bay of Bengal to the east, the Pennaiyar River Basin to the north, and the Vellar River Basin to the south and west. The study area's location and rain gauge sites are illustrated in Figure 1.

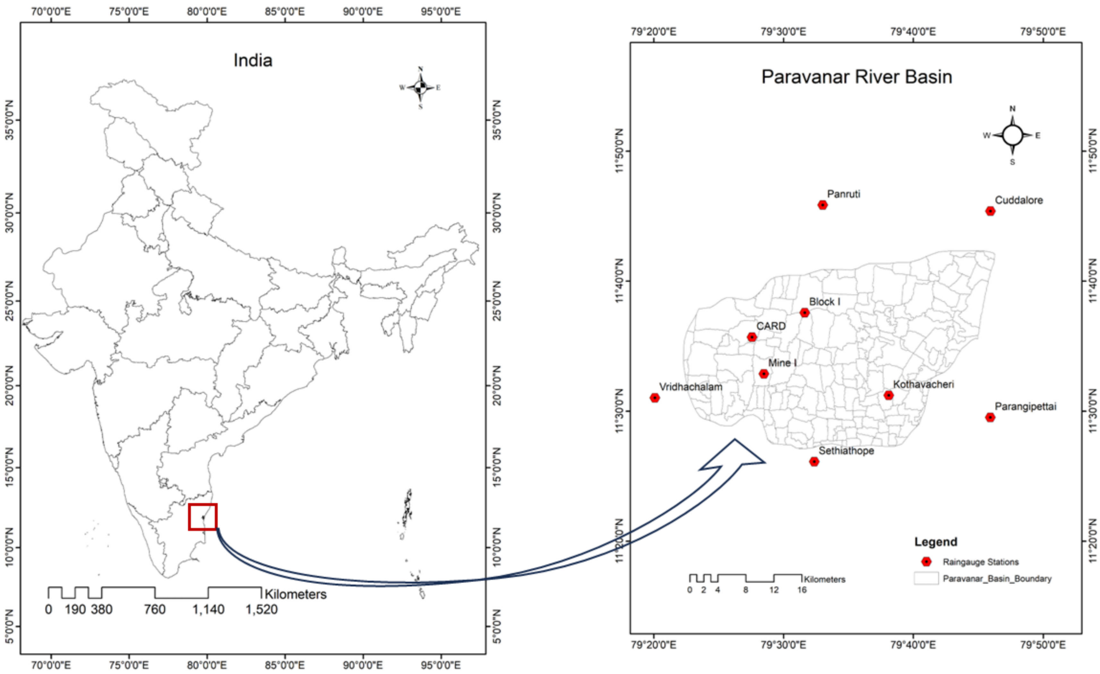

Figure 1. Location map of the study area.

The basin's topography is predominantly plain, with elevations ranging from near sea level to 110 m, sloping towards the south and southeast. Geologically, the basin is characterized by sedimentary formations, with approximately 70% of the area covered by Cuddalore sandstone and the remaining 30% consisting of river and coastal alluvium.

The basin's soil types include red sandy soils in the upper reaches, alluvial soils along river valleys, and coastal alluvial soils near the plains [25].

Precipitation in the region is largely cyclonic, driven by low-pressure systems forming over the Bay of Bengal. The mean annual rainfall is 1369 mm, with the majority occurring during the northeast monsoon and a smaller portion during the southwest monsoon [26]. Despite receiving substantial rainfall, the region often experiences water scarcity. The area also faced significant challenges during the 2004 tsunami disaster [27].

Groundwater resources in the basin are found in both shallow and deep aquifers. The first two aquifers are located just beneath lignite layers at a depth of approximately 122 m below ground level. The third aquifer lies between depths of 122 and 305 m. The Neyveli Lignite Corporation, situated within the Paravanar River Basin, operates three mines (Mine 1, Mine 1A, and Mine 2). Groundwater extracted from these mines serves as a vital water source for the region, with the water being channeled to the Perumal Tank via the Walajah Tank. This resource is primarily used for irrigation purposes in the region's tanks.

The Paravanar River Basin is one of the agricultural basins in India. According to the [28] *Paravanar Basin Report* by the National Water Mission, Government of India, the agricultural area expanded from 357 sq km to 456 sq km between 2004 and 2015. But the agricultural yield data from the Ministry of Agriculture and Farmers Welfare, Government of India [29], indicate a decline in crop yield. In addition to that, Ref. [30] discovered that the study region, previously considered the most efficient cropping zone for coriander from 2006 to 2010, shifted to a highly inefficient cropping zone for coriander after 2015. Therefore, this location was selected as the study area to identify the causation underlying the decline in production.

The major crops cultivated in the Cuddalore District include cashew nut, paddy, sorghum, coriander, sugarcane, sweet potato, turmeric, and various horticultural flowers [15]. The area under cultivation for the designated primary crops throughout the study period is analyzed, with data gathered up to the year 2019 from the Ministry of Agriculture and Farmers Welfare. With 29,175 hectares, cashew nut occupies the biggest area, accounting for 63.8 percent of the total area under cultivation. Sugarcane comes second at 15,248 hectares, accounting for 33.34 percent of the area. Coriander is grown on 985 hectares, which is 2.15 percent of the cropped area. Turmeric and sweet potato occupy 239 hectares and 82 hectares, accounting for 0.52 and 0.18 percent of the area, respectively.

Rainfall data for the study area were collected from nine different locations over a 40-year period (1981–2020). These data were categorized into three cropping seasons: Kharif 1 (June to August), Kharif 2 (September to November), and Rabi (December to May), along with annual rainfall. Table 1 below provides the geographical locations and elevation details of the rain gauge stations.

Table 1. Description of rain gauge stations used in the study.

Station Name	Latitude	Longitude	Elevation (m)
Block I	11.6261	79.5272	71
CARD	11.5948	79.4594	86
Cuddalore	11.7564	79.7658	17
Kothavacheri	11.5202	79.6352	19
Mine I	11.5478	79.4747	89
Panruti	11.7642	79.5503	37
Parangipettai	11.4919	79.7655	21
Sethiathope	11.4353	79.5394	28
Vridhachalam	11.517	79.3347	60

The Paravanar River Basin faces several challenges related to water resources, including water scarcity, pollution, salinity, environmental degradation, and coastal seawater intrusion. Inefficient and underutilized water resource management exacerbates these issues. To address these challenges, it is crucial to gain a comprehensive understanding of the basin's hydrological cycles, water supply, and consumption patterns. This knowledge can inform the development of sustainable strategies to mitigate water shortages, reduce pollution, and prevent environmental damage. Ultimately, such efforts will help secure the basin's long-term water availability and ecological health.

3. Methodology

This research employed a combination of qualitative and quantitative techniques to assess crop risk associated with heavy rainfall. The study was carried out in several stages, as outlined below:

- Rainfall trend analysis;
- Heavy rainfall frequency analysis;
- Questionnaire survey;
- Risk analysis;
- Cause-and-effect analysis.

3.1. Rainfall Trend Analysis

The Mann–Kendall test [31,32] and Spearman's rank correlation coefficient test [33,34] are among the most widely used non-parametric methods for trend analysis. These tests do not require the data to follow a normal distribution, and their statistical power has been reported as comparable. The magnitude of trends was estimated using Sen's slope method [35,36]. In contrast, alternative methods like linear regression can be sensitive to outliers and rely on the assumption of normality [37]. Therefore, the non-parametric nature of the Mann–Kendall and Spearman's tests makes them particularly robust and well suited for environmental data analysis. All the aforementioned statistical analyses were conducted using the open-source R package modifiedmk version 1.6 [24].

For a timeseries $X_i = x_1, x_2, \ldots, x_n$, the Mann–Kendall test statistic S is calculated as

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(x_j - x_i\right) \quad (1)$$

where n is the number of data points, and x_i and x_j are the data values in timeseries i and j ($j > i$), respectively. sign($x_j - x_i$) is the sign function:

$$Sign\left(x_i - x_j\right) = \begin{cases} -1 & if\ \left(x_j - x_i\right) < 0 \\ 0 & if\left(x_j - x_i\right) = 0 \\ 1 & if\ \left(x_j - x_i\right) > 0 \end{cases} \quad (2)$$

The statistic S will be normally distributed with parameters $E(S)$ and variance $V(S)$ as given below

$$E(S) = 0 \quad (3)$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(k)(k-1)(2k+5)}{18} \quad (4)$$

where n is the number of data points, m is the number of tied groups, and t_k denotes the number of ties of extent k. The standardized test statistic Z is calculated using the formula below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \frac{S+1}{\sqrt{var(S)}} & if\ S < 0 \end{cases} \quad (5)$$

To test for a monotonic trend at the α significance level, the alternate hypothesis of the trend is accepted if the absolute value of the standardized test statistic Z is greater than the $Z1 - \alpha/2$ value obtained from standard normal cumulative distribution tables. If Z is positive, then the trend is increasing, and if Z is negative, then the trend is decreasing.

The Spearman rank correlation coefficient $\mathrm{r_{SRC}}$ [33,34]) for a given timeseries $X_i = x_1$, $x_2, \ldots, x_n$ is given as

$$\mathrm{r_{SRC}} = 1 - \left\{ \frac{6\sum_{i=1}^{n} [d_i]^2}{\mathrm{n}(\mathrm{n}^2 - 1)} \right\} \quad (6)$$

where $d_i = (RX_i - RY_i)$. RX_i is the rank of the variable X_i and RY_i is the chronological order of observations. $i = 1, 2, \ldots, n$ in series of size n. The test statistic $\mathrm{t_{SRC}}$ is given by

$$\mathrm{t_{SRC}} = \mathrm{r_{SRC}} \sqrt{\frac{(\mathrm{n}-2)}{1 - \mathrm{r_{SRC}^2}}} \quad (7)$$

The test statistic $\mathrm{t_{SRC}}$ follows a t-distribution with degrees of freedom ν and significance level α. The null hypothesis of the trend is not rejected if t_(ν,(α/2)) < t_SRC < t_(ν, 1 − (α/2)). For both the Mann–Kendall test and Spearman's rank correlation test, the critical Z values are 1.64, 1.96, and 2.57 at 90%, 95%, and 99% percent confidence levels, respectively.

Sen's slope β_i for a given timeseries $X_i = x_1, x_2, \ldots, x_n$ with N pairs of data is calculated as

$$\beta_i = \frac{x_j - x_k}{j - k}, \forall k \leq j \text{ and } i = 1, 2, \ldots, N \quad (8)$$

The median of N values of β_i gives Sen's estimator of slope β.

$$\beta = \begin{cases} \beta_{\frac{N+1}{2}} & \text{if } N \text{ is odd} \\ \frac{\left(\beta_{\frac{N}{2}} + \beta_{\frac{N+2}{2}}\right)}{2} & \text{if } N \text{ is even} \end{cases} \quad (9)$$

3.2. Heavy Rainfall Frequency Analysis

Frequency analysis is an effective tool for understanding the number of heavy rainfall occurrences over time and their impacts on agriculture. In this study, all heavy rainfall events, as defined by the Indian Meteorological Department (64.5 mm to 115.5 mm), were enumerated for the period 1981–2020. Additionally, the study analyzed the occurrence of heavy rainfall over four decades in relation to five major crops grown in the area: cashew nut, coriander, sugarcane, sweet potato, and turmeric.

Trend analysis methods are valuable for identifying overall upward or downward trends in rainfall data; however, they do not adequately address extreme events [38]. Similarly, while various statistical models assess the impact of rainfall on crop yields [39], many researchers focus primarily on rainfall intensity, often overlooking the frequency of heavy rainfall events. Investigating heavy rainfall in terms of both frequency and intensity is essential for effective agricultural planning [40–42].

This dual approach enables researchers to establish flooding thresholds, assess crop risks during critical growth stages, and develop strategies for agricultural resilience. Frequency analysis, in particular, helps policymakers formulate strategies to mitigate the adverse effects of heavy rainfall on agricultural systems.

3.3. Questionnaire Survey

Questionnaire surveys are widely used in research due to their ability to efficiently gather qualitative and quantitative data from large populations. Previous studies have shown that questionnaire surveys are a valuable tool for identifying the main crops grown in vulnerable villages and emphasized the importance of local knowledge and the ethnographic approach in agricultural research within these communities [43]. While qualitative methods like focus group discussions and Participatory Rural Appraisal offer valuable insights, they often fall short in providing the comprehensive data that surveys can generate [44,45]. Remote sensing is well suited for large-scale assessments but may miss important local details [23].

In this study, questionnaire surveys were employed for their ability to efficiently gather qualitative and quantitative data from large populations, facilitating a comprehensive analysis of agricultural practices, particularly within vulnerable communities. Since our focus is on heavy rainfall, trend analysis is performed to figure out increasing rainfall trends. Based on the results from the trend analysis, questionnaire surveys were performed in villages exhibiting increasing trends to ascertain the primary crops cultivated and to evaluate the impact of increasing rainfall on agriculture. Also, from the Integrated Water Resource Management Perspective, a participatory approach is essential to understand the more detailed and practical situations during an extreme event [46]. Therefore, by using the results of the statistical analysis, a questionnaire survey was conducted. A total of 165 respondents participated in this study, including 19 with bachelor's degrees in agriculture and 5 with degrees in water resource engineering. A detailed demographic profile of the participants is presented in Table 2.

Table 2. Descriptive summary of questionnaire survey participants.

Characteristics	Frequency	Percentage
	Gender	
Male	98	59.39
Female	67	40.61
	Age	
21–45	47	28.48
45–60	94	56.97
>60	24	14.55
	Landholding size	
Marginal (<1 Ha)	140	84.85
Small (1–2 Ha)	25	15.15
	Education	
Primary or Below	54	32.73
Higher Secondary	67	40.61
Bachelors	35	21.21
Masters	9	5.45
	Household Income (INR)	
<50,000	71	43.03
50,000–100,000	59	35.76
100,000–500,000	23	13.94
>500,000	12	7.27

Questionnaire surveys were administered to farmers and experts in two rounds: September 2021, before the monsoon, and December 2021, after the monsoon season. The objective of these surveys was to identify the crop cycles, major crops, and water sources in the study area, and to assess the impacts of heavy rainfall and local management practices aimed at mitigating adverse effects. Based on survey data, the impacts of heavy rainfall on agriculture were categorized into eight distinct types as shown in Table 3. These categories will serve as the basis for a Delphi analysis to assess the corresponding risks.

Table 3. Identified impacts of heavy rainfall on agriculture.

Impact	Description
Yield Reduction	Decrease in production; however, the crops do not experience significant damage.
Crop Damage	Harm to crops that may diminish their health and productivity, though it does not invariably lead to total failure.
Soil Erosion	Water absorption capacity of the soil is exceeded, resulting in surface runoff that erodes soil particles is called soil erosion.
Nutrient Loss	Fertilizers leach rapidly due to excessive water movement, resulting in the washing away of essential nutrients from the root zone. Farmers can identify nutrient loss through chlorosis, characterized by yellowing of leaves, dry soil crusts, and an increase in the growth of broadleaf weeds
Waterlogging	Soil becomes saturated, resulting in excessive moisture within the root zone

Table 3. *Cont.*

Impact	Description
Diminished Microbial Activity	A condition in which the typical functions of soil microorganisms are adversely impacted. The farmers assess microbial activity through the soil's color and odor. Healthy soils typically exhibit a darker coloration attributable to their organic matter content. A lighter or grayish soil color may signify a reduction in organic material and microbial activity. An unpleasant odor arising from the soil may signify anaerobic conditions, typically resulting from diminished microbial activity.
Disease Outbreak	Caused by a variety of environmental and management variables, including heavy rainfall and waterlogging.
Crop Failure	A complete loss of the crop, representing the maximum extent of yield loss—100% yield loss.

3.4. Delphi Analysis

The Delphi analysis, developed by Norman Dalkey and Olaf Helmer at the RAND Corporation in the late 1950s [47], systematically gathers expert opinions to support decision-making and forecasting. This method is particularly effective for score-based risk assessment, where experts assign scores to potential hazards, enabling structured and quantitative risk analysis [21]. The Delphi method is recognized for its robustness and has been widely applied in industries such as engineering, finance, healthcare, and social research [48].

Relying solely on coarse-gridded data from available sources including remote sensing observations and IMD as well as hydrological assessments cannot provide a comprehensive understanding of on-field impacts without incorporating the farmer inputs. For any adaptation measures, linking physical data to the stakeholders' approach is key for a better understanding, and that is what our study is attempting to achieve. The United Nations emphasizes participatory research in agriculture as being vital to its Sustainable Development Goals (SDGs). Ref. [49] present a comprehensive assessment of participatory action research methodologies for climate change adaptation in Africa. It underscores the significance of engaging local populations in the research process to design effective and sustainable adaptation solutions. The Environmental Agency [50] highlights the significance of participatory research in adapting to climate change. It offers insights into how participatory research can enhance knowledge exchange and aid in the formulation of effective adaptation strategies. We have also incorporated specialists, including agricultural engineers and water resource engineers, to obtain a comprehensive understanding of the effects of heavy rainfall. Additionally, institutions such as the World Bank [46,51,52] encourage participatory research to ensure a sustainable agricultural future.

In this study, a Delphi analysis was conducted using multiple rounds of questionnaire surveys in December 2021 to obtain ranking scores. The first round focused on identifying the frequency of intense rainfall, its effects, and prioritizing crops based on the extent of damage caused by heavy rainfall. In subsequent rounds, each impact was ranked based on rainfall frequency, crop loss due to heavy rainfall, and agricultural vulnerability.

The risk associated with each of the eight impacts of heavy rainfall from the previous exercise were quantified using the following formula:

$$\text{Risk Score} = \text{Frequency} + \text{Crop loss} + \text{Vulnerability} \tag{10}$$

For each of the three factors, namely frequency, crop loss, and vulnerability, the range of values and descriptions are presented in Table 4.

Table 4. Risk scores for frequency, crop loss and agricultural vulnerability.

Risk Score	Frequency		Crop Loss		Vulnerability of the Area	
	Duration Between Events (Years)	Description	Range of Crop Loss (%)	Description	Vulnerability (%)	Description
1	100	Much less frequent	0–5	Minor Loss	0–10	Slightly Vulnerable
2	50	Less frequent	5–20	Small Loss	10–30	Moderately Vulnerable
3	25	Moderately frequent	20–60	Medium Loss	30–50	Highly Vulnerable
4	10	Highly frequent	60–80	Heavy Loss	50–80	Very Highly Vulnerable
5	5	Extremely frequent	80–100	Total Loss	80–100	Extremely Vulnerable

The risk score values ranging from 1 to 5 represent a quantifiable assessment of severity, for all three factors involved in calculating the risk score as mentioned in Equation (10) above. The frequency section of the table presents the relationship between the risk score and the frequency of occurrence of heavy rainfall events. The duration between events indicates the average time interval between occurrences. A lower duration value suggests a higher frequency of heavy rainfall, while a higher value indicates a lower frequency of heavy rainfall. The crop loss section of the table presents the relationship between the risk score and the percentage of crop loss due to heavy rainfall, with higher scores indicating more significant losses and lower scores reflecting smaller or negligible losses. Lower scores indicate minor crop loss whereas higher scores are associated with greater crop losses. The agricultural vulnerability section presents the relationship between risk score and vulnerability percentage. Lower risk scores represent a minimal percentage of vulnerability, classified as 'slightly vulnerable', whereas higher risk scores are classified as 'Extremely vulnerable'. Based on the score assigned to each factor, the combined risk score ranges from 3 to 15. This is further grouped into five categories as shown in Table 5 below.

Table 5. Risk classification.

Risk Classification	Low	Moderate	High	Very High	Extreme
Risk Score Range	1 to 3	3 to 6	6 to 9	9 to 12	12 to 15

Based on the risk scores assigned to each heavy rainfall impact for different crop types, mitigation strategies were formulated through collaborative efforts involving local farmers and subject matter experts. This participatory approach ensured that the strategies were both practical and tailored to the specific needs of the farming community, integrating local knowledge with expert insights to enhance resilience against heavy rainfall.

3.5. Cause-and-Effect Analysis Performed by Farmers

Cause-and-effect analysis, rooted in Aristotle's philosophical principles, has been systematically applied in agricultural research to evaluate the impact of practices on outcomes. Methods such as correlation analysis [37] and longitudinal studies [53] provide valuable statistical insights into the relationships among variables under study. However, these methods are limited in their ability to establish causation. Cause-and-effect analysis is preferred for its ability to identify practices that enhance decision-making [54] and support agricultural sustainability [55]. This type of analysis is essential for helping farmers adapt to evolving agricultural challenges.

In this study, the results from the questionnaire survey, Delphi risk assessment, and proposed mitigation strategies for heavy rainfall were presented to farmers through focus group discussions. Farmers were then tasked with performing cause-and-effect analyses and creating fishbone diagrams. These causal analyses and diagrams demonstrated the farmers' understanding of how heavy rainfall affects their crops.

4. Results and Discussion

The research progressed through multiple phases, starting with an analysis of rainfall trends that examined historical data to identify precipitation patterns. This was followed by an analysis of heavy rainfall frequency, focusing on the occurrence of extreme rainfall events. Vulnerable villages were identified based on the findings of the trend and frequency analyses. A questionnaire survey conducted in these villages collected data from farmers about their primary crops and their perceptions of the impacts of heavy rainfall. Subsequently, a Delphi analysis ranked the risks associated with each crop, identifying the most vulnerable crops by assessing the effects of heavy rainfall. Finally, a cause-and-effect analysis engaged farmers in reviewing their understanding of heavy rainfall events and their implications for agricultural practices.

4.1. Rainfall Trend Analysis

Analyzing rainfall trends is essential for interpreting climate variability, managing water resources, and formulating sustainable agricultural and disaster preparedness plans. Regions with growing rainfall trends may become vulnerable to agricultural vulnerabilities, including waterlogging, soil erosion, and crop damage, whereas areas with decreasing trends confront issues such as drought and water scarcity [56]. Figure 2 illustrates the rainfall trend at nine rain gauge stations, Block I, CARD, Cuddalore, Kothavacheri, Mine I, Panruti, Parangipettai, and Sethiathope, from 1980 to 2020. It underscores considerable variations in yearly precipitation, signifying an inconsistent monsoon pattern affected by climatic variations. Specific years, such as the mid-1980s, late 1990s, and mid-2010s, exhibit significant increases in rainfall, presumably attributable to cyclonic storms or strengthened monsoons, potentially resulting in flooding in vulnerable regions. In contrast, the late 1980s and early 2010s demonstrate markedly reduced rainfall, indicating drought conditions that may affect agricultural and water supply. Regional variations in rainfall trends are visible, with coastal regions such as Cuddalore and Parangipettai likely experiencing increased rainfall due to their closeness to the Bay of Bengal, while interior areas like Panruti exhibit rather steady patterns. The fluctuation in rainfall throughout the course of time and space underscores the necessity for sustainable water management measures, rainwater harvesting and climate-resilient agricultural practices.

The study of rainfall patterns within the Paravanar River Basin was conducted over three distinct crop seasons: Kharif 1 (June to August), Kharif 2 (September to November), and Rabi (December to May). In the study region, there are two harvests throughout the kharif season. The first harvest is referred to as Kharif 1 which is from June to August, while the second harvest is referred to as Kharif 2 which is September to November. As we delve into the findings of Table 6 from the Kharif 1 season, the analysis reveals an intriguing picture.

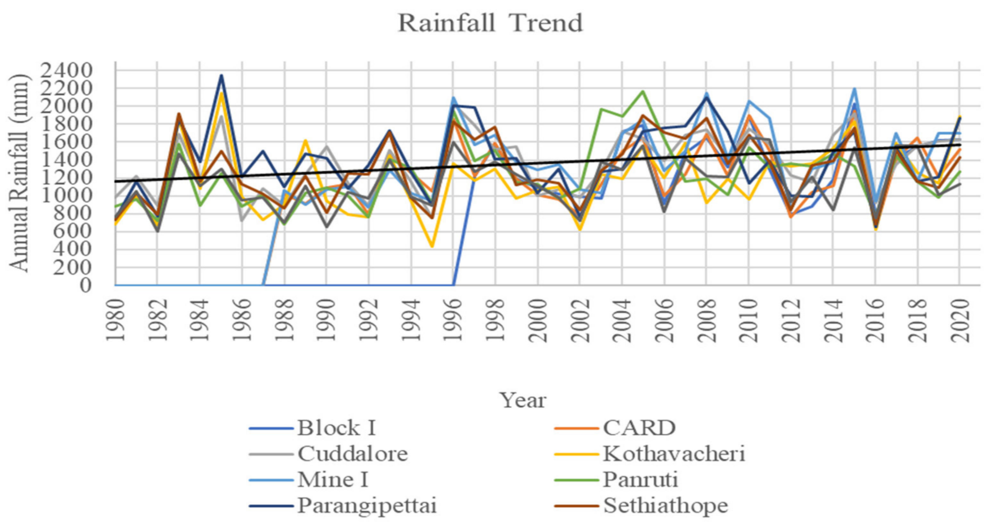

Figure 2. Rainfall trend during the study period (1980–2020).

Table 6. Test statistic of Mann–Kendall (Z_M) and Spearman Rho (Zs) during crop seasons.

Station Name	Kharif 1		Kharif 2		Rabi	
	ZM	ZS	ZM	ZS	ZM	ZS
Block I	1.57	1.58	1.11	1.60	1.57	1.70
CARD	1.47	1.40	0.94	1.01	1.54	1.41
Cuddalore	1.57	1.61	1.99 **	1.98 **	1.67 *	1.74 *
Kothavacheri	1.29	1.24	1.97 **	1.96 **	1.37	1.28
Mine I	1.42	1.48	1.25	1.44	1.15	0.99
Panruti	1.23	1.31	1.50	1.52	1.25	0.65
Parangipettai	1.36	1.36	1.05	1.20	1.04	0.94
Sethiathope	1.49	1.51	2.31 **	2.33 **	1.65 *	1.96 *
Vridhachalam	0.97	1.08	2.06 **	2.09 **	0.99	0.94

Note: Significance levels * = 90%, ** = 95%. All rain gauge stations analyzed demonstrated a rising trend in rainfall across all seasons. None of the stations indicated any statistically significant trends during the Kharif 1 season. The Cuddalore, Kothavacheri, Sethiathope, and Vridhachalam stations exhibited a significant positive increase in rainfall during the Kharif 2 season at a 95% significance level. During the Rabi season, the Cuddalore and Sethiathope stations indicated increasing rainfall trends at the 90% significance level. This comprehensive analysis identifies specific areas within the basin that are likely to experience increased rainfall trends in the future. The findings offer valuable insights for policymakers, planners, and local communities as they prepare for the potential impacts of climate change, such as increased flooding, erosion, and challenges in water resource management. Similar studies have indicated that the Cuddalore District is particularly vulnerable to high-intensity rainfall, often driven by cyclonic events during the monsoon season [57]. This analysis has helped identify vulnerable areas with a potential increase in heavy rainfall events.

4.2. Heavy Rainfall Frequency Analysis

Determining the number of occurrences of rainfall events following a rainfall trend analysis is essential for various reasons. Trend analysis offers insights into long-term changes in rainfall patterns; however, it may fail to account for the frequency of extreme events. Examining the frequency of heavy rainfall events enhances trend analysis by providing a deeper understanding of rainfall variability [58]. This extensive knowledge facilitates risk assessment, as heavy rainfall events frequently result in waterlogging, crop damage, and crop failure, allowing regions to develop suitable mitigation plans [49]. The integration of trend analysis with the evaluation of heavy rainfall events offers a comprehensive perspective on rainfall patterns, thereby facilitating enhanced decision-making and improved preparedness for extreme weather events [59].

The analysis of the relationship between heavy rainfall occurrences and crop seasons has unveiled several important insights into agricultural practices in the region. Over the span of 40 years, the frequency of heavy rainfall occurrences for five primary crops has been documented, providing a comprehensive view of how heavy rainfall impacts these agricultural activities. Table 7 presents an analysis of heavy rainfall events documented over a 40-year period at nine stations of the study area during Kharif 1, Kharif 2, Rabi seasons, and annual totals.

Table 7. Number of heavy rainfall events over 40 years.

Station Name	Kharif 1	Kharif 2	Rabi	Total
Block 1	2	22	5	29
CARD	3	22	5	30
Vridhachalam	2	21	5	28
Parangipettai	2	20	4	26
Kothavacheri	2	24	3	29
Sethiathope	2	16	3	21
Panruti	3	23	3	29
Mine 1	3	25	2	30
Cuddalore	4	32	5	41

The analysis of heavy rainfall frequency indicated that the Kharif 2 season experiences the highest number of heavy rainfall events. The Cuddalore station reported the highest frequency of 41 heavy rainfall events, with the highest occurrence of 32 events during the Kharif 2 season, 4 events recorded in Kharif 1, and 5 in Rabi. The Sethiathope station demonstrated the lowest frequency of heavy rainfall events, comprising 2 events in Kharif 1, 16 in Kharif 2, and 3 in Rabi. This analysis underscores the significance of seasons in precipitation patterns, revealing that certain regions consistently experience higher or lower frequencies of heavy rainfall events. Such variability is critical for farmers to consider when planning crop cycles and managing resources, ensuring that agricultural practices align effectively with prevailing weather conditions. Based on the analysis of rainfall trends and the frequency of heavy rainfall, the following villages have been identified as vulnerable: Kothavacheri, Ellaikudi, Sirupalaiyur, B. Kolakudi, Seeyapadi, Manjakollai, and B. Odaiyur. Further investigations will focus on these villages, all of which are located near Cuddalore, Panruti, Kothavacheri, Sethiathope, and Vridhachalam.

4.3. Questionnaire Survey

The primary agricultural crops and the impacts of heavy rainfall are identified from the questionnaire survey. The important questions asked in the survey are shown in Table 8. The table presents key questions from the questionnaire survey conducted pre- and post-monsoon season, emphasizing agricultural practices and perceptions of heavy rainfall impacts.

In response to the inquiry regarding the crop season, 32.7% (n = 54) indicated cultivation of crops across multiple seasons, whereas 26.1% (n = 43) reported participation in Kharif 1. In terms of major crops cultivated, 32.7% (n = 54) reported "mixed" crops, while 18.8% (n = 31) indicated the cultivation of coriander. Water sources for agriculture primarily consist of mixed sources at 50.9% (n = 84), while rainfed water represents 34.5% (n = 57) during the pre-monsoon period. In response to enquiries regarding the effects of heavy rainfall on crops, 28.5% (n = 47) indicated crop damage, while 17.6% (n = 29) identified waterlogging as a notable concern. To mitigate the effects of heavy rainfall, 41.2% (n = 68) implemented crop management practices, whereas 37.6% (n = 62) utilized a combination of methods. The data illustrate the variety of agricultural practices and challenges encountered by farmers, underscoring the necessity of adaptive strategies in response to changing rainfall patterns.

Table 8. Key results from the questionnaire survey.

Significant Questions Asked		Description Frequency	Percentage
During which Crop Season do you practice agriculture?	Annual	19	11.5
	Kharif 1	43	26.1
	Kharif 2	31	18.8
	Rabi	18	10.9
	More than one season	54	32.7
What are the Major Crops grown?	cashew nut	19	11.5
	Coriander	31	18.8
	Sugarcane	21	12.7
	sweet potato	21	12.7
	Turmeric	19	11.5
	Mixed	54	32.7
What is the source of water for agriculture?	Bore	12	7.3
	Drip	3	1.8
	Well	9	5.5
	Rainfed	57	34.5
	Mixed	84	50.9
How the Heavy rainfall impacted your crops	Yield reduction	25	15.2
	Crop damage	47	28.5
	Soil erosion	13	7.9
	Nutrient loss	12	7.3
	Waterlogging	29	17.6
	Disrupted microbial activity	16	9.7
	Disease outbreak	5	3
	Crop failure	14	8.5
	others	4	2.4
What are the methods used to mitigate heavy rainfall	Crop management	68	41.2
	Soil management	12	7.3
	Drainage enhancement	23	13.9
	Mixed	62	37.6

The crop seasons and major crops cultivated remain consistent during both pre-monsoon and post-monsoon periods. Water sources indicated a change, with 34.5% (n = 57) depending on rainfed water in the pre-monsoon period, rising to 38.8% (n = 64) post-monsoon. Meanwhile, the percentage utilizing mixed sources remained stable at 50.9% (n = 84). The effects of heavy rainfall exhibited variability; 28.5% (n = 47) reported crop damage prior to the monsoon, which increased to 32.1% (n = 53) following the monsoon, indicating increased vulnerability after the rainfall. The prevalence of waterlogging issues went up from 17.6% (n = 29) before the monsoon to 20.6% (n = 34) after the monsoon. The survey revealed that the predominant crops cultivated in this region are cashew nut, coriander, sugarcane, sweet potato and turmeric. Farmers in this region cultivate a diverse range of crops recommended by the Tamil Nadu Agricultural University. The properties and variety of crops that are cultivated in this region are shown in Table 9.

Table 9. Properties of the selected crops for this study.

Crops	Properties
Cashew nut	Clonal selection from an accession of germplasm housed at the Virdhachalam Regional Research Station produced the variety cultivated here. The average annual production per tree is 7.12 kg. With 5 g nuts, 20% shelling, and 5–7 fruits per panicle, it yields 1700 kg of nuts per kg. This variety has a lot of branching. The 240 W counts of kernels are of excellent quality. The cultivation period is February to December.
Coriander	Here, they grow a variety of crops, including CO1, with excellent germplasm selection (TNAU). There are 110 days in all. It produces seeds and leaves for two purposes. When the crop is nourished by rain, the yield is 800 kg/ha. Coriander is cultivated during the Kharif season, benefitting from two harvests—one in Kharif 1 and another in Kharif 2.
Sugarcane	This area is home to several types. This crop has two primary seasons: December to May, and June to September, which is a special season. There are two methods for planting these crops: the standard method and pit planting method. The yield from pit planting is 10–15% higher than that from the conventional method. The main cultivation season is Kharif 1, but it is also cultivated in Rabi, which is considered a special season.
Sweet potato	The primary crop farmed in this area is sweet potato CO3. It grows well in warm, humid climates with loamy soil. About 20–25 tonnes is produced on average per hectare. There are 110–120 days in the growth season altogether. Cultivated exclusively during Kharif 1.
Turmeric	This area grows a variety of turmeric kinds. This calls for tropical temperatures and loamy soil that drains properly. Turmeric is also grown with coriander as an intercrop. About 25–30 tonnes is produced on average per hectare. The cultivation period is June to March.

4.4. Delphi Analysis

This research utilized the Delphi method to comprehensively assess the potential risks associated with heavy rainfall on agricultural crops within the study region. The expert panel, comprising farmers, water managers, and agricultural engineers with a combined experience of over 20 years, evaluated and allocated a risk score for each impact across crop types to identify the most vulnerable crops to heavy rainfall. The results of the Delphi analysis, highlighting the potential impacts of heavy rainfall on various cultivated crops, are presented in Table 10.

Cashew nut is found to be at very high risk of crop failure, exhibiting a combined risk score of 11. It is further identified as being in the high-risk class for crop damage, soil erosion, and waterlogging. Coriander is identified as the most vulnerable crop to heavy rainfall, with associated impacts ranging from extreme to very high risk. Crop damage, yield reduction, nutrient loss, and crop failures are classified as extremely risky impacts of heavy rainfall. Additionally, the crop is at very high risk of soil erosion, waterlogging, disrupted microbial activity, and disease outbreak. Sugarcane is at high risk of soil erosion and very high risk of waterlogging. Sweet potato shows a very high risk of crop damage, yield reduction, waterlogging, disease outbreak, and crop failures. Turmeric is at extreme risk of waterlogging and very high risk of crop damage, yield reduction, soil erosion, disease outbreak, and crop failures.

The results reveal that heavy rainfall events significantly threaten crop health and yield, primarily due to water-related problems such as waterlogging, crop damage, yield reduction, soil erosion, disease outbreak, and complete crop failure. Based on the identified impacts of heavy rainfall and the classification of crop risks, several mitigation measures were proposed. Mitigating techniques cover multiple impacts including waterlogging, crop damage, soil erosion, and yield reduction. The mitigation techniques are classified into four categories: crop management, soil management, drainage management and knowledge sharing. Using crop covers, integrated pest management, crop rotation, and access to weather forecasts, crop management consists of scheduling sowing and harvest. Raised beds, mulching to stop erosion, and tillage following harvests are among the soil management techniques. Drainage management guarantees that, in heavy rain, all drainage systems are connected to avoid waterlogging. By means of information and methodologies to address agricultural difficulties, knowledge sharing is essential to counteract nutrient loss, microbial decline, and disease outbreaks. The proposed mitigation strategies focus on enhancing crop management, soil management, drainage management, and knowledge sharing to reduce these impacts.

Table 10. Score-based crop risk assessment for the selected crops.

Impacts of Heavy Rainfall	Cashew Nut				Coriander				Sugarcane				Sweet Potato				Turmeric			
	F	CL	V	Total	F	CL	V	Total	F	CL	V	Total	F	CL	V	Total	F	CL	V	Total
Yield Reduction	2	2	1	5	4	5	5	14	3	2	1	6	3	3	3	9	4	3	3	10
Crop Damage	3	2	2	7	5	5	5	15	3	3	2	8	3	4	3	10	4	4	3	11
Soil Erosion	2	3	1	6	3	4	4	11	3	4	3	10	2	1	1	4	4	3	2	9
Nutrient Loss	2	2	1	5	4	4	4	12	2	3	2	7	4	2	1	7	3	3	1	7
Waterlogging	4	2	2	8	4	4	3	11	4	4	4	12	4	4	3	11	5	4	4	13
Disrupted Microbial Activity	3	1	1	5	3	3	3	9	3	3	2	8	4	2	1	7	3	2	2	7
Disease Outbreak	1	1	1	3	4	4	3	11	3	3	2	8	4	3	2	9	4	2	3	9
Crop Failure	4	3	4	11	5	5	5	15	3	2	1	6	4	3	2	9	4	3	2	9

Notes: F = frequency of heavy rainfall; CL = crop loss; V = heavy rainfall vulnerability of the area; low risk: 1–3; moderate risk: 3–6; high risk: 6–9; very high risk: 9–12; extreme risk: 12–15.

Overall, this assessment underscores the need for targeted management strategies, particularly for coriander, to mitigate the adverse effects of heavy rainfall on agricultural productivity. This finding is further supported by [30], who reported a reduction in coriander cultivation in Cuddalore.

4.5. Cause-and-Effect Analysis Performed by the Farmers

To assess the impact of our research on local farmers, we engaged them in a cause-and-effect analysis focusing on crop risks associated with heavy rainfall. This approach utilized a fishbone diagram, which is recognized as an effective tool for managing risks [21].

The results of the analysis revealed that farmers have a strong understanding of the risks to their crops. They demonstrated the ability to identify at-risk crops, categorize associated risks, and seek guidance from field experts. Additionally, they actively implement response plans and work to raise awareness among their peers regarding these risks. What sets this analysis apart is that it was crafted entirely by the farmers, inspired by the findings of the score-based crop risk assessment. This grassroots initiative underscores the importance of local knowledge in addressing agricultural challenges.

In collaboration with water resource engineers, village leaders, and agricultural specialists, the farmers provided critical insights into potential risks, strategies for understanding these risks, and effective response methods. Moreover, they discussed ways to share knowledge within their community, fostering a collective approach to risk management. The outcomes of the cause-and-effect analysis, as conducted by the farmers, are visually represented in Figure 3. This diagram illustrates their insights and highlights the collaborative nature of the analysis, emphasizing the vital role of local expertise in enhancing agricultural resilience.

Figure 3. Cause-and-effect analysis performed by farmers.

5. Conclusions

This study offers a quantitative and participatory evaluation of heavy rainfall impacts on agriculture in the Paravanar River Basin, aiming to support farmers by identifying crop risks from adverse rainfall. The analysis of rainfall trends revealed no significant trends during Kharif 1, whereas Kharif 2 showed notable increases at four stations—Cuddalore, Kothavacheri, Sethiathope, and Vridhachalam. The Rabi season also exhibited significant increases at Cuddalore and Sethiathope. Our examination of heavy rainfall frequency indicates that Kharif 2, occurring from September to November and coinciding with the post-monsoon period, is the most affected season, resulting in increased soil moisture, which can impact crop health and growth. The trend and frequency analyses identified several vulnerable villages, including Kothavacheri, Ellaikudi, Sirupalaiyur, B. Kolakudi, Seeyapadi, Manjakollai, and B. Odaiyur. These villages are located near weather stations with increased rainfall trends, highlighting their vulnerability to heavy rainfall impacts.

The predominant crops in the region, such as cashew nut, coriander, sugarcane, sweet potato, and turmeric, were identified through a comprehensive questionnaire survey. This survey also pinpointed eight major impacts of heavy rainfall, including yield reduction, crop damage, crop failure, waterlogging, and nutrient loss.

According to the Delphi analysis, coriander emerged as the most vulnerable crop to heavy rainfall. Suggested mitigation measures focus on crop management, soil management, drainage maintenance, and raising awareness among farmers. To further disseminate the findings, discussions were held with farmers and experts to facilitate a cause-and-effect analysis. This analysis demonstrated that farmers are now better equipped to identify at-risk crops, classify potential dangers, seek assistance from specialists, implement effective mitigation strategies, and share knowledge with their peers. Overall, this study underscores the critical need for proactive measures in agricultural practices to minimize the adverse effects of heavy rainfall. These measures aim to foster resilience among farmers in the Paravanar River Basin.

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