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RESEARCH ARTICLE

FLOOD MAGNITUDE AND DYNAMICS IN THE UNGAUGED VELABISHT RIVER BASIN, ALBANIA, BASED ON RAINFALL–RUNOFF MODELING

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Abstract

Reliable estimation of flood magnitudes is a fundamental requirement for the design of hydraulic infrastructure, flood risk management, and the mitigation of flood-related impacts. In ungauged river basins, where discharge observations are unavailable, this task becomes particularly challenging and is associated with considerable uncertainty. This study presents a comprehensive assessment of flood hydrographs in the ungauged Velabisht River basin, which forms part of the Osumi river system in Albania. Flood simulation was performed using the semi-distributed Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS). Six independent meteorological scenarios were developed on the basis of precipitation data collected from stations located within and in the vicinity of the basin. A frequency analysis of annual maximum daily precipitation was conducted, resulting in depth–duration–frequency (DDF) relationships for each scenario. Design storm hyetographs were constructed using regional rainfall characteristi cs and the alternating block method. Precipitation losses were estimated using the Curve Number method, with spatially distributed curve numb ers derived through Geographic Information System (GIS) analysis under average antecedent moisture conditions. Surface runoff hydrogra phs were generated using the synthetic unit hydrograph recommended by the Natural Resources Conservation Service, while baseflow was represented by an exponential recession approach. Flood routing along the river network was simulated using the Muskingum–Cunge method.

The model produced complete flood hydrographs for return periods of 2, 10, 20, 50, and 100 years, including peak discharges, flood volumes, and temporal flow distributions. Model results were evaluated through comparison with peak flows estimated using the method of hydrological analogy, indicating acceptable agreement for low and medium exceedance probabilities. The outcomes of this research provide valuable insights for flood risk assessment and hydraulic design in ungauged basins and may support decision-making processes for engineers, researchers, and policymakers in the region.

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Introduction:-

Flood estimation plays a central role in hydraulic engineering, land-use planning, and disaster risk reduction. Accurate knowledge of flood magnitudes and their temporal characteristics is required to design bridges, culverts, flood protection works, and reservoirs, as well as to assess flood hazards and potential damages. However, in many regions, especially in developing countries, hydrometric networks are sparse, and long-term discharge records are unavailable. Under such conditions, river basins are classified as ungauged, and conventional flood frequency analysis based on observed streamflow data cannot be directly applied.In ungauged basins, rainfall data are often more readily available than discharge measurements. As a result, hydrological modeling approaches that transform precipitation into runoff have become an essential tool for flood estimation. Advances in computational capabilities and the development of physically based and conceptual hydrological models have significantly improved the reliability of rainfall–runoff simulations. Semi-distributed models, in particular, offer a balance between spatial representation and data requirements, making them suitable for catchments where detailed observations are lacking.

The HEC-HMS model, developed by the U.S. Army Corps of Engineers, has been widely applied for flood simulation, design storm analysis, and watershed management studies. Its flexible structure allows the integration of various loss methods, runoff transformation techniques, baseflow representations, and routing approaches. In Albania, several river basins remain ungauged, and systematic flood studies are limited. The Velabisht River, a tributary of the Vjosa River, is one such basin where flood behavior has not been previously quantified in detail.The primary objective of this study is to estimate flood hydrographs with different return periods for the ungauged VelabishtRiver basin using the HEC-HMS semi-distributed model. Specific objectives include: (i) conducting precipitation frequency analysis and deriving basin-average DDF curves; (ii) constructing design storm hyetographs for selected exceedance probabilities; (iii) estimating precipitation losses and runoff generation parameters using GIS-based analysis; (iv) simulating flood hydrographs and routing flood waves through the river network; and (v) validating peak flow estimates through comparison with results obtained using the method of hydrological analogy. The results aim to contribute to improved flood risk understanding and provide a scientific basis for hydraulic design and flood management in the basin.

Materials and Methods:-

Setting up the Velabisht flood model

The VelabishtRiver is one of the principal tributaries of the Osumi River, which in turn forms part of the Osumi River system in southern Albania. The basin covers an area of approximately 183 km² and exhibits a predominantly mountainous to pre-mountainous topography. The average elevation of the catchment is around 750 m above sea level, with steep slopes in the upstream areas and gentler terrain downstream.The regional climate is Mediterranean, characterized by cold and wet winters and dry, relatively mild summers. Mean annual precipitation in the basin is approximately 1109 mm, while average annual evapotranspiration is estimated at about 615 mm. The long-term mean discharge of the river has been estimated at 2.9 m³/s based on regional hydrological studies, corresponding to a specific discharge of approximately 16 l/s/km² and an annual runoff coefficient of 0.45. Despite its hydrological importance, the river is ungauged, and no continuous streamflow records are available.

The Velabisht River basin map.

HEC-HMS model setup:-
Flood modeling was carried out using the HEC-HMS software. The model setup required the definition of several interconnected components, including basin geometry, meteorological inputs, precipitation loss methods, runoff transformation techniques, baseflow representation, channel routing, and simulation control specifications.A digital elevation model (DEM) was used to delineate the basin, extract the drainage network, and subdivide the catchment into hydrologically meaningful subbasins. Basin parameters such as area, slope, flow length, and stream characteristics were derived directly from the DEM within a GIS environment and imported into HEC-HMS.Six meteorological scenarios corresponding to different exceedance probabilities were defined. For each scenario, precipitation inputs were specified as design storms derived from frequency analysis. The Curve Number method was selected to estimate precipitation losses, while runoff transformation was performed using the NRCS synthetic unit hydrograph. Baseflow was simulated using an exponential recession approach, and flood routing through the river reaches was carried out using the Muskingum–Cunge method. Simulation periods were defined to exceed the duration of rainfall events, ensuring full representation of flood hydrographs.

Precipitation frequency analysis and meteorological scenarios:-
Flood generation in the basin was based on precipitation frequency analysis using data from meteorological stations located near the study area, with particular emphasis on the Sinjë station. Due to the characteristics of the available records, precipitation data were available at daily time steps. Annual maximum daily precipitation series were extracted and subjected to statistical frequency analysis.Several probability distributions were tested to identify the most appropriate model for extreme precipitation. Goodness-of-fit was evaluated using the Kolmogorov–Smirnov test, and the Generalized Extreme Value (GEV) distribution was found to best represent the observed extremes. Based on the selected distribution, precipitation quantiles corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and 50% were estimated. These quantiles represent potential meteorological conditions capable of generating floods of varying magnitudes.Since the basin concentration time is shorter than 24 hours, it was necessary to derive precipitation depths for durations shorter than one day. Regional reduction relationships were applied to transform daily precipitation quantiles into rainfall depths for durations ranging from 5 minutes to 12 hours.

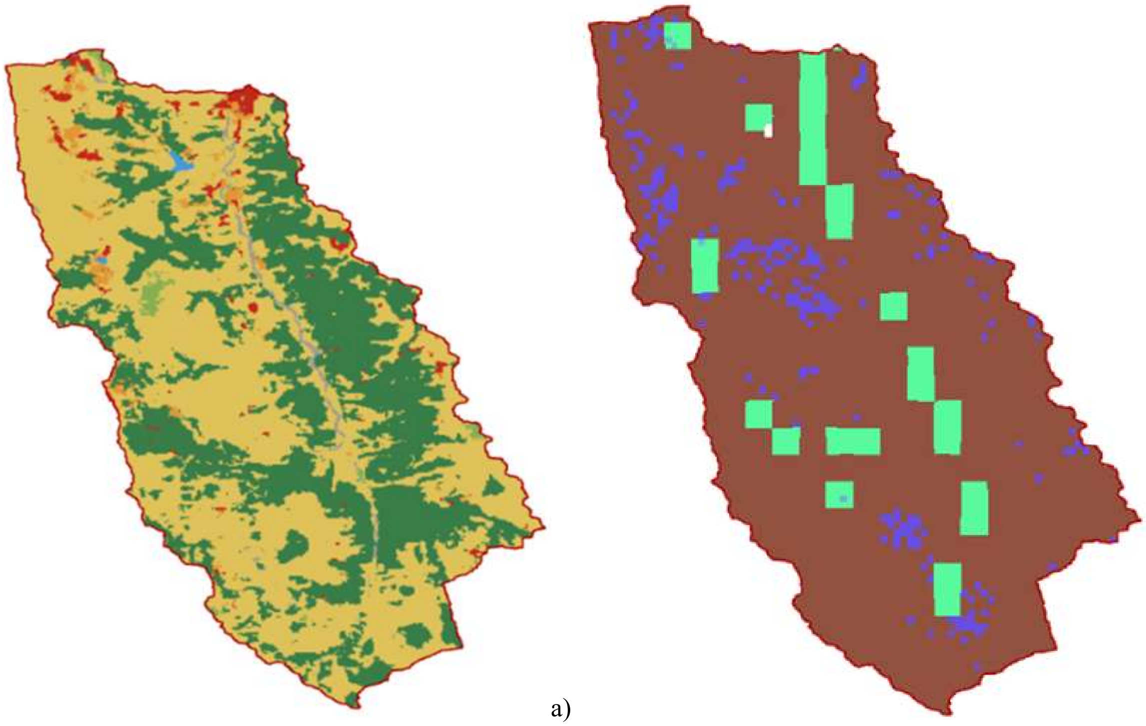
The transformation was performed using the following empirical relationship:

$$h_{p,t} = H_{p,24}\left(\frac{t}{24}\right)^{n} \tag{1}$$

where $h_{p,t}$is the precipitation depth for duration t(hours) and exceedance probability p(mm), $H_{p,24}$is the 24-hour precipitation depth with exceedance probability p(mm), and nis a station-specific reduction exponent derived from regional analyses.

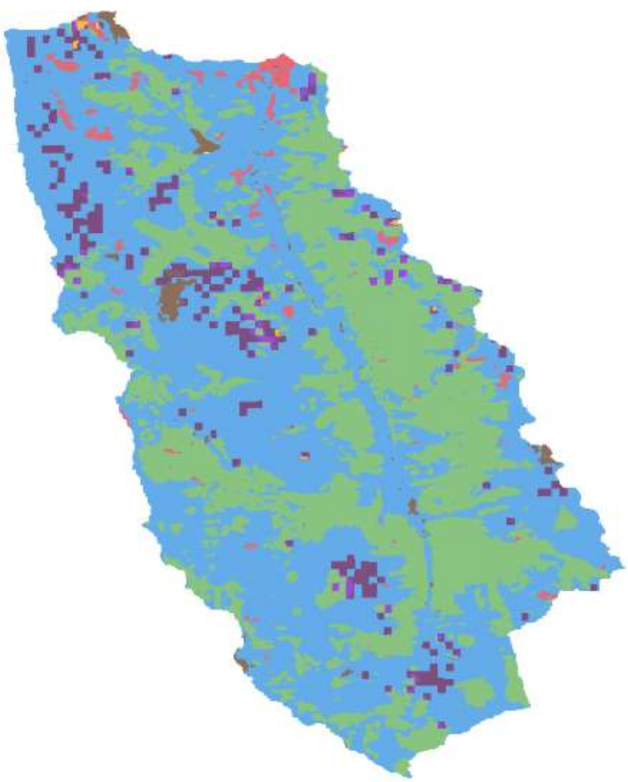
Basin-average precipitation values were estimated using the Thiessen polygon method, assuming a uniform spatial distribution of rainfall across the basin. Since precipitation depths measured at a point exceed those averaged over an area, areal reduction factors (ARF) were applied to account for spatial variability. For the basin area of 183 km², an ARF of 0.93 was applied for the 24-hour storm duration. For shorter storm durations, appropriate ARFs were automatically selected within the HEC-HMS modeling environment.Depth–duration–frequency (DDF) curves derived from statistical analysis represent probabilistic rainfall estimates rather than actual storm events. Therefore, frequency-consistent hypothetical storm events were constructed to serve as model inputs. To generate realistic temporal rainfall distributions, the alternating block method recommended by Chow et al. [7] was employed. Incremental rainfall depths were arranged such that the maximum intensity occurred at the midpoint of the storm duration, producing temporally consistent design hyetographs for each exceedance probability.

Net precipitation:-
Effective rainfall was calculated using the Curve Number method developed by the Natural Resources Conservation Service. This method relates direct runoff to total precipitation through a dimensionless parameter known as the curve number (CN), which reflects the combined effects of land use, soil type, and antecedent moisture conditions.Land use information was obtained from high-resolution spatial datasets, while soil properties were derived from the Harmonized World Soil Database. Hydrologic soil groups were identified and combined with land use classes to assign CN values based on standard NRCS tables. Average antecedent moisture conditions were assumed, consistent with typical design practice.GIS analysis was used to overlay land use and soil maps and generate a spatially distributed CN grid for the entire basin. Weighted CN values were then calculated for each subbasin and used as input parameters in the HEC-HMS model to estimate precipitation losses



. a) b)

Spatial distribution of Land Use (a) and Hydrological soil groups in Velabisht basin (b).



c)

Spatial distribution of Curve Number values(c).

Hydrographs generation

In the absence of observed rainfall–runoff data, flood hydrographs were generated using the NRCS synthetic unit hydrograph (UH) method. This approach is widely applied in ungauged basins and requires limited input data derived from measurable basin characteristics. The Velabisht River basin is ungauged and lacks historical rainfall–runoff observations; therefore, no direct information regarding the shape or magnitude of flood hydrographs could be obtained from measurements.Effective precipitation generated within each subbasin was transformed into direct runoff hydrographs using the NRCS synthetic unit hydrograph. This method is suitable for ungauged basins and is applicable to drainage areas well within the size of the Velabisht basin (183 km²) [10]. The unit hydrograph approach assumes linearity and time invariance of the watershed response, allowing runoff hydrographs to be obtained through convolution of excess rainfall with the unit hydrograph.The NRCS unit hydrograph is a dimensionless function whose ordinates are defined based on the time-to-peak and peak discharge. The time-to-peak depends on basin lag time and rainfall duration, while the peak discharge is calculated as a function of basin area and time-to-peak [10]. Basin lag time represents the time elapsed between the centroid of net precipitation and the peak of the resulting runoff hydrograph and reflects the physical runoff characteristics of the basin.

Lag time for each subbasin was estimated using the NRCS empirical relationship:

$$t_l = \frac{L^{0.8}(2540 - 22.86\ CN)^{0.7}}{14104\ CN^{0.7} Y^{0.5}}$$

where $t_l$is the basin lag time (hr), Lis the hydraulic length (m), CNis the runoff curve number, and Yis the average basin slope (m/m). Subbasin characteristics, including hydraulic length, curve number, and slope, were used to compute lag times, which were subsequently entered into the hydrologic model as transformation parameters for hydrograph generation.

Base flow:-

Baseflow was incorporated into the simulations using the exponential recession method, which is commonly applied in event-based hydrologic modeling. This approach represents groundwater contributions to streamflow during and after storm events using a simple conceptual formulation. An initial discharge was specified at the beginning of each simulation and distributed among subbasins in proportion to their respective drainage areas.

According to this method, the recession limb of the hydrograph follows the exponential relationship:

$$Q_t = Q_o k^t$$

where $Q_t$is the discharge at time t, $Q_0$is the discharge at the start of the recession, and kis the exponential recession constant. Three parameters are required to simulate baseflow using this method: the initial discharge, the recession constant, and a threshold value that determines when the recession curve is initiated.Historical records from the Velabisht River indicate an average annual discharge of 2.9 m³/s. Assuming that average flow conditions prevail in the river at the onset of flood events, an initial discharge of 2.9 m³/s was adopted and apportioned to each subbasin based on its contributing area. The recession constant was set to 0.55, following values recommended by Pilgrim and Cordery for basins with similar hydrological characteristics [2]. The baseflow initiation threshold was defined as a ratio of peak discharge and assigned a value of 0.001, reflecting the perennial nature of the river and ensuring a continuous baseflow contribution throughout the simulation period.

Channel routing:-

Flood routing along the river network was performed using the Muskingum–Cunge method, a physically based extension of the classical Muskingum routing approach. Unlike the original Muskingum method, Muskingum–Cunge incorporates channel geometry, slope, and roughness, allowing wave celerity and attenuation to vary with flow conditions. These features make the method particularly suitable for rivers with limited or no observed discharge data, such as the Velabisht River.Routing parameters, including reach length, channel bed slope, Manning's roughness coefficient, and cross-sectional geometry, were estimated using GIS-derived data and available field information. Automatic selection of space–time intervals and the celerity index method were employed within the modeling framework to ensure numerical stability and realistic simulation of flood wave propagation.The Muskingum–Cunge method simplifies the Saint-Venant equations by retaining the continuity equation and approximating the momentum equation using a diffusive-wave assumption, thereby neglecting inertial (acceleration) terms [11,12].

The governing equations can be expressed as:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = ql$$

$$S_f = S_o - \frac{\partial y}{\partial x}$$

where $A$is the cross-sectional flow area, $Q$is discharge, $q_l$represents lateral inflow per unit channel length, S_f is the friction slope, S_o is the channel bed slope, and $\frac{\partial y}{\partial x}$denotes the water surface slope along the channel. In these equations, $\frac{\partial A}{\partial t}$represents the temporal change in flow area, while $\frac{\partial Q}{\partial x}$represents the spatial variation of discharge along the channel.

Comparison of flood peaks results:-

Despite the absence of observed flood data in the Velabisht basin, an independent validation of the model simulation results was required. To this end, the method of analogy was employed, whereby peak discharges for various return periods were estimated for the Velabisht River based on data from a hydrologically similar, nearby gauged basin.The hydrometric station of Ura Vajgurore, located on the Osumi River, was selected as the analogous basin due to its proximity and comparable hydrological characteristics.

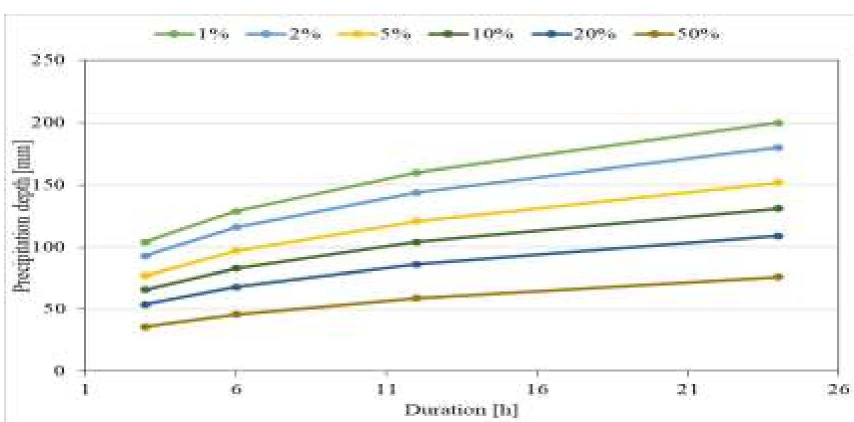
Flood quantiles observed at the Ura Vajgurore station were transferred to the Velabisht River using the following empirical area-scaling relationship:

$$Q_p = Q_a \left(\frac{A_a}{A}\right)^n$$

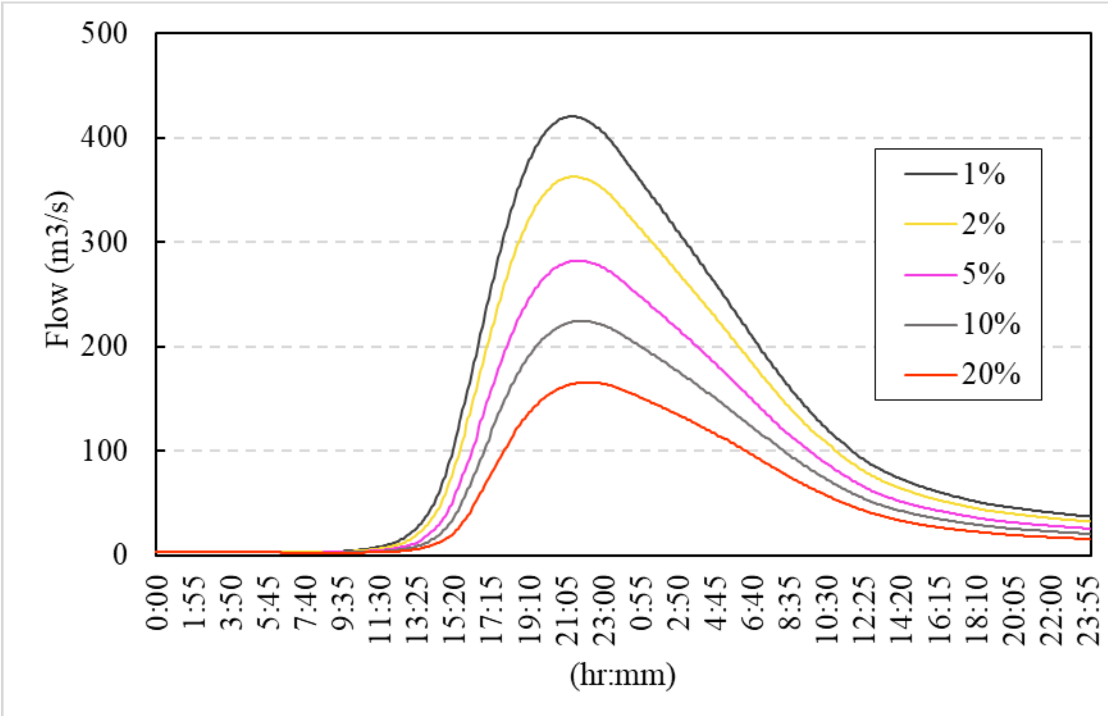
where Q_p is the flood quantile at the Velabisht River, Q_a is the corresponding flood quantile at the analogous station, $A$is the drainage area of the Velabisht basin, A_a is the drainage area of the analogous basin, and $n$is a regional reduction exponent, assumed equal to 0.5 based on literature recommendations [14].Flood quantiles estimated for the Velabisht River using the analogy method were subsequently compared with the peak discharges obtained from the hydrologic model simulations. Relative percentage differences (RPD) were calculated for each return period to quantify the level of agreement between the two estimation approaches.

Results:-

The precipitation frequency analysis demonstrated that the Generalized Extreme Value (GEV) distribution provides an adequate representation of annual maximum daily rainfall in the study area. Based on the selected distribution, basin-average depth–duration–frequency (DDF) curves were derived and subsequently transformed into design storm hyetographs. In total, six meteorological scenarios corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and 50% were simulated.Hydrologic model simulations produced complete flood hydrographs for return periods of 2, 10, 20, 50, and 100 years. For each scenario, key flood characteristics—including peak discharge, flood volume, and hydrograph shape—were obtained. As expected, peak discharges increased consistently with decreasing exceedance probability, reflecting the increasing intensity and severity of the design storm events.To ensure full development and recession of the flood hydrographs, the simulation duration for all scenarios was set to 48 hours. The resulting flood hydrographs corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and 50% were analyzed. Flood volumes and peak discharges for each return period are summarized in Table below.



Average depth-duration-frequency curves



Flood hydrographs with exceedance probabilities of 1%, 2%, 5%, 10% and 20%.

Flood hydrographs characteristics for different return periods

	Return periods (years)					
	100	50	20	10	5	
Volume (Mm^3)	147.32	127.82	101.03	81.49	97.4	
Peak discharge (m^3/s)	420.4	362.7	282.2	224.3	166	

To assess the plausibility of the simulated peak discharges, the results were compared with flood quantiles estimated using the hydrological analogy method, based on data from the Ura Vajgurore hydrometric station on the Osumi River. Flood quantiles transferred to the Velabisht River using basin-area scaling were compared with the simulated peak flows, and relative percentage differences (RPD) were calculated for each return period.

	Return periods (years)					
	100	50	20	10	5	
Simulated (m^3/s)	420	363	282	224	166	
By analogy (m^3/s)	407	362	300	250	200	
RPD (%)	13	1	-18	-26	-34	

The comparison indicates good agreement between simulated and analogously estimated peak flows for high and medium return periods, particularly for the 50- and 100-year events. Larger discrepancies observed for lower return periods may be attributed to increased uncertainty in regional scaling relationships and model sensitivity under smaller flood conditions. Overall, the results support the plausibility of the simulated flood hydrographs and confirm the suitability of the adopted modeling framework for flood estimation in the ungauged Velabisht basin.

Discussion:-

Flood hydrographs corresponding to different return periods were simulated under the assumption that the return period of precipitation events is identical to the return period of the resulting flood events. Although this assumption does not necessarily hold in reality—since antecedent moisture conditions, soil saturation, and basin storage vary stochastically and may lead to flood events with return periods differing from those of precipitation—it is widely adopted in design hydrology. This simplification allows for a consistent and systematic assessment of flood magnitudes and provides decision-makers with a coherent framework for flood risk evaluation and infrastructure design.All simulated flood hydrographs exhibit an identical shape, irrespective of their magnitude or exceedance probability. This behavior is a direct consequence of the linear response assumption inherent in the unit hydrograph theory, whereby runoff discharge is directly proportional to increments in effective rainfall. Consequently, the temporal characteristics of the hydrographs remain unchanged across scenarios. The time to peak is constant for all return periods, as the design storm hyetographs were constructed using the alternating block method with the maximum rainfall intensity positioned at the midpoint of the storm duration. Furthermore, the recession limb of the hydrographs is governed by a fixed recession constant, implying that baseflow decay does not significantly affect peak flow values, even if subsequent flood events were to occur shortly after the simulated storms.The comparison between peak discharges derived from the hydrological model simulations and those estimated using the method of hydrological analogy indicates a generally good level of agreement. For return periods ranging from 20 to 100 years, absolute percentage differences between the two approaches vary between approximately 3.1% and 6.3%, suggesting that the simulated flood peaks are plausible within the context of the inherent uncertainties associated with both hydrological modeling and regional transfer methods.

For lower return periods (5–10 years), the absolute percentage differences are notably higher, ranging from approximately 11% to 21%. These discrepancies are most likely influenced by the shape of the flood frequency curve derived for the Ura Vajgurore hydrometric station. Flood frequency curves for Albanian rivers are commonly characterized by positive skewness. A positively skewed distribution tends to overestimate flood quantiles associated with higher exceedance probabilities, while the lower tail of the distribution is associated with increased uncertainty and wider confidence intervals. Consequently, flood estimates corresponding to frequent events are less reliable when transferred using analogy-based methods, particularly when they rely on the extrapolation of the less well-fitted portion of the frequency curve at the gauged site.Based on these considerations, it can be inferred that the simulated flood peaks for higher return periods are more physically consistent and reliable than those estimated using the analogy method for frequent events. Overall, the modeling results demonstrate reasonable agreement with the analogy-based estimates, particularly for low and medium exceedance probabilities, thereby supporting the robustness of the adopted hydrological modeling framework.Nevertheless, uncertainties remain in the simulation results due to assumptions related to model parameters, particularly those associated with flood routing and loss estimation. Muskingum–Cunge routing parameters are ideally calibrated using observed inflow–outflow hydrographs; however, such data were unavailable due to the ungauged nature of the Velabisht basin. Even in gauged basins, routing parameters are known to vary between events, introducing additional uncertainty. Similarly, the use of design storm hyetographs further complicates parameter evaluation, as routing parameters cannot be dynamically adjusted based on observed flow responses.

Curve Number (CN) values, although generally associated with lower uncertainty compared to routing parameters, also contribute to overall model uncertainty. These values were selected from standard NRCS tables, which were originally developed based on small experimental watersheds and may not fully represent local hydrological conditions.To reduce these uncertainties and improve the reliability of future flood assessments, the establishment of systematic hydrometric and pluviometric monitoring in the Velabisht River basin is essential. Continuous discharge measurements would enable calibration and validation of model parameters, leading to more accurate flood predictions and improved flood risk management.

Conclusion:-

In this study, the semi-distributed HEC-HMS hydrological model was applied to simulate flood hydrographs corresponding to exceedance probabilities of 1%, 2%, 5%, 10%, 20%, and 50% in the Velabisht River basin, Albania. Basin-average depth–duration–frequency (DDF) curves were derived from annual maximum daily precipitation records and subsequently used to construct design storm hyetographs that served as model inputs. Loss parameters and basin lag times were estimated for each subbasin to compute effective precipitation and generate synthetic unit hydrographs.Flood wave propagation through the river network was simulated using the Muskingum–Cunge routing method, with routing parameters determined for each river reach based on channel geometry and slope characteristics. Baseflow contributions were incorporated using literature-based parameter values. The hydrological model produced complete flood hydrographs for return periods of 2, 10, 20, 50, and 100 years, thereby providing a comprehensive representation of flood magnitudes within the Velabisht River basin.The results demonstrate that variations in assumed model parameters can influence the temporal distribution of flood hydrographs and, consequently, peak discharge estimates. Simulated peak flows were compared with flood quantiles derived using the hydrological analogy method, showing good agreement for low and medium exceedance probabilities. Given the ungauged nature of the basin, the simulated flood hydrographs cannot be regarded as exact representations; however, they provide a reasonable and physically consistent approximation of flood behavior in the Velabisht River basin.The findings underscore the importance of establishing systematic hydrometric monitoring within the basin to reduce uncertainty and improve model calibration and validation. Nevertheless, the results offer valuable insights into flood characteristics and can support policymakers in developing flood risk management strategies and informed decision-making. Furthermore, the outcomes of this study are relevant for engineers and researchers involved in flood analysis and water resources management in the Velabisht River basin and the broader Osumi River catchment.

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