ISSN: 2634 - 8845

Journal of Earth and Environmental Sciences Research

SCIENTIFIC Research and Community

Research Article

Open Access

A Projected Hydrological Study and Catchment-Level Hydrograph Modelling for Channel Stabilisation

Hafiz Muhammad Nadir*

Civil Engineering Group, School of Built Environment & Engineering, Leeds Beckett University, Leeds, UK

ABSTRACT

The environmental impacts and anthropogenic activities in the name of the development of water streams, like the construction of bridges, roads, and built-up areas across water drainage paths, disturb the natural flow pattern and give rise to inundation and flood disasters in low-lying areas. These phenomena are incredibly pronounced in the absence of concerted hydrological modelling and environmentally friendly construction materials while planning for construction in a river basin for flood prevention, hydromodifications or hydraulic structures. This study has endeavoured to conduct the hydrological study of one of the fastest-flowing rivers in the UK, 'The Swale River', as a projected case study to assess a projected 200-year rainfall/ storm event, statistical modelling for catchment level efficiency, discharge quantum, lag time, projected hydrograph analysis for extracted rainfall, runoff, discharge flow data and exceedance from existing 48 months rainfall/ runoff data. The potential impact of these findings on future construction projects is significant, as they can guide the development of more sustainable and environmentally friendly construction practices. The statistical modelling proposed a heavy 200-year flood of 360 m3/sec discharge for a catchment area of 1446 km2 and 118 km length, using a projected heavy flood event of 6 cm precipitation in 8 hours for Swale River to ascertain the formation of discharge in the river after a 6-8 hours lag time with 30% catchment efficiency. This hydrograph modelling gives detailed working for the requirement of flood protection and placement of rescue and relief operations in case of flooding caused by the overflowing of the river to stretch of 1-2 km along the channel having a water depth of 2-10 feet, likely to impact the life and properties.

***Corresponding author**

Hafiz Muhammad Nadir, Civil Engineering Group, School of Built Environment & Engineering, Leeds Beckett University, Leeds, UK.

Received: September 16, 2024; **Accepted:** September 23, 2024; **Published:** October 05, 2024

Keywords: Hydrology, Statistical Modelling, Hydrograph Analysis, Rainfall/ Discharge Forecasting, Lag Time, Flooding Extent

Introduction

Water is crucial in humankind's advent and mega population centres' establishment. However, the powerful human desire to tame natural water resources for their benefit grossly impacts the ecology and natural inhabitants, the local/ regional climatic variations and disturbed transborder stream flow. The reclamation of land for agricultural purposes, deforestation, peatland modification, the convergence of vast flood plains to narrow streams, heavy hydro-structural modifications, surface runoff obstructions, disturbed water cycle, lesser sub-soil absorption and increased runoff velocity are among the significant anthropogenic activities in river basins. The cloud bursts due to global warming/ climatic variations cause heavy precipitation in short intervals, thus decreasing the lag time between a storm event and a peak discharge, resulting in flash flooding/ disasters. Researchers endeavoured to restore the floodplains using natural and structural methods separately or in combination. The natural methods of floodplain restoration are short-lived, limited and less efficient, especially for the extensive stretches of more significant streams. This necessitates the incorporation of structural methods of flood protection in the form of dams, reservoirs, barrages, channels, the lining of rivers and the erection of artificial means/ hydraulic structures, which are considered robust, strong, efficient and resilient but likely to cause environmental/ ecological disorder [1-3]. Therefore, deliberate hydrological/ statistical studies and deployment of suitable flood protection techniques/rescue/ relief equipment as per the lag time are imperative for the catchment-level safe management of river discharge.

Historical Flood Events

Water has a special place in the life of human beings as a basic necessity, and all civilisations developed along the waterfront which resulted in ecological modifications/ climate changes, glaciers melting, extraordinary precipitation events, flooding and damage to aqua life and wildlife [4,5]. The disturbance in transborder water streams results in demand-supply gaps and international conflicts to establish control over land/ water resources. In the South Asian sub-continent, Kashmir is the originating point of many significant rivers of Pakistan and India. Both countries fought three major wars in the last around 75 years, and the region is still considered a nuclear war flash point. Moreover, these rival countries' construction of dams and unannounced water storage/ release in upstream/ downstream of the transborder rivers resulted in floods and drought events even in the recent past [6]. Yangtze River in China has a history of devastating floods periodically, especially the worst floods in 1911, 1935 and 1954, which resulted in the deaths of millions of people and the swapping of properties/ land in a 6300 km stretch, Yellow River in China, Indus in Pakistan, Ganges, Jumna and Brahma Putra in India and Bangladesh are the major flood causing rivers mainly arising from climatic changes and urbanisation/ modifications along natural rivers flood plains [7,8]. The flood in 2011 in the Mississippi River was the worst of its kind, impacting 31 American states, causing hundreds of casualties and destruction/evacuation of millions of people [9-12]. Europe has had numerous casualties and property losses in the last few decades because of heavy rain/ flood events due to climatic changes and heavy hydraulic modifications [13]. Elbe flooding in 2002 in central Europe, the UK flooding in 2007 and the Copenhagen, Denmark flooding in 2011 caused horrific losses of Billions of dollars in the economy/ routine life [6,14,15].

Rainfall/ Discharge Statistical Forecasting Techniques

Conducting storm/flood frequency analysis for a river basin is imperative to statistically predict the future occurrence for hazard assessment and risk mitigation [16-20]. Selection of the best statistical technique, suitable probability distribution function and the best goodness of fit ranking impart the suitability of such hydrology studies, the nature/ suitability of available long-term past data and adoption of suitable estimation parameters [21-23]. Log Pearson 3 (LP3), Generalized Extreme Value (GEV) and Gumbel Maximum (Gum Max) are considered among the better fitting probabilistic approaches with better goodness of Fit ranking on Kolmogorov Smirnov, Anderson Darling and Chi-Squared methods [23,24]. The EasyFit software developed by Mathwave.com can be used to analyse the existing rainfall/ discharge data sets statistically. The EasyFit software uses the given data on the horizontal axis as "x." It provides the probability distribution function, cumulative distribution and hazard function on the vertical axis as a function of x "f(x)" [25]. In this study, Log Pearson 3 (LP 3), Generalized Extreme Value (GEV), and Gumbel Maximum (Gumb Max) were recommended for statistical analysis of rainfall/ discharge data using EasyFit software. These are considered among the top best-fit probability distribution functions (PDF) and were used by several researchers [23]. LP 3, GEV and Gumb Max are preferred as they fit the data well to predict storm/ flood frequency return periods with a better ranking of the goodness of the fit test [26-30]. These methods use estimation parameters based on the technique of methods of movements (MOM) or method of long movements (extended dataset) as per the length of the given data set (less than 50 entries or more than 50 entries) [26]. The Goodness of Fit of these probability functions can be evaluated using Anderson Darling, Kolmogorov Smirnov and Chi-Squared using EasyFit inbuilt programming to statistically forecast the precipitation and discharge in a river [6,23,31].

Use of Log Pearson 3 Equations to Ascertain the Probability of Storm/ Discharge Events with Return Periods

Oke and Aiyelokun and Nadir and Ahmed observed in their hydrology studies that the Log Pearson 3 performed at the top with the best goodness of fit test ranking for all kinds of data; therefore, they chose it for further calculation using its equations for the determination of return periods [6,32]. The given annual 24-hour max rainfall "R" and annual peak discharge "Q" data is converted into Logarithm values using Equation 1 (use R for Rainfall and Q for discharge data in these equations):

Equation 1: $R_i = \text{Log}(R)$

Mean, Standard deviation, Skewness coefficient and Return Periods for storm/ flood frequency analysis are ascertained using Equation 2 – 7 [32]. The mean "Rm" of Ri is calculated by Equation 2, summing all rainfall values and dividing by the total number of readings/ years.

Equation 2: $R_m = 1/n \sum R_i$

Standard deviation is calculated using the Equation 3:

Equation 3: $S_d = (\sum (\text{Log}(R)\text{-Avg}(\text{Log } R))^2/(n-1))^{1/2}$

Skewness is calculated by Equation 4:

Equation 4: $\text{Skewness} = (\text{Log}(R)\text{-Avg}(\text{Log } R))^3$

Skewness coefficient G is calculated using Equation 5 to determine the value of a frequency factor constant "K" from the Table in Haan's book [33].

Equation 5: $\text{Skewness coefficient } G = n*(\sum (\text{Log}(R)\text{-Avg}(\text{Log } R))^3/((n-1)*(n-2)*S_d)$

The return period is calculated using Equation 6 by putting the rank of the value of rainfall/ discharge in the data set "m" and the total number of entries/ years in the data "n":

Equation 6: $\text{Return Period } (T_r) = 2n/(2m-1)$

Where m=Rank, n=No of years

Exceedance probability is the reverse of the return period and is calculated by using Equation 7:

Equation 7: $\text{Exceedance probability } R_m = 1/T_r$

All the above equations are also used to calculate the discharge by substituting "Q" in place of "R." Now, predicted/ designed rainfall "Rp" or discharge "Qp" is calculated for 2, 5, 10, 25, 50, 100, and 200 years, taking the value of Kt from Table 7.7 of Haan's study for each period and then taking the antilogarithm of the results obtained from equations 8 – 11 [33].

Equation 8: $R_t = R_m + K_t * S_d$

Equation 9: $R_p = \text{Anti Log } R_t = (10)^{(R_t)}$

Equation 10: $Q_t = Q_m + K_t * S_d$

Equation 11: $Q_p = \text{Anti Log } Q_t = (10)^{(Q_t)}$

Equations 9 and 11 give the predicted designed rainfall Rp/ discharge Qp as per the Log Pearson 3 method of probability distribution function [6,32]. The Log Pearson 3 Equations 1-11 can help ascertain the exceedance/ probability of storm/ discharge events with the 10 to 200-year return periods. The results obtained can then be verified with statistical analysis using Easyfit software to determine the probability distribution factors [6,32].

Stage Guaging-Discharge Empirical Relationship

The discharge in a stream can also be calculated using the correlation between the stage gauge reading placed inside a stream and the discharge measurement directly from the stream. The direct discharge measurement includes calculating the direct flow of water in lesser depths and small water paths using the velocity area method of float gauging and current metering. The empirical correlation between stream discharge and stage gauge reading is then calculated using Equation 12. Using the empirical relationship for respective daily stage gauge height, a total volume of direct runoff per hour VDRH is calculated from the total discharge multiplied by 3600 using Equation 13 [34,35].

Equation 12: $Q = a(h)^b$ **and** $Q = AV$

Where Q = discharge, a = coefficient of correlation, h = height of water level/ stage gauge reading and b = exponent of the correlation matrix.

$$\textbf{Equation 13: } V_{DRH} = \int_t^0 Q_{DRH}(t)\,dt \cong \sum_i Q_{DRH}\,\Delta$$

Hydrograph Analysis

The hydrograph analysis elaborates on the pattern of a storm event obtained by plotting runoff on the x-axis versus the discharge on the y-axis showing the essential segments in time t incorporating the elements of lag time, concentration time, inflection time, recession time, channel storage/ base flow, intensity/ period of storm and area under S curve as the storm of 1cm/hr over catchment area, as shown in Figure 1 [36]. The storm events generally resemble each other in particular catchment areas if they occur in the same season and with a specific frequency of rainfall. However, a storm event profile may be different for different regions based on spatial/ temporal variations as the catchment could be plain/ uneven, barren/ vegetated, smooth/ slopy, saturated/ unsaturated, clayey/ silty/ sandy/ rocky resulting in varying infiltration index. Flood event profile changes due to the time of the season as saturated/ unsaturated soil conditions, the scale of vegetation, infiltration capacity of the soil, rate of evaporation and obstruction to flow of water from catchment to river due to vegetation may vary with the season/ weather. It is difficult to assess a precise flood event trend; however, a predicted storm event based on the historical flow pattern could demonstrate ideal conditions for flood/ storm forecasting. A unit hydrograph analysis is helpful in the assessment of the effective runoff in a catchment by a storm event for essential flood plain mapping/ zoning, estimation of precipitation/ discharge in a river basin, catchment parameters and rain/ flood frequency duration curves [37-40].

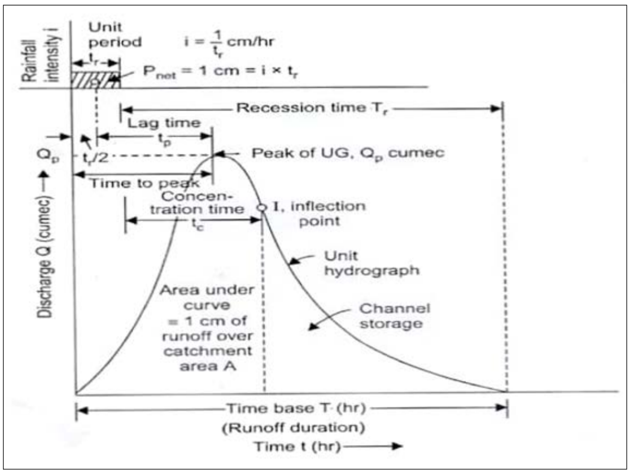

Figure 1: Unit Hydrograph Analysis Diagram [36]

Study Site

Swale River is one of the fastest rising and fastest flowing water streams in the UK due to the mountainous geography of the catchment areas in the Swaledale originating from the humble bogs/ watery mires of Birkdale Common, which peaks at White Mossy Hill (660m above sea level), drains west/ south through Birkdale Deck, East/ North through Whitesundale Beck and the most extensive peatland of Lady Dyke Head constituting numerous crisscrossing gills, rills, water channels to make the fastest flowing Swale river in a storm event, overflowing the banks within hours. It is the northernmost tributary of River Ouse in Yorkshire Dale. It flows easterly over the hamlet of Keld, passes through significant settlements like Richmond and Catterick southwards and ultimately joins River Ure at Myton-on-Swale in the Vale of York near Boroughbridge, stretching 118 km length draining a catchment area of 1446 km^2, as shown in the layout map in Figure 2 [41-43].

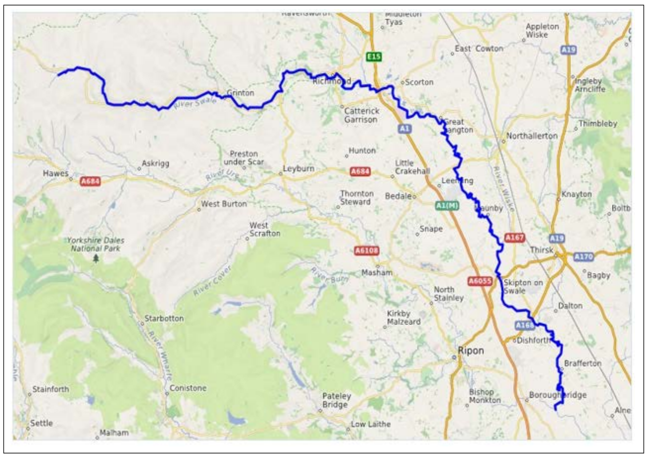

Figure 2: River Swale Map [43]

Methodology

Hydrological Assessments using Stage Guage-Discharge Readings

The research incorporated the hydrological assessments of water channels on a catchment scale to determine the quantum of rainfall/ discharge in a stream and to calculate the strength requirements of greener materials for channel stabilisation/ hydromodifications. Forecasting the predicted precipitation in a stream's catchment and discharge due to a storm event was essential before designing the parameters of channel stabilisation/ lining/ hydromodifications. Stage or staff measurements were used to determine pre-surveyed sections of water streams as per the staff readings. The empirical correlation between stream discharge and stage gauge reading has been calculated using Equation 12. River Swale's four years of data from 2019-2022 was obtained from the School of Geography, University of Leeds and the "National River Flow Archives" department for known values of stage gauge reading and discharge to empirically deduce the relationship for future discharge using the stage readings, as shown in Figure 3. Direct runoff volume per hour (VDRH)is calculated from the total discharge multiplied by 3600 using Equation 13 and the empirical relationship for respective daily stage gauge height [34,35]. This VDRH is converted into equivalent rainfall depth in "mm" by dividing it by catchment area in m^2. The comparison of effective rainfall depth in "mm" with the actual rainfall figures in "mm" helped ascertain the catchment efficiency in terms of rainfall intensity. The catchment efficiency, infiltration index and rainfall losses were calculated, which helped to determine/ explain how much water is absorbed/ stored by the total catchment area and how much water drains into the stream as surface runoff. This water inflow is the actual flow, determining the channel's required capacity and the flood protection techniques.

Hydrograph Analysis

The difference between observed flow and base flow calculates storm flow. A correlation between rainfall and discharge data showed the runoff formation with lagtime after a storm event, as shown in Figure 4. The total runoff volume is calculated using Equation 13 or by calculating the area under the curve in the hydrograph (Table 3A and Figures 7A and B). The equivalent rainfall depth RE of the adequate surface runoff volume is calculated by dividing VDRH by the catchment area in meters and multiplying it by 100 to get the equivalent rainfall depth in cm. The difference between RT and RE then calculates the rainfall loss. The infiltration index is computed using Rl/RE, and effective rainfall is obtained by subtracting the infiltration index from the hourly rainfall of the storm event (only positive values are considered, and negative values are taken as zero). The hydrograph calculations are shown below (Table 3A and Figure 7A). The unit hydrograph obtained by this calculation could now be used to calculate the storm hydrograph of any rainfall duration for the same section/ catchment. After conducting the hydrograph analysis, the exact cross-section, discharge, area, wet perimeter, and thickness of lining were calculated using the Manning Equation (Equation 14), UK Flood Estimation Handbook (FEH), Rational method Equation 15 (for small catchments), lag time Equation 16 and USGS handbooks [44-46].

Equation 14: Manning Equation $Q= 1/n \ AR^{(2/3)} S^{(1/2)}= 1/nP \ A^{(5/3)} S^{(1/2)}$

Where Q is discharge in m^3/sec, "n" is Manning N number from Manning Table, A is the area in m^2, R is the hydraulic radium in m, and S is the gradient in m/m.

Equation 15: Rational method Equation $Q= 1/360 \ CiA$

Where Q is "discharge" in m3/sec, C is the runoff coefficient (Ø) dimensionless, "i" is the mean rainfall intensity in mm/hr, and A is the catchment area in hactors.

Equation 16: Lag time $t_c = 0.01947*L^{0.77} /S^{0.385}$

Where L is the length of the catchment in feet, S is the slope of the catchment in foot/foot, and tc is the lag time between storm and flood events in minutes.

Results and Discussion

Case Study of Swale River

River Swale's four-year daily rainfall data (Table 1, Appendix I) and monthly rainfall data (Table 2) were used to calculate the hydrological parameters for assessing materials' strength requirements. Figure 3 shows an empirical equation $y = 3.5(x)^{1.412}$ by using an X-Y plotter to identify the values of "a" (3.5) and "b" (1.412) where y is "discharge (Q)" and X is stage gauge reading "h". This characteristic empirical relationship was used to determine the discharge value for any future storm event by substituting the values in Equation 12. Using the empirical relationship for respective daily stage gauge height, a total volume of direct runoff per hour VDRH is calculated from the total discharge of 20407 m3 using Equation 13 [34,35] and comes out to be 73465200 m3 (VDRH= 20407*3600=73465200 m3) in the river in four years as shown in Table 3A. This VDRH is converted into equivalent rainfall depth in "mm" to compare with the actual rainfall figures and ascertain the catchment efficiency.

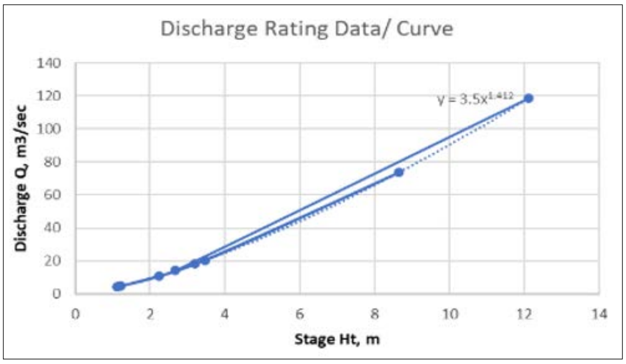

Figure 3: Empirical Correlation Between Stream Discharge and Stage Gauge Reading

Table 2: River Swale Monthly Rainfall Data, Discharge, VDRH and Catchment Efficiency

Rainfall (mm)	2019	2020	2021	2022	Total
January	57.6	13	108.4	38.4	217.4
February	80.6	109.8	76.2	69	335.6
March	40.2	21	78.2	33	172.4
April	18.2	20.8	131.6	137.2	307.8
May	38	68.4	38.8	277.6	422.8
June	22	75.4	116.8	176	390.2
July	60.2	53.8	57.4	61.4	232.8
August	101.8	33.6	49.2	98.6	283.2
September	27.4	11.8	43.2	111.6	194
October	84	73	106.8	87.4	351.2
November	68.2	92.4	46	49.8	256.4
December	74.8	95.6	26.6	114.2	311.2
Total	673	668.6	879.2	1254.2	3475
Annual Discharge m^3/sec	3951	3925	5161	7362	20407
Average VDRH (m^3)	14227893	14134873	18587167	26515042	73465200
Equivalent Rainfall Depth (mm)	216.6	215.1	282.9	403.6	1118.2
Catchment Efficiency (%)	32.2	32.2	32.2	32.2	32.2

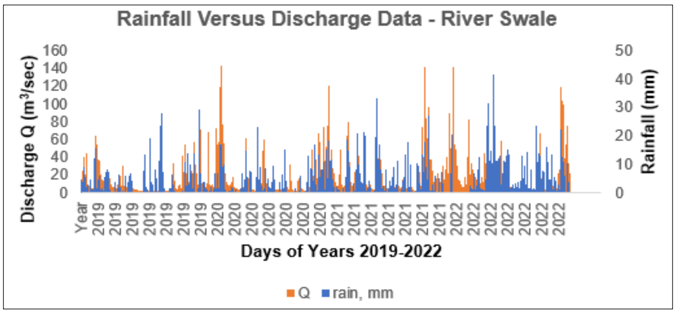

Figure 4: Analysis/ Correlation of Rainfall Versus Discharge Data-River Swale

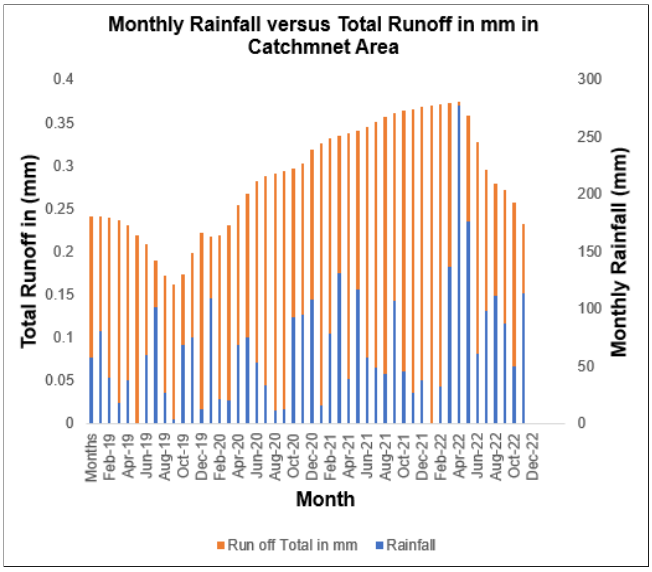

Figure 5: Comparison of Monthly Rainfall Versus Total Runoff (in Mm)in the Swale River Catchment Area to Ascertain a Storm Event and Resultant Discharge

The graph in Figures 4 and 5 shows that rainfall and discharge/ total runoff have a proportional relationship. If the rainfall at a particular time increases in the catchment of River Swale, then discharge in the river also increases due to increased surface runoff. However, rainfall and total runoff vary monthly depending on seasonal/ temporal variations. Figure 5 shows the monthly rainfall with corresponding total runoff (mm) on the catchment. A maximum rainfall was observed in May 2022, resulting in maximum runoff from the river catchment and maximum discharge in the River Swale. However, it could be inferred from Figures 4 and 5 that a rainfall/ storm event did not result in the immediate runoff/ discharge event in the stream. Instead, a lag is observed in the creation of increased flow in the stream after rainfall, necessitating conducting a hydrograph analysis of the catchment to ascertain the time lag between a storm and a discharge. This time lag between the conversion of rainfall into a flooding flow allows the designer to plan the storage ponds in the catchment, plan the placing of further obstructions to deter flash flooding and placement of flood prevention/ rescue/ relief mechanisms as per the creation of flash flood basing on catchment efficiency, lag time and hydrograph analysis. The exceedance probability of discharge is a statistical technique used to assess the occurrence of certain flooding levels, considering the streams' average flow levels over an extended duration of past data. It is used to plan preventive measures, protection against flooding, community hazards due to flash discharge events after a storm in a river catchment, surge in a base flow of a stream, replenishment of reservoirs through the storm events, regulation of storage water in the reservoirs to determine how much water is required to store and how much should be released on the occurrence of a storm so that existing water is gradually released. Fresh stormwater is stored in the reservoir instead of being converted into an accumulated flash flood [34]. Figure 6 shows the exceedance probability of converting a storm event into a flash flood in the Swale River catchment. The flow duration curve showed less than a 1% chance that the base flow discharge would be more than 143 m^3/sec as per the given discharge data. There is a chance that 90% of the time, it would be more than 1.7 m^3/sec, even if there is no rain. The river catchment could generate a maximum of 140m^3/sec base flow discharge. However, the flow range of 10-80 m^3/sec is a normal range for the river in a regular storm event. Therefore, the designers must plan the flood prevention infrastructure's capacity/ strength/ placement to cater to a minimum flood event of 150 m^3/ sec (rounded up). However, for design considerations, the forecast of maximum rainfall/ discharge is done on 100-200 years precedence, which comes to be around 360 m^3/sec, 3 times more than the maximum base flow of 150 m^3/sec.

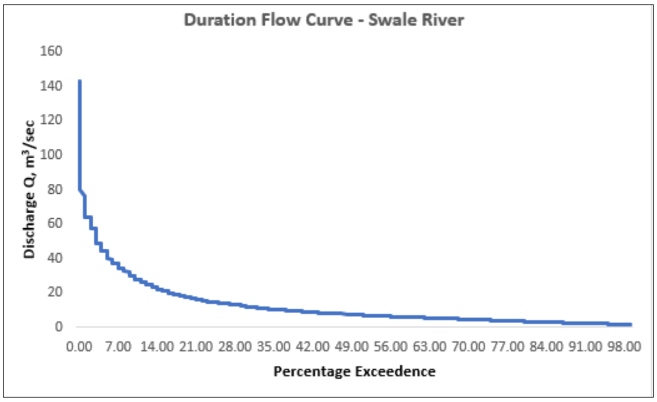

Figure 6: Duration Flow Curve to Assess the Probability of Maximum Base Flow in River Swale

Hydrograph Analysis for Assumed/ Predicted 200 Years Return Period

Table 3A and Figure 7A illustrate a hydrograph analysis for a 200-year-return period storm of 2.75 cm/hr, generating a 200-year discharge event of 360 m^3/sec in Swale River having a catchment area of 1446 km^2 based on a 30% catchment efficiency index. Base flow is subtracted from observed flow to obtain storm flow, and then, the total runoff volume is calculated using Equation 13 or calculating the area under the curve in the hydrograph (Table 3A and Figure 7A). The equivalent rainfall depth RE has been calculated by dividing VDRH by the catchment area in meters (1446,000,000 m2) and multiplying it by 100 to get the equivalent rainfall depth in cm. The difference between RT (6 cm) and RE (1.3 cm) indicates 4.7 cm of rainfall loss due to water absorption/ evaporation. The infiltration index of around 30% has been calculated using the expression RE/Rl. The effective rainfall is obtained by subtracting the infiltration index from the hourly rainfall of the storm event. The hydrograph calculations are shown in Table 3A and Figure 7A. The unit hydrograph obtained by this calculation has been used to calculate the storm hydrograph of any rainfall duration for the same section/ catchment (Table 3A and Figure 7A).

Total Discharge = 14130000 m^3

Equivalent rainfall of total VDRH (in-depth cm) = RE = 14,130,000 /(1446x1000x1000) * 100 = 1.3cm

Total rainfall during the storm event = RT = 0.25+2.75+2.75+0.25 = 6 cm

Total losses of rainfall volume in cm depth = RL = RT (Total Rainfall) – RE (Equivalent Rainfall of total VDRH) = 6 – 1.3 = 4.7 cm

infiltration index (Ø) = RE / RL = 1.3/4.7 = 28% ≈ 30%

Effective rainfall = Total rainfall – Ø (no negative value to be considered)

The existing Swale River natural channel average cross-section around 10-12 m wide and 5-10 m deep can accommodate a maximum flow of 140-150 m^3/ sec. A 360 m^3/sec flooding event will likely overflow the banks to around 1-2 km width within an hour, making a flood water depth of 2-10 feet with the immediate danger to adjacent villages/ towns near the stream. Therefore, construction of housings/ infrastructure very close to the stream should not be considered, giving a stretch of 1-2 km of the floodplain to the river in case of overflowing of the banks [41-43].

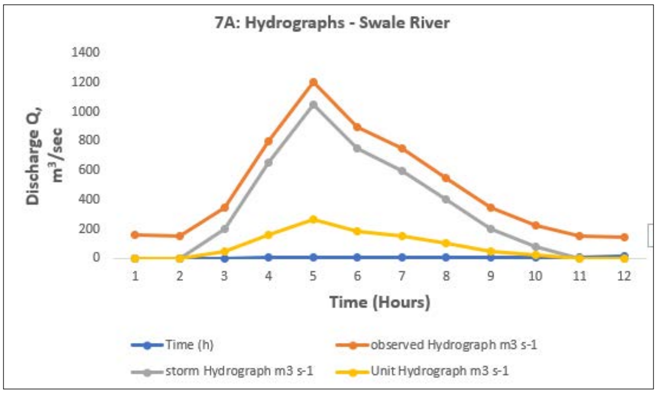

Figure 7A: Hydrographs Analysis for 200 Years Predicted Storm Event - Swale River

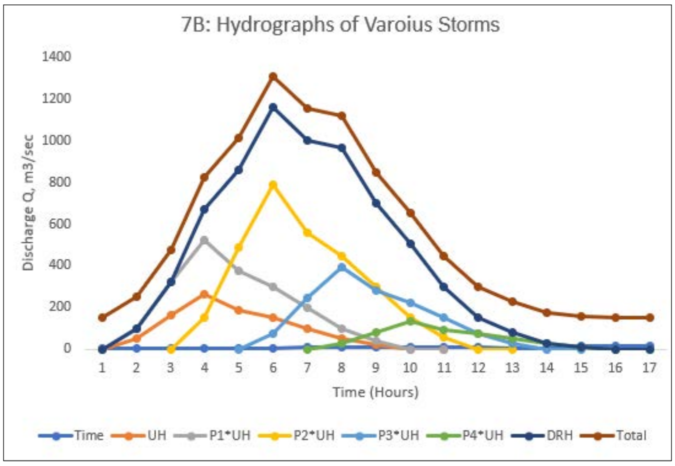

Figure 7B: Hydrographs of Storms of Different Rainfall Intensity/ Intervals

Table 3A: Quantities of Discharge and Precipitation Duration for a 200-Year Predicted Hydrograph Analysis

Rainfall Duration (h)	Total Rainfall (cm/hr)	RE	Flow Time (h)	Observed Hydrograph m^3/sec	storm Hydrograph m^3/sec	Unit Hydrograph m^3/sec	Runoff Volume m^3
			0	150	0	0	0
0 - 1	0.25	0	1	150	0	0	0
1 - 2	2.75	2.25	2	350	200	50	720000
2 - 3	2.75	2.25	3	800	650	162.5	2340000
3 - 4	0.25	0	4	1200	1050	262.5	3780000
			5	900	750	187.5	2700000
			6	750	600	150	2160000
			7	550	400	100	1440000

			8	350	200	50	720000
			9	225	75	18.75	270000
			10	150	0	0	0
			11	150	0	0	0
Total	6						14130000

Table 3B: Hydrographs for Different Storms

Time (h)	Unit Hydrograph (UH.)	P1*UH	P2*UH	P3*UH	P4*UH	Storm Hydrograph (DRH)	Total Hydrograph (TH.)
1	0	0				0	150
2	50	100				100	250
3	162.5	325	0			325	475
4	262.5	525	150			675	825
5	187.5	375	487.5	0		862.5	1012.5
6	150	300	787.5	75		1162.5	1312.5
7	100	200	562.5	243.75	0	1006.25	1156.25
8	50	100	450	393.75	25	968.75	1118.75
9	18.75	37.5	300	281.25	81.25	700	850
10	0	0	150	225	131.25	506.25	656.25
11	0	0	56.25	150	93.75	300	450
12			0	75	75	150	300
1			0	28.125	50	78.125	228.125
3				0	25	25	175
14				0	9.375	9.375	159.375
15					0	0	150
16					0	0	150

Generally, in the given catchment area of Swale River in the above data, flood events occurred after the peak rainfall with a 1 to 5-hour lag time and finished in 12 hours to return to the regular base flow. The probability of getting high discharge runoff in lesser lag time is higher in case of more rain in consecutive intervals of time in wintery/ wet conditions, concluding that a prolonged spell of rain has a higher probability of a flash flood event.

Storm Hydrograph Calculations using the Unit Hydrograph

Once the unit hydrograph analysis is completed for a given section of a river catchment, the unit hydrograph value could be used to calculate the hydrographs of different rainfall intensities in the same section of the river/ catchment further. Table 3B and Figure 7B show the 2-hour storm hydrographs P1, P2, P3, and P4, obtained for the same section of the river using unit hydrograph (hydrograph of 1 cm rainfall in a river catchment), using 2 hours effective rainfall interval for a total storm event of 8 hours. The summation of all storm hydrographs (P1-P4) would be the accumulated storm hydrograph for the hourly direct runoff (DRH) in 8 hours. Adding the maximum forecasted base flow of 150 m^3/sec would give the total storm hydrograph likely to enter the river after the start of the storm. The storm event would take 17 hours to complete an entire cycle, starting from 0 hours (base flow) to reach the peak at the 8th hour and then return to the regular base flow after 17 hours, as shown in Figure 7B. The peak discharge is used to design the channel's capacity, and the hydrograph gives the time lag to plan flood prevention/ rescue infrastructure placement.

Recommended Channel Lining and Stabilisation Methods

The recommended methods of channel lining/ stabilisation and flood protection are illustrated in Figures 8 and 9. These include; bricks, breakstone, break walls, readymade/ insitu concrete canvas, gabions, flood protection walls, weirs, notches, dams, docks, scour protection for bridges, embankments, erosion control for industrial sites, mines, water storage/wastewater treatment plants/ storage, landfills, locks/ dykes, marine/ coastal erosion control, harbours, ports, river and canal erosion and roads/ highways/ airports erosion control and stabilisation using lining, side drains, paver tiles, and concrete canvas (Figures 8 and 9). The channel lining designing parameters have been devised by the different researchers/ departmental proceedings [8,35,45,47-71].

Significance of Research

The findings of this research can be used to plan the channelisation/ flood protection planning to cater for heavy flooding of around 360 m^3/sec discharge in case of a heavy cloud burst, incorporating different natural/ structural techniques devised by proper designing studies separately.

Pyramid breakwater stones with Raised berms/ walls and edges, River Wharfe Weir at Tadcaster [78,79]

Figure 9: Recommended uses of SCMs as Flood Protection

Conclusions

The coordinated hydrological analysis, statistical modelling, geographical studies and selection of eco-friendly construction materials are paramount to any infrastructure construction, especially along the water channels. Such anthropogenic activities impact the environment, ecology, habitats, living organisms, water cycles, and food cycles and may result in natural disasters like flooding, drought and increased CO_2 / greenhouse gas emissions globally. The unplanned hydromodifications/ channel lining sometimes instead causes more environmental impacts than economic/ environmental benefits. Therefore, sufficient hydrological modelling and political/ geographical considerations must be catered to, especially for trans-border streams incorporating eco-friendly low CO_2 embodied materials. The natural methods of flood protection/ channel stabilisation, although limited in nature, durability and effectiveness should be preferred where feasible. However, structural interventions become inevitable in the case of heavy water bodies, more extensive stretches, and technologically advanced solutions. Still, they always result in some environmental implications, such as increased pollution and disturbance to biodiversity. Therefore, minimum structural invention with maximum natural flood protection/ channel stabilisation techniques considering the lag time, water management capability, storage ponds capacity and channel dredging/ maintenance should be ensured for smooth flow of storm discharges [80-84].

Acknowledgement

The author acknowledges the University of Leeds for providing the necessary data and details.

Appendix I

Table 1: River Swale 4 years Rainfall Data

Sum of rain, mm	Year	2019												2019 Total
	Month	1	2	3	4	5	6	7	8	9	10	11	12	
Day	1	4.6	0.4	1.2	0	0.6	0	0	0	7.4	2	0	6.2	22.2
	2	0	0.2	1.8	0	0.2	0	7.2	0	1	0	0	3.4	13.8
	3	0.8	1.2	1.2	0	0	0.2	7.8	0	1.6	1	0	14	27.2
	4	2.2	0	0	0	0	0	0.4	0	0	0	0	0	2.8
	5	4	0	0	0	0	0	0	0	0	0	11	0.2	15.2
	6	9	1	0.6	0.2	0	0	0.2	8.2	0	0	2.2	0	21.4
	7	0.4	0.4	0	0	0	0	13.4	0	0	0	0	0	14.4
	8	6.8	1.4	2.4	0	0.4	0	1.4	1.2	0	0	2.4	0	16
	9	0.4	12	0	0	0	0	0	7	0	0	0	0	19.4
	10	0.2	1.8	0	1.8	5.8	0	0	5	0.4	0	0	0.2	15.2
	11	5.6	15.8	5.4	3.6	2.2	0	2	1.2	0.4	0	14	0	50.2
	12	5	13.4	7.4	0	1.4	0	0	0	0	0	0.2	1.4	28.8
	13	2	1.4	0.2	0	0	0	0	0	0	0	0.4	0	4
	14	0	0	0.2	0.4	0	0	0	0	0	0	0	0	0.6
	15	0	0.6	0	0	0	0	0	0	0	0	0	0.6	1.2
	16	0	0.2	8.4	1.6	0.4	0	1	0	0	0	2.4	0.2	14.2
	17	0	4.2	0.2	0.6	0	0	0	0	0	0	2.8	0.8	8.6
	18	0.4	1.2	0.2	1.2	3.8	0	0	0	1	0	0	29	37
	19	3	4.6	0.6	0.2	0.8	0	0	0	1.4	0	10	7	27.6
	20	1.4	4.2	0.4	0.2	1	0	0	11.2	0.4	0	3.2	0	22.2
	21	0.4	6	7.2	0	0	0	0	0	0	0	3.2	0	16.8
	22	0	0.2	0.8	6.4	6.2	0	0	10.2	0	0	1	0.2	25.2
	23	0	3.2	0	2	2.6	0	19.2	23.8	0	0	2.2	0	53
	24	0	6.2	0	0	0.2	0	0	2.4	1.8	0	6.8	0.2	17.6
	25	0.2	1	1	0	0	0	0	0.2	0	0	3.8	0.2	6.4
	26	4	0	0.6	0	7	0	0	28	2.2	0	0	0	41.8
	27	4.6	0	0	0	0.2	0	0	0.6	0.6	0	0	1	7
	28	1.6	0	0.2	0	0.4	0	3.6	1.6	6.4	0	1.8	0	15.6
	29	1	0	0	0	4.4	0	3	0	2.8	1	0.6	4	16.4
	30	0		0.2	0	0.4	0	0.6	1.2	0	0	0.4	2.4	5.2
	31	0		0		0		0.4	0		0		3.8	4.2
Grand Total		57.6	80.6	40.2	18.2	38	0.2	60.2	101.8	27	4	68	75	571

Sum of rain, mm	Year	2020												2020 Total
	Month	1	2	3	4	5	6	7	8	9	10	11	12	
Day	1	2.2	0.8	10	0	0	0	1	0	0	0	0.8	0	14.6
	2	1.4	0	1	0.2	0	0	9	0	3.2	0	0.2	0	14.6
	3	0	7	0	0.6	4.4	0	3	0	4.4	0	0	0.8	19.8
	4	0	1.8	0	0	15	0	3	0	1	0	3.6	0.2	24.6
	5	1.6	0	1	1.2	13	6	0	0	0	0	0.8	0.2	23.4
	6	0	1.6	0	0	1	3	0	0	0.4	0	0	0.2	6.6
	7	0	0	0	0	1.4	1	0	0	0	0	13	0.2	15.4
	8	0	0.2	0	0	4.4	11	0	0	0	0	3.4	5.2	24.6
	9	0	2	0	0	0.2	1	5	0	0	0	0.4	14	22.2
	10	0	5.8	0	0	5.6	3	0	0	0	1	0.2	5.2	20.4
	11	1.2	7	0	0	2.8	23	0	0.2	0	0	0.2	5.6	40
	12	0	1.8	0	0	0.2	5	0	0	0	0	0	0	7
	13	0	0	0	0	0	1	0	3.6	0.2	0	0	0	5.6
	14	0	0	0	0	0	0	0	0	0	6	0.4	0	6.4
	15	0	1.4	0	0	0	0	0	0	0.2	4	0.4	1.4	8.2
	16	0.2	5.8	0	0	3.8	0	2	0	0.4	1	8.8	0	21.6
	17	0.8	17	1	0	7.6	9	2	0	0	0	5.8	4.6	47
	18	0	4.8	1	0.6	0.4	0	0	0.2	0	0	4.2	8.2	19.6
	19	2	16	0	0.4	7.2	3	0	0	0	0	6.2	8.4	43
	20	0	17	0	0	1	1	0	1.2	0	0	8.4	0	29
	21	0.4	0	0	1.8	0.2	1	0	0.4	0	0	0	0.2	4.2
	22	1	0.8	1	0	0.4	1	0	0.2	0	0	1	3.8	10
	23	0	4	2	0	0	1	4	6.4	0	0	4.2	4.6	25.6
	24	0	9	2	7	0	0	9	0.6	0	0	0.8	11	39.8
	25	0	4.4	0	1	0.4	0	0	0	0	0	1.2	9.4	17
	26	0.2	0	0	1.8	0	0	8	0	0	0	7	0	17.4
	27	1.2	2	2	1.2	0	1	0	1.4	0	0	1	0.6	9.6
	28	0	0	0	0.2	0	1	0	0.8	0.2	0	17	1	19.8
	29	0		0	0	0	1	3	3	0	1	3	0.6	11.6
	30	0		0	4.8	0	1	0	0.4	1.8	0	0.2	11	19.4
	31	0.8		0		0		5	15		0		0	20.6
Grand Total		13	110	21	21	66	75	54	34	12	13	92	96	609

Sum of rain, mm	Year	2021												2021 Total
	Month	1	2	3	4	5	6	7	8	9	10	11	12	
Day	1	15.4	0	2.4	1.6	0	1.4	0.4	0	5.8	1.8	0	0	28.8
	2	8	0	6	21	0.6	33	0	3	0	0	27	0	99.2
	3	4.4	0.4	19	2.4	0	0.2	0	0.2	0.2	3.4	5.6	0	35.6
	4	5	0	5	15	0	0	1.6	0	0	9.6	0.8	5	41.8
	5	0	0	3	0	1.4	3.2	0	0	0	3.4	0	0.2	11.2
	6	3.2	1.2	15	8.2	0.6	12	0	0	0.2	0	0	0	39.8
	7	2.4	0	1.6	3	1.6	0	0	0.2	2	0.6	0	0.2	11.6
	8	18.4	0	0	9.8	1.4	12	4	0	1.4	0	0.8	0	48.2
	9	0	0	0.4	0.4	0	1	0.2	0	10	0.8	0.4	0	13.2
	10	0	1	9.2	6.8	4.2	17	1.6	0	3.6	0.4	0	0.4	44
	11	0	0.4	0	1.2	2.2	1	4.2	0.2	1.4	1	0.6	3.6	15.8
	12	0.8	0	2	0.2	0.2	0	2.6	0	0.8	0.2	0	2.8	9.6
	13	11.2	0	0	0	0	6.4	0.4	1	0	3.4	0	7.2	29.6
	14	4.4	0	0	0.2	0	8.4	0.6	0.4	0	0	0	2.2	16.2
	15	4.6	0.2	0	0	0	1.2	0	0	0	0.4	0.2	0	6.6
	16	0.2	0.2	0	4	0	1.4	1	4.2	0	13	3	0	27.4
	17	5.4	0	0	1.8	0	0.6	5	0	0	7.2	0.4	3.2	23.6
	18	11.6	0	0	0	0	1.6	0	0	0	0	0	0	13.2
	19	1.2	0	0	3.4	0	0	5.4	0	0	0.4	0.2	0	10.6
	20	1.4	0	0	0	0.2	1.2	9.2	1.2	0	7	0.8	0.4	21.4
	21	4.6	1.6	0	2.8	0	0	0.4	0.8	0	1	0	0.2	11.4
	22	1	0	0	21	0	2.6	2.6	1	0	9.2	0	0.2	38
	23	2	0	2.4	0.2	0.4	0	0	5.6	0	0.2	0	0	10.8
	24	0.4	0	3.4	0.2	0	0.6	0	0	0	18	5.8	0	28.4
	25	0	0	0.8	0.2	0.6	0	0	14	0.6	0.2	0	0.4	16.4
	26	0	0	0.4	1.6	0.2	8.4	1.4	0	0.6	9.2	0	0	21.8
	27	0	5.6	0	6	1.2	3.2	0.8	0	4.6	7.2	0.2	0	28.8
	28	0	5.6	0	20	20	0	1.6	0	0.8	4	0.2	0.4	52.4
	29	0		8	0	1.8	0	0.2	0	0.6	4.8	0	0	15.4
	30	2		0	0	2.6	0.2	2.8	0	11	0	0	0.2	18.4
	31	0.6		0		0		11	18		0		0	29.8
Grand Total		108	16	78	132	39	117	57	49	43	107	46	27	819

Sum of rain, mm	Year	2022												2022 Total
	Month	1	2	3	4	5	6	7	8	9	10	11	12	
Day	1	0	0	0	12	16	0	3	1.4	1.6	13	4.6	5.6	57
	2	0	0	0	3.6	8.8	11	13	1	0	7.2	0.6	22	68
	3	0.2	0	0	2	6.4	12	2	1	1.2	1.2	0.2	1.2	26.6
	4	0	0	0	0.4	8.8	1.8	1	1.8	1.8	0	1	2.2	18.4
	5	0.4	0	2.4	0	11	13	1	4.4	0	4.6	14	1.4	52.8
	6	0	0	0.2	1.4	2	0.4	1	2.4	8.2	1.8	0	6	23.2
	7	5.2	0	0	0.6	16	0	2	3.4	0.4	1	1.8	0.8	29.4
	8	6.8	0	0	1.2	9.4	0.8	1	13	1	0.2	0.2	13	46.4
	9	3	0	0	0.4	8	2.8	2	9.8	0	7.6	0	1.6	35.2
	10	20.4	0	0.2	1	6.8	6.8	0	0.2	0.8	0.4	0	8.4	45
	11	0.8	0	1.8	0.6	9.4	0.6	2	4.4	1.6	0	1.2	11	33
	12	1.2	0	0.2	0.6	3.4	3.6	3	1.2	1.4	0	3.6	1	19
	13	0	0	0.8	1.2	11	7	0	5.2	0	7.2	1.6	0	34
	14	0.4	0	1	0.4	9.2	4.2	3	4	0.6	0	5.4	1.6	29.6
	15	0	0	0.2	1	42	2.4	2	1.2	1	0	0	6.2	55.6
	16	0	0	0.2	0.4	7.8	11	1	0.8	0.8	0	0	1.6	24
	17	0	0	6.8	0	0.2	4	2	6.4	0.6	0	0	0.2	20
	18	0	0	0.6	0.8	5.4	5.4	1	9.6	0.4	0	4.2	0.2	27.8
	19	0	0	3.2	0.8	24	3.2	3	0.2	24	0.4	2.4	0	61
	20	0	0	0.4	0.2	6.4	5.6	3	2.8	7.2	0	0	0	25.8
	21	0	0	0.2	1.8	7.4	11	0	0	7.2	16	0.6	6.4	50.6
	22	0	0	0	2.8	11	13	2	0	15	0.4	0	4	48.8
	23	0	0	1.2	1.4	2.6	1.8	2	0	11	0.8	0	5.4	26
	24	0	0	0.6	4.6	4.4	8.6	0	6	0.4	11	28	11	49.4
	25	0	0	0	20	0.6	3	1	14	2.2	0.2	1.2	3.8	45.6
	26	0	0	0.4	0	9.4	15	1	0	5.4	6.4	28	0.2	40.4
	27	0	0	2.6	17	7.8	1.6	4	1.4	14	0	0.2	0	48.2
	28	0	0	0.6	24	0.8	13	0	0.8	2.8	2.8	1	0	45.6
	29	0		0.8	32	11	0	2	1.8	0	0.2	0.4	0	47.8
	30	0		0.6	5.4	0	13	4	0	1.4	4.8	0.4	0.2	29.6
	31	0		8		12		1	0		0		0	21.4
Grand Total		38.4	0	33	137	278	176	61	99	112	87	50	114	1185

References

1. Nadir H, Ahmed A, Paul P, Mitchell M (2022) Potential of Utilising Coir, Straw, and Recycled PET Fibres as Sustainable & Economical Alternative in Fibre Reinforced Concrete. Research and Developments in Materials Science 16: 1885-1897.
2. Nadir HM, Ash Ahmed, Molly Asher, Chris Goodwin, Oliver Kenyon, et al. (2024) Strategic Integration of Catchment Level Natural and Structural Methods of Sustainable Flood Management: A Case Study of River Wharfe Catchment Area. Adv Earth & Env Sci 5: 01-11.
3. Nadir HM (2024) Evaluation of Water Quality and Scarcity Issues for Sustainable Water Management Strategy in Twin Cities of Rawalpindi/ Islamabad, Pakistan. International Journal of Environment and Geoinformatics 11: 076-089.
4. Shirleyana S, Anindya SA (2012) The Emergence of Informal Riverside Settlements and Challenges for Planning. https://www.researchgate.net/publication/281765440_the_emergence_of_informal_riverside_settlements_and_challenges_for_planning_the_case_of_kali_mas_in_surabaya_indonesia.
5. World Wildlife Fund. Living Planet Report 2012: Biodiversity, Biocapacity and Better Choices. https://www.worldwildlife.org/publications/living-planet-report-2012-biodiversity-biocapacity-and-better-choices.
6. Nadir H, Ahmed A (2022) Hydrological Analysis and Statistical Modelling of Swat River Basin for Flood Risk Assessment. Advances in Earth & Environmental Science 3: 13.
7. Kumar V (2017) 15 Biggest and Worst Floods Ever in History. https://www.rankred.com/top-10-biggest-and-worst-floods-ever-in-history/.
8. Kumar A (2020) Department of Civil Engineering B.TECH -6 The SEM Water Resources and Irrigation Engineering (WRE) CE-603(A) LNCT Group of Colleges, Bhopal. https://lnct.ac.in/wp-content/uploads/2020/03/UNIT-IV-CANALS-AND-STUCTURE-WORD-PDF.pdf.
9. Schleifstein M (2011) The Times-Picayune. Mississippi River flooding in the New Orleans area could be massive if the Morganza spillway stays closed. https://www.nola.com/news/weather/.
10. National Mississippi River Museum. http://www.shootforthemoon.com/our_work/river-museum-expansion/.
11. The 2011 Flood in Mississippi River. https://wiki2.org/en/2011_Mississippi_River_floods
12. US Army Corps of Engineers Mississippi River Restoration Report 2024. Upper Mississippi River Restoration (UMRR) Program. https://www.mvr.usace.army.mil/Missions/Environmental-Stewardship/Upper-Mississippi-River-Restoration/.
13. Europe disaster statistics. Prevention Web. http://www.preventionweb.net/english/countries/statistics/index_region.php?rid.
14. Flood risk assessment and flood risk management, an introduction and guidance based on experiences and findings of Flood site. http://www.floodsite.net/html/partner_area/project_docs/T29_09_01_Guidance_Screen_Version_D29_1_v2_0_P02.pdf.
15. Shandana M (2012) The Copenhagen Post: Half fear home flooding. http://cphpost.dk/news/half-fear-home-flooding.2106.html
16. Stewart EJ, Reed DW, Faulkner DS, Reynard NS (1999) The FOREX method of rainfall growth estimation I: a review of requirement. Hydrol Earth Syst Sci 3: 187-195.
17. Helsel DR, Hirsch RM (2010) Statistical Methods in Water Resources. http://water.usgs.gov/pubs/twri/twri4a3.
18. Saleh AA (2011) Developing an empirical formula to estimate rainfall intensity in Riyadh region. Journal of Engineering Sciences King Saud University 23: 81-88.
19. Renard B, Kochanek K, Lang M, Garavaglia F, Paquet E, et al. (2013) Data-based comparison of frequency analysis methods: a general framework. Water Resour Res 49: 825-843.
20. Benameur S, Benkhaled A, Meraghni D, Chebana F, Necir A (2017) Complete flood frequency analysis in Abiod watershed, Biskra (Algeria). Nat Hazards 86: 519-534.
21. Saghafian B, Golian S, Ghasemi A (2014) Flood frequency analysis based on simulated peak discharges. Nat Hazards 71: 403-417.
22. Kamal V, Mukherjee S, Singh P, Sen R, Vishwakarma CA, et al. (2016) Flood frequency analysis of Ganga river at Haridwar and Garhmukteshwar. Applied Water Science 7: 1979-1986.
23. Millington N, Das S, Simonovic SP (2011) The Comparison of GEV, Log-Pearson Type 3 and Gumbel Distributions in the Upper Thames River Watershed under Global Climate Models. http://ir.lib.uwo.ca/wrrr/40/.
24. Singo LR, Kundu PM, Odiyo JO, Mathivha FI, Nkunan TR (2013) Flood frequency analysis of annual maximum streamflow for Luvuvhu River catchment, Limpopo Province, South Africa. https:// www.researchgate.net.
25. 1-month Trial version provided by www.mathwave.com.
26. Rowinski PM, Strupczewski WG, Singh VP (2002) A note on the applicability of log-Gumbel and log-logistic probability distributions in hydrological analyses: I. Hydrol Sci J 47: 107-122.
27. Bezak N, Brilly M, Sraj M (2014) Comparison between the peaks-over threshold method and the annual maximum method for flood frequency analysis. Hydrol Sci J 59: 959-977.
28. Deng X, Ren W, Feng P (2016) Design flood recalculation under land surface change. Nat Hazards 80: 1153-1169.
29. Rulfova Z, Buishand A, Roth M, Kysely J (2016) A two-component generalised extreme value distribution for precipitation frequency analysis. J Hydrol 534: 659-668.
30. Liu Y, Liu H, Chen Y, Gang C, Shen Y (2022) Quantifying the contributions of climate change and human activities to vegetation dynamics in China based on multiple indices. Science of The Total Environment 838: 156553-156553.
31. Cunnane C (2010) Statistical distributions for flood frequency analysis. J Hydraul Res 5: 28.
32. Oke MO, Aiyelokun OA (2014) Statistical Approach to Flood Disaster Management and Risk Reduction in Ibu River Basin. www.researchgate.com.
33. Haan CT (1977) Statistical Methods in Hydrology, Published by Iowa State University Press 1977 ISBN 081381510X, 9780813815107
34. Doston J (2020) Published by Sciencing. How to Calculate Exceedance Probability. https://sciencing.com/calculate-exceedance-probability-5365868.html.
35. Application of Unit Hydrograph To Derive Runoff Hydrograph. https://www.scribd.com/document/394224482/Application-of-Unit-Hydrograph-to-Derive-Runoff-Hydrograph.
36. Adeyi GO, Adigun AI, Onyeocha NC, Okeke OC (2020) Unit Hydrograph: Concepts, Estimation Methods and Applications in Hydrological Sciences. https://www.researchgate.net/publication/344596311_Unit_Hydrograph_Concepts_Estimation_Methods_and_Applications_in_Hydrological_Sciences.
37. Jena J, Nath S (2019) An Empirical Formula for Design Flood

Estimation of Un-Gauged Catchments in Brahmani Basin, Odisha. Journal of The Institution of Engineers (India): Series A 101: 01-06.
38. Iresh ADS, Athapattu BCL, Obeysekera J, Fernando (2024) Floodplain Zoning and Mapping for Lower Kelani River, Sri Lanka. Engineer Journal of the Institution of Engineers Sri Lanka 57: 23-33.
39. Iresh ADS, Dilthara GWAS, Sugeeshwara SPC (2024) Estimation of Catchment Parameters of Snyder's Synthetic Method for Water Resources Planning and Flood Management in Sri Lanka. Engineer Journal of the Institution of Engineers Sri Lanka 57: 81-86.
40. Shashika D, Jayantha Obeysekera, Bandunee Champika Liyanage Athapattu, Fernando (2024) Rainfall Intensity–Duration–Frequency Curves Using Cluster and Regional Frequency Analyses. Journal of Hydrologic Engineering 29.
41. River Swale. https://www.ydrt.org.uk/home-2/river-swale/.
42. Circular walk from Richmond along the River Swale and via Easby Abbey. https://www.daleswalks.co.uk/walks/river-swale-and-easby-abbey-from-richmond/.
43. River Swale. https://en.wikipedia.org/wiki/River_Swale#/media/File:Swale_(rivi%C3%A8re).png.
44. Water Science School. https://www.usgs.gov/special-topics/water-science-school.
45. Manning's Roughness Coefficients. https://www.engineeringtoolbox.com/mannings-roughness-d_799.html.
46. Using the Rational formula Q = (CIA) / 3.6. https://www.chegg.com/homework-help/questions-and-answers/1-using-rational-formula-q-cia-36-reference-drainage-reference-data-appendices-calculate-p-q51245994.
47. Gnilsen R (1987) Plain Concrete Tunnel Lining-Design Concepts. https://onlinepubs.trb.org/Onlinepubs/trr/1987/1150/1150-003.pdf.
48. Laying cement concrete/ stone slab Lining on canals – Indian code of practice. https://ia600403.us.archive.org/26/items/gov.in.is.3873.1993/is.3873.1993.pdf.
49. Leika et al., 2000. DESIGN OF SPRAYED CONCRETE FOR UNDERGROUND SUPPORT 2. Available at: https://tunnel.ita-aites.org/media/k2/attachments/public/recommendations%20AFTES%20sprayed%20concrete.pdf.
50. IFEH, (2008). Joint Defra / Environment Agency Flood and Coastal Erosion Risk Management R&D Programme Improving the FEH statistical procedures for flood frequency estimation Science Report: SC050050. Available at: https://assets.publishing.service.gov.uk/media/602e5c0f8fa8f54331b080e6/Improving_the_FEH_Statistical_Procedures_for_Flood_Frequency_Estimation_Technical_Report.pdf.
51. Abdu Tahir, Tarig El Gamri Ibrahim, Isam Mohammed Abdel-Magid (2011) Design Considerations of Concrete Lined Channels: Experience of Rawakeeb Research Station. Sudan Academy of Sciences Journal 4: 01-16.
52. Flood studies and update programme. https://opw.hydronet.com/data/files/FSU%20Work%20Package%204_2.pdf.
53. Flood Estimation Handbook Web Service. https://fehweb.ceh.ac.uk/.
54. Memon AA, Leghari KQ, Agha Khatri KL, Syed Attique Shah, Pinjani KK, et al. (2013) Design and Evaluation of Dadu Canal Lining for Sustainable Water Saving. Journal of Water Resource and Protection 5: 689-698.
55. How are Flows Measured? National River Flow Archive. https://nrfa.ceh.ac.uk/how-are-flows-measured.
56. Bakhshi M, York N (2016) Resilient Infrastructure Design of Fiber-Reinforced Tunnel Segmental Lining According to New Aci Report. https://core.ac.uk/download/pdf/61694293.pdf.
57. Open Channels County of Roanoke Chapter 5 -Open Channels. https://www.roanokecountyva.gov/DocumentCenter/View/7709/Ch-5-Open-Channels---2016-Design-Manual.
58. Chapter 7 -Ditches and Channels. https://www.virginiadot.org/business/resources/LocDes/DrainageManual/chapter7.pdf.
59. Ssection 44 -shotcrete, cast concrete channel lining, and grouted cobble. https://saccountyspecs.saccounty.gov/Documents/PDF%20Documents%202016/Specifications/Section%2044.pdf.
60. Canal Linings - Types and Advantages. The Constructor. https://theconstructor.org/water-resources/canal-linings-types-advantages/11052/.
61. Concrete Channel Lining Details N/A. https://www.fusedind.com/wp-content/uploads/2019/11/Concrete-Channel-Lining-Details.pdf.
62. Thomason C (2019) Hydraulic Design Manual Manual: Hydraulic Design Manual. http://onlinemanuals.txdot.gov/TxDOTOnlineManuals/TxDOTManuals/hyd/hyd.pdf.
63. Highway Design Manual CHAPTER 860 -ROADSIDE CHANNELS Topic 861 -General. https://dot.ca.gov/-/media/dot-media/programs/design/documents/chp0860-a11y.pdf.
64. Irrigation ditch lining by United States Department of Agriculture. https://www.nrcs.usda.gov/sites/default/files/202209/Irrigation_Ditch_Lining_428_NHCP_CPS_2020.pdf.
65. Fluvial design guide. https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/fluvial-design-guide.
66. Waqas-Chaudhry (2021) What Is Channel Lining? Which types of lining are mostly used? https://civilrack.com/construction/channel-lining/.
67. Flood Estimation Guidelines. https://www.gov.uk/government/publications/flood-estimation-guidelines.
68. Kim MS, Lee SS (2021) Design Study of Steel Fibre Reinforced Concrete Shaft Lining for Swelling Ground in Toronto, Canada. Applied Sciences 11: 3490.
69. Notice of Proposed Changes to the National Handbook of Conservation Practices for the Natural Resources Conservation Service. https://www.nrcs.usda.gov/sites/default/files/2022-12/468-NHCP-CPS-Lined-Waterway-or-Conveyance-Channel.pdf.
70. Flood Estimation Handbook and Flood Studies Report. https://www.ceh.ac.uk/services/flood-estimation-handbook.
71. Concrete Channel Lining Solutions. https://synthetex.com/erosion-and-scour-solutions/channel-lining/.
72. Team G (2023) Channel Lining: Material dan Perencanaannya - Geosinindo. https://www.geosinindo.co.id/post/channel-lining-fungsi-jenis-material-dan perencanaannya.
73. Erosion-Control-or-River-Slope-Control-Blocks. https://www.fakhris.com/view-product/5#gallery-2.
74. Bosun (2023) Bosun Precast Water Channel Linings and V-Drain Channels - Learn More. https://www.bosun.co.za/products/erosion-control/bosun-precast-water-channel-linings-and-v-drain-channels/.
75. https://www.concretecanvas.com/uploads/CC-Channel-Lining-HS2-Compound-0-UK-1.pdf.
76. Flood Protection Bunds and Gabions. www.pixshark.com.
77. Hospital Featured in FEMA Floodproofing Publication. https://floodbreak.com/hello-world/.
78. Pyramid breakwater stones with Raised berms/ walls and edges.https://www.geograph.org.uk, 2023/photo/1897792.
79. Glazzard P (2007) River Wharfe Weir at Tadcaster.

https://www.northyorks.gov.uk/sites/default/files/fileroot/Environment.pdf.

80. Fiber Reinforced Concrete: A Sustainable Building Material for the Future. https://www.constructionplacements.com/fiber-reinforced-concrete-frc/.
81. Doston J (2020) Published by Sciencing. How to Calculate Exceedance Probability. https://sciencing.com/calculate-exceedance-probability-5365868.html.
82. Han X, Wang X, Zhu Y, Huang JS, Yang L, et al. (2020) An Experimental Study on Concrete and Geomembrane Lining Effects on Canal Seepage in Arid Agricultural Areas. Water 12: 2343-2343.
83. Nadir HM, Ahmed A, Moshi I (2024) Elucidation of novel, alternative, fiber-reinforced iron-based pozzolanic composites as SCMs. Academia Materials Science 1: 01-21.
84. Application of Unit Hydrograph To Derive Runoff.https://www.scribd.com/document/394224482/Application-of-Unit-Hydrograph-to-Derive-Runoff-Hydrograph.