08 – HYDROLOGY OF THE NEALE FLOOD RELIEF SCHEME STUDY AREA IN SOUTH COUNTY MAYO AND CLIMATE CHANGE

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Abstract

The Neale Flood Relief Scheme study area lies in a highly karstified limestone area in South Mayo which includes a high concentration of turlough and groundwater floodplains in a glacial outwash plain. The study area's karst groundwater system drains to the Cross River via a series of springs at Toberfraughaun, Cross West and Tobernatinnew which in turn drains to Lough Corrib downstream of Cross Village. The South Mayo region historically experienced the impacts of extreme groundwater flooding during winter 2006, November 2009, winter 2015-16, and again in February-March 2020. During the winter 2015-16 period the Neale area experienced the worst flooding in living memory which resulted in properties being flooded and inundation of regional and local roads which cut off access to communities for prolonged periods. This paper summarises the data gathering and the topographical and hydrological surveys, and the rainfall analysis undertaken to understand the karst groundwater drainage system in the study area, and the groundwater hydrological model developed to simulate the current scenario karst groundwater flood risk for the feasibility stage of the Neale Flood Relief Scheme on behalf of Mayo County Council. The paper also concludes on the potential impact of climate change on flood risk in karst drainage areas with the Neale study area as a case study.

1. INTRODUCTION

Ryan Hanley Consulting Engineers were commissioned by Mayo County Council, following preparation of a pre-feasibility study for flood relief schemes (FRS) throughout the South Mayo region, to prepare a flood relief scheme feasibility study for The Neale village area. 'The Neale' is located 5.5 km south of Ballinrobe and 6.5 km east of Lough Mask in a highly karstified limestone area in South Mayo which includes a high concentration of wetlands, turlough and groundwater floodplains in a glacial outwash plain. The village of Cross is located 3.5 km south of The Neale (See Figure 1).

The area, which has historically been prone to extensive and prolonged groundwater flooding, was severely impacted during the Winter 2015 -16 (W1516) period resulting in flooding of houses, farm buildings, and regional and important local roads for prolonged durations resulting in access to communities being cut off. Figure 2 presents the surveyed extents of groundwater flooding at the peak during W1516 in the study area.

The study area is located within the Cross River catchment which in turn drains to Lough Corrib (See Figure 3). The river and associated catchment underwent significant modifications during the period between post-1847 and pre-1888 when a drainage channel was excavated north eastwards from Cross village to alleviate flooding in the Kilmaine area. The drainage channel was later incorporated into Corrib Headford Drainage Scheme (1967-1973) and in the intervening years further minor extension and maintenance works have been undertaken to alleviate flooding in the Kilmaine area and at Cross Village. No arterial drainage works, however, were undertaken in the lands in the vicinity of The Neale.

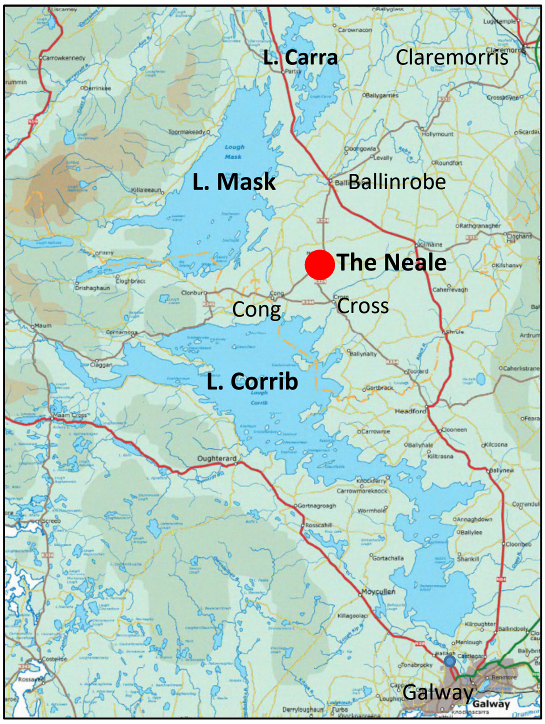


Figure 1: *The Neale's location relative to the Great Western Lakes*

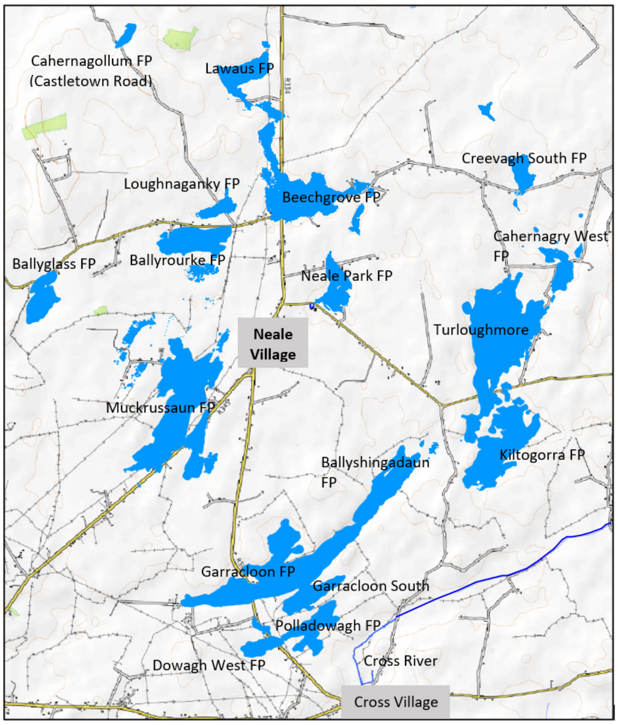


Figure 2: *Extent of Maximum Historic Flooding*

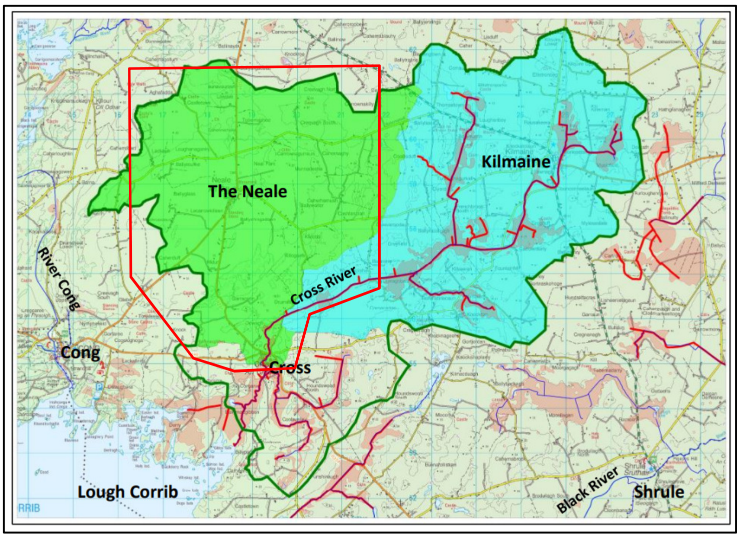


Figure 3: *Cross River Catchment and The Neale's location relative to the Great Western Lakes.*

This paper presents a summary of the following topics associated with the Neale FRS feasibility study as a case study and the theme of this year's National Hydrology Conference theme of Climate Change Impacts.

1. Flood risk assessment methodology for the Neale area
2. Summary of the Rainfall Analysis undertaken for the study area
3. Overview on feasibility study surveys and the study area hydrology
4. Potential impact of climate change on flood risk in the study area

2. FLOOD RISK ASSESSMENT METHODOLOGY

As part of the pre-feasibility study Ryan Hanley reviewed the available flood risk data for the South Mayo region and attended a public consultation meeting in October 2016 at 'The Neale' Hall to gather information regarding the location and extents of historical flooding in the region, and in particular the impact the Winter 2015/16 flood event had on the community. At the outset it was evident that no significant flood risk data was available for the study area and therefore Ryan Hanley were tasked with the development of a bespoke methodology to determine the groundwater flood risk in the study area.

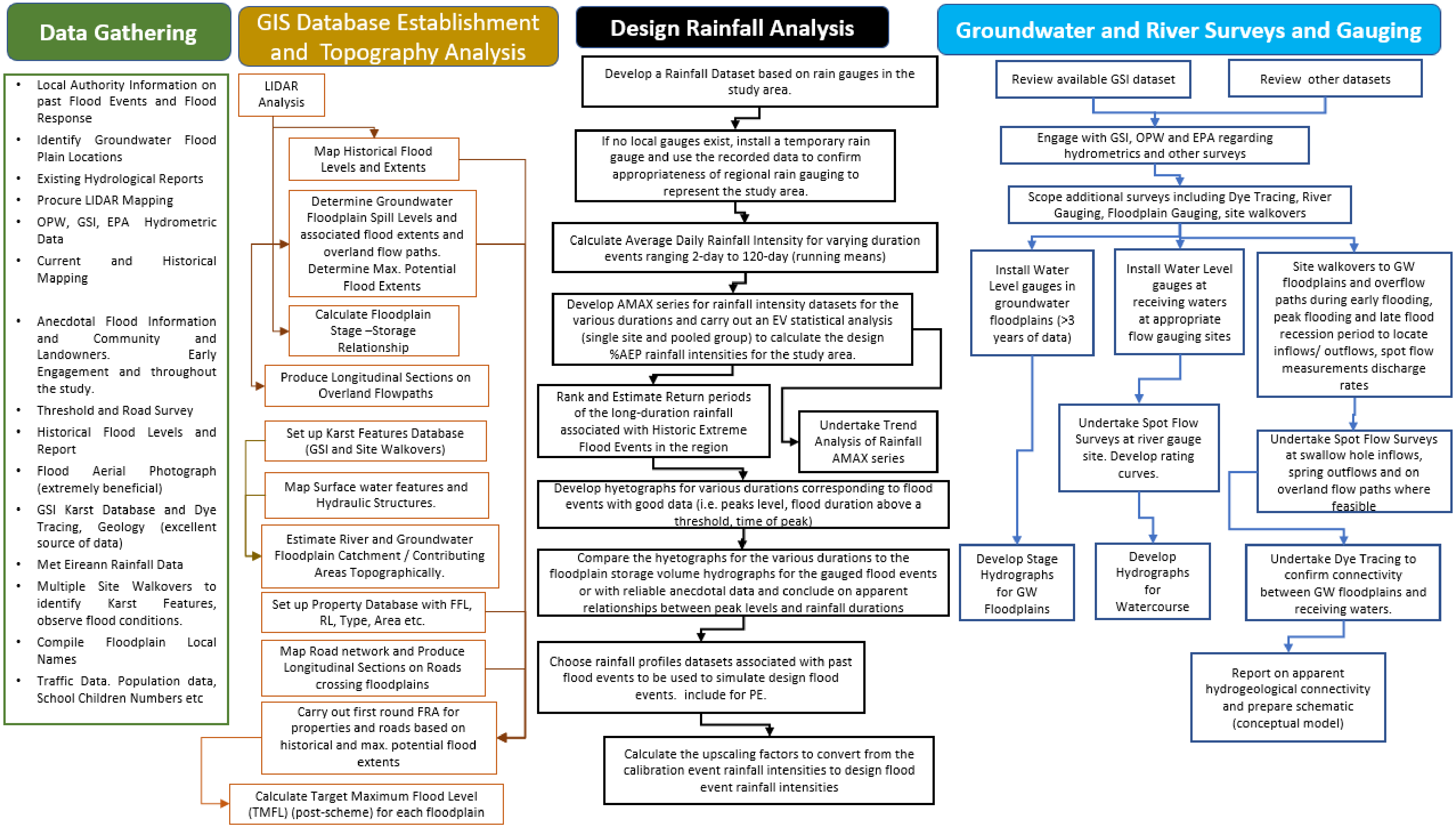
The following flow-charts summarise the methodology that emerged as the study progressed which may prove to be of benefit in developing best-practice guidelines for flood risk assessment in similar hydrological karst drainage areas throughout Ireland. The topics covered by the methodology include:

- Data Gathering
- GIS Database Establishment and Topography Analysis
- Design Rainfall Analysis
- Groundwater and River Surveys and Gauging
- Hydrological Assessment
- Hydrological Modelling and Flood Risk Assessment

The methodology has been developed based on flood alleviation schemes experience in karst environments, on consultation with the local authority, Geological Survey of Ireland (GSI) and other hydrology and hydrogeology specialists, and, in particular regarding the groundwater flood modelling, on the approaches developed by the GSI and Trinity College Dublin (TCD) for a similar project in South Galway.

Figure 4: *Flooding at Garracloon 27th February 2020.*

Figure 5: *Flooding at Turloughmore 27th February 2020*

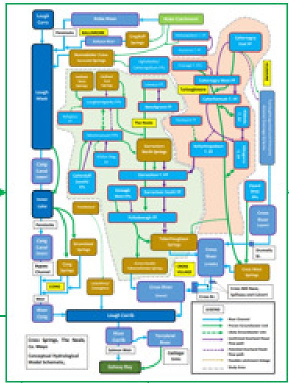

Data Gathering
Local Authority Information on past Flood Events and Flood Response
Identify Groundwater Flood Plain Locations
Existing Hydrological Reports
Procure LIDAR Mapping
OPW, GSI, EPA Hydrometric Data
Current and Historical Mapping
Anecdotal Flood Information and Community and Landowners. Early Engagement and throughout the study.
Threshold and Road Survey
Historical Flood Levels and Report
Flood Aerial Photograph (extremely beneficial)
GSI Karst Database and Dye Tracing, Geology (excellent source of data)
Met Eireann Rainfall Data
Multiple Site Walkovers to identify Karst Features, observe flood conditions.
Compile Floodplain Local Names
Traffic Data. Population data, School Children Numbers etc
GIS Database Establishment and Topography Analysis
LIDAR Analysis
Map Historical Flood Levels and Extents
Determine Groundwater Floodplain Spill Levels and associated flood extents and overland flow paths. Determine Max. Potential Flood Extents
Calculate Floodplain Stage –Storage Relationship
Produce Longitudinal Sections on Overland Flowpaths
Set up Karst Features Database (GSI and Site Walkovers)
Map Surface water features and Hydraulic Structures.
Estimate River and Groundwater Floodplain Catchment / Contributing Areas Topographically.
Set up Property Database with FFL, RL, Type, Area etc.
Map Road network and Produce Longitudinal Sections on Roads crossing floodplains
Carry out first round FRA for properties and roads based on historical and max. potential flood extents
Calculate Target Maximum Flood Level (TMFL) (post-scheme) for each floodplain
Design Rainfall Analysis
Develop a Rainfall Dataset based on rain gauges in the study area.
If no local gauges exist, install a temporary rain gauge and use the recorded data to confirm appropriateness of regional rain gauging to represent the study area.
Calculate Average Daily Rainfall Intensity for varying duration events ranging 2-day to 120-day (running means)
Develop AMAX series for rainfall intensity datasets for the various durations and carry out an EV statistical analysis (single site and pooled group) to calculate the design %AEP rainfall intensities for the study area.
Rank and Estimate Return periods of the long-duration rainfall associated with Historic Extreme Flood Events in the region
Undertake Trend Analysis of Rainfall AMAX series
Develop hyetographs for various durations corresponding to flood events with good data (i.e. peaks level, flood duration above a threshold, time of peak)
Compare the hyetographs for the various durations to the floodplain storage volume hydrographs for the gauged flood events or with reliable anecdotal data and conclude on apparent relationships between peak levels and rainfall durations
Choose rainfall profiles datasets associated with past flood events to be used to simulate design flood events. include for PE.
Calculate the upscaling factors to convert from the calibration event rainfall intensities to design flood event rainfall intensities
Groundwater and River Surveys and Gauging
Review available GSI dataset
Review other datasets
Engage with GSI, OPW and EPA regarding hydrometrics and other surveys
Scope additional surveys including Dye Tracing, River Gauging, Floodplain Gauging, site walkovers
Install Water Level gauges in groundwater floodplains (>3 years of data)
Install Water Level gauges at receiving waters at appropriate flow gauging sites
Site walkovers to GW floodplains and overflow paths during early flooding, peak flooding and late flood recession period to locate inflows/ outflows, spot flow measurements discharge rates
Undertake Spot Flow Surveys at river gauge site. Develop rating curves.
Undertake Spot Flow Surveys at swallow hole inflows, spring outflows and on overland flow paths where feasible
Develop Stage Hydrographs for GW Floodplains
Develop Hydrographs for Watercourse
Undertake Dye Tracing to confirm connectivity between GW floodplains and receiving waters.
Report on apparent hydrogeological connectivity and prepare schematic (conceptual model)

Flow Chart #1

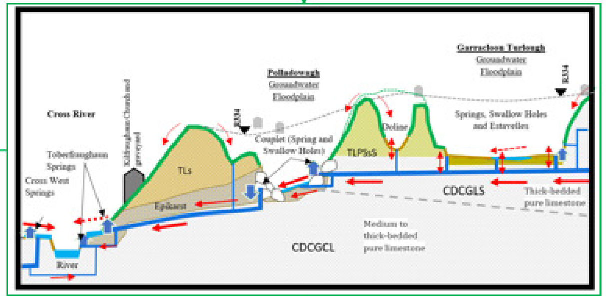
Hydrological Assessment

Groundwater

Develop a schematic (conceptual model) for the study area showing floodplain connectivity and springs etc. based on dye tracing, topography, gauging etc. Refine through the study



Produce Longitudinal Sections through floodplains and develop conceptual models



From the gathered data identify the historic extreme flood events [calibration events] for which good data exists for the study area groundwater floodplains including water level gauged data, peaks water levels, flood duration above a threshold, approximate time of peak flood level. (i.e. Winter 2015/16, 2018 – 2019, Early Spring 2020)

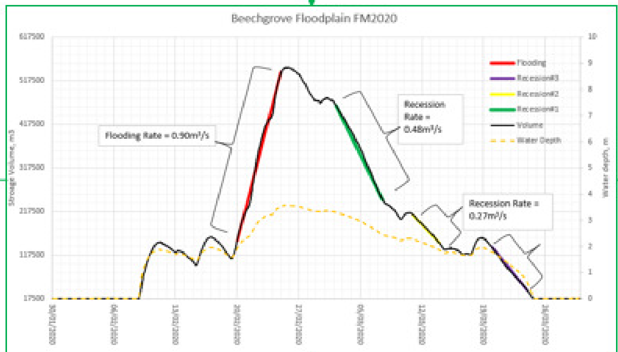
Produce Historic Flood Event Stage and Storage Hydrographs for gauged GW floodplains (Calibration Data)

Calculate upscaling factors from calibration event rainfall intensity to design flood events rainfall intensities.

Develop hyetographs corresponding to flood events with good data. (Calibration Events)

Compile Inputs for Hydrological Model

Calculate infill rates (rising limb) and drawdown (recession) rates and duration from hydrographs



Approximate GW FP karst drainage capacity from storage hydrographs recession slopes

Compile Inputs for Hydrological Model

Classify the karst drainage flow regime from hydrograph (predominately karst conduit dominated flow in this case)

Back calculate the GW FP contributing catchment areas from hydrograph and estimate catchment runoff rates. Iterative process.

Estimate Groundwater Floodplain Catchment / Contributing Areas.

Surface Waterbodies

Review springs flow data relative to receiving watercourse flows. (GSI and RH)

Compare spot flow gauged springs to receiving watercourse flows data. Confirm likely range.

Gather anecdotal information from community local to the watercourse regarding maximum water levels, duration of high flows, frequency of high flows, response time of flood flows to rainfall.

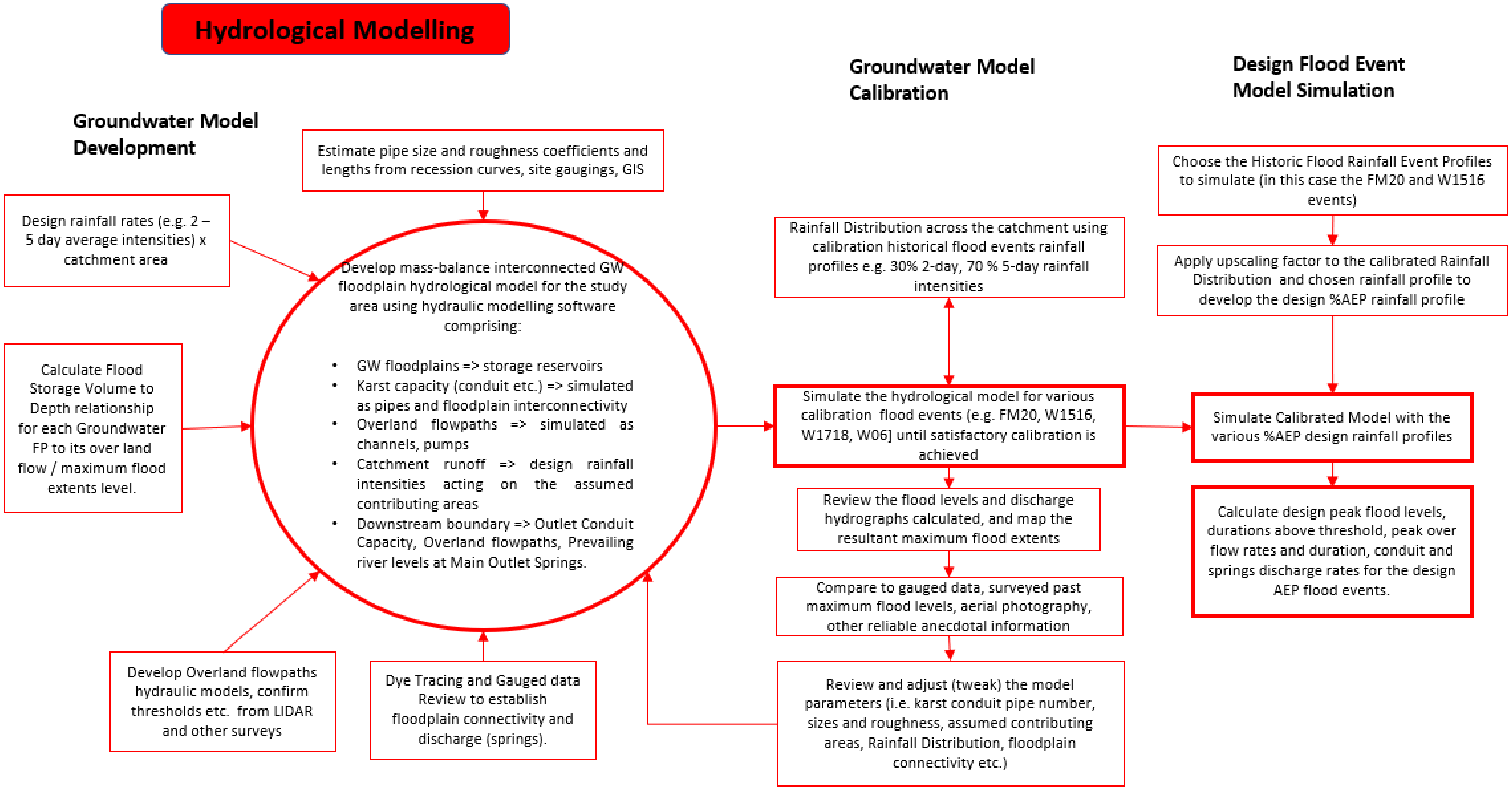
Estimate Qmed for receiving watercourse upstream of Cross springs from PCDs, assess flow to rainfall intensity relationship.

Calculate upstream river flood flows and develop hydrograph based on river gauge data and rainfall profiles.

Compile Inputs for Hydrological Model

Assess Lough Corrib gauged data (Cong Pier) and estimate design downstream boundary condition for river model

Flow Chart #2


Hydrological Modelling
Groundwater Model Development
Estimate pipe size and roughness coefficients and lengths from recession curves, site gaugings, GIS
Design rainfall rates (e.g. 2 – 5 day average intensities) x catchment area
Develop mass-balance interconnected GW floodplain hydrological model for the study area using hydraulic modelling software comprising:
• GW floodplains => storage reservoirs
• Karst capacity (conduit etc.) => simulated as pipes and floodplain interconnectivity
• Overland flowpaths => simulated as channels, pumps
• Catchment runoff => design rainfall intensities acting on the assumed contributing areas
• Downstream boundary => Outlet Conduit Capacity, Overland flowpaths, Prevailing river levels at Main Outlet Springs.
Calculate Flood Storage Volume to Depth relationship for each Groundwater FP to its over land flow / maximum flood extents level.
Develop Overland flowpaths hydraulic models, confirm thresholds etc. from LIDAR and other surveys
Dye Tracing and Gauged data Review to establish floodplain connectivity and discharge (springs).
Groundwater Model Calibration
Rainfall Distribution across the catchment using calibration historical flood events rainfall profiles e.g. 30% 2-day, 70 % 5-day rainfall intensities
Simulate the hydrological model for various calibration flood events (e.g. FM20, W1516, W1718, W06] until satisfactory calibration is achieved
Review the flood levels and discharge hydrographs calculated, and map the resultant maximum flood extents
Compare to gauged data, surveyed past maximum flood levels, aerial photography, other reliable anecdotal information
Review and adjust (tweak) the model parameters (i.e. karst conduit pipe number, sizes and roughness, assumed contributing areas, Rainfall Distribution, floodplain connectivity etc.)
Design Flood Event Model Simulation
Choose the Historic Flood Rainfall Event Profiles to simulate (in this case the FM20 and W1516 events)
Apply upscaling factor to the calibrated Rainfall Distribution and chosen rainfall profile to develop the design %AEP rainfall profile
Simulate Calibrated Model with the various %AEP design rainfall profiles
Calculate design peak flood levels, durations above threshold, peak over flow rates and duration, conduit and springs discharge rates for the design AEP flood events.

Flow Chart #3

Hydrological Modelling

River Model Development, Calibration and Simulation

Develop a hydraulic model for the receiving waters (e.g. river reach, sea , lake) (Cross River in this case) with hydraulic modelling software comprising:
- River Cross-section data
- Hydraulic structures (bridges, weirs, bypass channels) and associated coefficients
- Overbank effective areas
- Overbank blockages (e.g. walls)
- Channel and Overbank Roughness Coefficients
- Upstream River Flows and hydrographs
- Hydrographs from springs from GW Model
- Hydrographs from Overflows from GW Model
- Downstream boundary condition (Lough Corrib in this case)

Calibrate the Hydraulic River using:
- Gauged flow and water level data (Drumelly Bridge and Cross Bridge gauges (set up for scheme).
- Water levels recorded along the river reach during the river topographical survey
- Anecdotal historic flood level data and estimated flow rates (historic rainfall in both the groundwater and river catchments
- Downstream boundary level (Cong Pier gauge)
- Adjust channel roughness coefficients and hydraulic structure parameters and overbank effective flow areas to calibrate the model

Simulate % AEP design flood:
- Design %AEP flood event upstream river flows
- The calculated GW springs discharge hydrographs for the %AEP design flood event
- The calculated GW floodplain overland flow hydrographs for the %AEP design flood event
- The downstream boundary hydrograph

From the Hydraulic River Model determine:
- peak water levels at receptors (i.e. low lying buildings adjacent to the river and roads crossing over the river, downstream low lying lands)
- peak water levels at the springs
- Hydrograph at downstream extents of the river

Flood Mapping and Flood Risk Assessment

Groundwater Flood Extents

Using Topographical Model Software, LIDAR, Survey data and the calculated GW floodplain design levels, produce the %AEP flood extents at the individual floodplains and project these onto GIS mapping.

Using hydraulic modelling software and associated topographical modelling tools, produce the overland %AEP flood flowpaths inundation extents and project these onto GIS mapping.

Compare flood mapping to aerial photography and reliable anecdotal information for flood events where available.

For elevated small enclosed topographical depressions floodplains (e.g. dolines etc.) which were not modelled directly, produce flood extents from:
- Anecdotally reported Historical Maximum Level
- Flood extents from aerial photograph taken at peak flood
- Design %AEP flood level from surrounding modelled GW floodplains (if similar)
- Maximum flood level corresponding to its natural spill 'lip' level (e.g. possibly a road level, field level) if located between floodplains of cascading Design %AEP flood levels

Surface Waterbodies

Using Topographical Model Software, Hydraulic Modelling Software, LIDAR, Survey data and the calculated flood levels, produce the %AEP flood extents at the surface waterbody floodplain e.g. river reach, lake, coast, and project these onto GIS mapping.

Flood Risk Assessment

Compare the property and road GIS database to the projected %AEP flood extents.
- Identify properties (e.g. houses, schools, businesses, farm buildings, slatted sheds, at risk of inundation (depth ranges) or at high flood risk
- Identify roads at risk of inundation above road centreline level
- Determine the duration at which the roads would be closed off to traffic.
- Determine the communities at risk of being cut-off entirely, and calculate the duration of this risk.
- Compare the calculated flood risk data to anecdotally reported data during recent extreme flood events of similar return periods and confirm results and revisit assessments if necessary.
- Review the TMFL for the floodplains and confirm appropriate for consideration as part of the flood risk management measures assessment

Flow Chart #4

3. REGIONAL RAINFALL ASSESSMENT AND TREND ANALYSIS

3.1 Background

At the commencement of the feasibility study there was no long-term water level gauge data available for the Neale groundwater floodplains to allow the return period of the recent flood events to be assessed and the probability of flood damage to be calculated. Extensive groundwater flooding in karst aquifer regions is, in general, associated with long duration rainfall events (extending over several weeks) which in general occurs in the October to March period in the west of Ireland. The most extreme groundwater flood conditions in karst aquifer regions would, therefore, be expected to coincide with above average seasonal antecedent rainfall depths, together with heavy and persistent rain (resulting in sustained high average daily rainfall depths) over an extended duration (perhaps 4 to 8 weeks) and potentially combined with a short-duration (2 to 5 day) extreme rainfall events (e.g. around 19th November 2009, Storm Desmond in early December 2015). The effective run-off rates in karst regions to the groundwater floodplains (observed responsiveness) during flood events has been shown to be relative to 1 to 5-day duration rainfall events.

3.2 Rainfall Analysis

The study area catchment is in a lowland plain, circa 6 km (to centroid) east from Lough Mask with an elevation range of between 20 mOD and 50 mOD. There are no Met Éireann rain gauges directly within the Neale study area.

Single site and pooled group statistical analysis (using EV1 (Gumbel) distribution method) has been undertaken for Met Éireann rain gauge datasets in the region to calculate rainfall annual exceedance probability (AEP) growth factors and in turn to calculate the design %AEP rainfall intensities for the study area.

The 6 No. Met Éireann rain gauges selected for the pooled group analysis are located within a 25km radius of the Neale study area catchment centroid, and to the east of the Lough Mask and Lough Corrib waterbodies. The rain gauges to the west of the study area are, in general, in a mountainous area and west of the great western lakes and these were therefore excluded from the analysis based on topography (aspect, terrain and elevation and location relative to the great lakes). Figure 6 and Table 1 present the location and summarises the rain gauges attributes that were analysed.

Table 1: *Selected Met Éireann Rain Gauges within 25 km radius of the Study Area*

Stn. Number	Rain Gauges	Elevation	Distance to Centroid	Centroid Distance to large Lake	Analysis	HY Used for Analysis
5627	Belcarra	72 mOD	24.4 km N	c6 km	Pooled Group	2004-2020
5127	Kilkeeran	27 mOD	15 km N	c2.5 km	Pooled Group	1994-2020
2175	Claremorris	68 mOD	22.5 km NE	c15km	Single Site & Pooled Group	1950-2020
3027	Miltown	50 mOD	23 km E	c26 km	Pooled Group	1998-2020
4527	Headford	30 mOD	14 km SE	c5 km	Single Site & Pooled Group	1981-2020
2227	Carndolla	24 mOD	23 km SE	c3 km	Pooled Group	1997-2020

Rolling average rainfall intensities were calculated from these rain gauges' datasets for durations ranging between 5-days to 50-days (in steps of 5-days) and for 60, 90 and 120 days durations. The associated annual maxima (AMAX) rainfall intensities for the various durations were in turn calculated for each hydrometric year (HY).

The growth factors calculated from the pooled group analysis (202 No. years) of these AMAX series were compared to those of the single site analysis for Headford and Claremorris, and they were found to agree closely, with relative average ratios of 1.03 and 1.00 respectively.

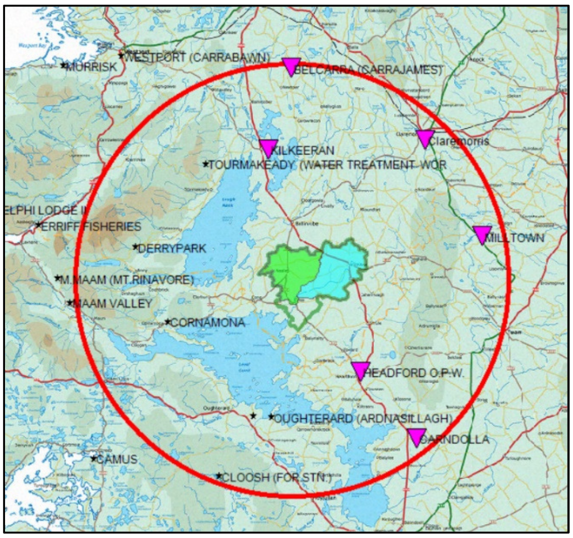


***Figure 6:** Met Éireann Rain gauges within 25km of The Neale*

A comparison of the Headford and Claremorris rainfall for the various AMAX series and associated with historical flood events confirmed that:

- on average that design rainfall intensities at Headford are 14% larger than those at Claremorris, and
- the Headford rain gauge consistently recorded higher rainfall intensities than those at Claremorris during flood events of the order of +5% to +29%.

A further assessment was undertaken, comprising the installation of a temporary rain gauge at Cross WWTP during Winter 2019/2020, to determine which of the existing rain gauge datasets would be suitable for estimating the extreme rainfall return periods for the Neale study area. An uninterrupted rainfall record of 59-day (between 1st December 2019 and 28th January 2020) was collected at the gauge. The 5-day, 10-day and 20-day rolling rainfall depths for this period were calculated and compared to the equivalent datasets at the Headford, Claremorris and Tourmakeady rain gauges. Figure 7 presents the comparison of the datasets for the monitored period.

The assessment identified that:

- Rainfall data recorded at Cross WWTP during the study period aligned well with the Headford and Claremorris gauges,
- Rainfall totals at Tourmakeady rain gauge appreciably exceeded those recorded at Cross WWTP, and
- the Headford rain gauge recorded consistently similar rainfall totals as those recorded at Cross WWTP.

The Headford rain-gauge's single site analysis design %AEP rainfall intensities datasets was selected, based on the above assessments and following a precautionary approach, as being appropriate to represent the prevailing rainfall regime in the study area.

The study area AMAX rainfall data was compared with the associated design %AEP rainfall to identify the years when the most extreme groundwater flooding would likely to have occurred in the study area, to rank the events and to estimate their associated flood return period. Hydrometric year 2015 was identified as clearly the most extreme rainfall event. Other hydrometric years of note include 2009, 2006, 2013, 1999 and 2019. Tables 2 to 4 below present the calculated extended duration rainfall intensities return periods, the hydrometric years ranked relative to their peak recorded rainfall intensities and the estimated flood event return of these events.

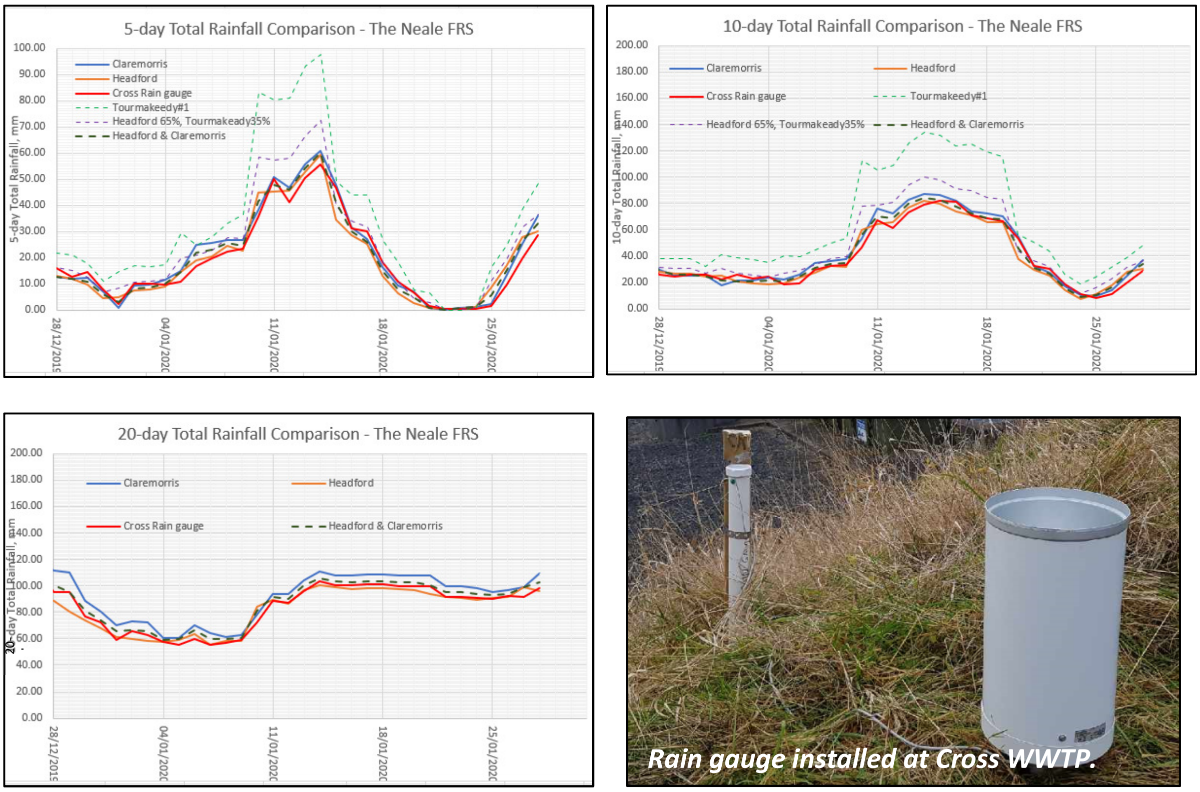


Figure 7: *5-day, 10-day and 20-day Rolling Rainfall Total for main rain gauges in Neale region*

Table 2: *Calculated Rainfall Intensities (mm/day) Return Periods for Extended Durations in the study area*

Return Period 1 in … Years	Rainfall Event Duration (days)												
	5	10	15	20	25	30	35	40	45	50	60	90	120
	Average Daily Rainfall Intensities (mm/day)												
5	19.7	14.0	12.2	10.7	10.0	9.4	8.8	8.3	8.0	7.8	7.4	6.3	5.8
10	22.0	15.5	13.5	11.9	11.0	10.4	9.8	9.2	8.8	8.7	8.2	7.0	6.4
20	24.3	17.0	14.8	13.0	12.0	11.4	10.7	10.0	9.6	9.5	9.0	7.7	6.9
30	25.6	17.9	15.5	13.6	12.6	11.9	11.2	10.5	10.1	9.9	9.4	8.1	7.3
50	27.2	18.9	16.4	14.4	13.3	12.6	11.8	11.1	10.7	10.5	10.0	8.6	7.7
75	28.5	19.8	17.1	15.0	13.9	13.2	12.4	11.6	11.1	11.0	10.5	8.9	8.0
100	29.4	20.3	17.6	15.4	14.3	13.6	12.7	11.9	11.5	11.3	10.8	9.2	8.2
200	31.6	21.8	18.9	16.5	15.3	14.5	13.6	12.7	12.2	12.1	11.5	9.9	8.8
500	34.4	23.6	20.5	17.8	16.6	15.7	14.7	13.8	13.2	13.1	12.5	10.7	9.5
1000	36.6	25.1	21.7	18.9	17.5	16.7	15.6	14.6	14.0	13.9	13.3	11.3	10.0

Table 3: *Calculated Rainfall Intensities (mm/day) Return Periods for Extended Durations in the study area*

Rank	Event Duration												
	5-day	10-day	15-day	20-day	25-day	30-day	35-day	40-day	45-day	50-day	60-day	90-day	120-day
1	2009	2009	2009	2009	2009	**2015**	**2015**	**2015**	**2015**	**2015**	**2015**	**2015**	**2015**
2	2015	2015	2015	2015	2015	2006	2009	2009	2013	2013	2013	2013	2013
3	1999	2006	2006	2006	2013	2009	2013	**2019**	2009	2009	2006	2006	2006
4	2006	1999	**2019**	**2019**	2006	1999	2006	1999	**2019**	1999	1999	*1994*	*1993*
5	1984	1989	1999	2013	**2019**	2013	1999	2013	1999	2006	2009	*1993*	*1994*
6	1995	2019	1989	1999	1999	**2019**	**2019**	2006	2006	**2019**	1986	**2019**	**2019**
7	1989	1998	2013	1989	1989	1989	1986	1994	1993	2011	**2019**	1999	2011

***Table 4:** Calculated Return Periods for the HY Peak Rainfall Intensities for Extended Duration Events*

Hydrometric Year	Event Duration												
	5-day	10-day	15-day	20-day	25-day	30-day	35-day	40-day	45-day	50-day	60-day	90-day	120-day
	Rainfall Return Period (1 in .... years)												
2015	30-50	30-50	30-50	30-50	30-50	50	50-75	50-75	50-75	50-75	75-100	75-100	75-100
2009	30-50	75-100	50	30-50	30-50	20-30	20-30	20	10-20	10-20	5-10	<5	<5
2006	10-20	20-30	30-50	20-30	20	30-50	10-20	10-20	5-10	5-10	10-20	10-20	10-20
2013	<2	<5	5-10	10-20	20-30	10-20	20-30	10-20	20-30	20-30	30-50	30-50	20-30
1999	30-50	10-20	10-20	10-20	10-20	10-20	10-20	10-20	10	10-20	5-10	5-10	5-10
2019	<5	5-10	10-20	10-20	10-20	10-20	10-20	10-20	10-20	5-10	5-10	5-10	5-10

3.3 Rainfall Trend Analysis

A trend analysis has been carried out on the available Claremorris and Headford rain gauge datasets to investigate if there is evidence of regional increases in AMAX rainfall intensities over the respective record periods. The AMAX rainfall data for event durations of between 5 days and 120 days were analysed using linear regression, 10-year rolling averages, Mann-Kendal test and Sen's Slope methods. The results from all the methods suggest a positive upward trend over the period.

Figure 9 presents the 10-year rolling average and associated trendlines of the 25-to-120-day duration AMAX rainfall intensities at Claremorris for the full rainfall dataset (1950 to 2020). Of note regarding the AMAX rainfall intensities on Figure 9 is the apparent oscillation in AMAX intensities from a peak in the mid 1950s, to a period of decline during the 1970s, followed a rise in AMAX intensities towards 1990-1995, followed by a period of general decline towards 2010, which was then followed once more by a rise towards 2015-2020. Overall, an upward trend is apparent.

Similarly Figure 10 presents the 10-year rolling average and associated trendlines at Claremorris and Headford for the full rainfall dataset (1980 to 2020). While a strong linear upward trend is apparent at Headford gauge for all durations, a linear upward trend for the longer durations (60-120 days) is less apparent at the Claremorris gauge for this record period.

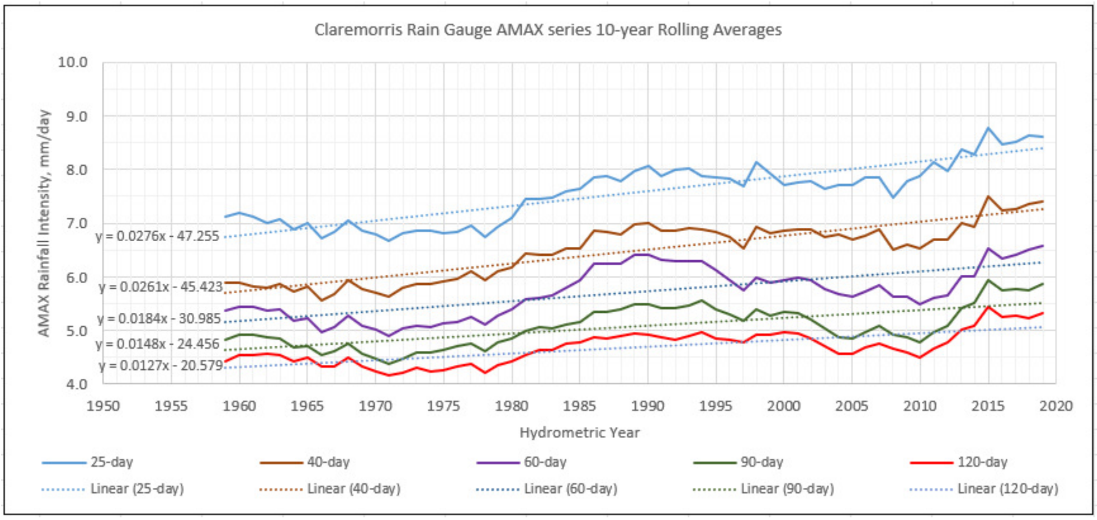


***Figure 9:** Claremorris Weather Station Rain Gauge Extended Duration Rainfall Intensities 10-year Rolling Average (HY 1950 to 2020)*

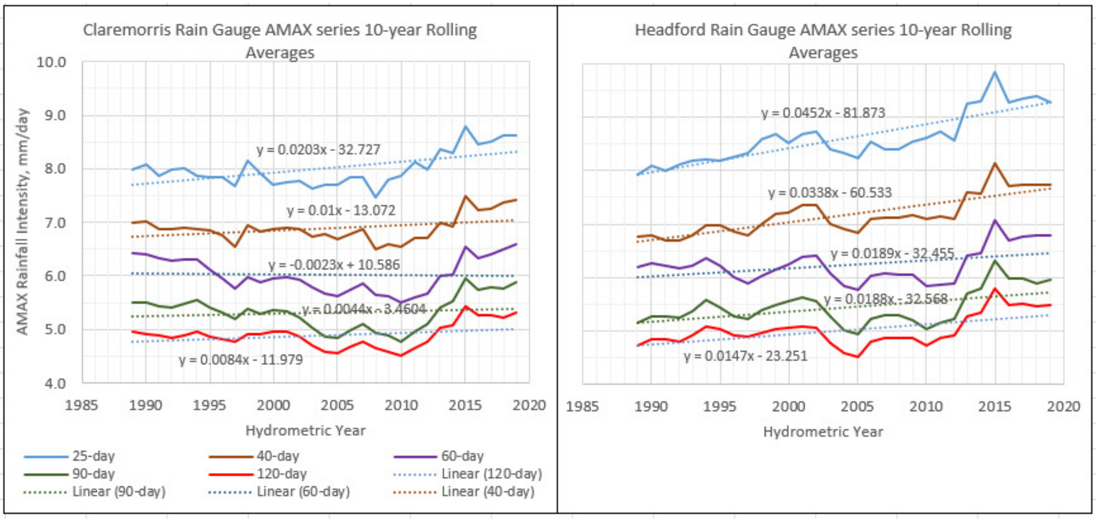


Figure 10: *Claremorris and Headford Rain Gauges Extended Duration Rainfall Intensities 10-year Rolling Average (HY 1980 to 2020)*

4. FEASIBILITY STUDY SURVEYS AND THE STUDY AREA HYDROLOGY OVERVIEW

4.1 Community Engagement

Ryan Hanley and Mayo County Council engaged with the Neale community throughout the study by consultation with the Cross-Cong-Neale Flood Relief Committee and site meetings with landowners. Reliable anecdotal information on historic peak flood levels and extents, the flooding and drainage regime of the floodplains, the flood durations and properties and communities impacted by flooding was gathered. In the absence of historic flood level gauge information, this anecdotal information proved fundamental to the study.

4.2 Data Gathering and Surveys

All available hydrological datasets e.g. Met Eireann, GSI, OPW, EPA were collected and reviewed. A LIDAR survey had been completed by the OPW for the majority of the study area prior to the commencement of pre-feasibility report.

Ryan Hanley engaged with the GSI's Groundwater Flood Project (2016-2019) at an early stage regarding the scope for floodplain gauging and other surveys in the Neale Study area. Subsequently the GSI installed 7 No. floodplain gauges (see Figure 11) and carried out dye tracing from 4 No. swallow holes to the Cross Springs. Discharge flow surveys were also completed at the springs.

During the feasibility study an additional 2 No. swallow hole tracings were identified as necessary to assess the karst drainage connectivity in the eastern extents of the study area. This study was completed during Spring 2021 by Ryan Hanley under the supervision of Dr. David Drew and with support from the GSI and Mayo County Council.

No river continuous gauging of the Cross River flows at Cross was available prior to the scheme and therefore a temporary gauging contract was undertaken by Hydro Environmental Ltd. with Ryan Hanley during the Winter 2019-2020 period at Cross Bridge and Drumelly Bridge. A temporary rain gauge was also installed (as described previously) at Cross WWTP as part of the river gauging contract.

Threshold Surveys were undertaken by Ryan Hanley of the properties and roads in areas reported to be at high flood risk. As part of this survey historic flood levels were collected. A topographical survey of the Cross River channel and hydraulic structures was completed by Bronra Surveys.

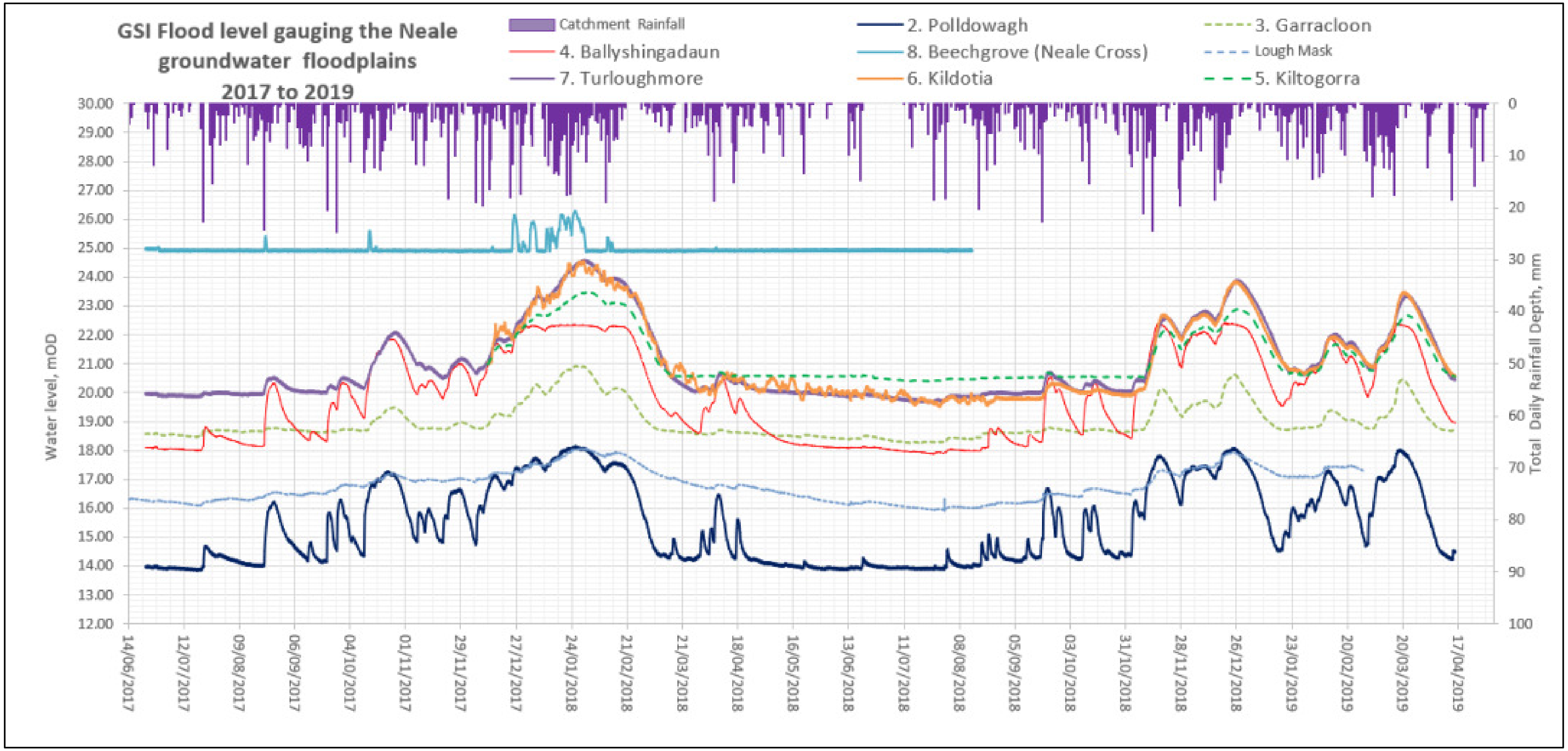


Figure 11: *GSI groundwater gauging in the study area from June 2017 to April 2019.*

Figure 12: *Flooding at Beechgrove (Neale Cross) during the Winter 2015-16 period.*

Figure 13: *Polladowagh swallow holes in drained down conditions in Late Spring 2021*

Mayo County Council carried out a drone surveys close to the peak of the flooding during February 2020. This survey, coupled with the drone survey at Beechgrove during the Winter 2015-16 floods were assessed during the study.

Site walkovers were carried out to identify the locations of karst drainage features which were visible on aerial photography, mapping, LIDAR and report anecdotally.

The data gathered was compiled in a GIS database for the scheme and the historic flood levels were projected onto mapping using LIDAR and topographical modelling software.

4.2 Groundwater Flood Event Return Period Estimation

Rainfall dataset for the study area has been compared to gauged water depths in the study area's groundwater floodplains to investigate if an apparent relationship between peak rainfall intensities and peak water depths exists. Figure 14 and Figure 15 present a comparison of the 20 to 35 day extended duration rolling average rainfall intensities relative to the floodplains gauged water depths during the periods of October 2017 to April 2018 and the February to March 2020. By inspection it is concluded that in general the peak 15-day to 30-day extended durations rainfall intensities event coincide with the gauged peak water depths of the floodplains (FP), however, with:

- The Turloughmore to Polladowagh FP peaks corresponding with the longer 30 - 40 day duration rainfall peaks,
- The upper floodplains, including Beechgrove FP, responding earlier with 15-25 day extended duration rainfall peaks,
- The flood flow rates in the Cross River, which peaked around the 25th- 28th February, corresponding with the 15 to 20 day extended duration rainfall peak.

It is concluded, therefore, that in the Neale study area, as a whole rather than each floodplain individually, the return period of the 25-35 day extended duration rainfall events are indicative of the peak groundwater flood event return period, e.g. the W1516 and FM20 flood events had return period of approximately 1 in 50 years (2% AEP) and 1 in 10 – 20 years (10% to 5% AEP) respectively.

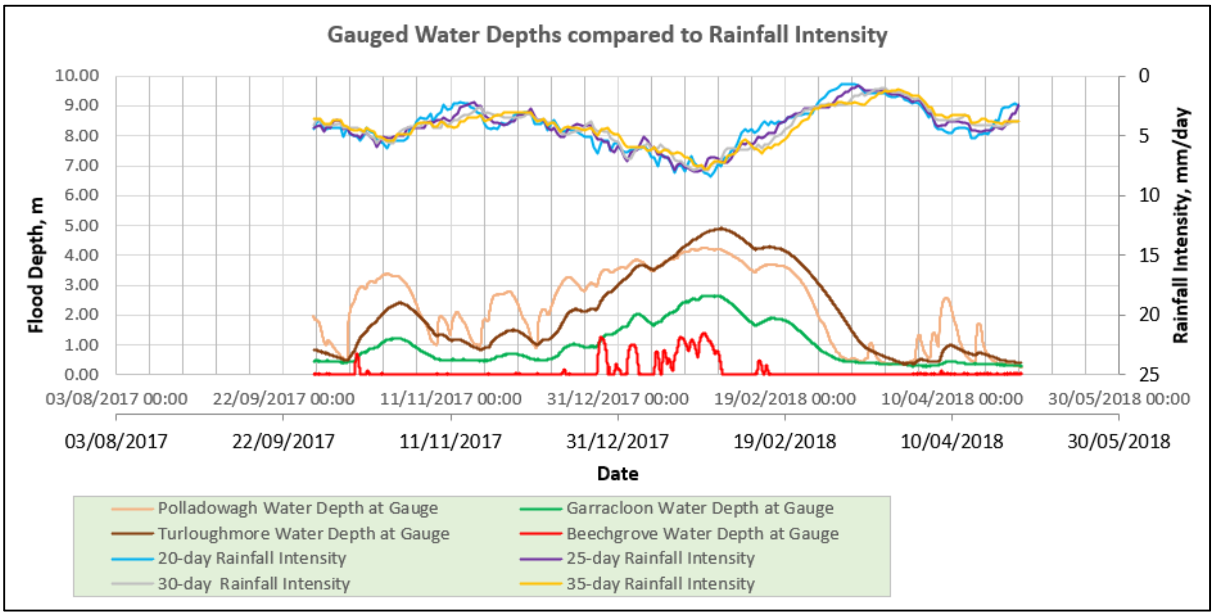


Figure 14: *Comparison between gauged water depths at Groundwater Floodplains and rainfall intensities recorded at Headford*

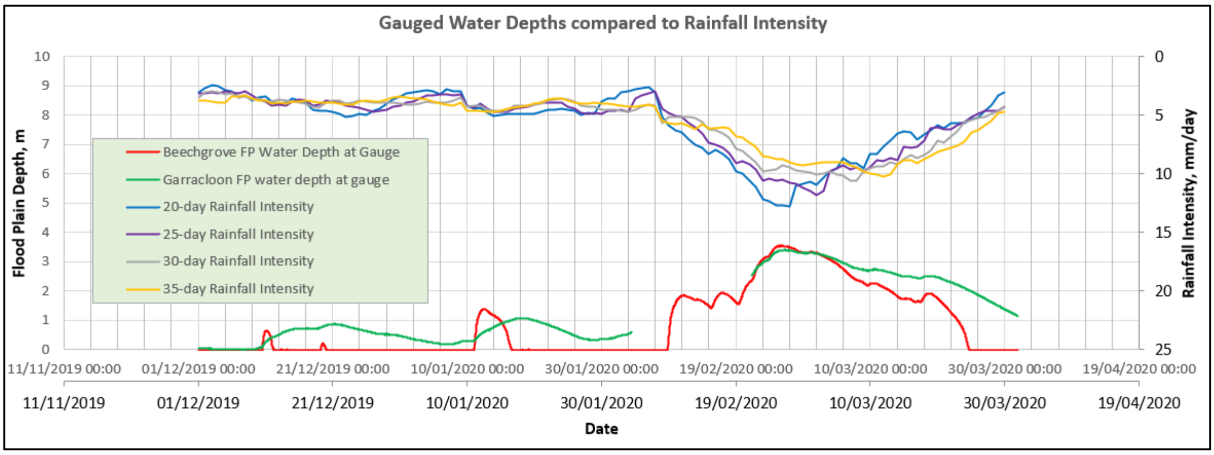


Figure 15: *Comparison between gauged water depths at Groundwater Floodplains and rainfall intensities recorded at Headford*

4.2 Study Area Hydrology Overview

The Neale area is underlain by highly karstified Dinantian Pure Bedded limestone, with areas of glacial till overburden and outcropping bedrock. The study area is within the Cong-Robe Groundwater Body (GWB) which is classed as a regionally important karst aquifer dominated by conduit flow. The study area is bound by the River Robe system to the north, Lough Mask and the Cong River system to the west, Lough Corrib to the south and the Cross River (Corrib Headford Drainage Scheme) to the east. There are no permanent surface water features (i.e. rivers) in the Neale area. At least 17 No. significant groundwater floodplains (many classed as turloughs) were identified in the study area comprising two distinct hydrological locations namely the western floodplains which have been traced to the Toberfraughaun and Tobernatinnew Springs, and the eastern floodplains which have been traced to the Cross West Springs. All the springs (grouped as the Cross Springs) discharge to the Cross River close to Cross Village which ultimately discharges to Lough Corrib.

Some of the groundwater floodplains (e.g. Beechgrove, Ballyrourke, Loughnaganky FPs) are located in improved grassland areas and would be best described as groundwater floodplains while others (i.e. Turloughmore, Garracloon, Lawaus, Kiltogorra, Ballyshingadaun FPs) can be classed as turloughs due their associated floodplain vegetation and hydrological regime. Turloughmore is fed by springs and ephemeral stream from Creevagh South and Cahernagry and drains to a series of swallow holes at Ballywalter. Similarly, Ballyrourke FP is fed by an ephemeral stream from springs a Lackaun during periods of heavy rainfall and an estavelle. There is a permanent lake at Kiltogorra which exists below an estavelle system. The high-water levels at the otherwise shallow wetland areas at Muckrussaun, Caherduff and Neale Park FPs also drain to swallow holes. Dolines, estavelles, swallow holes and springs are found at the other groundwater floodplains. Walled excavated wells are located at estavelles features at Ballyshingadaun and Garracloon. Polladowagh floodplain is the site of a large spring and swallow hole couplet system. A stream between these two features is reported to never run dry. There are multiple springs at Dowagh East, fed from Polladowagh, located along 100 m of the right bank of the Cross River with the largest one known as Toberfraughaun located 350 m southeast of Polladowagh This spring runs dry once floodwaters at Polladowagh have receded while the remaining springs at lower levels continue to discharge. The Cross West Springs discharge as a significant permanent stream approximately 300 m downstream of Toberfraughaun on the left bank of the river. Tobernatinnew which discharges on the right bank Cross River is located a further 550 m downstream from Cross West Springs and has been traced to Polladowagh.

Figure 16 presents the Winter 2015-2016 (W1516) peak flood extents, the proven dye tracing and the conceptual groundwater model connectivity in the study area. Figure 17 presents the groundwater floodplains' elevation – storage relationship.

The steeply undulating landscape and deep enclosed topographical depressions in the eastern floodplains area are understood to comprise glacial moraine deposits and include 'Kettle Hole' features (blocks of ice surrounded by sediment by retreating glaciers). Such features are confirmed to exists at Clyard immediately to the east of the study area. The glacial ice flow direction during the Late Pleistocene across the region of the study area was in a north -north-easterly direction from the mountains and high lands to the west (GSI Quaternary Geomorphology mapping).

The combined study area catchment area to the Cross springs (excluding connectivity from the Kilmaine area) has been approximated at 27 km^2 with a 53%:47% western: eastern split. The Cross River catchment area upstream of Drumelly Bridge is approximated at 32 km^2. A minor groundwater floodplain to the northeast at Cahernagollum discharges to the Bunnadober-Mask System.

The Beechgrove, Muckrussaun and Loughnaganky FPs have been proven by dye tracing to drain to Polladowagh. The Beechgrove and Lawaus FPs are understood, based on peak flood levels, anecdotal information on the flooding patterns and aerial photography, to drain to the same karst conduit system. Lawaus FP, being deeper, begins to flood first. During extreme flood conditions an overland flowpath can become established between the two floodplains with flow direction varying depending on whether the system is flooding or receding. The high-level overflow from the Beechgrove floodplain southwards towards Neale Park is a further 1.5m higher than the highest water levels recorded historically at the floodplain (W1516).

The dye tracing, floodplain gauging and aerial photography significantly improved the understanding of the karst drainage system in the eastern study area and confirmed also that the Ballyshingadaun and Garracloon floodplains drain to separate karst conduit systems during non-flood conditions. During flood events the Ballyshingadaun turlough floodplain (filling via an estavelle connected with the Turloughmore conduit system) promptly exceeds its topographical basin extents and overflows into the Garracloon turlough floodplain. Subsequently, Garracloon FP (which is also connected with the upper western floodplains catchment) fills rapidly and begins to backwater into Ballyshingadaun FP and then in turn (during extreme flood conditions) overflows overland into the Polladowagh FP. At the peak of W1516 flood event it is likely that a continuous overland flowpath temporarily established from Ballyshingadaun FP to the Cross River via the Garracloon and Polladowagh FPs.

During flood events the Turloughmore and Kiltogorra/ Kildotia floodplains merge due to a combination of a shared karst conduit system and establishment of overland flowpaths as determined by dye tracing, gauge analysis and aerial photography. While an overland flow from this merged floodplain to Ballyshingadaun FP did not establish in W1516, it is apparent that such a flowpath could feasibly establish in a moderately more extreme flood event (+20% rain intensities) (see Table 7) Ephemeral streams from Creevagh South and Cahernagry FPs discharging to Turloughmore FP establish most winters.

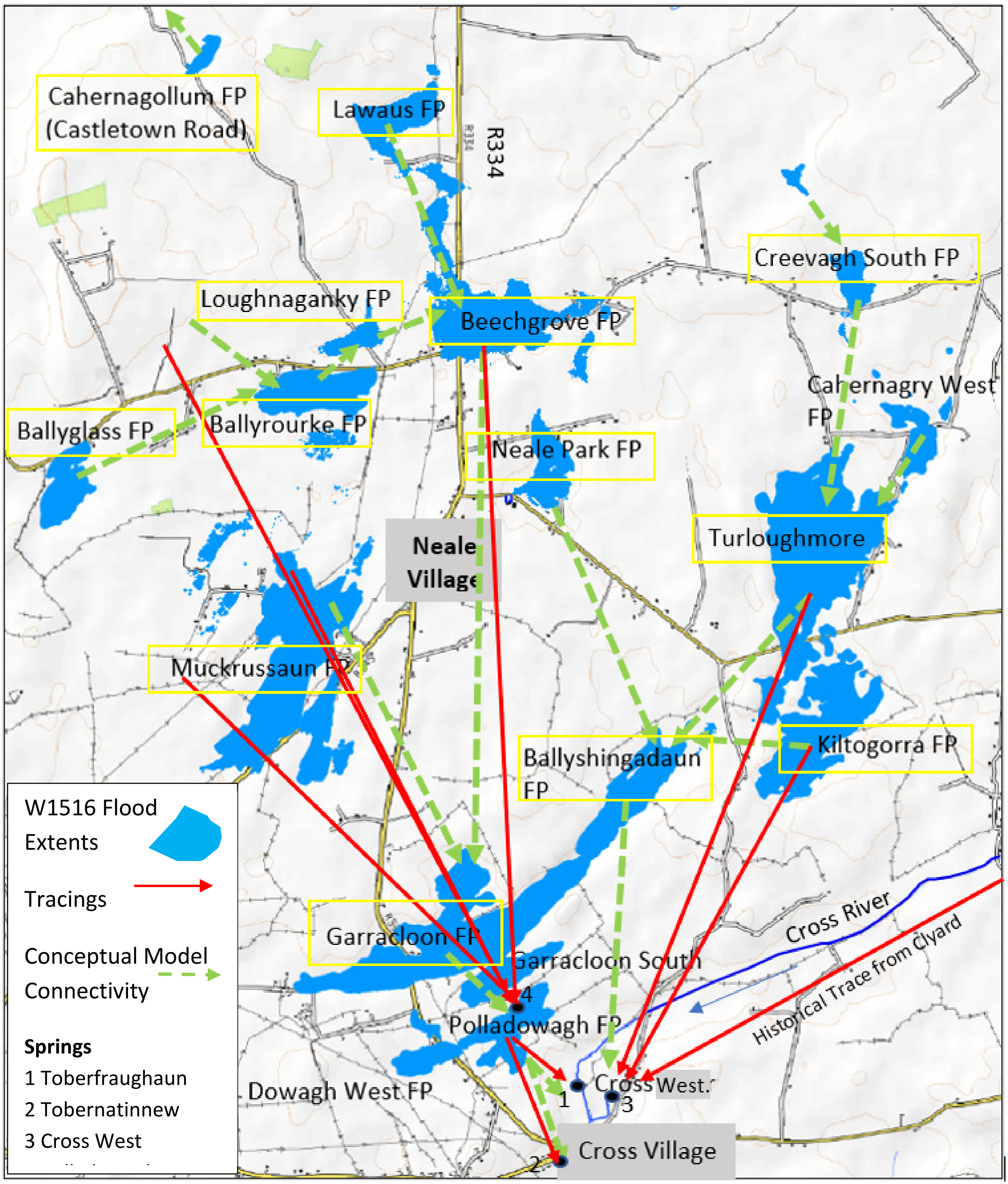


Figure 16: *Neale Study Area, W1516 Flood Extents, Dye Tracings to the Cross Springs and Conceptual Model Connectivity*

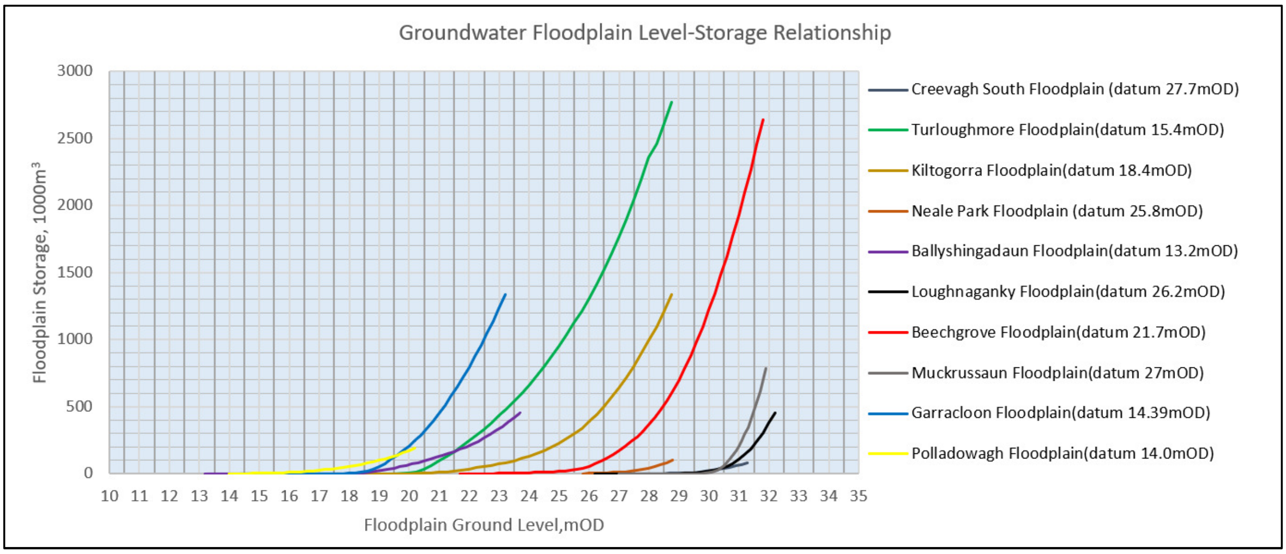


Figure 17: *Neale Study Area, Groundwater Floodplains Elevation-Storage Volume Relationship*

The Cross River originally comprised a relatively short overground river channel (circa 3 km long) whose headwaters were the outflows from the large springs to the north of Cross Village at Toberfraughaun and Cross West and which ultimately drained to Lough Corrib at Ballymacgibbon South. The original river channel and associated catchment upstream of Drumelly underwent significant modifications during the period between post-1847 and pre-1888 when a drainage channel was excavated north eastwards from Toberfraughaun to alleviate flooding in the Kilmaine area. The drainage channel was later incorporated into Corrib-Headford Drainage Scheme (1967-1973) and in the intervening years further minor extension and maintenance works have been undertaken to alleviate flooding in the Kilmaine area. A four arch bridge traverses the river and millrace at Cross Village, and a single arched local road bridge crosses the arterial drainage channel at Drumelly, 1 km upstream of Cross Bridge. A mill, now disused, was constructed upstream of Cross Bridge before the mid 1800's and included a mill race, mill wheel, sluices and foot bridges. Anecdotal information and site observations have confirmed that flows in the Cross River are never 'large', and in general respond slowly to rainfall events, remain at 'high flow rates' for prolonged periods and never runs dry. Dense weed growth is evident in the channel at Cross Bridge most summers.

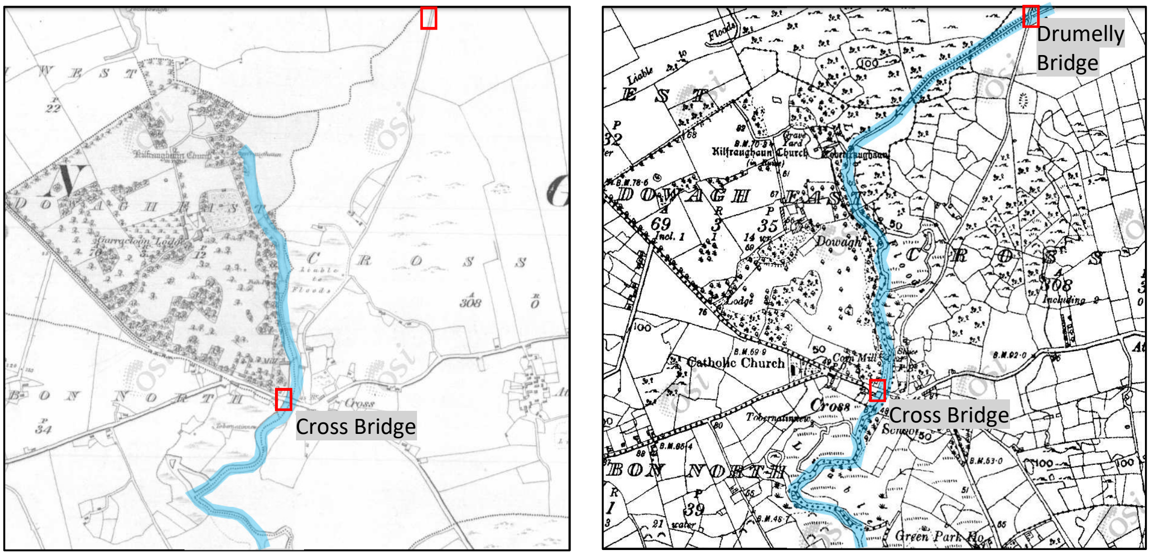


Figure 18: *Cross R. between Cross and Drumelly Bridges as shown on 1st and Last Edition 6" Historical Mapping*

Figure 19 presents the gauged and calculated flows in Cross River and from the Cross Springs during March 2020 coinciding with the peak flood and early flood recession conditions in the Neale area. The graph shows the total springs discharge ranged between 1.7 and 2.5 m^3/s, while peak flow rates at Drumelly Bridge were approximately 3.5 m^3/s during the period.

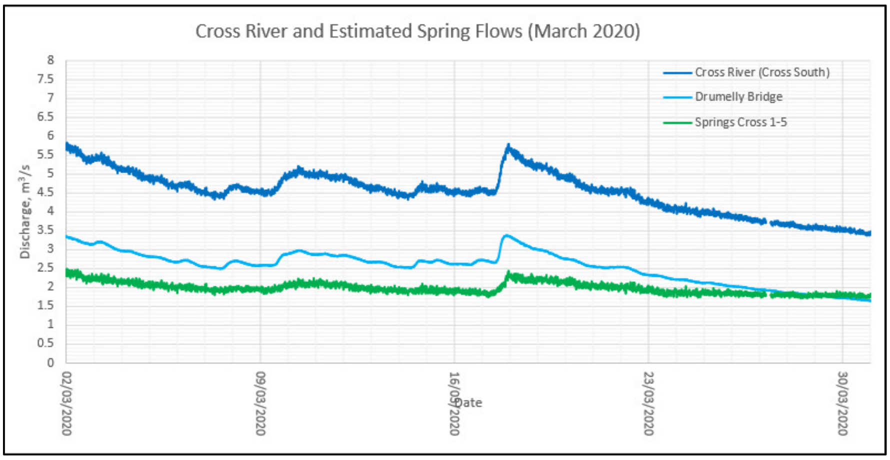
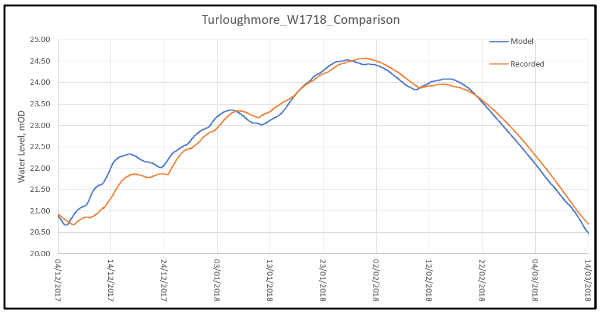


Figure 19: *Gauged and calculated flows in Cross River during March 2020*

4.3 Hydrological Model

A hydrological model (reservoir routing/ mass balance model) has been developed for the karst groundwater floodplain system as set out in the methodology in Section 2 above using Hec-Ras hydraulic modelling software. The model parameters (i.e. pipe conduit sizes and roughness, assumed contribution areas and rainfall distribution) were calibrated based on rainfall datasets, gauged data, surveyed peak historical flood levels and anecdotally reported flood durations. Figures 20 and 21 present examples of gauged and calculated hydrographs developed during the hydrological model calibration process.

The February-March 2020 and Winter 2015-16 rainfall events have been selected as the design rainfall profiles for upscaling to simulate the %AEP design flood events with the calibrated hydrological model. The derived rainfall upscaling factors are presented in Table 5. The calculated 10%, 1% and 0.1% AEP flood levels and recorded peak W1516 flood levels at the principal floodplains are summarised in Table 6. These current scenario design flood levels were used to determine flood risk in the study area. Table 7 presents the calculated design groundwater floodplain overflow and main springs discharge rates. Examples of calculated 1% AEP Hydrographs are presented in Figure 22.



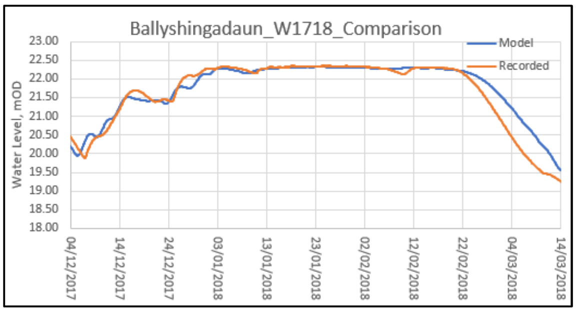


Figure 20: *Calibration Hydrographs comparison (Turloughmore FP and Ballyshingadaun FP W1718)*

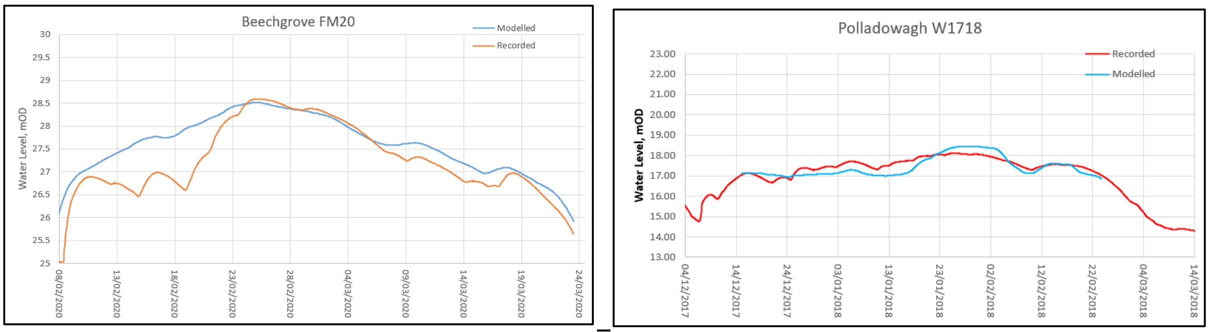


Figure 21: *Calibration Hydrographs comparison (Beechgrove FP FM20 and Polladowagh FP W1718)*

Table 5: *Design Rainfall Profiles Upscaling Factors*

Design AEP	**Design Rainfall Profile**	
	FM20	**W1516**
20%	0.919	*0.772*
10%	1.016	*0.854*
5%	1.112	*0.934*
2%	1.231	1.034
1%	*1.323*	1.111
0.5%	*1.416*	1.189
0.1%	*1.625*	1.364
1% (MRFS)(+20%)	*1.587*	1.333

Table 6: *Calculated Design Flood Levels*

Floodplain	**10% AEP, mOD**	**1% AEP, mOD**	**0.1% AEP, mOD**	**Reported Past Maximum (W1516), mOD**
Beechgrove/ Lawaus	28.51	29.79	30.84	29.20
Turloughmore	26.16	27.64	28.23	27.13
Garracloon	22.28	22.65	22.77	22.6
Polladowagh	18.75	19.75	19.80	19.65

Table 7: *Calculated Design Groundwater Overland flow and Spring Discharge rates*

Overland Flows and Spring	**1% AEP,** m^3/s
Garracloon FP to Polladowagh FP overland flow	1.15
Polladowagh FP to Cross River FP overland flow	0.78
Ballyshingadaun FP to Garracloon FP overland flow	1.78
Polladowagh FP to Cross River overland flow	0.78
Toberfraughaun and Tobernatinnew Springs to Cross River	1.83
Cross West Springs to Cross River	1.18 Note 1

Note 1: Estimated maximum discharge capacity of the springs, comprising 0.55 m^3/s from Turloughmore (confirmed by modelling) and 0.63 m^3/s from the Kilmaine-Clyard area.

The peak 1% AEP flow rate in the Cross River at Tobernatinnew has been calculated at 10.7 m^3/s comprising 6.9 m^3/s discharging from the catchment upstream of Drumelly Bridge and the remainder associated with the Cross Springs discharges and overland flood flows from Polladowagh Floodplain.

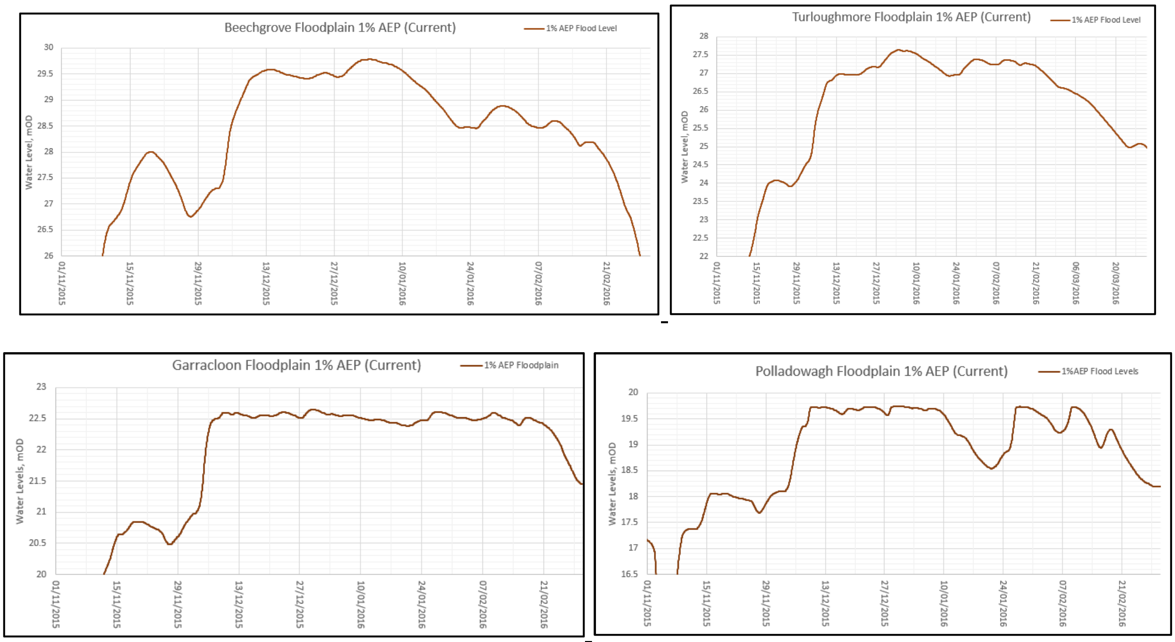


***Figure 22:** Calculated 1% AEP Groundwater Floodplain Hydrographs for Beechgrove, Turloughmore, Garracloon, and Polladowagh*

5. Potential Impact of Climate Change on High Flood Risk Karst Drainage Areas: Case Study

In this section the potential impact of climate change on flood risk in lowland karstified limestone areas is examined using the Neale study area's hydrological regime as a case study.

As discussed above the design extreme rainfall events for the study area were simulated using rainfall profiles associated with two recent extreme flood events, namely the February-March 2020 and Winter 2015-16 flood events, and upscaling of the calibrated floodplain rainfall models to achieve the desired design AEP% event rainfall intensities.

In accordance with the OPW CFRAM approach, the recommended upscaling parameters for the assessment of the flood risk associated with Mid-Range and High-End future climate change scenarios (MRFS and HEFS) are +20% and +30% respectively for Extreme Rainfall Depths and Peak Flood Flows.

As presented in Section 3.3 of this paper a positive upward trend has been identified in the extended duration AMAX rainfall intensities in the study area, at an apparent increased average rate of 0.3 mm (range 0.15– 0.45 mm) /day/10 years for the 25 to 60 day extended duration rainfall events. If this trend was to hold true for, say, the next 50 years (to HY 2071), the average increase in AMAX rainfall intensities over the period would be of the order of 1.62 (range 0.74 to 2.26) mm/day. This increase calculates for this study area at an average increase +13% (median +14%) in extended duration AMAX rainfall intensities over the 50-year period.

As part of the South Galway Flood Relief Scheme hydrological study, TCD with GSI assessed the future (2071 – 2100) climate of the Gort Lowlands study area using various methodologies including Regional Climate Model (RCM) approach and the OPW CFRAM approach (upscaling rainfall by 20% to represent the MRFS). It was concluded that upscaling the existing stochastic rainfall time series using the average increases observed within the Representative Concentration Pathway (RCP) 4.5 RCM datasets offered the most balanced approach. Following this approach, an average increase of +7.7% in rainfall over the winter period (October to March) was concluded as appropriate for the future climate hydrologic simulations for the Gort Lowlands study area. TCD has reported that, as rainfall patterns can vary significantly spatially across Ireland, this upscaling factor would be considered specific to the South Galway region.

The Neale FRS feasibility study has identified in the current scenario 1% AEP design event that, in addition to properties being at risk of flooding or being at high flood risk, access routes to several communities are at risk of being cut-off for prolonged durations due to groundwater flooding. The W1516 flood event in the study area, which is estimated to have been equivalent to a 2% AEP flood event, is reported to have flooded 8 No. properties and cut off access to c100 houses for 10days in the Neale area.

The potential climate change impact on the Neale study area's flood risk associated with two rainfall upscaling scenarios to represent the MRFS, namely +13% and +20% scenarios, compared to the February- March 2020 and Winter 2015-16 flood events has been assessed and the associated results summarised in Table 8 below. The 10% AEP and the 0.1% AEP are also included for comparative purposes. Upscaling the W1516 flood event rainfall by +13% and +20% are approximately equivalent to current scenario design 1% AEP and 0.5% flood events. Similarly, upscaling the current scenario design 1% AEP flood event rainfall by +13% and +20% are approximately equivalent to current scenario design 0.5% AEP and 0.1% flood events.

The flood risk parameters examined in this assessment included peak flood level, road flooding duration, groundwater floodplain overflow being established, properties flooding and access routes to communities being cut-off.

It is concluded from the above assessment that climate change will increase flood risk in the Neale study area significantly with the following likely impacts relative to the past W1516 and the design 1% AEP flood current scenario:

- The frequency of significant flooding in groundwater floodplains will increase,
- Peak flood levels in the groundwater flood plains will increase,
- Most of the floodplains will reach or exceed their overflow threshold level resulting in a long duration overland flowpath becoming established directly to the Cross River at Kilfraughaun from as far up catchment as Turloughmore and Cahernagry,
- The duration of overland flow and associated rate from the Polladowagh floodplain to Cross River will increase appreciably,
- The Beechgrove (Neale Cross) floodplain could overflow for a short duration into the Neale Park floodplain, increasing flood risk at the National School significantly (extreme scenario),
- The number of properties at risk of flooding throughout the study area will increase,
- The duration of regional and important local road closures due to flooding will increase appreciably. The R334 (Headford- Cross- Ballinrobe Road) at Beechgrove (Neale Cross) will be at risk of closure for 2 – 3 months in a MRFS 1% AEP flood event.
- The duration of access being cut-off to communities will increase significantly. Access to >100 houses could potentially be cut off for over a month.

In summary, the potential climate change impact on flood risk in the Neale study area in specific, and in the South Mayo region as a whole, will be more frequent, widespread and prolonged flooding, which overtime could threaten the viability of communities, businesses and farms in the area. Other potential impacts due to climate change include increased negative impacts on water quality in the Cross River (receiving watercourse) due to the flooding out of farm complexes and slatted sheds, and septic tanks directly into the groundwater floodplains which ultimately discharge to the river which, in turn, drains to the Lough Corrib SAC less than 1 km downstream of Cross Bridge.

Table 7: *Calculated Design Groundwater Overland flow and Spring Discharge rates*

Current and Future Scenario Event	**FM20**	**W1516 - Current**	**W1516 +13%**	**W1516 +20% / 1% AEP+ 13%**	**1% AEP +20%**
Approximate Equivalent Design AEP (current scenario)	**10% AEP**	**2% AEP**	**1% AEP**	**0.5% AEP**	**0.1% AEP**
Peak Flood level at **Turloughmore,** mOD	26.16	27.28	27.64	27.99	28.23
Duration that L5659 road flooded, days	0	53	69	>70	>70
Floodplain Overland flowpath established	no	no	no	yes	yes
Peak Flood level at **Beechgrove,** mOD	28.51	29.39	29.79	30.14	30.84
Duration that R334 road flooded, days	16	52	77	>80	>90
Floodplain Overland flowpath established	no	no	no	no	yes (shallow)
Peak Flood level at **Garracloon**, mOD	22.28	22.64	22.65	22.67	22.77
Duration that R334 road flooded, days	0	3	6	13	29
Floodplain Overland flowpath established	no	yes	yes	yes	yes
Peak Flood level at **Polladowagh**, mOD	18.75	19.74	19.75	19.76	19.8
Duration that R334 road flooded, days	0	31	52	>60	>70
Floodplain Overland flowpath established	No	Yes	Yes	Yes	Yes
Peak Overland Discharge to Cross River, m^3/s	0	0.66	0.78	0.91	2.34
Duration of Overland Discharge, days	0	>20	>35	>50	>65
Total Number of Properties Flooded in study area	0	8	16	18	27
Total Number of Houses Cut-off					
5 or more days	*3*	*180*	*194*	*225*	*225*
10 or more days	*3*	*98*	*181*	*225*	*225*
15 or more days	*3*	*57*	*180*	*181*	*225*
20 or more days	*3*	*22*	*180*	*181*	*225*
30 or more days	*2*	*22*	*112*	*146*	*190*

6. REFERENCES

Mayo County Council – Ballinrobe Area Office and Flood Risk Management Division

Reports prepared by Ryan Hanley Consultants on behalf of Mayo County Council.

- South Mayo Flood Relief Scheme – Scoping Report – April 2017
- The Neale (south Mayo) Flood Relief Scheme – Feasibility Report and associated appendices - September 2021

Cross Cong Neale Flood Relief Committee (CCN) and Neale community – Winter 2015- 2016 Flood Impact Analysis Report and Historic Water Levels

Consulting Hydrologist who assisted Ryan Hanley in preparation of the Neale FRS Feasibility Report – Appendix A Hydrology Report

- Tony Cawley (Hydro Environmental Ltd.) – River and rainfall gauging in the Neale area, hydrological assessment and topographical modelling guidance.
- Dr. David Drew – Dye Tracing Guidance and Karst feature identification.
- Ted McCormack, Natalie Duncan, Caoimhe Hickey - GSI Groundwater Team – Dye Tracing Equipment and Guidance.

Geological Survey of Ireland (GSI) (source: www.gsi.ie) for geological, groundwater and recorded karst features and dye tracing datasets in South Mayo and for floodplain gauging datasets surveyed as part of the Groundwater Flood Project (2016-2019) and the subsequent permanent gauges at Garracloon and Beechgrove (Neale Cross).

Met Éireann (source www.met.ie) for rain gauge data in the Mayo- Galway region

OPW (Hydrometrics) (source: https://waterlevel.ie/) for Lough Corrib and Lough Mask gauge data and OPW FSU Portal (source: https://opw.hydronet.com/)

EPA (Hydrometrics) (source: https://epawebapp.epa.ie/hydronet/#Water%20Levels) for historic and active gauge data.

Ordnance Survey Ireland (OSi), (source www.osi.ie, https://www.geohive.ie/) – vector and raster, and historical mapping in the South Mayo Region. CYAL50251149 © Ordnance Survey Ireland / Government of Ireland

National Parks and Wildlife Service (source www.npws.ie) for Clyard Kettle-holes SAC data.

Drew, D. 2018. Karst of Ireland: Landscape Hydrogeology Methods. Published by Geological Survey Ireland.

Doherty, D., Duncan, N., Kelly, C., McCormack, T., Lee, M., (GSI): Groundwater Trace at Neale, County Mayo, February/March 2018,

Kelly, C., McCormack, T., Lee, M., (GSI): Groundwater Trace at Neale, April 2018, Round 2

Naughton, O., Johnston, P.M., Gill, L., 2012. Groundwater Flooding in Irish Karst: The Hydrological Characterisation of Ephemeral Lakes (Turloughs). Journal of Hydrology, 470- 471: 82-97.

Morrissey, P., Gill, L., McCormack, T., Naughton, O., Johnston, P., (2020) Gort Lowlands Groundwater Flood Modelling Final Project Report – TCD/ GSI

Morrissey, P., Gill, L., McCormack, T., Johnston, P., (2020) Gort Lowlands Climate Change Analysis Results & Summary – TCD/ GSI

Waldren, S. 2015, Ed. Turlough Hydrology, Ecology and Conservation. Unpublished Report, National Parks & Wildlife Services. Department of Arts, Heritage and the Gaeltacht, Dublin, Ireland.