

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
AFRICAN RAILWAY CENTER OF EXCELLENCE



**FLOOD ANALYSIS AND HYDRAULIC
COMPETENCE ASSESSMENT OF
RAILWAY DRAINAGE STRUCTURES A
Case of Meganagna-Ayat AALRT Line**

A Thesis in MSc. In Railway Engineering (Civil Infrastructure)

By Kajubi Enock

July, 2019

Addis Ababa

A Thesis

Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Science In
Railway Engineering (Civil Infrastructure)

The undersigned have examined the thesis entitled '**FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT FOR RAILWAY DRAINAGE STRUCTURES**' presented by KAJUBI ENOCK, a candidate for the degree of **Master of Science in Railway Engineering (Civil Engineering)** and hereby certify that it is worthy of acceptance.

Dr. Yilma Seleshi	_____	_____
Advisor	Signature	Date
_____	_____	_____
Internal Examiner	Signature	Date
_____	_____	_____
External Examiner	Signature	Date
_____	_____	_____
Chair person	Signature	Date

UNDERTAKING

I certify that research work titled “Flood analysis and hydraulic competence assessment for railway drainage structures along Meganagna- Ayat AALRT line” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

.....

Kajubi Enock

ABSTRACT

The flooding problem along the magenagna-Ayat Addis Ababa Light Rail Train line has persisted since its construction. Therefore, flood analysis has been carried out as well as the hydraulic competence of the existing drainage structures along the line. Flood frequency analysis was carried out using the Gumbel distribution after best fit tests and the design storms that correspond to the 25, 50, 100 and 200-year return periods were computed. Using a high resolution Digital Elevation Model (DEM) of 12.5m, a watershed delineation was carried out and the sub-basin parameters calculated accordingly. A total of seven (7) watersheds fourteen (14) sub watersheds were obtained in project area. The drainage basins ranged between 1.02sq. Km for catchment six to 10.27 sq. Km for catchment five. Using the watershed parameters obtained, time of concentration, lag time and the storage attenuation coefficients were computed for each sub-basin to be used in the hydraulic computations. A rainfall-runoff transformation was carried to assess the hydraulic competence for the existing drainage structures for 25-year and 50-year return period for all culverts and 50-year and 100-year return periods for the bridges. One culvert was found over designed, three under designed, two inaccessible on site and one competent as well as the bridge. Poor interoperability between the railroad grade and the highway grade at the level crossing was identified as one of the major causes for flooding at level crossings thus must be redesigned. Transverse aggregate drains as well as silt traps in the longitudinal railroad side drains have been proposed, jointing of the railroad drainage system with the road system, public sensitization towards municipal solid waste management and establishment of a railway drainage asset management policy have been recommended to mitigate the and improve the infrastructure drainage to be safe, sustainable and resilient.

KEY WORDS: Flood analysis, Hydraulic competence, and Railway level crossing drainage.

ACKNOWLEDGMENTS

First and foremost, I thank the almighty sovereign God to have blessed me with a gift of life, protection and guidance to allow me accomplish master's research.' Asante Mungu'.

I would like to thank Dr. Yilma Seleshi for the expanse of knowledge he rained unto me as my supervisor towards the accomplishment of this research. His supervision, mentorship and time he offered as a sacrifice to me is highly esteemed to me was added a more knowledge diversity and resourcefulness.

My whole-hearted thanks also go to the entire master's class of MSc. Railway Engineering (Civil Engineering) students in 2019 for their academic, social and moral support. Their academic combined support extended not only my academic relationship but also the entire professional development.

TABLE OF CONTENTS

ABSTRACT.....	III
ACKNOWLEDGMENTS.....	IV
TABLE OF CONTENTS	V
LIST OF ABBREVIATIONS	VIII
LIST OF TABLES.....	IX
LIST OF FIGURES.....	X
CHAPTER 1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Problem statement.....	3
1.3 Objectives.....	4
1.3.1 Main objective	4
1.3.2 Specific Objectives	4
1.4 Scope.....	4
1.5 Justification	4
1.6 Research questions.....	5
CHAPTER 2 LITERATURE REVIEW.....	6
2.1 Forms of Floods in Ethiopia.....	6
2.1.1 River floods	6
2.1.2 Urban floods	6
2.2 Historical Development of Urban Drainage Systems	7
2.3 Watershed hydrological modelling	8
2.4 Hydrological modelling	9
2.4.1 Rational method.....	9
2.4.2 SCS Method.....	9
2.4.3 Unit Hydrograph.....	10
2.5 Types of Track Drainage.....	10
2.5.1 Surface Drainage	11
2.5.2 Subsurface Drainage.....	11

2.5.3	Flooding on railways	11
CHAPTER 3 RESEARCH METHODOLOGY.....		12
3.1	Project location	12
3.1.1	Soil.....	13
3.1.2	Land use and Land cover.....	13
3.1.3	Temperature.....	13
3.1.4	Rainfall	14
3.2	Data and data sources.....	15
3.2.1	Field visits.....	15
3.2.2	DEM/DTM	15
3.2.3	Land use and Digital Soil.	15
3.2.4	Topographical map.	16
3.2.5	Precipitation records.	16
3.3	Materials and software	16
3.4	Data screening.....	17
3.5	Gumbel Generalized Distribution	19
3.6	Watershed characteristics computation.....	20
3.6.1	Drainage Area (A):	20
3.6.2	Watershed length (L):	20
3.6.3	Watershed Slope (S):	20
3.6.4	River length	21
3.6.5	River slope	21
3.6.6	Watershed perimeter	21
3.6.7	Watershed shape	21
3.7	Time of concentration	23
3.7.1	Watershed lag method	23
3.7.2	Velocity method.....	24
3.8	Storage coefficient	26
3.9	Triangular hyetograph generation.....	27

3.10	Hydraulic competence assessment.....	30
3.10.1	Side drainage assessments	31
3.10.2	Cross drainage structures	32
3.10.3	Railroad drainage system.....	34
CHAPTER 4	RESULTS AND DISCUSSIONS	37
4.1	Flood frequency assessment.....	37
4.1.1	Best fit results	37
4.1.2	Gumbel results	37
4.1.3	Flood prone points calculation.....	39
4.2	Hydraulic competence assessment.....	42
4.2.1	Cross drainage structures	42
4.2.2	Railroad drainage.....	55
CHAPTER 5	CONCLUSION AND RECOMMENDATION.....	57
5.1	Conclusion	57
5.2	Recommendation	57
REFERENCES	60
APPENDIX.....	64
Appendix A:	Time of Concentration Computation Spreadsheet	65
Appendix B:	Hyetographs for Different Gages in the Project Area.....	74
Appendix C:	Generated Hydrographs from each Watershed along the Railway Infrastructure.....	80

LIST OF ABBREVIATIONS

AALRT	Addis Ababa Light Rail Track
AACRA	Addis Ababa City Roads Authority
ERC	Ethiopian Railway Corporation
IUH	Instantaneous Unit Hydrograph
Tc	Time of concentration
HEC- HMS	Hydrologic Engineering Center -Hydrologic Modeling System
TAD	Time Area Diagram
GPS	Global Positioning System

LIST OF TABLES

Table 3-1: Tools, materials and software	16
Table 3-2: Equations and assumptions developed from figure 5	25
Table 3-3: Values of $K=k*i$ (m/s) for various slopes.	36
Table 4-1: The Anderson-Darling test statistics for flood frequency analysis.	37
Table 4-2: The precipitation data statistics	37
Table 4-3 Rainfall Frequency Analysis using Gumbel Distribution.	38
Table 4-4: Watershed parameters, Storage coefficient and T_c	41
Table 4-5: Runoff volumes from each watershed.....	41
Table 4-6: Summary for the hydraulic competence assessment for the highway infrastructure.....	54
Table A-1: Time of concentration computation spreadsheet.....	65
Table B-1: Annual daily 35-Minute Hyetograph of Gage 1	75
Table B-2: Annual daily 40-Minute Hyetograph of Gage 2	76
Table B-3: Annual daily 30-Minute Hyetograph of Gage 3	77
Table B-4: Annual daily 45-Minute Hyetograph of Gage 4	77
Table B-5: Annual daily 20-Minute Hyetograph of Gage 5	78

LIST OF FIGURES

Figure 3.1: Project Location Map	12
Figure 3.2: Project Watershed land use segmentation graph.....	13
Figure 3.3: Minimum and Maximum monthly temperatures for Addis Ababa City	14
Figure 3.4: Mean monthly precipitation depth for Addis Ababa city:	14
Figure 4.1: Flood drainage points along the Railway line.....	39
Figure 4.2: Delineated Basins for the Flood susceptible Points along the Track	40
Figure 4.3: Entrance of the culvert Figure 4.4: Exit of the Culvert.....	43
Figure 4.5: Culvert Entrance view	44
Figure 4.6: Closer view of the halfway blocked barrel	44
Figure 4.7: Culvert simulation with the 25-yr discharge and shows being hydraulically competent.....	45
Figure 4.8: Hydraulic simulation of the culvert showing its incompetence with the check flood of 50-yr.....	45
Figure 4.9: Hydraulic simulation of the culvert adjusted to 4 barrels to accommodate the check discharge of 50-yr flood.	46
Figure 4.10: Simulation results after culvert adjustment to accommodate the check flood	46
Figure 4.11: Bridge Hydraulic flow path Figure 4.12: Side view of the bridge hydraulic flow path	47
Figure 4.13: Bridge Hydraulic simulation for 100-yr flood	47
Figure 4.14: Hydraulic simulation results of discharge, velocity, headwater depth and HGL.	48
Figure 4.15: Culvert with growing heap of municipal solid wastes around the pier.....	49
Figure 4.16: Hydraulic simulation of the culvert using the original 2 barrels with 50-yr check flood.....	49
Figure 4.17: Hydraulic simulation of the culvert using the original single barrel with 50-yr check flood.	50
Figure 4.18: Hydraulic simulation results of discharge, velocity, headwater depth and HGL.	50
Figure 4.19: The two barrels of culvert on site Figure 4.20: The right hand blocked barrel	51

Figure 4.21: Hydraulic simulation of the culvert using the original barrel with 25-yr design flood.....	51
Figure 4.22: Hydraulic simulation of the culvert using the original single barrel with 50-yr design flood.	52
Figure 4.23: Hydraulic simulation results of discharge, velocity, headwater depth and HGL. for existing structure.....	52
Figure 4.24: Hydraulic simulation results of discharge, velocity, headwater depth and HGL for recommended structure.	53
Figure 4.25: Level crossing one.....	56
Figure B.1: Annual daily 35-Minute Hyetograph of Gage 1	74
Figure B.2: Annual daily 40-Minute Hyetograph of Gage 2.....	76
Figure B.3: Annual daily 30-Minute Hyetograph of Gage 3.....	76
Figure B.4: Annual daily 45-Minute Hyetograph of Gage 4.....	77
Figure B.5: Annual daily 20-Minute Hyetograph of Gage 5.....	78
Figure B.6: Velocity versus slope for shallow concentrated flow	79
Figure C.1: 5-yr Hydrograph for drainage point 1	80
Figure C.2: 5-yr Hydrograph for drainage point 2	80
Figure C.3: 5-yr Hydrograph for drainage point 3	81
Figure C.4: 5-yr Hydrograph for drainage point 4	81
Figure C.5: 5-yr Hydrograph for drainage point 5	82
Figure C.6: 5-yr Hydrograph for drainage point 6	82
Figure C.7: 5-yr Hydrograph for drainage point 7	83
Figure C.8: 10-yr Hydrograph for drainage point 1	83
Figure C.9: 10-yr Hydrograph for drainage point 2	84
Figure C.10: 10-yr Hydrograph for drainage point 3	84
Figure C. 11: 10-yr hydrograph for drainage point 4	85
Figure C.12: 10-yr hydrograph for drainage point 5	85
Figure C. 13: 10-yr hydrograph for drainage point 6	86
Figure C.14: 10-yr hydrograph for drainage point 7	86
Figure C.15: 25-yr hydrograph for drainage point 1	87
Figure C.16: 25-yr hydrograph for drainage point 2	87
Figure C.17: 25-yr hydrograph for drainage point 3	88
Figure C.18: 25-yr hydrograph for drainage point 4	88
Figure C.19: 25-yr hydrograph for drainage point 5	89

Figure C.20: 25-yr hydrograph for drainage point 6	89
Figure C.21: 25-yr hydrograph for drainage point 7	90
Figure C.22: 50-yr hydrograph for drainage point 1	90
Figure C.23: 50-yr hydrograph for drainage point 2	91
Figure C.24: 50-yr hydrograph for drainage point 3	91
Figure C.25: 50-yr hydrograph for drainage point 4	92
Figure C.26: 50-yr hydrograph for drainage point 5	92
Figure C.27: 50-yr hydrograph for drainage point 6	93
Figure C.28: 50-yr hydrograph for drainage point 7	93
Figure C.29: 100-yr hydrograph for drainage point 1	94
Figure C.30: 100-yr hydrograph for drainage point 2	94
Figure C.31: 100-yr hydrograph for drainage point 3	95
Figure C.32: 100-yr hydrograph for drainage point 4	95
Figure C.33: 100-yr hydrograph for drainage point 5	96
Figure C.34: 100-yr hydrograph for drainage point 6	96

CHAPTER 1 INTRODUCTION

1.1 Background

Infrastructure is the physical structures needed for society to operate. It is described as the foundation for economic productivity and human wellbeing because it provides the energy, water resources and transportation utilities that society needs to function, and enable people, information and goods to move efficiently and safely. Hence the growth of a city or an urban Center is greatly synonymous with the growth of its infrastructure [1].

As the amount of infrastructure grows it comes with a consequence to natural hydrological makeup of the urban area. Before the increase of built up percentage, greater amount of rain water used to percolate through the earth surface and join the ground water or be used by the plants. Increase in the built-up areas will alter the hydrological makeup by blocking natural streams or/and by reducing the water absorption capacity of the surface. This will result in the demand for a manmade drainage infrastructure in order to deal with the water that ‘lost its way by human action’ thus leading to flooding. [1]. In the same manner, human activities can also influence the prevalence of flooding. Examples are changes in land use resulting in increase in runoff and depletion of flood storage; blockage of natural drainage systems by refuse, agricultural wastes or silt arising from both natural erosion and construction activities; indiscriminate land filling; and lack of comprehensive maintenance of natural watercourses due to land access problems [2].

Drainage systems are needed in developed urban areas because of the interaction between human activity and the natural water cycle [3]. The covering of land with impermeable surfaces that divert rainwater away from the local natural system of drainage accumulates storm water. If storm water were not drained properly, it would cause inconvenience, damage, flooding and further health risks [3].

Several studies have shown that water plays a significant role in phenomena that weaken track geometry. For instance, water may cause frost heave, thaw softening, attrition of ballast, and weakening of the load bearing capacity of a track. Functioning drainage can prevent water damage, but no researched data on the magnitude of the impacts exist [4]. Water content does not have an impact only on things related to the freezing of soil. Surplus water in a structure may cause” mud pumping” which weakens it and leads to attrition of ballast [5].

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

The presence of water, along with the cyclic loading due to passing trains, has a great importance on the railroad deterioration process. Even small increases in the moisture content of track bed layers can often result in significant reductions in the bearing capacity and stability of the composing soils contributing to a deficient deformational behavior which, in general, will affect track geometry degradation rates. In this sense, the design of an adequate drainage system maintaining low levels of moisture in the subsoil layers plays an important role in the maintenance needs of a railway track highly influenced by the condition of its infrastructure along the entire life cycle [6]. Railway track materials and underlying soil layers are subjected to traffic loading and their mechanical behavior is highly controlled by the initial state, hydraulic condition, temperature and water/moisture transfer due to atmospheric actions. Changes in water content, especially excess moisture in track bed layers combined with traffic loads can significantly reduce railway track service life [6]. The deterioration of railroad track geometry due to both ballast and subgrade differential settlement is usually responsible for the most relevant part of track maintenance costs. Recent studies have shown that the contribution of the subgrade settlement can play an important part on this degradation phenomenon, even in the case of new high-speed lines [7]. Therefore, one of the best mitigation measures for excessive water content within the track bed layers is to protect the rail track from flooding due to accumulated run-off from the neighboring catchments by designing sustainable, appropriate and feasible off-track drainage systems. This involves assessment of the flood analysis and the hydraulic competence of the existing off-track drainage systems so that viable flood mitigation solutions can be acquired.

The assessment/quantification of the benefits of more effective drainage has, however, proved challenging. For instance, it is difficult to devise assessment and classification methods for the functioning of drainage, and to determine the magnitude of the change in the moisture condition attainable by more effective drainage and the advantageousness of different renovation alternatives. The overall aim of the on-going ‘Technical and economic efficiency of improved drainage of existing rail lines’ study at Tampere University of Technology is to provide a reasoned assessment of the impacts improved drainage can have, and the conditions under which it is technically and economically justifiable to repair track unevenness by improving drainage [4].

Therefore, with the prevalent flooding that is occurring along the Ayat-Meganagna Light Rail route, there is need to assess the competence of the existing off-track drainage structures and their structural flood vulnerability so as to obtain better understanding of the technical problem which may suggest redesigning a new system, improving their maintenance or replacing the incompetent ones and this is the reason for this project study.

1.2 Problem statement

Storm water management systems are designed purposefully to handle peak flow resulting from rainfall of return period equal or greater to their design year [8]. Drainage system of a road or railway are expected to operate normally in conveying the designed flow along or across the alignment. Therefore, drainage planning is required to develop safe, sustainable and resilient drainage systems to enable water to flow through the railway infrastructure from point of entry to point of exit in such a way as to allow earthworks, track and structures works to perform in an optimal manner. Unfortunately, after the establishment of the designed drainage system, annual proliferating flooding occurs across the drainage structures for the Addis Ababa Light Rail Train infrastructure after every rainfall storm [9]. The increasing annual frequency and intensity of flooding of the line from Ayat to Magenagna, has increased the rate of ballast fouling due to the silt carried by the storm water into the line along a number of points along the line. This has led to growth of vegetation within the track which reduces the vertical drainage of precipitation within the railway track.

The water retention along the track weakens the sub-ballast and subgrade which on saturation under normal loading, the subgrade is overloaded and begins to displace. When this occurs, ballast pockets begin to form and mud pumping arises. Furthermore, lateral resistance of the track is reduced due to poisoned ballast thus leading to alignment irregularities hence derailments. Therefore, before the problem matures to cause severe hazards on the railway track, there is need for researchers to evaluate the performance and competence of the existing drainage structures and their flood vulnerability such that immediate mitigation measures are recommended.

1.3 Objectives

1.3.1 Main objective

The main objective of this research project is to carry out a performance evaluation and flood analysis for the railway drainage system.

1.3.2 Specific Objectives

- 1) To carry out a hydro-statistical analysis that will give responsive flood volumes with corresponding return periods.
- 2) Develop a hydrological model to obtain susceptible flood prone points along the railway line.
- 3) Assess the hydraulic competence of the existing railway drainage system to examine its response with various flood storms and recommend optimization measures for the system.

1.4 Scope

This research project is limited to assessing the response of the existing railway drainage system to various flood storms expected within the project area and devising for immediate mitigation measures for the proliferating flood problem. Only surface water drainage has been assessed. The project is carried out on the AALRT line from Megenagna to Ayat stations and it is expected to be carried out within a period of six (5) months from January, 2019 to May, 2019.

1.5 Justification

This research has been conducted to analyses the flood problem along the line, and find mitigation measures for the flood problem. It's also been intended to find the hydraulic competence of all the drainage structures along the line. This project has been designed to address the problem through both descriptive and explanatory research criteria. Through descriptive research, the project has addressed the existing extent of flood occurrence within the community while through explanatory research, the project has addressed the hydraulic competence of the existing drainage structures, and proposed possible mitigation measures against the problem.

1.6 Research questions

The following research questions have been developed to help the researcher achieve the specific objectives set up above. They include the following:

- i. Which rainfall depth/intensity received in the catchments corresponds to the 10-, 25-, 50-, 100- and 200-year (for bridges) return periods respectively?
- ii. Along which points of the railway line does the natural drainage of the catchment interact with the railway line?
- iii. How much runoff crosses the railway line from the catchment from the 5-, 10-, 25-, 50- and 100-year return periods of rainfall through the existing cross drainage structures?
- iv. Can the existing drainage structure convey the above run-off volumes across the railway infrastructure safely?
- v. What mitigation measures can be employed in the project area to deter flooding?

CHAPTER 2 LITERATURE REVIEW

2.1 Forms of Floods in Ethiopia

There are different types of floods, categorized according to the source [10], spatial scale and temporal scale. In all cases their common agreement on the following major types:

- **Flash floods:** is a special type of flood which is caused by extreme heavy rainfall or snow melt within short period of time which leads to the excess runoff which cannot be managed by natural and manmade drainage systems [11].
- **River floods:** this is the type of flood mainly due to river flow exceeding the stream channel capacity and over-spilling the natural or artificial banks [12].
- **Coastal floods:** this is the flood in low-lying coastal area, including estuaries and the deltas, involve the inundation of land by blackish or saline water, normally due to high tide or large wind generated waves are driven into semi-enclosed bay during severe storm [12]

While Flooding can be classified into several different types but the most common types in Ethiopia are river and urban floods. The flood types are briefly explained below;

2.1.1 River floods

These can be further classified by the rapidity of flooding or magnitude of flooding. Within the first classification, a flood is either a flash or normal flood. The flash floods normally occur in the mountainous areas or within urban cities located near mountains/ highlands. Flash flooding is caused by heavy, short and intense rainfalls which result in high speed flowing storm water and rising flood waters. Under normal flood, the river rises gradually which gives time to people before the actual arrival of the flood [13]. If this is given much attention, people can easily relocate the flood plain areas where normal floods are expected to occur.

2.1.2 Urban floods

Urban flooding is defined as a natural process in which drainage network systems overflow all over their floodplains during rain storms. Flooding within urban areas occurs when the existing capacity of drainage system does not have enough space to convey the flow. Floods differ considerably in size and duration. Field-scale flooding is usually due to intense local storms where water and soil can flow straight off the land surface. With prolonged rain falling over wide areas rivers are fed by a network of ditches, streams and flows build up to the point where the normal channel is overcome and water floods onto surrounding areas [14]

Urban drainage systems are needed in urban areas because of their interaction between human daily activity and the natural water circulation. This interaction has two main forms: the removal of wastewater after using human daily activities, institutions' activities, and the consumption of industrial and commercial products; and secondly, systematically avoiding unwanted rainwater from the covering lands of impermeable surface areas away from existing natural areas [1]. When the above interactions are not satisfied with the capacity of existing urban drainage systems, flooding will occur.

2.2 Historical Development of Urban Drainage Systems

History of human society and its ancient civilization show suggest that urban drainage systems were constructed with great care. Furthermore, historical accounts show that the objectives of the systems were to collect rainwater, prevent flooding, and convey wastes. They were able to find the systems that met their objectives after trial-and-error modifications [15]. At the time, planning and design were limited. Few numerical standards existed for urban drainage and engineering calculations were not used during design. Despite the lack of optimization and the use of trial-and-error construction methods, numerous ancient urban drainage systems can be rated very successful. Lewis Mumford summarized the state of ancient urban infrastructure. When he stated that ancient sewer systems were an uneconomic combination of refined technical devices and primitive social planning (Burian, 2004).

Urban drainage was firmly established as a vital public works system in the early parts of the twentieth century. Engineers continued to improve design concepts and methods. During the second half of the twentieth century regulatory elements were spread in the United States, Europe, and other locations addressing urban drainage issues [16]. Computer modelling tools advanced the methods used to design and analyze urban drainage systems. Regulations, monitoring, computer modelling, and environmental concerns have altered the perspective of urban drainage from a public health and nuisance flooding concern during the first half of the twentieth century into a public health and nuisance flooding with additional concerns for ecosystem protection and urban sustainability [9].

2.3 Watershed hydrological modelling

In a hilly landscape, topographic ridgelines serve as natural drainage boundaries. A geographical area separated by surrounding ridges is a hydrological unit defined as a watershed. Within the basin all land area contributes its runoff to a common point [32]. As water tends to move downwards by the forces of gravity, the common point is normally situated in a watercourse at the bottom of the basin [33]. Because of the physical attributes of the environment, such as topographic and climatic conditions, the characteristics of a watershed will vary [32].

Modern GIS software often provide watershed extraction tools [32]. Although the accuracy of the modelled drainage divide will partly depend on the resolution of the input DEM. A watershed can further be divided into sub-catchments based on the hierarchy of the stream channels. As the drainage network within a catchment varies (depending on surface material, local slopes, drainage density etc.), the number and appearance of the sub-catchments will differ. Sub-catchments may also be user induced, by choosing an arbitrary point to make an estimation of estimation the drainage area and flow pattern to that point. A sub-catchment can in its turn be separated into micro-catchments and so forth [32].

In this project, watershed delineation was carried out following the deterministic eight-node algorithm (D8) approach described in various hydrology basics and principles. This is one of the commonly used raster-based SDF algorithms. It was first introduced by O'Callaghan & Mark (1984), and was further improved by Jenson [34]. Due to its simplicity and its efficiency in deriving hydrological features, the D8 algorithm is used in today's geographical Information Systems software like ArcGIS, QGIS, SAGA GIS, and ILWIS.

In the D8 model, cells are treated as points located in the center of each cell. Slope gradients in each direction will be determined by calculating the point-to-point relationship from the center of the focusing cell to the center of its adjacent cells. As the possible flow directions will be either cardinal or diagonal, the potential routes are 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°, counted clockwise from the north [34]. From which the flow direction and flow accumulation from each cell within the area is calculated. Using the flow direction raster, the stream links, networks and segmentation are computed using a

threshold number of cells that define a stream. The defined streams, flow accumulation and flow direction rasters are then used to delineate the watersheds, sub-watersheds, drainage lines and monitoring points on defined sub-watershed outlet points. These defined outlet points (pour points) were considered as the flood prone points along the infrastructure along which the natural drainage interacts with the railroad thus required to have cross-drainage structures that would later be assessed for their hydraulic competence.

2.4 Hydrological modelling

This hydrological modelling involves the transformation of rainfall that falls in the catchment to runoff that reaches the railway drainage systems to be conveyed by the drainage structures [17]. The following methods are the most used in rainfall/runoff modelling:

2.4.1 Rational method

The method is based on the assumption that a constant intensity of rainfall is spread over an area, and the effective rainfall is falling on the most remote part of the basin takes a certain period of time which is known as the time of concentration (T_c), to arrive at the basin outlet. If the input rate of excess rainfall on the basin continues for the period of time of concentration, then the part of excess rain that fell on the most remote part of the basin will just begin its outflow at the basin outlet and with it, the runoff will reach its ultimate and the maximum rate [18].

The Rational Method is used for flood estimation and can also be used for estimating storm water runoff peak flows for the design of gutter flows, drainage inlets, storm drain pipe, culverts and small ditches. It's most applicable to small (normally less than 0.5km^2 area as recommended by Ethiopian Road Authority drainage modeling manual) and highly impervious areas [8].

2.4.2 SCS Method

The Soil Conservation Service (1972) developed a method for computing abstractions from storm rainfall. The volume of storm runoff can depend on a number of factors. Certainly, the volume of rainfall will be an important factor. For very large watersheds, the volume of runoff from one storm event may depend on rainfall that occurred during previous storm events. However, for smaller watersheds, design hydrologists usually

assume that runoff for the current storm event is independent of the rainfall of previous storm events [11].

2.4.3 Unit Hydrograph

The introduction of the unit hydrograph concept was brought up by an American engineer called Sherman in 1932. He defined the unit hydrograph as the storm hydrograph resulting from an isolated storm of unit duration occurring uniformly over the entire catchment area which produces a unit, 1cm depth of direct runoff. The unit duration is usually expressed in hours. The unit duration of the storm normally depends on the catchment area [19]. A unit hydrograph is used to relate the direct runoff hydrograph and effective rainfall. The unit hydrograph method is based on the following assumptions:

- There is a direct proportional relationship between the effective rainfall and surface runoff
- Superposition: the response to successive blocks of effective rainfall each starting at particular times may be obtained by summing the individual runoff hydrographs starting at the corresponding times.
- The effective rainfall-direct runoff relationship does not change with time.

2.5 Types of Track Drainage

An appropriate drainage system must be installed in a newly built or upgraded track structure. In-case of inappropriate track drainage system, it will lead to weakening of the track structure hence subsequent failure. Drainage planning is required in-order to come up with a safe, sustainable and resilient drainage systems to enable water to flow through the railway infrastructure from point of entry to point of exist in such a way as to allow earthworks, track and structures / works to perform in an optimal manner [20]. When ditches along the track line are not well maintained, debris clogs in them whereby the ditches end up holding water at a higher level hence obstructing drainage from the track section. This retained water weakens the sub-ballast and subgrade [21]. It's sad that often times the track inspectors do not easily notice the drainage problem until the mud appears in the ballast section which means that the water has saturated the subgrade. Then, under normal loading, the subgrade is overloaded and begins to move from its original position. Track drainage system is made up of two types [22].

- Surface drainage
- Sub-surface drainage

2.5.1 Surface Drainage

This drainage system conveys surface runoff before it ends up into the track structure, as well as collecting water percolating out of the track structure. It begins with the basic grading of the ground on either side of the track, and allows water flowing out of the track structure to be removed. A shoulder grading can be used in very flat areas where it is difficult to get sufficient fall for either surface or subsurface drains. Cross drainage structures like culverts and bridges can be used for disposing off surface water [22].

2.5.2 Subsurface Drainage

The increase in moisture content of soil reduces its bearing capacity. Thus keeping this point in view, there should not occur any change in moisture content of the subgrade of the rail track or road. The change in moisture content of the subgrade is due to fluctuations in the ground water table, seepage flow, percolation of rain water and capillary water. Thus the aim of the sub soil drainage is to prevent changes in the moisture content of the subgrade [23].

2.5.3 Flooding on railways

The main purpose of track drainage system is to convey water away from the track support System. The main sources of water that can affect the track support system include; Precipitation on the track, run off from areas adjacent to the track including catchments external to network rail boundaries, groundwater from underlying permeable layers, and perched water tables and infiltration through the ballast and ditches [4]. Proper surface water control and discharge from railway property is critical to maintaining the stability of railway embankments. Without this, track is at risk of flooding and becoming structurally unsafe. Any blockage of ditches and drains can allow flooding of track and adjacent land [4].

CHAPTER 3 RESEARCH METHODOLOGY

This section of this research report addresses the materials, methods, tools and equipment that have been used during its execution. The section addresses how the inclusion of field visits have been an integral part of the projects execution to obtain more dependable results. Thereafter, the data required, how it has been collected, analyzed and used to produce reliable results that can prompt professional decision making as far as the floods problem is concerned in the project area is described.

3.1 Project location

The flood analysis and hydraulic competence assessment project is undertaken for part of the Addis Ababa Light Rail Track that runs from Meganagna to Ayat town. The stretch is approximately 8kms long housing seven (8) intermediate and one (1) terminal stations. The project line lies in the north-eastern area of the Region 14 zone surrounded by the zones of West Shewa, South West Shewa, East Shewa, and North Shewa. The project line also doubles as a political boundary between Yeka and Bole Woredas. The project line lies above 2300m above sea level.

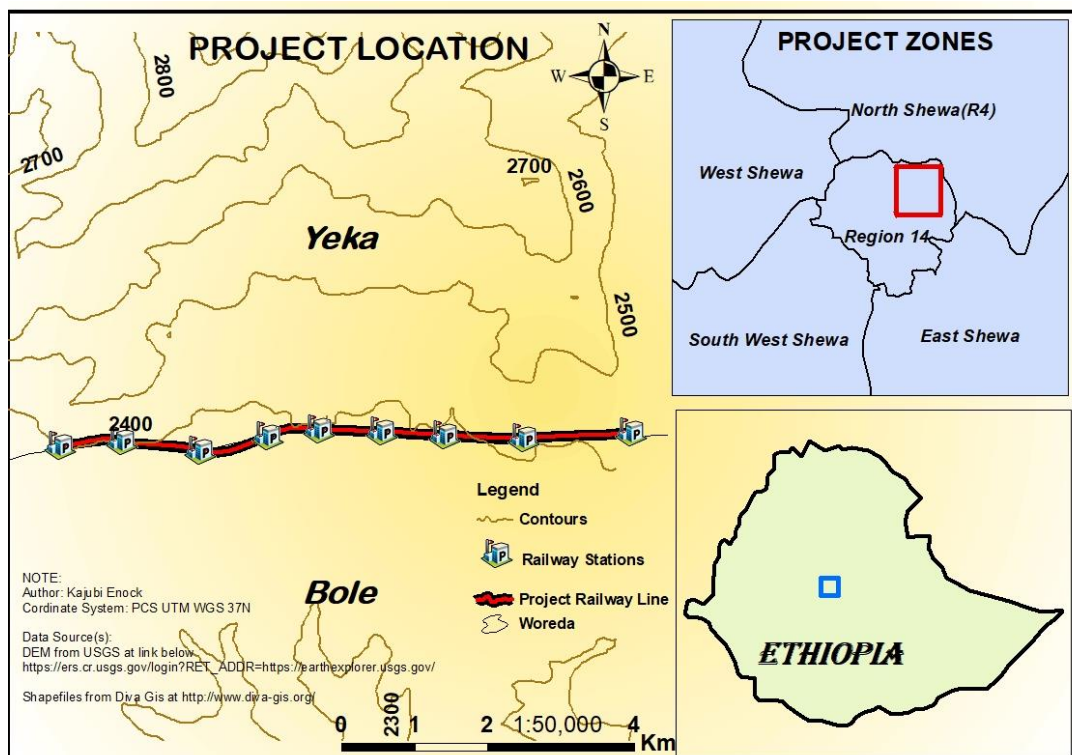


Figure 3.1: Project Location Map

3.1.1 Soil

The soils in the area are dominantly loamy. During the field visit, the soils in the surrounding of the project line watershed were also found to have some clayey extents. This illustrates that there a moderate potential for water infiltration in the loamy soils and accumulated runoff along the clayey extents.

3.1.2 Land use and Land cover

The land use and land cover of the watershed of the project line is 49% covered with built-up settlements, 33% covered by agricultural land and the rest being covered by Acacia, Eucalyptus and sugarcane plantations as illustrated below.

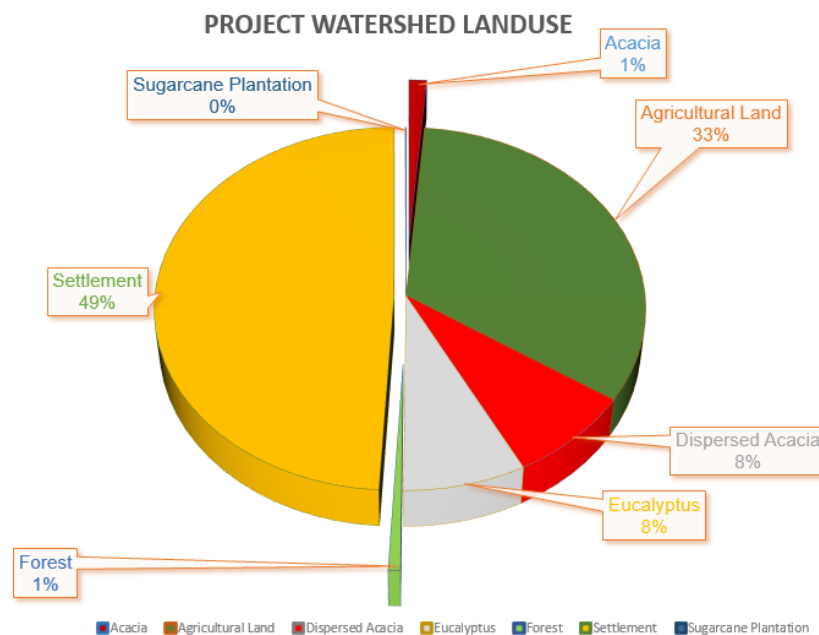


Figure 3.2: Project Watershed land use segmentation graph

3.1.3 Temperature

Ethiopia being a purely tropical country, the variation in temperature for the project line watershed is infinitesimal with an annual difference of 10°C-15°C with the region being hotter between months of February- June every year. The temperature normally ranges from 12 to 27 degrees centigrade estimated from the meteorological data from the Ethiopian meteorological Authority as shown in figure.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

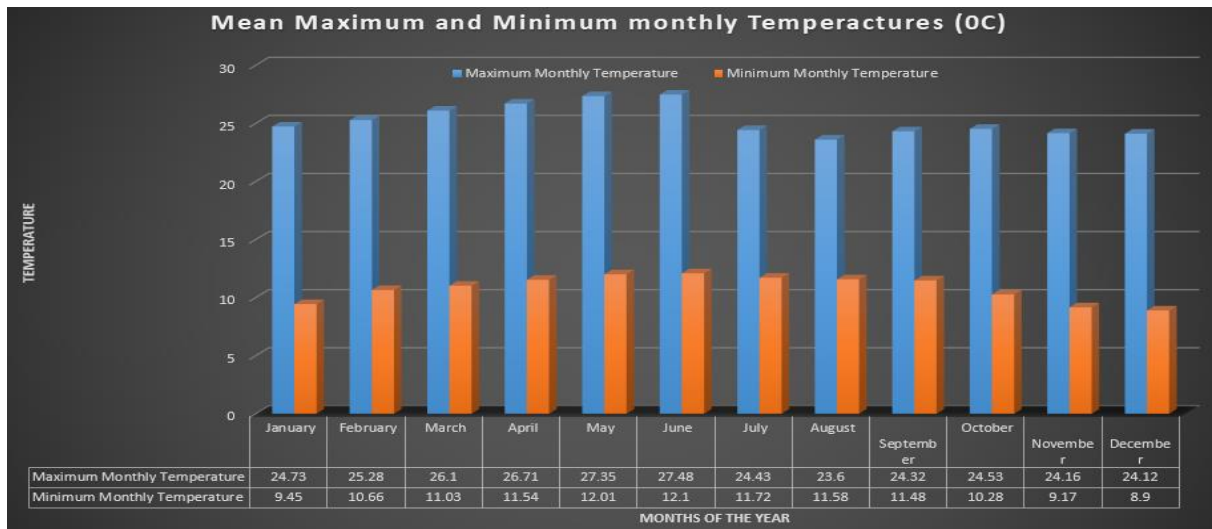


Figure 3.3: Minimum and Maximum monthly temperatures for Addis Ababa City

3.1.4 Rainfall

The rainfall data relating to the project area was obtained from the available records and documents. The mean annual rainfall in the project area is approximately 1700mm. The project area is characterized by unimodal rainfall (one rainfall peak in a year, from June to September). The average rainfall obtained from the meteorological data from the Ethiopian meteorological Authority is given in Figure 3.4

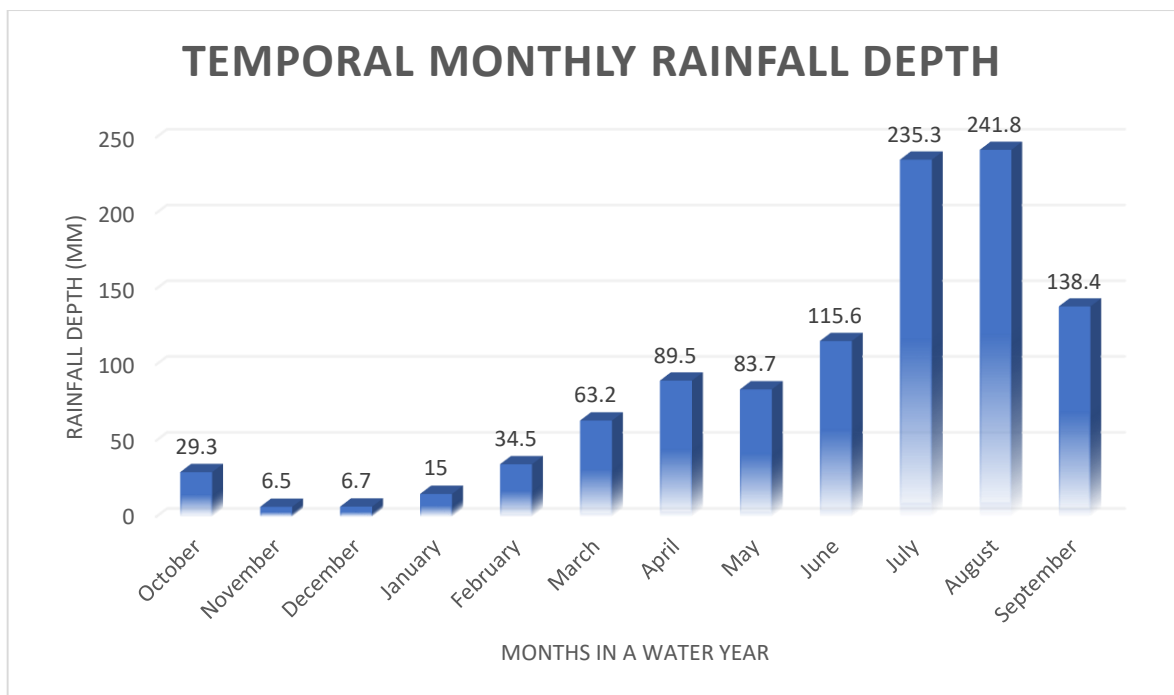


Figure 3.4: Mean monthly precipitation depth for Addis Ababa city:

3.2 Data and data sources

3.2.1 Field visits.

Various field visits have been made as part of the methodology to accomplish this project successfully. The reasons for carrying out field visits include the following:

- To ascertain the land uses and soil types that are exhibited within the catchments developed as this is fundamental knowledge to the research during both the hydrological model development and hydraulic simulation for the project area.
- To correlate the designed data from drainage drawings and specifications with what was constructed on the ground.
- To locate the hydrological points along which the infrastructure crosses the natural drainage of the area on ground as a method of ground truthing from the hydrological model that has been developed using geospatial tools.

The project to be accomplished required geospatial, hydrological and hydraulic datasets. The different types of data needed and their sources of are summarized as shown in the below:

3.2.2 DEM/DTM

A Digital Elevation Model (DEM) of the study area was identified to be the major source of elevation profiles of the project area. Therefore, due to the limited access to high resolution DEM files, a 12.5m resolution DEM was obtained from the Alaska Satellite Facility website (<https://www.asf.alaska.edu/>) and has been used in this research to generate all Watersheds and all its corresponding properties and natural drainages.

3.2.3 Land use and Digital Soil.

Land use and digital soil datasets were required during the hydrological modelling of the project area since the rainfall loss, infiltration, interception, runoff generation and groundwater contribution depends on land use, soil and elevation datasets. Thereafter, field work was carried out to ascertain the land uses and soil types that are found in the generated watersheds within the project area. This has provided a deeper understanding of the major land uses and soils types that contribute to run-off generation within each catchment and those that are likely to be more affected by the flooding hazard within communities along the railway track. The field work results were correlated with the Ethiopian land use and

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

soil shape files obtained from the USGS website at;

https://ers.cr.usgs.gov/login?RET_ADDR=https://earthexplorer.usgs.gov/.

3.2.4 Topographical map.

The topographical information of the project was needed to analyse the area drainage, topographical profile of the railway track and the infrastructure network of the project area. A topographical map of scale 1:5,000 has been used as obtained from the Geological Survey of Ethiopia.

3.2.5 Precipitation records.

Precipitation records of over 30 years were required for this research to be used in the flood frequency analysis, rainfall-runoff modelling and flood analysis. Therefore, 24-hour rainfall records were obtained from five (5) meteorological stations in the project neighborhood with two (2) having fifty (50) annual records, one (1) having twenty (20) and two (2) having nine (9) annual records. These have been used to provide sufficient precipitation data for this research.

3.3 Materials and software

For the success of this project, various materials, tools and software have been used as tabulated below:

Table 3-1: Tools, materials and software

S/N	TOOL	FUNCTION
1	Measuring tape	Measure dimensions of existing drainage structures and their offset distances from neighbouring structures.
2	Digital Camera	To capture all field work photos that were rendered useful for data analysis and project documentation.
3	Note Book	To jot down every necessary record from the field that were necessary for data analysis and documentation after the fieldwork before it's forgotten.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

4	GPS	For georeferencing drainage structure locations, locating pour points, recording the field work tracks and locating waypoints for flood mitigation measures proposed.
5	GIS software	For spatial analysis, Catchment delineation and Map generation.
6	HEC-GeoHMS	For hydrological simulation of the catchments and zoning out flood prone points along the track.
7	HEC-HMS	For Hydrographs' generation as a final stage of rainfall-runoff modelling.
9	Civil 3D and hydraulic toolbox	For hydraulic modelling and simulation of drainage structures, and investigating the impact of various floods on structural resiliency.

3.4 Data screening

a) Missing records

Daily rainfall is one of the basic inputs into hydrologic modelling in order to generate the responsive runoff that comes from the catchment as storm water to reach the railway permanent way through natural drainages. However, most datasets were received with missing records that could affect the statistical results which influence the design of storm water management facilities. Therefore, the regression method has been adopted to fill in the missing datasets of rainfall values that were missing.

b) Data consistency check

Before hydro-statistics analysis was carried out, the data provided for the station to be adopted was to be checked for consistency in relation to other stations using Double Mass Curves (DMCs). DMC technique is often used to test the consistency of rainfall record. This technique is based on the principle that when each recorded data comes from the same parent population, they are consistent. A group of 5 to 10 base stations in the neighborhood of the problem station X is selected [27]. The procedure is that accumulated rainfall at the gauge station whose record is under consideration is plotted as ordinate versus the average

concurrent accumulated average rainfall of nearby stations whose rainfall data are reliable [8].

Having received data from five (5) meteorological stations surrounding the project line, the number of stations recommended to carry out the double analysis could not be reached as they are expected to at least five (5) [27]. Therefore, from field visits and the metrological network analysis to assess the proximity of each of the remaining four stations to the assumed led to a conclusion that the data from Addis Ababa Bole station is consistent with the nearby stations' datasets.

c) Goodness of fit

A variety of statistical tests has been proposed including the chi-square test, the Kolmogorov-Smirnov test [28] and, most recently, the Anderson-Darling test [29]. There are two main problems [30]:

The tests tend to concentrate on the fit of the probability distribution in the center of the data region, and do not pay attention to the extremes. Unfortunately, it's these extremes which are of the greatest interest to a frequency analyst and where alternative estimation procedures show the greatest differences. The Anderson-Darling test however has been designed to provide greater discrimination at the extremes.

Each test involves the comparison of a calculated statistic and tabulated critical value to determine the degree of difference between the observed and estimated frequencies. The test would show, for example, that the observed and estimated frequencies are not significantly different at the 5% level. Unfortunately, the critical values depend on the probability distribution and parameter estimation procedure used. The values tabulated in statistical tables assume that the true probability distribution is known. This is not the case in frequency analysis when the parameters must be estimated from the sample. It's therefore not possible to compare the magnitudes of a given test statistic calculated for different frequency estimation procedures, and it would be necessary to compare the statistical significance of each statistic. Tables of critical values are not widely available at present, although Ahmad in [29] produced critical values for the application of Anderson-Darling test in the special case when frequencies are estimated using the Generalized Extreme Value distribution with parameters determined by the method of probability-weighted moments [30].

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Therefore, the Anderson-Darling was chosen to be used in carrying out a goodness of best fit for the precipitation data. The Anderson-Darling test compares an observed CDF to an expected CDF. This method gives more weight to the tail of the distribution than KS test, which in turn leads to the AD test being stronger, and having more weight than the KS test. The test rejects the hypothesis regarding the distribution level if the statistic obtained is greater than a critical value at a given significance level (α). The significance level most commonly used is $\alpha=0.05$, producing a critical value of 2.5018. This number is then compared with the test distributions statistic to determine if it can be rejected or not. The AD test statistic (A^2) is shown in equation 3.1 [31]:

$$A^2 = -n - \frac{1}{n} \sum_{i=1}^n (2i - 1) \cdot [\ln F(x_i) + \ln(1 - F(x_{n-i+1}))] \quad 3.1$$

The goodness of fit tests were executed in the environment of an open source software EasyFit, available at <http://www.mathwave.com/easyfit-distribution-fitting.html>.

3.5 Gumbel Generalized Distribution

The extreme value Type 1 distribution is a member of the extreme value family of the distributions as proposed by Gumbel (1941). It has two parameters and has been widely used in frequency analysis, partly because of its ease of application and partly due to the theoretical arguments Gumbel developed to support his family of distributions. The distribution function has the form shown in equation 3.2:

$$F_{(x)} = \exp \left\{ -\exp \left\{ -\left(\frac{x-u}{\alpha} \right) \right\} \right\} \quad 3.2$$

Where u is a location parameter and α is a scale parameter. The skewness of the distribution was left variable.

The magnitude of an event with return period T can be estimated from equation 3.3

$$X_T = u + \alpha y_T \quad 3.3$$

Where y_T the “Gumbel reduced variate” is calculated from equation 3.4

$$y_T = -\ln\left(-\ln\left(1 - \left(\frac{1}{T}\right)\right)\right) \quad 3.4$$

Therefore, since using Gumbel distribution, there are two parameters required for estimation of design precipitation depths corresponding to a specific return period, they were computed and the corresponding rainfall depths to the 2, 5, 10, 25, 50, and 100-yr return intervals were calculated.

3.6 Watershed characteristics computation

3.6.1 Drainage Area (A):

This is the calculated area covered by the whole watershed. It's a measure for watershed size which is most important for hydrologic design. It's an indication of the potential runoff that can be obtained from the received precipitation within the catchment. This was computed using Arc Hydro tools.

3.6.2 Watershed length (L):

This is another measure of watershed size which increases as the drainage increases. Watershed length is very important in hydrologic computations. It's defined as distance measured along the main channel from the watershed outlet to the basin divide and it's measured along the principal flow path. Most times it's used in computing time parameters such as the measure of travel time, lag time and time of concentration of water through a watershed. It was computed using HEC-GeoHMS tools.

3.6.3 Watershed Slope (S):

Flood magnitudes reflect the momentum of the runoff generated throughout the watershed. Slope is an important factor in the momentum. Watershed slope reflects the rate of change of elevation with respect to distance along the principal flow path. This was calculated using the equation 3.5:

$$S = \frac{\Delta E}{L} \quad 3.5$$

Where:

ΔE is difference in elevation (between the end points of the principal flow path);

L is the *Hydrologic* length of the flow path.

3.6.4 River length

This is the hydrological distance measured along the main channel from the watershed outlet to the end of the channel. It is frequently used in many hydrological computations. The river length was calculated using HEC-GeoHMS tools.

3.6.5 River slope

The river slope is a fundamental parameter in drainage and hydraulic modelling. It's responsible for the flow velocity as well as the local losses in drainage channels. It can be computed by the equation below. If the channel slope is not uniform, a weighted slope may provide an index that reflects effect of slope on the hydrologic response of the watershed from equation 3.6.

$$S_c = \frac{\Delta E_c}{L_c} \quad 3.6$$

Where ΔE is the difference in elevation between the points defining the upstream and downstream of the channel and L_c is the horizontal length of the channel between the same two points.

3.6.6 Watershed perimeter

This is the length of a map line that encloses the catchment area of a drainage basin. Topographic maps were used for determining the perimeter of basin.

3.6.7 Watershed shape

Watersheds have an infinite variety of shapes, and the shape supposedly reflects the way that runoff will build up throughout the basin and its response at the outlet. Watershed shape can be described as circular, rectangular, triangular, or pear. The latter is most common. Shape can also be quantified using equations of the four major parameters which are discussed below:

- i. Length to the center of area (L_{ca})

The length to the center of area also known as the basin centroid flow length is the distance in meters measured along main channel from basin outlet to the point on the main channel opposite the basin centroid.

- ii. Form factor (L_1)

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Form factor is defined by the ratio of the basin area to the square of the basin length. Form factor is dimensionless and its value will always be less than 0.754 (for a perfectly circular watershed). The smaller the value of the form factor, the more elongated will be the watershed. The watershed with a high form factor has high peak flows with a shorter duration while elongated watersheds with low form factors below 0.54 indicate a longer duration of flow with relatively less peak flows.

iii. Circularity ratio (R_c)

This is the ratio of basin area to the area of circle having equal perimeter as the perimeter of drainage basin whose maximum value is a unit. The circularity ratio can be computed by the equation 3.7:

$$\text{Circularity ratio, } R_c = A/A_c \quad 3.7$$

Where:

A_c Is the area of a circle with equal perimeter as the basin.

A is the basin area

iv. Elongation ratio (R_e)

The elongation ratio whose maximum value is a unit is the ratio of diameter of a circle having same area as the basin to the maximum basin length of the basin parallel to the principle drainage lines. It can be computed using the equation 3.8:

$$\text{Elongation ratio, } R_e = D/L' \quad 3.8$$

L' is the maximum length of the basin parallel to the principle drainage lines.

D is the diameter of the circle with equal area as the basin.

Therefore, as far as this research is concerned, the HEC-GeoHMS program was used to compute the Watershed perimeter, drainage area, river slope, river length, watershed slope, and the watershed length (Longest flow length). The watershed shape four parameters were also computed using the above equations for each watershed outside the program.

3.7 Time of concentration

Time of concentration (T_c) is the time required for runoff to travel from the hydraulically most remote point of the watershed to the outlet. Time of concentration will vary and depending on the slope and character of the surface. When the drainage area consists of several different types of surfaces, time of concentration is calculated by adding the time for each type of flow along the flow path from the watershed divide to the watershed outlet. Time of concentration is generally applied only to surface runoff [35]. Two primary methods of computing time of concentration were developed by the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS):

3.7.1 Watershed lag method

The SCS method for watershed lag method was developed by Mockus in 1961. It spans a broad set of conditions ranging from heavily forested watersheds with steep channels and a high percent of the runoff resulting from subsurface flow, to meadows providing a high retardance to surface runoff, to smooth land surfaces and large paved areas [35]. The time of concentration through this method is computed by the equation 3.9:

$$T_c = (l^{0.8}) \left[\frac{(S+1)^{0.7}}{1140Y^{0.5}} \right] \quad 3.9$$

Where:

L = Lag time (hours)

T_c = Time of concentration (hours)

L = flow length (ft)

Y = Average watershed land slope, (%)

S = Maximum potential retention (inches)

The maximum potential retention, S and the is further given by equation 3.10

$$S = \left[\frac{1000}{cn'} \right] - 10 \quad 3.10$$

Where cn' is the retardance factor, a measure of surface conditions relating to the rate at which runoff concentrates at some point of interest [35]. In practical usage, the runoff Curve numbers are used as retardance factors.

3.7.2 Velocity method

Another method for determining time of concentration normally used within NRCS is called the velocity method. The velocity method assumes that time of concentration is the sum of travel times for segments along the hydraulically most remote flow path [35]. The time of concentration is divided into three segments. The time of travel of each segment is computed and the summation of all the time of travel gives the ultimate time of concentration of the catchment. The three main segments include:

i. Sheet flow

Sheet flow is flow over plane surfaces. It usually occurs in the headwaters of a stream. A simplified version of the kinematic equation that was developed by Welle and Woodward (1986) is used to compute the sheet flow travel time as in equation 3.11:

$$T_t = \frac{0.007(nl)^{0.8}}{[(P_2)^{0.5}S^{0.4}]} \quad 3.11$$

Where:

T_t = Travel time (hours)

n = Roughness coefficient

l = flow length (ft)

P_2 = 2-year, 24-hour rainfall (inches)

S = Slope of hydraulic grade line (ft/ft)

ii. Shallow concentrated flow

After approximately 100 feet, sheet flow usually becomes shallow concentrated flow collecting in swales, small rills, and gullies. Shallow concentrated flow is not assumed to have a well-defined channel. Velocities are developed using wide, rectangular channel flow concepts. Average velocity for shallow concentrated flow can be determined using figure 5, in which average velocity is a function of watercourse slope and type of channel [36]. Thereafter, after estimating the velocity, equation 3.12 is used to compute for the shallow concentrated flow travel time

$$T_t = \frac{l}{3600V} \quad 3.12$$

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Where: T_t = travel time (hours)

l = Flow length (ft)

V = Average velocity (ft/s)

For slopes below 0.0005 ft/ft, the following relationships in table 2 below have been developed by [36] for simplified applications in time of concentration computations. These relations have been developed from figure B-6 in appendix B.

Table 3-2: Equations and assumptions developed from figure 5

Flow type	Depth (ft)	Manning's n value	Velocity Equation (ft/s)
Pavement	0.2	0.025	$V = 20.328(S)^{0.5}$
Grass waterway	0.4	0.05	$V = 16.1345(S)^{0.5}$
Nearly bare alluvial fans	0.2	0.051	$V = 10.277(S)^{0.5}$
Cultivated straight row	0.2	0.056	$V = 9.0125(S)^{0.5}$
Short grass pasture	0.2	0.07	$V = 6.957(S)^{0.5}$
Trash fallow	0.2	0.101	$V = 5.06(S)^{0.5}$
Forest	0.2	0.175	$V = 2.53(S)^{0.5}$

iii. Open channel flow

The open channel flow is always analysed using the hydraulic manning's equation. Therefore, it's used to obtain the average channel velocity in equation (xiii). On the computation of the average open channel flow velocity from the manning's equation, equation 3.13 is used to compute for the open channel flow travel time.

$$V = \frac{1.49r^{\frac{2}{3}}S^{\frac{1}{2}}}{n} \tag{3.13}$$

Where:

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

V = average velocity (ft/s), S = Slope of hydraulic gradient line (Channel slope), n = Manning's n value for open channel flow, r = Hydraulic radius, (ft) given by equation 3.14:

$$r = \frac{A}{P} \quad 3.14$$

Where:

A = Cross-sectional flow area (sq. ft), P = wetted perimeter (ft)

From time of concentration computation methods above, the velocity method was adopted in the methodology of this research and tables have been generated and attached in Appendix A showing the time of concentration computation for each sub-watershed.

3.8 Storage coefficient

The storage attenuation is also another very critical watershed parameter used in watershed hydrological analysis. The value of the storage attenuation coefficient, K is usually obtained by using the slope of the recession curve (which is negative) at the point of inflection for a gauged catchment hydrograph as shown by equation 3.15 and 3.16. At the point of inflection, the inflow into the channel has ceased and beyond this point, the flow is entirely due to withdrawal from the channel storage. While from the ungauged catchments where no hydrograph is established, Clark proposed an empirical formula below for determining the storage attenuation coefficient of the basin [37].

$$K = \frac{CL}{\sqrt{S}} \quad 3.15$$

Although further, Linsley further modified the above equation to a simplified empirical equation below [38]:

$$K = \frac{bL\sqrt{A}}{\sqrt{S}} \quad 3.16$$

Where:

K is the storage attenuation coefficient of the basin in hours

L is the length of the longest flow path length of the basin in miles

A is the drainage area of the basin sq. miles

S is the basin slope in percentage rise.

C has a range from 0.8 to 2.2 and b has a range of 0.04 to 0.08.

The storage attenuation coefficient used in the hydrological modelling in this research was computed according to equation (xvi) and the results are tabulated in table 11 of this report.

3.9 Triangular hyetograph generation

This method developed by the U.S Department of Agriculture (1972) SCS models the shape of a unit hydrograph as a triangular shape. In this method, a single triangle can be developed by approximating the base time as 2.67 times the peak time T_p (21). A triangle is a simple shape for a design hyetograph because once the design precipitation depth P and a duration T_d are known, the base length and height of the triangle are determined. The base length (base time) is T_d and the height h , so the total depth of precipitation in the Hyetograph is given by P as in equation 3.17 (18).

Where:

$$h = \frac{2 * P}{T_d} \quad 3.17$$

In this method, a single triangle can be developed by approximating the base time as 2.67 times the peak time, T_p (21). Thus by equation 3.18,

$$T_d = 2.67 * T_p \quad 3.18$$

The base time (Rainfall duration) for each of the hyetographs that has been generated with respect to each sub watersheds, was approximated with respect to the time of concentration as this approach produces a higher peak flow that will be used for drainage design purposes (22). And a storm advancement coefficient, r was also determined as the ratio of the peak time to the base time (total storm duration). Therefore, from the equation (xviii), the storm advancement coefficient, r was adopted as 0.3745. Then recession time (T_b) was also obtained from the equation 3.19.

$$T_b = (1 - r) * T_d \quad 3.19$$

Therefore, from this methodology, parameters in the table 13 for each sub-basin developed was generated to show the peak time, base time and recession time as well as the hyetograph height and thereafter, hyetographs were developed as shown in APPENDIX B were constructed and since only one meteorological station was adopted for use, all sub-

basins with the same time of concentration were found to have the same hyetograph as shown below. Rainfall-runoff modelling.

3.9.1.1 Transformation method

Clark in 1945, was the first to use the concept of IUH. The Clark method requires three parameters to calculate IUH: t_c , the time of concentration for the basin; K, storage coefficient, and a time-area diagram (TAD).

The original Clark model is a lumped model which means that it could only provide one hydrograph at the watershed outlet. In line with modern watershed analysis, the Clark Model has been extended to accommodate a spatially distributed rainfall data. This practice effectively extends the Clark model to the realm of quasi-distributed surface runoff modelling. The revised version of the Clark model is referred to as the ModClark method. The ModClark method for rainfall transformation was adopted due to its simplest and accuracy in scenarios of inadequate Land Use, discharge and digital soil datasets. This required two parameters of the time of concentration and storage attenuation coefficient which were computed as explained earlier on.

3.9.1.2 Loss method

While a sub-basin element conceptually represents infiltration, surface runoff, and subsurface processes interacting together, the actual infiltration calculations are performed by a loss method contained within the sub-basin. A total of twelve different loss method are provided within the HEC-HMS program. Some of the methods are designed primarily for simulating events while others are intended for continuous simulation. All of the methods conserve mass. Therefore, the sum of infiltration and precipitation left on the surface will always be equal to total incoming precipitation. Due to the insufficient soil data in the project area, the initial and constant loss method was adopted in this research.

The initial constant loss method is very simple but still appropriate for watersheds that lack detailed soil information [39]. The initial and constant loss method requires only three inputs for the infiltration computation which include: the initial loss, the constant rate and the percentage of imperviousness.

The initial loss specifies the amount of incoming precipitation that will be infiltrated or stored in the watershed before surface runoff begins. There is no recovery of the initial loss during periods without precipitation [39]. The initial loss might reflect both antecedent

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

moisture conditions and losses prior to reaching the ultimate infiltration capacity [40]. [40] Proposed a better approach to estimate the initial loss depth in relation to the project vegetation cover. Therefore, the initial loss was approximated using the existing vegetation cover of the project area with reference to [40].

The constant rate determines the rate of infiltration that will occur after the initial loss is satisfied. The same rate is applied regardless of the length of the simulation [39]. The constant rate was taken as the ultimate infiltration capacity of the soil. Therefore, a maximum value and a minimum value were estimated depending on the most dominant soil hydrological groups in each catchment with reference to [39].

The percentage of the sub-basin which is directly connected to impervious area was specified and computed using the existing land use maps, Google earth Pro program and ground truthing through field visits. No loss calculations are carried out on the impervious area; all precipitation on that portion of the sub-basin becomes excess precipitation and subject to direct runoff.

3.9.1.3 Routing method

While a reach element conceptually represents a segment of stream or river, the actual calculations are performed by a routing method contained within the reach [39]. Flood routing is the technique of determining the flood hydrograph at a section of a river, channel or stream by utilizing the data of flood flow at one or more upstream sections. The hydrologic analysis of problems such as flood forecasting, flood protection, reservoir design and spillway design invariably include flood routing. In this research project, the HEC-HMS program was adopted and it contains over seven (7) flood routing methods which vary in complexity, number of input parameters and accuracy.

Due to the limited amount of data required, the Lag method was used as the routing method in this research project. In this method, the translation of flood waves is represented and no representation of neither attenuation nor diffusion is accounted for. The inflow hydrograph to the reach is delayed in time by an amount equal to the specified lag time and then becomes the outflow hydrograph. Therefore, the major parameter in this method was the lag time which was computed for each sub-basin from its time of concentration from the equation 3.20:

$$\text{Lag time (hrs.)} = 0.6 * T_c,$$

3.20

Where: T_c is the time of concentration for each sub-basins?

3.10 Hydraulic competence assessment

The drainage system of the project line consists of three different systems: The concrete curb-opening inlets and lockable gullies that collect the water from the road carriageway into longitudinal sealed carrier pipes. The carrier pipes drain into cross drainage structures which are either culverts or bridges. On addition is the railroad bed drainage which through this research, there were no evidence of its existence and interaction with the roadway drainage system according to the various discussions we held with various public offices from ERC and AACRA. Therefore, hydraulic competence assessment of all the hydraulic structures within the project area was carried out in three major phases:

- i. Side drainage assessment
- ii. Cross drainage assessment
- iii. Railroad bed drainage system

Therefore, throughout this research, while the side drainage and cross drainage systems were assessed to ascertain their hydraulic competence, the railroad drainage system was designed according to various case studies, hydrology of the project area and other railway drainage design manuals. This was carried out through three major steps which involved discussions and interviews with key informants in ERC and AACRA, field visits to measure and locate the drainage structures and the simulation of the watershed generated runoff through the structures to assess their functionality and resilience to flooding.

Field visits have been carried out, dimensions of each structure measured using measuring tapes and their locations captured using the Global Positioning System (GPS) receiver. On addition of the field visits, various secondary datasets like excel spreadsheets that describe the drainage design along the infrastructures was acquired from the Addis Ababa City Roads Authority (AACRA) office however insufficient they were. Furthermore, interviews were conducted with the ERC drainage officials and AACRA design engineers to ascertain the missing drainage details on the two transportation infrastructures. The combination of the three sources of drainage datasets was used to evaluate the design details of the existing structures.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

After ascertaining the existing drains, culverts and the bridge, the various drainage structures' dimensions were imported into the HEC-RAS (for longitudinal side drains on railroad) and the Autodesk Civil 3D extension of Hydra express launch (for carriage way side drains, culverts and the bridge) so as to simulate the hydraulic flow of runoff through the structures and the results were discussed through the following chapter of this report.

3.10.1 Side drainage assessments

The two directional infrastructure was divided into thirteen (13) different side drains sections in relation to their longitudinal surface slope and the location of the cross-drainage structures like culverts and bridges. The side drains were assessed depending on their capacity to convey the accumulated runoff from the four (4) lane carriage way with a total width of fourteen (14) meters in each of the two directions and the corresponding watersheds along the carriage way to the cross drainage structures.

Storm drains flow is unsteady and non-uniform. However, for design purposes, it can be assumed that it is steady and uniform at peak flow rate, thereby allowing Manning's equation 3.21 to be applied for checking if the pipe capacity can match the expected runoff to be conveyed downstream.

$$Q = \left(\frac{1}{n}\right) A \left(R^{2/3}\right) S_f^{1/2} \quad 3.21$$

Where: Q= flow rate in cms, A=flow area in sq.m, R= hydraulic radius in m, n=Manning's coefficient factor, and S_f is the friction slope (To be assumed as the storm drain slope in m/m in this assessment).

For full flow in circular pipes equations 3.22 and 3.23 are used,

$$A = A_f = \frac{\pi D^2}{4} \quad 3.22$$

$$R = R_f = \frac{D}{2} \quad 3.23$$

Where: D = pipe diameter (m), A_f = flow area at full flow (sq.m) and R_f = Hydraulic radius at full flow (m)

If the flow is pressurized (i.e., surcharging at the manholes or inlets is occurring), $S_f \neq S_o$ where S_o is the longitudinal slope of the storm drain pipe. Design of storm drains assumes just-full flow, a reference condition referring to steady, uniform flow with a flow depth, y,

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

nearly equal to the pipe diameter, D . Just-full flow discharge, Q_f , is calculated using equation 3.24:

$$Q = \left(\frac{1}{n}\right) A \left(R^{2/3}\right) S_o^{1/2} \quad 3.24$$

Storm drains are sized to flow just full. The design discharge is determined first using the rational method as previously discussed, then the Manning's equation is used (with $S_f = s_o$) to determine the required pipe size. For circular pipes equation 3.25 was used,

$$D_r = \left[\frac{2.16nQ}{\sqrt{s_o}}\right]^{3/8} \quad 3.25$$

Where D_r is the minimum diameter required to convey the maximum design flow rate calculated from the rainfall-runoff transformation methods

Two carriage pipes of diameters of 750mm and 1200mm were identified within the field visits and therefore, the hydraulic competence assessment was carried out using these two longitudinal sealed concrete pipe drains and the results per section were obtained from the FHWA hydraulic toolbox program and discussed in the chapter 4 of this report.

3.10.2 Cross drainage structures

The infrastructure which is approximately 8kms long, was found to consist of seven(7) culverts with six(6) of them reachable and therefore can be assessed through the hydraulic measurements that were obtained from the field and the one(1) culvert inaccessible which will require redesigning. It also included one bridge. Due to limited costs, field instruments, and field restrictions of the researcher from reaching these structures, only the opening dimensions of these structures were measured therefore this limits the research from assessing the scouring on both culverts and the bridge.

Therefore using the measuring tape, the dimensions of the openings of each of these structures were measured and recorded. The dimensions were then imported into the hydra flow express package of the Civil 3D Autodesk software from which simulations were carried to assess the hydraulic capacity of each structure to see if they are in position to convey the collected runoff across the highway and the railway infrastructure safely.

This was done considering the two most hydraulic regimes of flow in culverts and bridges as follows where both were computed and the larger was considered in this research for each structure:

i. Inlet control

The hydraulics of the inlet control presume that its more difficult for flowing water to go into the entrance of the culvert/bridge than it is to go through it. It takes its assumptions from the appearance of traffic of four-lane going through a two-lane tunnel. There must be constriction of flow that leads into reduction in velocity for the approaching flow to the entrance and once under the culvert/bridge, flow normalizes and speeds up a little bit downstream. This makes the flow to occur under culverts in partial depths throughout its barrels while under inlet control regime. Inlet control is largely influenced by the entrance geometry of the culverts and the bridges such as edge configuration, culvert pipe shape and area. The following inlet control equations were used where if the headwater depth above invert is above the crown, the equation for submerged was adopted and elsewhere, the one of unsubmerged was used in computations.

For submerged conditions, equation 3.26 was applied

$$Hw = D * \left[Y - 5S + c \left(\frac{Q}{A\sqrt{D}} \right)^2 \right] \quad 3.26$$

For unsubmerged conditions, equation 3.27 was applied

$$Hw = D * \left[K \left(\frac{Q}{A\sqrt{D}} \right)^M \right] \quad 3.27$$

Where:

Hw = Headwater depth above invert

D = Line rise (m)

Q = Flow rate (cms)

A = Full cross-sectional area of pipe, sq. meters

K, M, c, Y = Coefficients based on edge configurations

S = Line slope, m/m

ii. Outlet control

This hydraulic principle presumes that flow finds it more difficult to go through the barrels than to enter it. The outlet control is basically influenced by the manning's n value

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

(roughness coefficient) of the barrel, flow area, shape, length and slope. During this research, an energy-based standard step was used to compute the hydraulic profile for the outlet control. It was an iterative procedure in which a Bernoulli's energy equation was applied between the upstream and downstream of the culvert/bridges and a Manning's equation was used to compute for the head losses due to culvert material lining friction. Therefore the equation 3.28 was adopted for use:

$$\frac{v_1^2}{2g} + Z_1 + Y_1 = \frac{v_2^2}{2g} + Z_2 + Y_2 + HL \quad 3.28$$

Where:

V = velocity in m/s

Z = Invert elevation in meters

Y = HGL minus the invert elevation in feet

And the friction losses were computed by equation 3.29 and 3.30:

$$HL = \frac{(hf_1 + hf_2)}{2} \quad 3.29$$

Where:

$$hf = \left(\frac{Qn}{KmAR^{0.667}} \right)^2 * pipe\ length \quad 3.30$$

Where:

Km = 1.486

n = Manning's m value (roughness coefficient)

A = Cross-sectional area of flow in sq. meters

R = Hydraulic radius.

3.10.3 Railroad drainage system

The railroad bed (on-track drainage system) is a network of both transverse and longitudinal drains that serve a similar purpose of evacuating water from the permanent way as soon as possible. The transverse drains purpose to drain water from the ballast bed into the longitudinal drains that convey the collected water into collector pipes in the

municipal storm water pipe network. While the longitudinal drains were open drains covered by concrete covers that could be easily visible from the field visits, the transverse drains were not visible and there was no clue of their existence even after various interviews with both the AACRA and ERC drainage engineers. Therefore, the existing longitudinal drains were evaluated and assessed but the feeding transverse aggregate drains were sized within this research to improve the drainage system efficiency of the permanent way.

3.10.3.1 Transverse aggregate drains

Sizing the aggregate drains were through two major steps which involved computation of surface runoff that drains through the ballast and using the accumulated runoff to obtain the optimal size of the aggregate drains. The capacity of the aggregate drains was computed using the basic Darcy's equation 3.31 of groundwater flow as shown below:

$$Q_1 = k * i * A \tag{3.31}$$

Where:

Q_1 = flow (m³/s), k = permeability of the aggregate, i = hydraulic gradient or slope, A = Cross-section area (m²)

Cross-sectional area

The cross-sectional area used in these computations were developed after measurements were carried out on the surface of the rail track bed. The transverse drains were proposed to be spaced in a distance of 100m apart that attracted a cross-sectional area of 343.5 sq. meters. The permeability of the aggregates used as ballasts were from ballast rocks mixed with scoria and Pumice. Its permeability was found to be 0.25m/s with a ballast aggregate size ranging between 28mm to 37.5mm from various sieve tests conducted.

The above equation can be adjusted so as to determine the size of the aggregate drains as shown by equation 3.32:

$$Q_1 = K * A \tag{3.32}$$

Where, K is a velocity constant that varies with the slope of the aggregate drain with the two mostly used aggregate sizes of 20mm nominal diameter and 53mm diameter of ballast used to determine their permeability as illustrated in the table below:

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Table 3-3: Values of $K=k*i$ (m/s) for various slopes.

Slope	20mm aggregate size	53mm aggregate size
1 in 100	0.00150	0.0040
1 in 200	0.00075	0.0020
1 in 300	0.00050	0.0013
1 in 400	0.00038	0.0010
1 in 500	0.00030	0.0008

Through this research, in order to ascertain the required drain size, the Q_1 was computed from the equation above and from the table above, the values of K were estimated so as from equation 2, the cross sectional area of the aggregate size can be estimate. Thereafter, the diameter of the required aggregate size.

3.10.3.2 Longitudinal drains

From the field work, the existing longitudinal drains were found to run along the whole stretch of railroad bed to collect the accumulating runoff from the ballast bed which is collected through the transverse drains within the ballast. The railroad is drained by two longitudinal drains sized 500mm by 800mm that are closed by concrete covers to protect them from solid waste being disposed into them that would block them in a long run.

To evaluate the efficiency and competence of these longitudinal side drains, the HEC-RAS package was used to simulate the water profiles and the flood depths as a result of the railroad bed runoff. The stretch of the project length was divided into sections according to their surface slopes and the surface slopes were assumed to be the same as the longitudinal drain slopes and the results a have been discussed in the next chapter of this report.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 Flood frequency assessment

4.1.1 Best fit results

The data while using the EasyFit program, the Anderson-darling Test statistic, mean and standard deviation of the precipitation depth was as shown in table 4-1:

Table 4-1: The Anderson-Darling test statistics for flood frequency analysis.

1	AD Statistic	0.3292
2	Mean	48.4
3	Standard Deviation	15.1306

Since the AD test statistic was found to be below the critical value of $\alpha = 2.5018$ for the significance level of a 95% confidence interval, the Gumbel distribution was accepted as a best fit for rainfall frequency analysis. The obtained sample mean and standard deviation were used to obtain corresponding precipitation depths to the return periods and the Gumbel reduced Variate.

4.1.2 Gumbel results

The precipitation depths corresponding to the average return intervals (ARI) of 2, 5, 10, 25, 50, 100-year were computed and tabulated as shown in table 4-2:

Table 4-2: The precipitation data statistics

Statistics	
Mean	53.047
Std. Error of Mean	2.6231
Std. Deviation	19.9769

Using the statistics in table 4-2, the rainfall depths in table 4-3 were computed using Gumbel method for extreme events flood frequency analysis as tabulated. Thereafter, the

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

rainfall depths were used to generate hyetographs as shown in appendix B that were used in rainfall-runoff transformation.

Table 4-3 Rainfall Frequency Analysis using Gumbel Distribution.

Return period (yrs.)	2	5	10	25	50	100	200
Reduced Variate	0.366	1.499	2.250	3.198	3.901	4.600	5.295
Rainfall depth (mm)	45	59	68	79	87	95	114

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

4.1.3 Flood prone points calculation

During this research, the watersheds were delineated in a GIS environment using the Arc Hydro tools. The flood prone points were calculated using the D8 algorithm and were identified as the points along which the railway infrastructure interacts with the natural and artificial drainage within the project area as shown in figure 4.1. Seven flood prone points were identified and for each a corresponding watershed was modelled as shown in figure 4.2. The watersheds were numbered from one (1) to seven (7) as they approach from the Ayat station towards Meganagna station. The Seven (7) watersheds are further sub-divided into a total of fourteen (14) sub-watersheds. The delineated watersheds with their corresponding sub-watersheds characteristics were tabulated in table 4-4.

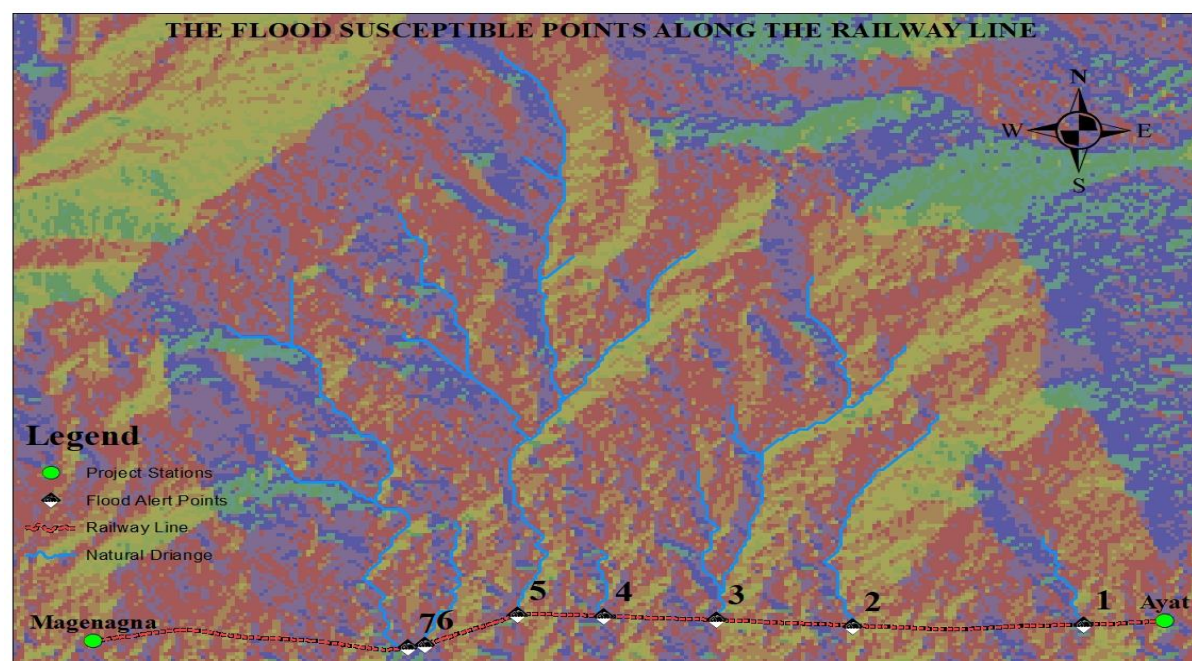


Figure 4.1: Flood drainage points along the Railway line

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

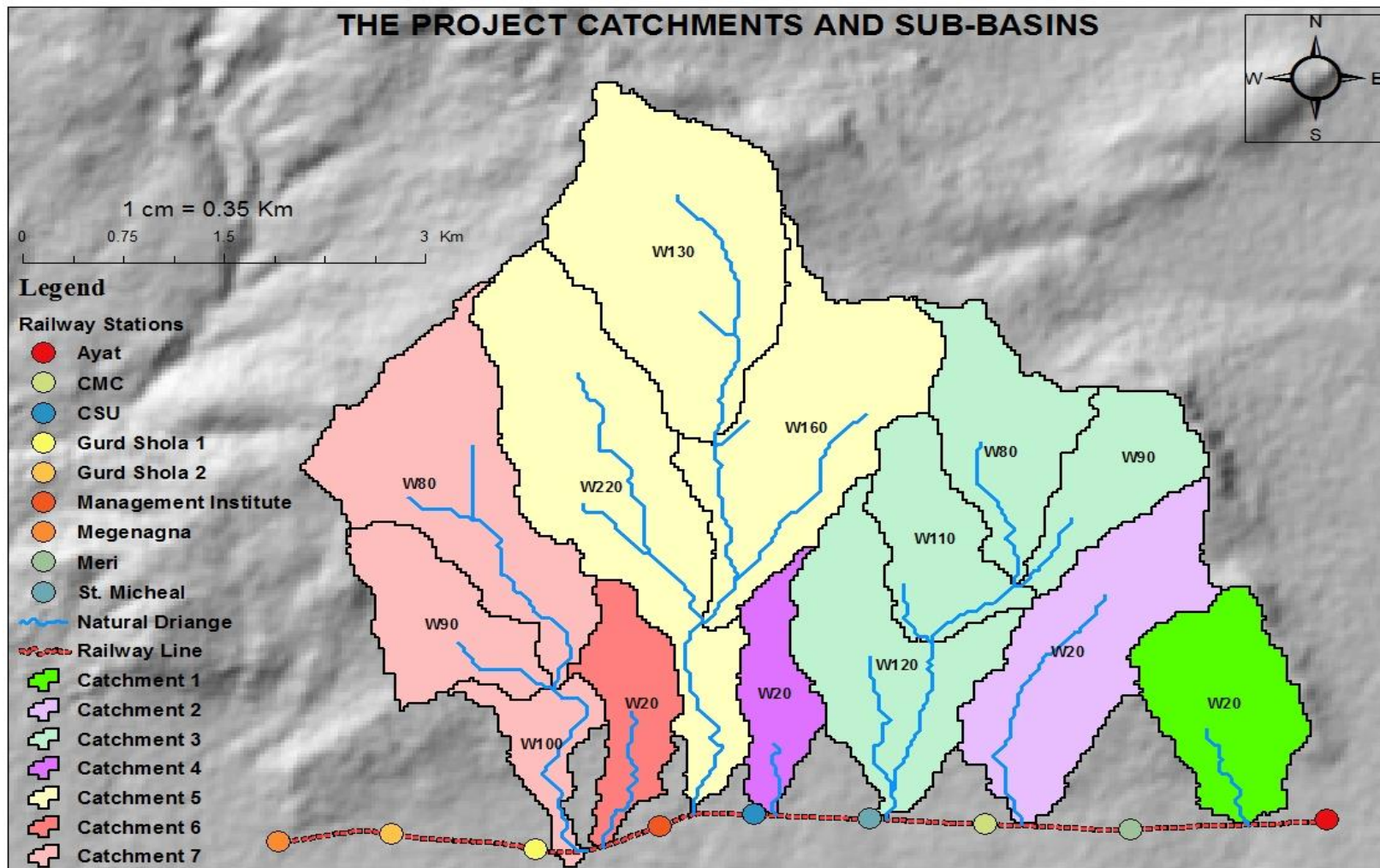


Figure 4.2: Delineated Basins for the Flood susceptible Points along the Track

Table 4-4: Watershed parameters, Storage coefficient and Tc

S/N	Catchment	Sub_Basin	Drainage Area (sq. km)	Basin Slope (%)	Time of Concentration (Min)	Basin Lag time (Min)	Watershed Length (miles)	Drainage Area (sq. miles)	(Square Column 5)/ (Column 6)	Storage attenuation Coefficient (min)	Watershed Length (m)	Centroid Flow Length (m)	Form Factor (Shape Factor)
1	1	W20	1.67	13.21	30.65	18.39	1.50	0.65	3.51	26.52	2422	1345	0.28
2	2	W20	2.46	11.55	35.38	21.23	2.36	0.95	5.87	37.19	3800	1928	0.17
3	3	W80	1.59	12.85	32.34	19.41	1.78	0.62	5.17	31.98	2872	1382	0.19
		W90	1.17	13.74	27.83	16.70	1.39	0.45	4.26	25.51	2233	1049	0.23
		W110	1.29	11.65	35.62	21.37	1.43	0.50	4.10	32.24	2299	1267	0.24
		W120	2.20	7.90	42.64	25.59	2.07	0.85	5.05	41.73	3335	1598	0.20
4		W20	0.83	6.52	39.56	23.74	1.66	0.32	8.62	55.51	2674	1285	0.12
5	5	W130	3.49	21.32	16.08	9.65	2.29	1.35	3.88	14.31	3678	1995	0.26
		W160	2.94	13.31	19.29	11.57	2.51	1.13	5.57	19.75	4045	2048	0.18
		W220	3.84	13.06	23.70	14.22	3.73	1.48	9.35	36.51	5996	3409	0.11
6	6	W20	1.02	7.57	39.87	23.92	1.84	0.40	8.52	55.29	2954	1456	0.12
7	7	W80	2.85	15.53	33.27	19.96	2.65	1.10	6.35	36.58	4257	2194	0.16
		W90	1.32	16.55	30.25	18.15	1.51	0.51	4.47	28.21	2429	1161	0.22
		W100	0.68	10.38	26.82	16.09	1.38	0.26	7.27	32.32	2216	1185	0.14

On calculation of the watershed parameters and precipitation frequency computations, the specified hyetograph method, initial and constant, lag method and ModClark method were adopted as precipitation, loss, routing and transformation methods respectively. The runoff volumes in table 4-5 were obtained from the rainfall depths in table 4-3 at each of the drainage outlet of the watersheds and thereafter used for hydraulic competence assessment of the corresponding cross drainage structures.

Table 4-5: Runoff volumes from each watershed

S/N	Water shed outlets	Drainage area (Sq. Km)	5-yr		10-yr		25-yr		50-yr		100-yr	
			Peak Discharge, Q (Cumecs)	Volume, V (1000' Cubic meters)	Peak Discharge, Q (Cumecs)	Volume, V (1000' Cubic meters)	Peak Discharge, Q (Cumecs)	Volume, V (1000' Cubic meters)	Peak Discharge, Q (Cumecs)	Volume, V (1000' Cubic meters)	Peak Discharge, Q (Cumecs)	Volume, V (1000' Cubic meters)
1	O-1	1.67	30.5	88.1	34.8	103.1	41	122.3	45.7	135.8	51.7	149.1
2	O-2	2.46	34.2	130.1	39.8	151.9	46.9	179.2	52.1	199.5	57.2	219.5
3	O-3	6.26	72.9	301.8	90.4	385.2	104	433.3	115.6	480.3	128.7	552.9
4	O-4	0.83	8.7	43.8	10.2	51.2	12	60.4	13.3	67.2	14.6	74
5	O-5	10.27	238.1	554.1	275.4	631.8	325	740.4	357.5	823.2	393.3	906.1
6	O-6	1.02	10.7	53.8	12.5	62.9	14.7	74.2	16.4	82.6	18	90.9
7	O-7	4.85	68.3	256.5	79.4	299.1	93.6	352.8	104	393	114.6	432.3

4.2 Hydraulic competence assessment

4.2.1 Cross drainage structures

The cross drainage structures were assessed and results are discussed below. They were identified by their respective chainages from the Meganagna station towards the Ayat station. For climate considerations, the design and check storms were multiplied by a - +20% respectively.

a) 1+910 Box Culvert

This was a 5m long concrete box culvert lined with masonry at the entrance and exit. The box culvert at this chainage was positioned to cross the carriage way accumulated runoff that follows through a total of 1.32km along the road and water from a small stream across the two existing infrastructures of highway and railway. The structure is being fed by two circular concrete carrier side drain pipes of diameters 750mm from both ends. The structure was found sufficient to pass the accumulated runoff but there is a likelihood of the accumulating boulders from upstream that have currently reduced the rise by 100m as shown by figure 4.3 and 4.4. Purposed, regular and constant maintenance works are required to keep the flow area of the culvert clear from any boulders, siltation and debris from the surrounding environment to reduce the likelihood of possible flooding in the near future. On addition this, a great degree of scouring is observed at the exit as tail water joins the stream which may require stream training works at the exit to improve the downstream slope for critical flow of the tail water.



Figure 4.3: Entrance of the culvert



Figure 4.4: Exit of the Culvert

b) 2+440 Culvert

This was a 2 barrel concrete box culvert lined with masonry at the entrance and exit. The box culvert at this chainage was positioned to cross the carriage way accumulated runoff that flows through a total of 360m along the road and runoff accumulated from two catchments (7 and 6) with a combined drainage area of 5.87 sq. km delivering a total of a 25-yr discharge of 108.3 cumecs across the two existing infrastructures of highway and railway with a cross-sectional length of 50meters. The structure is being fed by two circular concrete carrier side drain pipes of diameters 750mm from both ends. Figure 4.5 and 4.6 show the current status of the structure.

The structure was found sufficient to pass the accumulated runoff structurally as shown with figure 4.7 with the measurements on the design but from field measurements, one barrel was found halfway blocked with debris, siltation and municipal solid wastes as shown in figure 4.6. Therefore, due to one barrel being blocked, the structure is found hydraulically incompetent to pass the 25-yr flood at the moment from both catchments. The structure was further tested with a 50-yr check flood but it was found incompetent as shown in figure 4.8. Therefore, purposed, regular and constant dredging maintenance works are required to be done to make the culvert clear and hydraulically competent to

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

pass the 25-yr design flood but for the structure to pass the check flood of 50-yr flood, a four barrel 2.4m by 3.6m flared wingwalled box culvert with 30D to & 75 wingwall flares at the culvert entrance must be installed that will ensure safe and sustainability of the transport infrastructure as shown in figure 4.9 and 4.10.



Figure 4.5: Culvert Entrance view



Figure 4.6: Closer view of the halfway blocked barrel

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

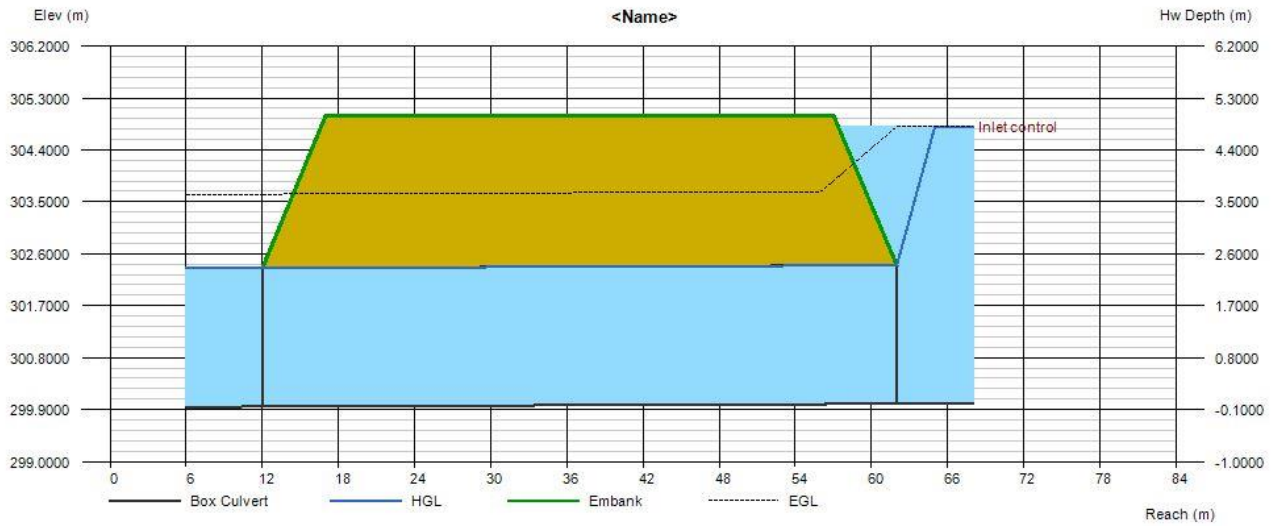


Figure 4.7: Culvert simulation with the 25-yr discharge and shows being hydraulically competent.

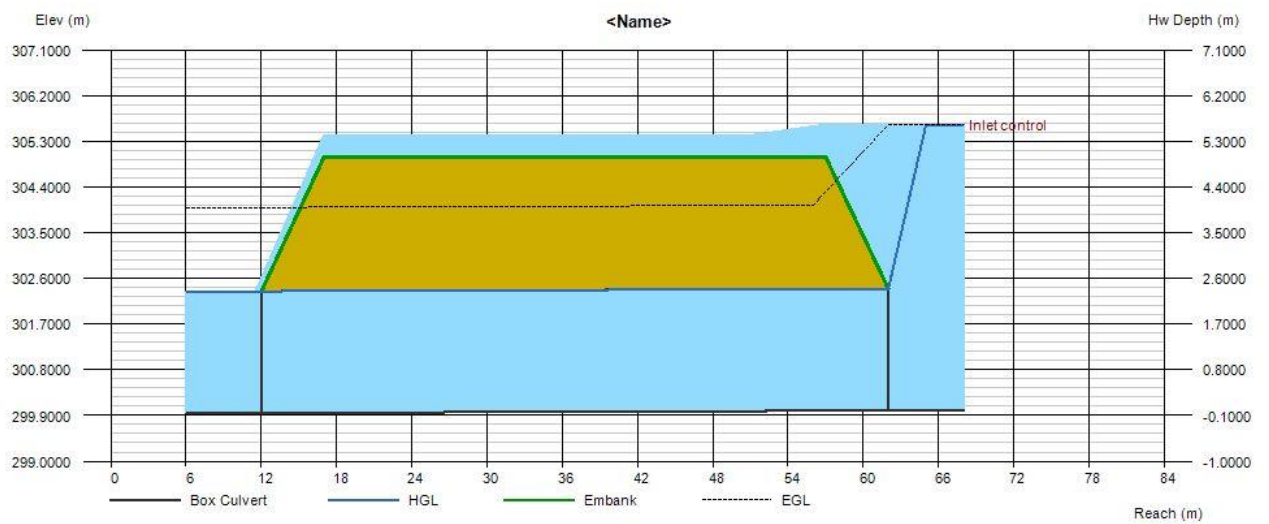


Figure 4.8: Hydraulic simulation of the culvert showing its incompetence with the check flood of 50-yr

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

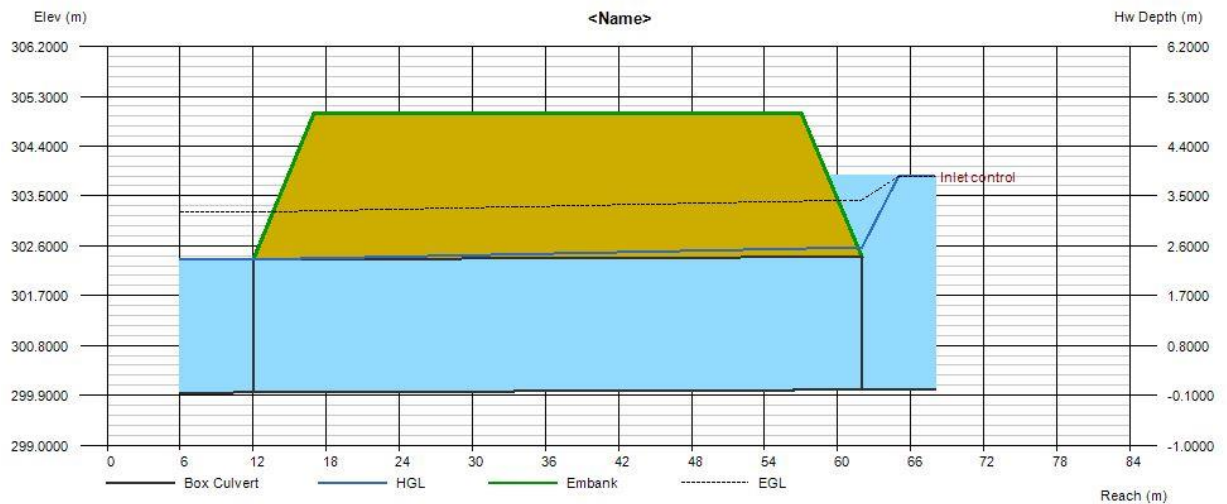


Figure 4.9: Hydraulic simulation of the culvert adjusted to 4 barrels to accommodate the check discharge of 50-yr flood.

Total (cms)	Q		Veloc		Depth		HGL
	Pipe (cms)	Over (cms)	Dn (m/s)	Up (m/s)	Dn (mm)	Up (mm)	Dn (m)
86.6400	86.6400	0.0000	2.5069	2.5069	2400.0000	2400.0000	302.3500
91.6400	91.6400	0.0000	2.6516	2.6516	2400.0000	2400.0000	302.3500
96.6400	96.6400	0.0000	2.7963	2.7963	2400.0000	2400.0000	302.3500
101.6400	101.6400	0.0000	2.9410	2.9410	2400.0000	2400.0000	302.3500
106.6400	106.6400	0.0000	3.0856	3.0856	2400.0000	2400.0000	302.3500
111.6400	111.6400	0.0000	3.2303	3.2303	2400.0000	2400.0000	302.3500
116.6400	116.6400	0.0000	3.3750	3.3750	2400.0000	2400.0000	302.3500
121.6400	121.6400	0.0000	3.5197	3.5197	2400.0000	2400.0000	302.3500
126.6400	126.6400	0.0000	3.6643	3.6643	2400.0000	2400.0000	302.3500
131.6400	131.6400	0.0000	3.8090	3.8090	2400.0000	2400.0000	302.3500
136.6400	136.6400	0.0000	3.9537	3.9537	2400.0000	2400.0000	302.3500
141.6400	141.6400	0.0000	4.0984	4.0984	2400.0000	2400.0000	302.3500

Figure 4.10: Simulation results after culvert adjustment to accommodate the check flood

c) 3+200

The bridge at 3+200 chainage was the only bridge within my case study. It was characterized by concrete piers lined with masonry works as shown in figure 4.11 and 4.12 along the pier walls. It was positioned to cross the carriage way accumulated runoff that flows through a total of 430m along the road with the runoff accumulated from catchment 5 which has a drainage area of 10.27 sq. km delivering a total of a 50-yr discharge of 357.5

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

cumecs across the two existing infrastructures of highway and railway with a cross-sectional length of 50 meters. The structure is being fed by two circular concrete carrier side drain pipes of diameters 750mm from both ends. Figure 4.11 and 4.12 show the current status of the structure. The structure was found to be hydraulically competent without any flood hazard associated to it. It was in position to convey the designed storm of 50-yr flood and it had the capacity to pass even the 100-yr check flood of 471.96 cumecs downstream without any signs of scouring and overtopping as seen in figure 4.13 and 4.14.



Figure 4.11: Bridge Hydraulic flow path



Figure 4.12: Side view of the bridge hydraulic flow path

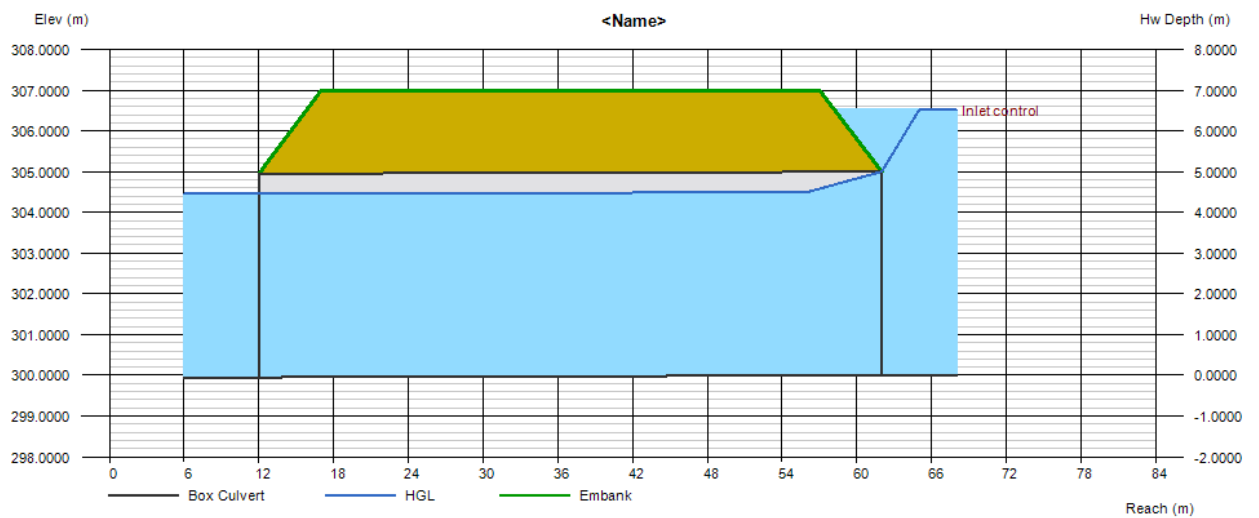


Figure 4.13: Bridge Hydraulic simulation for 100-yr flood

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Q			Veloc		Depth		HGL
Total	Pipe	Over	Dn	Up	Dn	Up	Dn
(cms)	(cms)	(cms)	(m/s)	(m/s)	(mm)	(mm)	(m)
286.0000	286.0000	0.0000	4.4177	4.4189	3236.9930	3236.0820	303.1870
296.0000	296.0000	0.0000	4.4629	4.4641	3316.2440	3315.3330	303.2663
306.0000	306.0000	0.0000	4.5141	4.5153	3389.3930	3388.4810	303.3394
316.0000	316.0000	0.0000	4.5631	4.5643	3462.5420	3461.6310	303.4126
326.0000	326.0000	0.0000	4.6101	4.6113	3535.7100	3534.7980	303.4857
336.0000	336.0000	0.0000	4.6552	4.6564	3608.8590	3607.9470	303.5589
346.0000	346.0000	0.0000	4.6985	4.6997	3682.0080	3681.0960	303.6320
355.9999	355.9999	0.0000	4.7478	4.7490	3749.0730	3748.1620	303.6991
365.9999	365.9999	0.0000	4.7878	4.7889	3822.2220	3821.3110	303.7722
375.9999	375.9999	0.0000	4.8338	4.8349	3889.2880	3888.3760	303.8393
385.9999	385.9999	0.0000	4.8707	4.8718	3962.4370	3961.5260	303.9124
395.9999	395.9999	0.0000	4.9138	4.9149	4029.4840	4028.5730	303.9795
405.9999	405.9999	0.0000	4.9554	4.9565	4096.5500	4095.6380	304.0466
415.9999	415.9999	0.0000	4.9883	4.9894	4169.6990	4168.7870	304.1197
425.9999	425.9999	0.0000	5.0274	5.0285	4236.7650	4235.8530	304.1868
435.9999	435.9999	0.0000	5.0652	5.0663	4303.8120	4302.9000	304.2538
445.9999	445.9999	0.0000	5.1019	5.1030	4370.8770	4369.9660	304.3209
455.9999	455.9999	0.0000	5.1375	5.1386	4437.9240	4437.0130	304.3879
465.9999	465.9999	0.0000	5.1720	5.1731	4504.9900	4504.0790	304.4550

Figure 4.14: Hydraulic simulation results of discharge, velocity, headwater depth and HGL.

d) 3+930 Culvert

This was a 2 barrel concrete box culvert lined with masonry at the entrance and exit wingwalls. The box culvert at this chainage was positioned to cross the carriage way accumulated runoff that flows through a total of 830m along the road and runoff accumulated catchment 4 with a drainage area of 0.83 sq. km delivering a total of a 25-yr and 50-yr discharge of 12 and 13.3 cumecs respectively across the two existing infrastructures of highway and railway with a cross-sectional length of 50meters. The structure is being fed by two circular concrete carrier side drain pipes of diameters 750mm from both ends which were found hydraulically competent to carry the carriage way runoff to the cross drainage structures. Figure 4.15 shows the current status of the structure.

The structure was found sufficient to pass the accumulated runoff structurally as shown with figure 4.16 with the measurements from field measurements, though it was found to have been over designed as shown in figure 4.16 and it was proposed that a single barrel

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

1.6 m by 2.5 m flared wingwalled box culvert with 30D to & 75 wingwall flares at the culvert entrance must be installed that will ensure safe and sustainability of the transport infrastructure as shown in figure 4.17 and 4.18. On addition, there were heaping poorly disposed municipal solid waste clinging on the piers as shown in the figure 4.15. Therefore, purposed, regular and constant dredging maintenance works are required to be done to make the culvert clear and hydraulically competent to pass the 25-yr design barrel 2.4m by 3.6m flared wingwalled box culvert with 30D to & 75 wingwall flares at the culvert entrance must be installed that will ensure safe and sustainability of the transport infrastructure as shown in figure 4.17 and 4.18.



Figure 4.15: Culvert with growing heap of municipal solid wastes around the pier

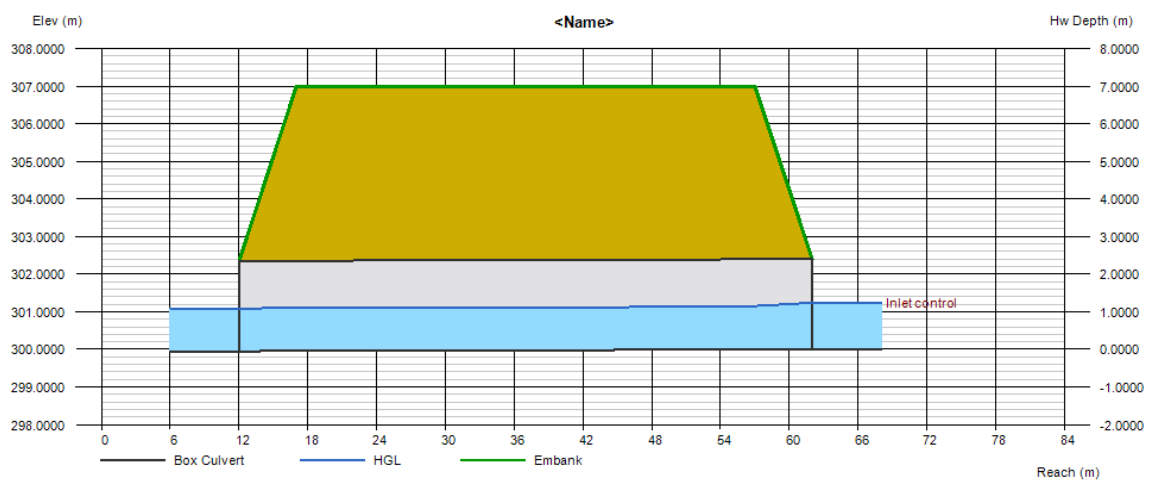


Figure 4.16: Hydraulic simulation of the culvert using the original 2 barrels with 50-yr check flood.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

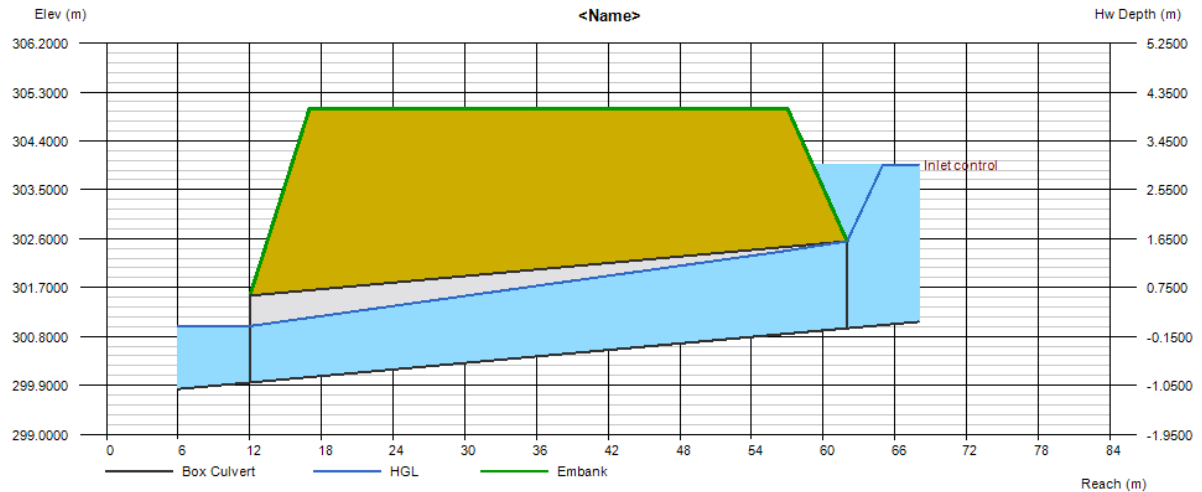


Figure 4.17: Hydraulic simulation of the culvert using the original single barrel with 50-yr check flood.

Q			Veloc		Depth		HGL
Total	Pipe	Over	Dn	Up	Dn	Up	Dn
(cms)	(cms)	(cms)	(m/s)	(m/s)	(mm)	(mm)	(m)
9.6000	9.6000	0.0000	3.4175	2.3570	390.1529	565.6957	300.3402
10.6000	10.6000	0.0000	3.5256	2.4363	417.5745	604.2794	300.3676
11.6000	11.6000	0.0000	3.6204	2.5108	445.0147	641.6724	300.3950
12.6000	12.6000	0.0000	3.7042	2.5811	472.4363	678.0051	300.4225
13.6000	13.6000	0.0000	3.8019	2.6478	496.8255	713.3890	300.4468
14.6000	14.6000	0.0000	3.8679	2.7113	524.2471	747.8985	300.4743
15.6000	15.6000	0.0000	3.9491	2.7719	548.6363	781.6453	300.4987

Figure 4.18: Hydraulic simulation results of discharge, velocity, headwater depth and HGL.

e) 4+630 Culvert

This was a 2 barrel concrete box culvert lined with masonry at the entrance and exit. The box culvert at this chainage was positioned to cross the carriage way accumulated runoff that flows through a total of 930m along the road and runoff accumulated from catchment 3 with a drainage area of 6.26 sq. km delivering a total of a 25-yr discharge of 104 cumecs across the two existing infrastructures of highway and railway with a cross-sectional length of 50meters. The structure is being fed by two circular concrete carrier side drain pipes of diameters 750mm from both ends that were found hydraulically competent. Figure 24 and 25 show the current status of the structure.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

The structure was found sufficient to pass the designed accumulated runoff with regards to the designed dimensions as shown in figure 4.21 but it could not convey the check flood of 50-yr flood safely as seen in figures 4.22 and 4.23 that it could only pass to a maximum of 88.2cumecs downstream safely without overtopping. From field surveys, one barrel has been rendered dysfunctional due to accumulated vegetation, debris, siltation and municipal solid wastes as shown in figure 4.20. Therefore, the existing structure was found hydraulically incompetent to pass the 25-yr and 50-yr flood by its current state. Therefore, purposed, regular and constant dredging maintenance works are required to be done to make the culvert clear and hydraulically competent to pass the 25-yr design flood but for the structure to pass the check flood of 50-yr flood, a three barrel 2.2m by 4.4m flared wingwalled box culvert with 30D to & 75 wingwall flares at the culvert entrance and exit must be installed that will ensure safe and sustainability of the transport infrastructure as shown in figure 4.24.



Figure 4.19: The two barrels of culvert on site



Figure 4.20: The right hand blocked barrel

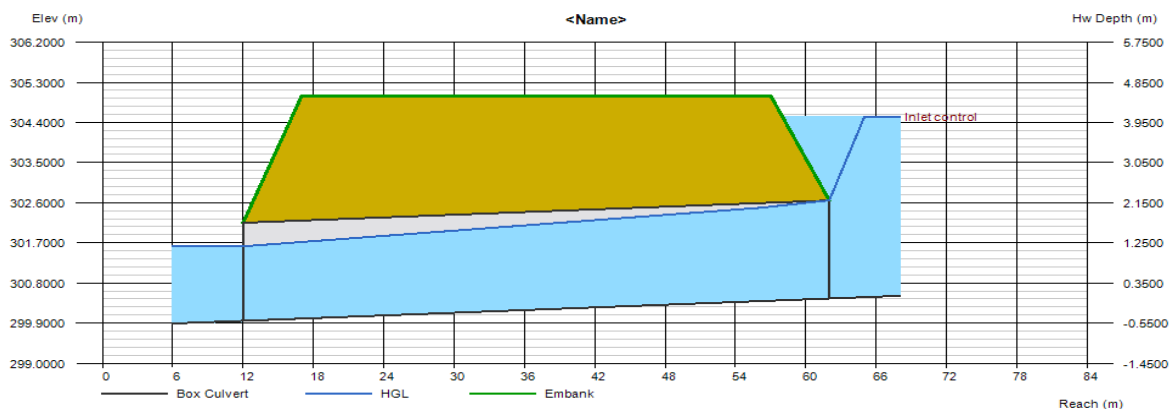


Figure 4.21: Hydraulic simulation of the culvert using the original barrel with 25-yr design flood.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

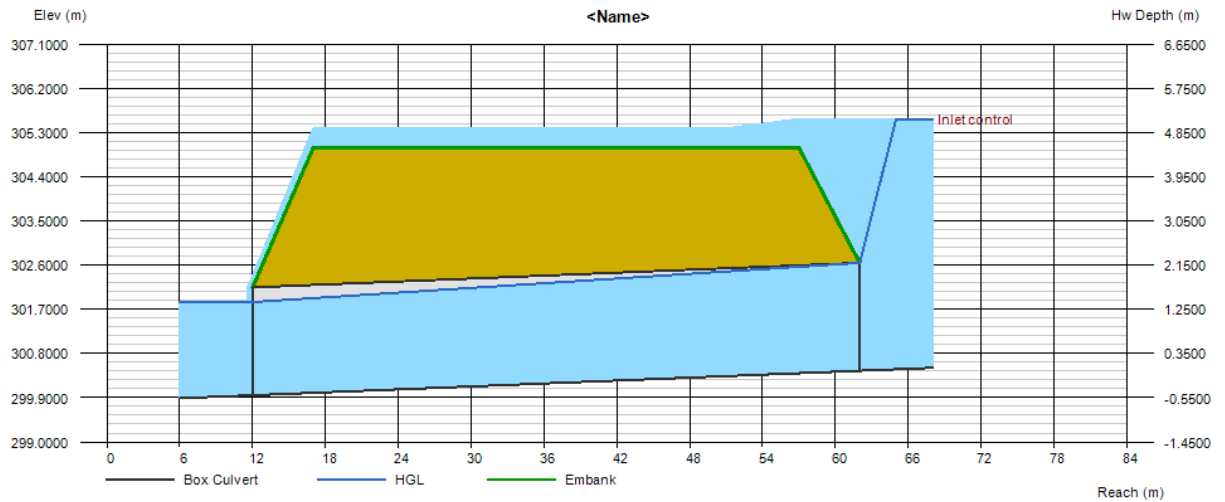


Figure 4.22: Hydraulic simulation of the culvert using the original single barrel with 50-yr design flood.

Q			Veloc		Depth		HGL
Total	Pipe	Over	Dn	Up	Dn	Up	Dn
(cms)	(cms)	(cms)	(m/s)	(m/s)	(mm)	(mm)	(m)
83.2000	83.2000	0.0000	5.9299	4.6051	1670.3170	2150.8080	301.6203
88.2000	88.2000	0.0000	6.0119	4.7727	1746.5170	2199.9960	301.6965
93.2000	92.1355	1.0645	6.0992	4.9857	1798.3270	2199.9960	301.7484
98.2000	93.6141	4.5858	6.1245	5.0657	1819.6660	2199.9960	301.7697
103.2000	94.7384	8.4616	6.1465	5.1265	1834.9020	2199.9960	301.7849
108.2000	95.7341	12.4659	6.1701	5.1804	1847.1060	2199.9960	301.7971
113.2000	96.6161	16.5839	6.1861	5.2281	1859.2910	2199.9960	301.8093
118.2000	97.5274	20.6726	6.2038	5.2774	1871.4950	2199.9960	301.8215
123.2000	98.2880	24.9120	6.2319	5.3186	1877.5780	2199.9960	301.8276
128.2000	98.9863	29.2137	6.2559	5.3564	1883.6800	2199.9960	301.8337
133.2000	99.7342	33.4657	6.2626	5.3969	1895.8660	2199.9960	301.8459
138.2000	100.4009	37.7990	6.2842	5.4329	1901.9680	2199.9960	301.8520

Figure 4.23: Hydraulic simulation results of discharge, velocity, headwater depth and HGL. for existing structure

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Q			Veloc		Depth		HGL
Total	Pipe	Over	Dn	Up	Dn	Up	Dn
(cms)	(cms)	(cms)	(m/s)	(m/s)	(mm)	(mm)	(m)
83.2000	83.2000	0.0000	5.3023	3.9598	1188.7270	1591.7350	301.1387
88.2000	88.2000	0.0000	5.3730	4.0378	1243.5890	1654.8200	301.1936
93.2000	93.2000	0.0000	5.4505	4.1128	1295.4000	1716.7140	301.2454
98.2000	98.2000	0.0000	5.5345	4.1853	1344.1780	1777.5100	301.2942
103.2000	103.2000	0.0000	5.6004	4.2553	1395.9890	1837.2830	301.3460
108.2000	108.2000	0.0000	5.6616	4.3230	1447.8000	1896.1080	301.3978
113.2000	113.2000	0.0000	5.7302	4.3888	1496.5780	1954.0200	301.4466
118.2000	118.2000	0.0000	5.7945	4.4526	1545.3380	2011.0770	301.4954
123.2000	123.2000	0.0000	5.8548	4.5146	1594.1170	2067.3530	301.5441
128.2000	128.2000	0.0000	5.9116	4.5750	1642.8760	2122.8470	301.5929
133.2000	133.2000	0.0000	5.9759	4.6339	1688.6040	2177.6350	301.6386
138.2000	138.2000	0.0000	6.0261	4.7589	1737.3640	2199.9960	301.6874

Figure 4.24: Hydraulic simulation results of discharge, velocity, headwater depth and HGL for recommended structure.

f) 5+570 and 7+350 culverts

The culverts at chainages 5+570 and 7+350 were not accessible due to their site restrictions, outgrown vegetation above the researcher’s that was rendered unhealth and dangerous due to possibility of poisonous reptiles. Therefore, under this research, they were not assessed.

A summary of the hydraulic competence assessment is shown in the table 4-6.

Table 4-6: Summary for the hydraulic competence assessment for the highway infrastructure.

S/N	Section	Start Chainage(m)	End Chainage(m)	Length (m)	Slope (%)	Description	Destination	Total Discharge (cms)		Design Discharges (cm)		Existing drainage structure				Recommendations		
								Minimum	Maximum	Minimum	Maximum	Type	Shape	No. of barrels	Dimensions (mm)		Materials	
1	I	0	1+440	1440	2	Simple drains to drain out water from carriage way runoff.						Side Drain	Circular		750	Concrete	Competent	
2	II	1+440	1+910	470	3	Simple drains to drain out water from carriageway runoff.	1+910					Side Drain	Circular		750	Concrete	Competent	
3		1+910				Cross Drainage structure is needed to drain away stormwater from carriageway and railroad.						Culvert	Box	1	1300 by 4200 by 50000 (entrance) then 1400 by 4200 by 50000 (exit)	Boulders	The structure was found hydraulically competent but with a flood risk threat due to the growing boulder accumulation at the culvert entrance. It requires regular and timely dredging works to maintain the culvert flow area.	
4	III	1+910	2+600	690	1	Simple drains to drain out water from carriage way runoff.	1+910					Side Drain	Circular		750	Concrete	Competent	
5	IV	2+600	2+440	160	4	Simple drains to drain out water from carriage way runoff.	2+440					Side Drain	Circular		750	Concrete	Competent	
6		2+440				Cross Drainage structure is needed to drain away storm water from catchment 7 & 6, carriageway and railroad runoffs		108.3	120.4	86.64	144.48	Culvert	Box	2	2400 by 3600 by 50000	Concrete	The structure was found hydraulic incompetent due to one barrel being blocked up halfway thus rendering it disfunctional. Constant and regular dredging works must be carried out to accommodate a 25-yr flood and upgraded to a 4 barrel box culvert system to accommodate the check flood of 50-yr with dimensions 2400 by 3600	
7	V	2+440	3+000	600	4.5	Simple drains to drain out water from carriage way runoff.	2+440					Side Drain	Circular		750	Concrete	Competent	
		3+000	3+200	200	3.8	Simple drains to drain out water from carriage way runoff.	3+200					Side Drain	Circular		750	Concrete	Competent	
8		3+200				Cross Drainage structure is needed to drain away storm water from catchment 5 carriageway and railroad runoffs		357.5	393.3		286	471.96	Bridge	Box	1	5000 by 20000 by 50000	Concrete	The bridge was found hydraulic competent.
9	VI	3+200	3+430	230	5.6	Simple drains to drain out water from carriage way runoff.	3+200					Side Drain	Circular		750	Concrete	Competent	
		3+430	3+930	500	3	Simple drains to drain out water from carriage way runoff.	3+930					Side Drain	Circular		750	Concrete	Competent	
10	VII	3+930				Cross Drainage structure is needed to drain away storm water from catchment 4 carriageway and railroad runoffs		12	13.3		9.6	15.96	Culvert	Box	2	2400 by 3600 by 50000	Concrete	The structure was found to have been over designed. Therefore a single barrel box culvert of 1600 by 2500 will be sufficient to pass on the design and check floods downstream. Public sensitization about municipal solid waste amnagement, dredging and contious maintenace need to be practised to keep the culvert entrance free of debris.
11	VII	3+930	4+260	330	2.5	Simple drains to drain out water from carriage way runoff.	3+930					Side Drain	Circular		750	Concrete	Competent	
12	VIII	4+260	4+630	370	3.3	Simple drains to drain out water from carriage way runoff.						Side Drain	Circular		750	Concrete	Competent	
13		4+630				Cross Drainage structure is needed to drain away storm water from catchment 3 carriageway and railroad runoffs		104	115.6		83.2	138.72	Culvert	Box	2	2200 by 4200 by 50000(300)	Concrete	The structure was found under designed, by its current state, it cant pass the runoff of 25-yr safely downstream, therefore, its recommended that its upgraded to a 3 barrel culvert system of 2200 by 4400
14	IX	4+630	5+190	560	4.1	Simple drains to drain out water from carriage way runoff.	4+630					Side Drain	Circular		750	Concrete	Competent	
15	X	5+190	5+570	380	1.2	Simple drains to drain out water from carriage way runoff.	5+570					Side Drain	Circular		750	Concrete	Competent	
16		5+570				Cross Drainage structure is needed to drain away storm water from catchment 2 carriageway and railroad runoffs		46.9	52.1	37.52	62.52	Culvert	Box	2	1700 by 3800 by 50000 (200)	Concrete	Inaccessible	
17	XI	5+570	6+450	880	3.2	Simple drains to drain out water from carriage way runoff.	5+570					Side Drain	Circular		750	Concrete	Competent	
18	XII	6+450	7+350	900	5.2	Simple drains to drain out water from carriage way runoff.	7+350					Side Drain	Circular		750	Concrete	Competent	
19		7+350				Cross Drainage structure is needed to drain away storm water from catchment 1 carriageway and railroad runoffs		41	45.7	32.8	54.84	Culverts	Box	2	1700 by 3800 by 50000 (200)	Concrete	Inaccessible	
20	XIII	7+350	7+660	310	5.4	Simple drains to drain out water from carriage way runoff.	7+350					Side Drain	Circular		750	Concrete	Competent	

4.2.2 Railroad drainage.

The railroad drainage designs were not accessible from all public offices contacted. Therefore, a simple recommendation from field work was made depending on the measured dimensions and the climate of the area. A system of transverse and longitudinal drains were recommended to effectively drive away rainfall run off from the ballast straight away to the cross drainages structures effectively. Due to the small runoff generated of 0.0535 cumecs, 30 cm diameter 20 mm-sized aggregate drains were recommended to be used in a spacing of 100 meters. These transverse drains shall be sufficient to drain the ballast runoff into the longitudinal rectangular drains. The longitudinal rectangular concrete drains from measurements were 40cm by 80m and were found competent to convey runoff from the ballast bed downstream to the cross drainage structures nearby.

The most vulnerable areas for flooding along the line were at the grade crossings especially at Level crossing one at 37N 480868.5m E 997051.54m N 2377m elevation and level crossing two at 37N 483763.3m E 997172.91m N 2391m elevation. This was caused by the interoperability difficulties between the road way grade and the railroad grade at the level crossings. The railway infrastructure was constructed over ten years later after the highway had been put in place. Therefore, with the railway track grade for light rail recommended to be not more than 0.4% by the American Railway Engineering and Maintenance-of-way Association (AREMA manual) and the road way grade recommended to be over 8%, there was need to balance the two grades at the level crossing which resulted into poor lateral drainage of the railroad resulting into carriageway runoff accumulating along the railroad thus leading to flooding of the line during heavy storms.

The figure 4.25 shows that however much water flows from all the shown four directions but it ends up into the railway track due to poor superelevation inclination which leads to flooding of the line during heavy downfalls leading to siltation and ballast fouling, thus blocking vertical drainage. The same situation was observed at level crossing two. Redesigning of both grade crossings has been recommended.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The purpose of the research was to assess the performance of the existing railway drainage structures and carry out a flood analysis of the whole railway line. Therefore through this research, the side drains, and bridge were found hydraulically competent, while culverts, some were over designed and others under designed. On the rail track, the transverse aggregate drains have been recommended, the longitudinal drains were competent while drainage at level crossings was the major cause of flooding due to the differential grades between the railway and the roadway.

5.2 Recommendation

With the railway drainage designed in order to prevent flooding and ponding on the railroad, to protect the bearing capacity of the railroad and the subgrade material and to protect the side slopes from erosion, the following recommendations have been developed from this research that has been carried out and by their Implementation, the flooding problem along the line shall have been mitigated as well as improving the drainage of the infrastructure.

Throughout the whole life time of the infrastructure, safety, sustainability and resilience of the railway infrastructure to the extreme weather events especially flooding are very core. This will only be achieved by considering railway drainage as a recognized autonomous system that contributes to the permanence of the infrastructure ominously. Therefore a railway drainage asset management policy needs to be developed with a vision to develop safe, sustainable and resilient drainage systems to enable water to flow through the railway infrastructure from points of entry to points of exit in such a way to allow earthworks, tracks and structures assets to perform in an optimal manner. The responsible authorities must comply with all legal, regulatory and environmental requirements in order by no means to compromise the safety of their personnel, customers and the public.

With the main drive being the railroad drainage, silt traps are commended to be placed along the longitudinal side quadrangular drains on the track. During operation, ballast

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

under sleepers breaks down due to the cyclic loading enforced onto it part of which becomes silt that settles down the transverse aggregate drains that lead the great percentage of it into the longitudinal drains during heavy rains. The accumulation of this siltation within the channels will lead to poor drainage of the drains. Well-spaced silt traps along the side drains can be used to amass this silt that can be scooped out during various regular maintenance practices. This will improve the useful life of the drainage infrastructure.

All culverts have been found with huge heaps of garbage, debris, siltation and boulders piled up along their piers all on the banks of the streams that reduce their designed hydraulic capacity by reducing the size of the culvert entrance that must pass the design flood from the entry point across the railway infrastructure. Regular maintenance must be carried out that involves clearing up of the entrance points so that the design purpose of these structures can be reached. Public sensitization campaigns about poor municipal solid management must be conducted so that the degree at which solids reach the streams and drainage structures is lowered to secure the public and the infrastructure from a high likelihood of flooding.

Currently from the community survey, flooding is higher along level crossings. This is caused by poor highway drainage that gives the road to have a convergent camber that makes all storm water that flows through the road wings which approach the level crossings to be drained into the railroad infrastructure thus causing flooding. A proper and competent design check with higher precision instruments is recommended to be carried out on all the three level crossings if possible redesigning the grade at these points is highly recommended to direct the highway storm water into the available drainage structures.

Through the interviews conducted by the personnel's from the ERC and AACRA, there was no evidence for existence of aggregate drains within the railroad. This makes drainage in a double track system very incompetent due to its width. Therefore, aggregate drains of smaller aggregate sizes than the available ballast sizes are recommended to be employed to protect the railroad infrastructure from flooding caused by extreme weather events that may cause ponding on its surface which may lead to compromised safety, sustainability and resilience of the railroad infrastructure.

The infrastructure under this research is a joint infrastructure that combines both highway and railroad. From the interviews conducted with AACRA officials, there was no

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

comprehensive drainage system installed during the construction of the railway line. Therefore, this suggests that the two infrastructures are independent of one another which makes rail road drainage have a dead end since it can't join the surrounding streams. Therefore for an effective drainage system, a joint railroad-highway drainage system is recommended where by all the water from the railroad joins the highway drainage along the cross drainage structures. This will ensure that all the water collected from the railroad is effectively and efficiently drained off into the municipal storm water drainage system.

REFERENCES

- [1] A. Z. Deriba, "Integrated Urban Drainage Ssystem; The Case of Ayat to Megenagna Light Rail Transit Ssystem Route," ADDIS ABABA UNIVERSITY, ADDIS ABABA, 2015.
- [2] D. S. Department, *STORMWATER MANAGEMENT MANUAL (Planning, Design and management)*, Special Adminsitrative Region: Government of the Hong Kong , 2018.
- [3] D. B. a. J. W. Davies, *Urban Drainage*, London: Spon Press of the Tylor and Francis Groupd, 2011.
- [4] A. N. a. H. L. Juha Latvala, "Problems with Railway Track Drainage in Finland," *Advances in Transportation Geotechnics*, vol. Volume 143, 2016.
- [5] A. Nurmikolu, "Degradation and frost susceptibility of crushed rock aggregates used in structural layers of railway track.," Tampere University of Technology, Tampere, 2005.
- [6] T. M. F. a. P. F. Teixeira, "Impact of different drainage solutions in the behavior of railway trackbed layers due to atmospheric actions," *World Congress on Railway research*, Lisbon, 2011.
- [7] P. F. T. C. C. L. U. F. R. Lopez Pita, "Evolution of track geometric qualities in high speed lines: ten years experience of the Madrid-Sevilla line," vol. Volume 221, no. Pg 147-155, 2007.
- [8] D. Y. Seleshi, "Engineering Hydrology," Addis Ababa Univeristy, Addis Ababa, 2005.
- [9] A. Zewdu, *Intergrated Urban Drainage System;The Case of Ayat to Magenagna Light Rail Route*, Addis Ababa: Addis Ababa University, 2015.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

- [10] O. & N. S. Dhar, Hydrometeorological aspects of Floods in India, Wagengen: The Netherlands Kluwer , 2003.
- [11] APFM, Management of flash floods: A Tool for integrated Flood Management switzerland:, W.M.O, 2012.
- [12] K. a. W. R. Smith, Floods: Physical processes and Human impacts. John Wiley and sons, Chichester, 1998.
- [13] S. P.C, Learning to live with floods: Natural Hazards and floods, Sri Lankan-Germany Development Corperation, 2006.
- [14] D. A., Assessment of flood risk in Dire Dawa toen, Eastern Ethiopia Using GIS, Addis Ababa: Addis Ababa University, 2007.
- [15] S. Burian, “Historical Perspectives of Urban Drainage,” in *Global Solutions for Urban Drainage*, 2002.
- [16] S. Burian, “Urban Wastewater Management in the United States: Past, Present, and Future,” *Journal of Urban Technology - J URBAN TECHNOL*, vol. 7, pp. 33-62, 2000.
- [17] R. K. P. K. S. M. S. K. K. Y. a. H. K. M. Manoj Kumar, Catchment delineation and morphometric analysis using geographical information system, Udaipur: IWA Publishing, 2015.
- [18] J. P. Wilson, “Digital terrain modeling. Geomorphology,” vol. 137, no. Geomorphology 137 (2012) 107–121, 2012.
- [19] s. K. J. a. O. Domingue, “Extracting Topographic Structure from Digital Elevation Data for Geographic Information System Analysis,” vol. 54, no. no. 11, 1988.
- [20] G. B. P. D. G. S. Gayathri K Devia*, “A Reviewon Hydrological Models,” in *INTERNATIONAL CONFERENCE ON WATER RESOURCES, COASTAL AND OCEAN ENGINEERING (ICWRCOE 2015)*, Karnataka, India, 2015.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

- [21] J. S. J. M. C. D. S. S. J. W. S.A. Brown, Urban Drainage Design Manual, Colorado: U.S Department of Transportation. Federal Highway Administration, 2013.
- [22] J. C. I. DOOGE, “A General Theory of the Unit Hydrograph,” *Journal for Geophysical Research*, vol. 64, no. 2, 1959.
- [23] *. M. B. G. G. Kristianto Usmana, “Railway track subgrade failure mechanisms using a fault chart approach,” *The 5th International Conference of Euro Asia Civil Engineering Forum (EACEF-5)*, no. 125 (2015) 547 – 555, 2015.
- [24] I. M. F. a. A. F. b. Cassio Paiva a, “Ballast drainage in Brazilian railway infrastructures,” *Construction and Building Materials*, no. 92 (2015) 58–63, 2015.
- [25] A. R. T. C. L. (ARTC), “Track Drainage: Design and Construction,” *Engineering Practices Manual: Civil Engineering*, 6 June 2013.
- [26] T. D. Khediya, Study of Surface and Sub Surface Highway Drainage Systems, Bhavnagar: Sir Bhavsinhji Polytechnic Institute-Bhavnagar-Gujarat, 2016.
- [27] P. A. I. Rugumayo, AN INTRODUCTION TO HYDROLOGY AND WATER RESOURCES IN UGANDA, Kampala, Uganda: Ndejje University, 2012.
- [28] B. a. R. i. R. Bobee, Correction for bias in the estimation of the coefficient of skewness., *Water Resources Research*, 1975.
- [29] M. S. C. a. S. B. Ahmad, Assessment of Flood Frequency models using EDF statistics, *Water Resources Research*, 1988.
- [30] I. o. Hydrology, Hydrological Frequency Analysis Package (HYFAP), Natural Environment Research Council, 1991.
- [31] S. D. & S. P. S. Nick Millington, The Comparison of GEV, Log-Pearson Type 3 and Gumbel Distributions in the Upper Thames river watershed under Global Climate Models, Ontario: The University of western Ontario Department of Civil and Environmental Engineering, 2011.

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

- [32] D. E. Woodward, "Time of Concentration," in *Part 630 Hydrology National Engineering Handbook*, Pennsylvania, United States Department of Agriculture (USDA), 2008.
- [33] K. K.M., Chapter 15 documentation., Washington DC: U.S. Dept. of Agriculture, Soil Conservation Service, 1964.
- [34] J. A. S. C. E. C. O Clark, *Storage and Unit Hydrograph*, California: American Society of Civil Engineers, 1852.
- [35] M. A. K. & J. L. P. Ray K. Linsley, *Hydrology for Engineers*, London, United kingdom: McGraw-Hill College Division, 1989.
- [36] W. Scharffenberg, *Hydrologic Modelling System (HEC-HMS)*, Davis: US Army Corps of Engineers- Hydrologic Engineering Center, 2016.
- [37] W. D. BROWN, *Flood-Runoff Analysis*, Washington D.C: U.S. Army Corps of Engineers, 1994.
- [38] OPW, *The Planning System and Flood Risk Management, Guidelines for Planning Authorities in Ireland*, Governmnet of Ireland, 2009.
- [39] FAO, "Land and Water," Food and Agricultural Organization of the United Nations, 12 March 2019. [Online]. Available: <http://www.fao.org/land-water/land/land-governance/land-resources-planning-toolbox/category/details/en/c/1032167/>. [Accessed 26 May 2019].
- [40] M. N. O. T. O. J. C. G. P. a. B. B. Khaliq, "Frequency analysis of sequence of dependent and/or non-stationary hydro-meteorological observations," *A review, journal of Hydrology*, no. 534-552,, 2006.
- [41] A. N. a. H. L. Juha Latvala, "Problems with Railway Track Drainage in Finland," in *Advances in Transportation Geotechnics 3*, Tampere, 2016.

APPENDIX

APPENDIX A: Time of concentration computation spreadsheet

Table A-1: Time of concentration computation spreadsheet

Catchment	Sub-basin	Sheet flow characteristics		Shallow concentrated flow characteristics		Channel flow characteristics	
		Surface description		Surface description (2-paved or 1-unpaved)		Cross-sectional flow area, a (ft ²)	
1	W20	Manning's coefficient, n	0.25	Flow Length L (ft)	4352	Wetted perimeter, Pw (ft)	20
		Flow length, L (L ≤ 100 ft)	100	Watercourse slope, s	0.1161	Hydraulic radius, r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077	Average velocity, V (Computed)	5.497581	Channel slope, s	0.0498
		Land slope	0.0656	Shallow concentrated, Tt (hours)	0.219895	Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.203294			Flow Velocity (ft/s)	11.08357
						Flow Length, (ft)	3493.864
						Channel flow, Tt (hours)	0.087564
				Time of concentration (minutes)	30.64516		
				Lag time (minutes)	18.3871		
						Storage coefficient	
2	W20	Surface description		Surface description (2-paved or 1-unpaved)	1	Cross-sectional flow area, a (ft ²)	20
		Manning's coefficient, n	0.25	Flow Length L (ft)	4451	Wetted perimeter, Pw (ft)	20
		Flow length, L (L ≤ 100 ft)	100	Watercourse slope, s	0.1083	Hydraulic radius, r	1

		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	5.31		Channel slope, s	0.0477
		Land slope	0.1312					Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.154068		Shallow concentrated , Tt (hours)	0.232864		Flow Velocity (ft/s)	10.84736
								Flow Length, (ft)	7915
								Channel flow, Tt (hours)	0.20269
								Time of concentration (minutes)	35.3773
								Lag time (minutes)	21.22638
<i>Catchment</i>	<i>Sub-basin</i>	<i>Sheet flow characteristics</i>			<i>Shallow concentrated flow characteristics</i>			<i>Channel flow characteristics</i>	
		Surface description			Surface description (2-paved or 1-unpaved)	1		Cross-sectional flow area, a (ft ²)	20
		Manning's coefficient, n	0.25		Flow Length L (ft)	4787		Wetted perimeter, Pw (ft)	20
		Flow length, L (L ≤ 100 ft)	100		Watercourse slope , s	0.0836		Hydraulic radius , r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	4.67		Channel slope, s	0.0644
		Land slope	0.1312					Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.154068		Shallow concentrated , Tt (hours)	0.285047		Flow Velocity (ft/s)	12.60399
								Flow Length, (ft)	4535
								Channel flow, Tt (hours)	0.099957
								Time of concentration (minutes)	32.34433
3	W80								

								Lag time (minutes)	19.4066
W90	Surface description			Surface description (2-paved or 1-unpaved)	1			Cross-sectional flow area, a (ft ²)	20
	Manning's coefficient, n	0.25		Flow Length L (ft)	4812			Wetted perimeter, Pw (ft)	20
	Flow length, L (L ≤ 100 ft)	100		Watercourse slope, s	0.1002			Hydraulic radius, r	1
	2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	5.11			Channel slope, s	0.0489
	Land slope	0.164		Shallow concentrated, Tt (hours)	0.261693			Manning's coefficient, n	0.03
	Sheet flow, Tt (hours)	0.140912					Flow Velocity (ft/s)	10.98	
							Flow Length, (ft)	2418	
							Channel flow, Tt (hours)	0.06115	
							Time of concentration (minutes)	27.82532	
					Lag time (minutes)	16.69519			
W110	Surface description			Surface description (2-paved or 1-unpaved)	1			Cross-sectional flow area, a (ft ²)	20
	Manning's coefficient, n	0.25		Flow Length L (ft)	5364			Wetted perimeter, Pw (ft)	20
	Flow length, L (L ≤ 100 ft)	100		Watercourse slope, s	0.0966			Hydraulic radius, r	1
	2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	5.01			Channel slope, s	0.0437

		Land slope	0.1312	Shallow concentrated , Tt (hours)	0.297145	Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.154068			Flow Velocity (ft/s)	10.38
						Flow Length, (ft)	5327
						Channel flow, Tt (hours)	0.142528
						Time of concentration (minutes)	35.62444
						Lag time (minutes)	21.37466
	W120	Surface description		Surface description (2-paved or 1-unpaved)	1	Cross-sectional flow area, a (ft ²)	20
		Manning's coefficient, n	0.25	Flow Length L (ft)	5517	Wetted perimeter, Pw (ft)	20
		Flow length, L (L ≤ 100 ft)	100	Watercourse slope , s	0.0803	Hydraulic radius , r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077	Average velocity, V (Computed)	4.57	Channel slope, s	0.0477
		Land slope	0.0984	Shallow concentrated , Tt (hours)	0.33516	Manning's coefficient, n	0.03
Sheet flow, Tt (hours)		0.172858	Flow Velocity (ft/s)			10.84736	
			Flow Length, (ft)			7915	
			Channel flow, Tt (hours)			0.20269	
			Time of concentration (minutes)			42.64243	
			Lag time (minutes)	25.58546			
<i>Catchment</i>	<i>Sub-basin</i>	<i>Sheet flow characteristics</i>	<i>Shallow concentrated flow characteristics</i>		<i>Channel flow characteristics</i>		

4	W20	Surafce description		Surface description (2-paved or 1-unpaved)	1	Cross-sectional flow area, a (ft^2)	20		
		Manning's coefficient, n	0.25		Flow Length L (ft)		6302	Wetted perimeter, Pw (ft)	20
		Flow length, L ($L \leq 100$ ft)	100		Watercourse slope , s		0.0661	Hydraulic radius , r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)		4.15	Channel slope, s	0.0423
		Land slope	0.0984		Shallow concentrated , Tt (hours)		0.421996	Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.172858					Flow Velocity (ft/s)	10.21
								Flow Length, (ft)	2373
		Channel flow, Tt (hours)	0.064518						
		Time of concentration (minutes)	39.56234						
		Lag time (minutes)	23.7374						
5	W130	Surafce description		Surface description (2-paved or 1-unpaved)	1	Cross-sectional flow area, a (ft^2)	20		
		Manning's coefficient, n	0.25		Flow Length L (ft)		100	Wetted perimeter, Pw (ft)	20
		Flow length, L ($L \leq 100$ ft)	100		Watercourse slope , s		0.1312	Hydraulic radius , r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)		5.84	Channel slope, s	0.0862
		Land slope	0.171		Shallow concentrated , Tt (hours)		0.004753	Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.138576					Flow Velocity (ft/s)	14.58

								Flow Length, (ft)	6546	
								Channel flow, Tt (hours)	0.124687	
								Time of concentration (minutes)	16.08098	
								Lag time (minutes)	9.648589	
W160	Surafce description			Surface description (2-paved or 1-unpaved)	1			Cross-sectional flow area, a (ft^2)	20	
	Manning's coefficient, n	0.25		Flow Length L (ft)	100			Wetted perimeter, Pw (ft)	20	
	Flow length, L (L ≤ 100 ft)	100		Watercourse slope , s	0.0656			Hydraulic radius , r	1	
	2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	4.13			Channel slope, s	0.0562	
	Land slope	0.1267		Shallow concentrated , Tt (hours)	0.006722			Manning's coefficient, n	0.03	
	Sheet flow, Tt (hours)	0.156234							Flow Velocity (ft/s)	11.77
									Flow Length, (ft)	6719
									Channel flow, Tt (hours)	0.158518
								Time of concentration (minutes)	19.28847	
								Lag time (minutes)	11.57308	
W220	Surafce description			Surface description (2-paved or 1-unpaved)	1			Cross-sectional flow area, a (ft^2)	20	
	Manning's coefficient, n	0.25		Flow Length L (ft)	-100			Wetted perimeter, Pw (ft)	20	

		Flow length, L ($L \leq 100$ ft)	100		Watercourse slope , s	0.0984		Hydraulic radius , r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	5.06		Channel slope, s	0.0646
		Land slope	0.1307					Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.154304		Shallow concentrated , Tt (hours)	-0.00549		Flow Velocity (ft/s)	12.62
								Flow Length, (ft)	11187
								Channel flow, Tt (hours)	0.246169
								Time of concentration (minutes)	23.69909
								Lag time (minutes)	14.21945
Catchment	Sub-basin	Sheet flow characteristics			Shallow concentrated flow characteristics			Channel flow characteristics	
		Surafce description			Surface description (2-paved or 1-unpaved)	1		Cross-sectional flow area, a (ft ²)	20
		Manning's coefficient, n	0.25		Flow Length L (ft)	4928		Wetted perimeter, Pw (ft)	20
		Flow length, L ($L \leq 100$ ft)	100		Watercourse slope , s	0.0652		Hydraulic radius , r	1
		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	4.12		Channel slope, s	0.0844
		Land slope	0.0984					Manning's coefficient, n	0.03
		Sheet flow, Tt (hours)	0.172858		Shallow concentrated , Tt (hours)	0.332256		Flow Velocity (ft/s)	14.43
								Flow Length, (ft)	8277
								Channel flow, Tt (hours)	0.159343

								Time of concentration (minutes)	39.86743
								Lag time (minutes)	23.92046
7	W80	Surafce description		Surface description (2-paved or 1-unpaved)	1	Cross-sectional flow area, a (ft^2)	20		
		Manning's coefficient, n	0.25	Flow Length L (ft)	5590	Wetted perimeter, Pw (ft)	20		
		Flow length, L (L ≤ 100 ft)	100	Watercourse slope , s	0.115	Hydraulic radius , r	1		
		2-yr 24-hour rainfall, P2 (inches)	1.8077	Average velocity, V (Computed)	5.47	Channel slope, s	0.0844		
		Land slope	0.2953	Shallow concentrated , Tt (hours)	0.283781	Manning's coefficient, n	0.03		
		Sheet flow, Tt (hours)	0.111373			Flow Velocity (ft/s)	14.43		
					Flow Length, (ft)	8277			
					Channel flow, Tt (hours)	0.159343			
					Time of concentration (minutes)	33.26983			
					Lag time (minutes)	19.9619			
	W90	Surafce description		Surface description (2-paved or 1-unpaved)	1	Cross-sectional flow area, a (ft^2)	20		
		Manning's coefficient, n	0.25	Flow Length L (ft)	4900	Wetted perimeter, Pw (ft)	20		
		Flow length, L (L ≤ 100 ft)	100	Watercourse slope , s	0.1306	Hydraulic radius , r	1		

		2-yr 24-hour rainfall, P2 (inches)	1.8077		Average velocity, V (Computed)	5.83		Channel slope, s	0.0607								
		Land slope	0.0656		Shallow concentrated , Tt (hours)	0.233429		Manning's coefficient, n	0.03								
		Sheet flow, Tt (hours)	0.203294					Flow Velocity (ft/s)	12.24								
								Flow Length, (ft)	2971								
								Channel flow, Tt (hours)	0.067433								
								Time of concentration (minutes)	30.24937								
								Lag time (minutes)	18.14962								
								W100		Surface description			Surface description (2-paved or 1-unpaved)	1		Cross-sectional flow area, a (ft ²)	20
										Manning's coefficient, n	0.25		Flow Length L (ft)	3740		Wetted perimeter, Pw (ft)	20
Flow length, L (L ≤ 100 ft)	100	Watercourse slope , s	0.0974	Hydraulic radius , r			1										
2-yr 24-hour rainfall, P2 (inches)	1.8077	Average velocity, V (Computed)	5.04	Channel slope, s	0.0306												
Land slope	0.1969	Shallow concentrated , Tt (hours)	0.206344	Manning's coefficient, n	0.03												
Sheet flow, Tt (hours)	0.130975			Flow Velocity (ft/s)	8.69												
				Flow Length, (ft)	3430												
				Channel flow, Tt (hours)	0.109663												
				Time of concentration (minutes)	26.81891												
				Lag time (minutes)	16.09135												

APPENDIX B: Hyetographs for different gages in the project area

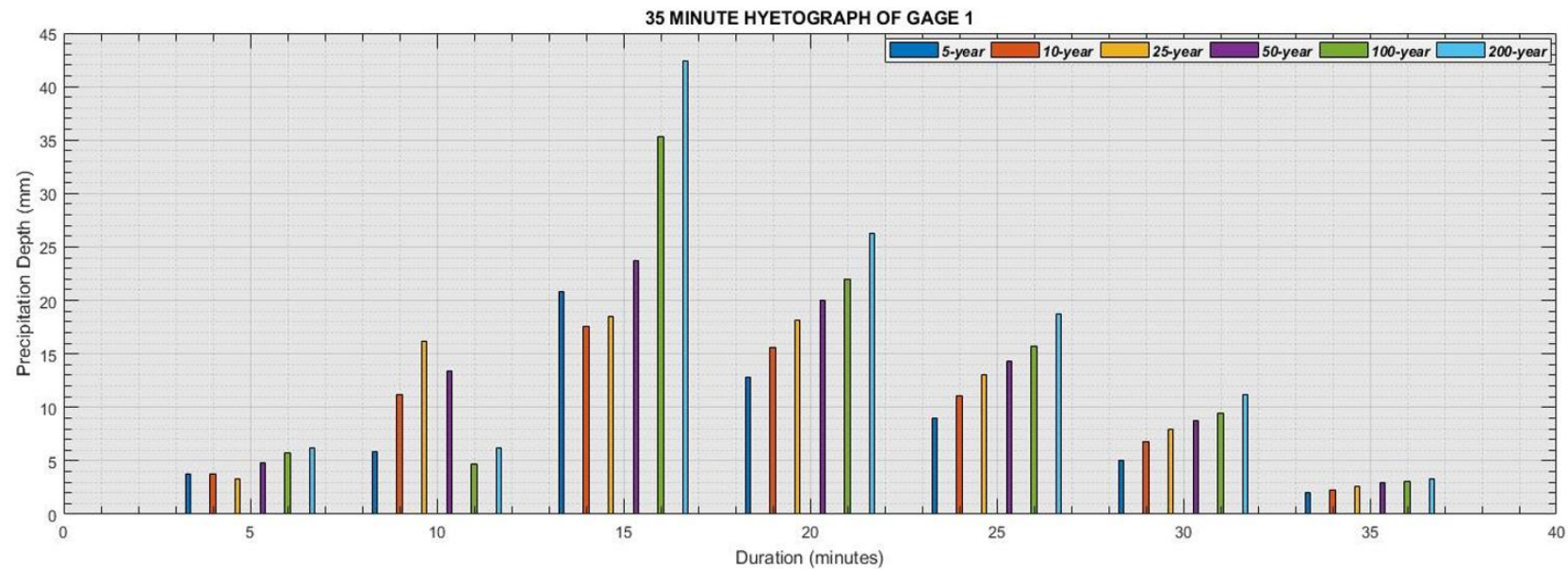


Figure B.1: Annual daily 35-Minute Hyetograph of Gage 1

**FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF
MEGANAGNA-AYAT LINE**

Table B-1: Annual daily 35-Minute Hyetograph of Gage 1

<i>Time (min)</i>	<i>Precipitation depths (mm)</i>					
<i>Return periods</i>	<i>5-year</i>	<i>10-year</i>	<i>25-year</i>	<i>50-year</i>	<i>100-year</i>	<i>200-year</i>
0	0.00	0.00	0.00	0.00	0.00	0.00
5	3.80	3.75	3.28	4.85	5.75	6.25
10	5.80	11.25	16.18	13.35	4.75	6.25
15	-4.58	-11.41	-15.25	-13.48	-5.21	-6.19
20	12.85	15.60	18.20	20.00	21.95	26.25
25	8.95	11.10	13.10	14.35	15.75	18.75
30	5.09	6.75	7.95	8.80	9.40	11.25
35	2.00	2.25	2.60	2.95	3.10	3.75
TOTAL PRECIPITATION DEPTH (mm)	33.90	39.29	46.06	50.82	55.49	66.31

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

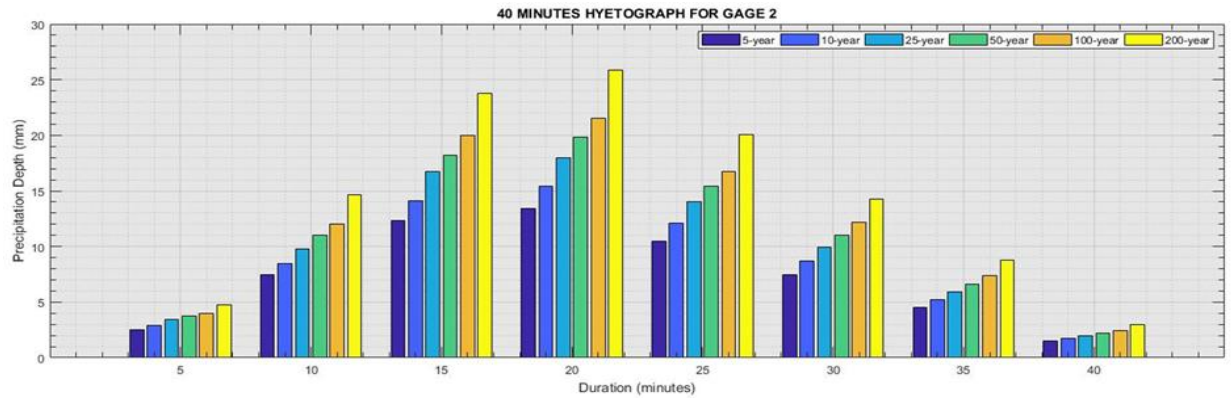


Figure B.2: Annual daily 40-Minute Hyetograph of Gage 2

Table B-2: Annual daily 40-Minute Hyetograph of Gage 2

<i>Time (min)</i>	<i>Precipitation depths (mm)</i>					
<i>Return periods</i>	<i>5-year</i>	<i>10-year</i>	<i>25-year</i>	<i>50-year</i>	<i>100-year</i>	<i>200-year</i>
0	0.00	0.00	0.00	0.00	0.00	0.00
5	2.50	2.93	3.45	3.78	4.00	4.75
10	7.50	8.48	9.75	11.03	12.00	14.65
15	12.35	14.10	16.73	18.20	20.00	23.80
20	13.45	15.40	17.98	19.85	21.50	25.90
25	10.50	12.10	14.00	15.45	16.73	20.05
30	7.50	8.70	9.95	11.00	12.18	14.30
35	4.50	5.25	5.95	6.60	7.40	8.75
40	1.50	1.75	2.00	2.20	2.45	3.00

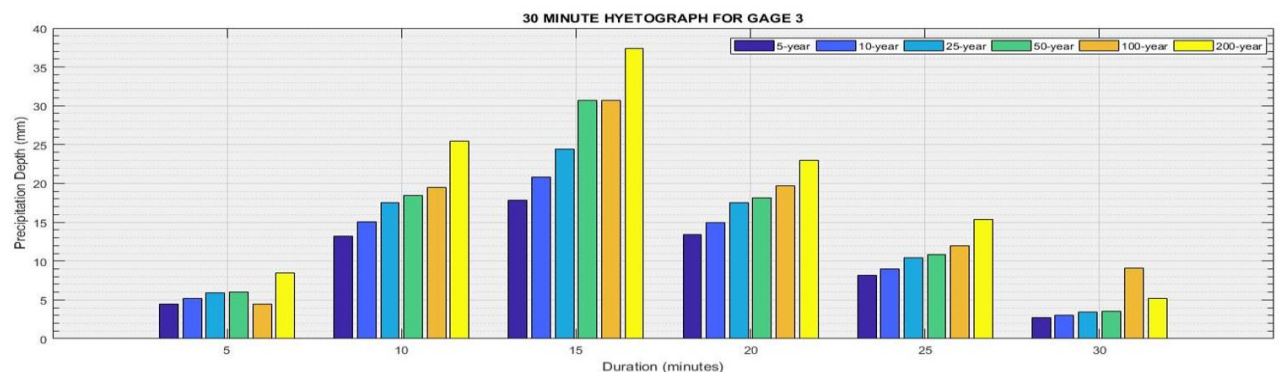


Figure B.3: Annual daily 30-Minute Hyetograph of Gage 3

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

Table B-3: Annual daily 30-Minute Hyetograph of Gage 3

<i>Time (min)</i>	<i>Precipitation depths (mm)</i>					
<i>Return periods</i>	<i>5-year</i>	<i>10-year</i>	<i>25-year</i>	<i>50-year</i>	<i>100-year</i>	<i>200-year</i>
0	0.00	0.00	0.00	0.00	0.00	0.00
5	4.50	5.20	5.95	6.05	4.50	8.50
10	13.25	15.10	17.55	18.45	19.50	25.50
15	-14.81	20.84	24.42	30.67	-19.52	37.34
20	13.40	15.00	17.50	18.15	19.65	23.03
25	8.13	9.00	10.45	10.80	11.95	15.35
30	2.68	3.00	3.45	3.50	9.10	5.18

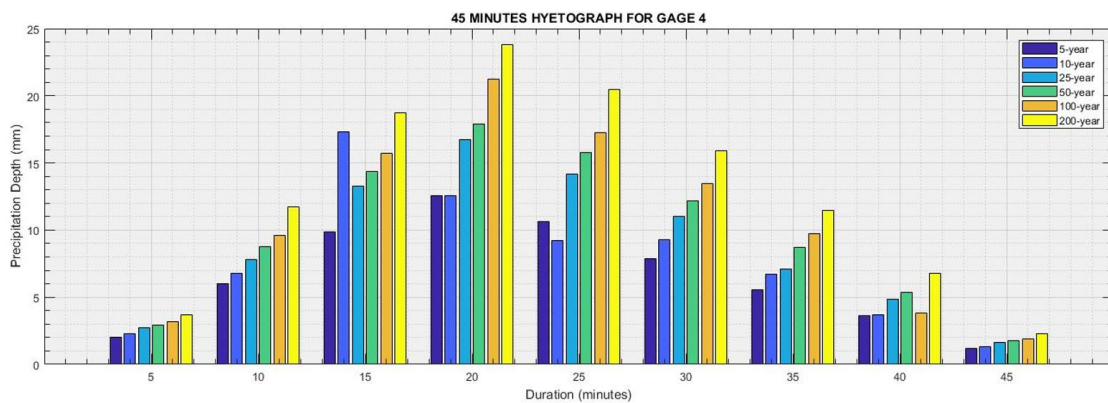


Figure B.4: Annual daily 45-Minute Hyetograph of Gage 4

Table B-4: Annual daily 45-Minute Hyetograph of Gage 4

<i>Time (min)</i>	<i>Precipitation depths (mm)</i>					
<i>Return periods</i>	<i>5-year</i>	<i>10-year</i>	<i>25-year</i>	<i>50-year</i>	<i>100-year</i>	<i>200-year</i>
0	0.00	0.00	0.00	0.00	0.00	0.00
5	2.00	1.25	2.70	2.95	3.20	3.68
10	6.00	6.75	7.80	8.80	9.60	11.73
15	9.85	17.34	13.28	14.35	15.70	18.73
20	12.54	12.57	16.75	17.88	21.21	23.81
25	10.65	9.25	14.20	15.75	17.25	20.45
30	7.89	9.29	11.00	12.20	13.45	15.90
35	5.54	6.70	7.09	8.70	9.75	11.45
40	3.61	3.69	4.85	5.25	3.80	6.80
45	1.20	1.30	1.65	1.75	1.90	2.25

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

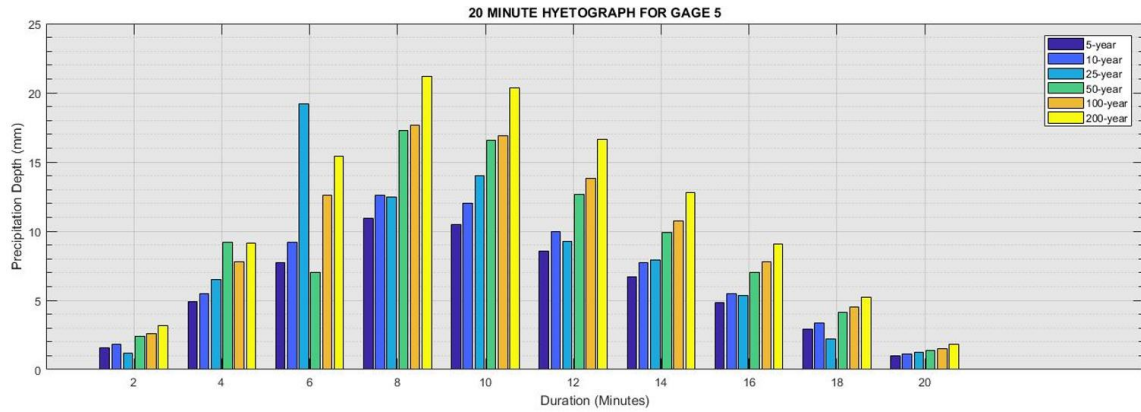


Figure B.5: Annual daily 20-Minute Hyetograph of Gage 5

Table B-5: Annual daily 20-Minute Hyetograph of Gage 5

<i>Time (min)</i>	<i>Precipitation depths (mm)</i>					
<i>Return periods</i>	<i>5-year</i>	<i>10-year</i>	<i>25-year</i>	<i>50-year</i>	<i>100-year</i>	<i>200-year</i>
0	0.00	0.00	0.00	0.00	0.00	0.00
2	1.60	1.80	1.20	2.40	2.60	3.20
4	4.90	5.50	6.50	9.20	7.76	9.16
6	7.75	9.20	19.20	7.00	12.59	15.39
8	10.92	12.58	12.50	17.26	17.64	21.19
10	10.45	12.05	14.00	16.58	16.90	20.35
12	8.58	9.95	9.24	12.65	13.80	16.65
14	6.73	7.70	7.90	9.93	10.75	12.80
16	4.83	5.50	5.35	7.04	7.80	9.10
18	2.93	3.35	2.18	4.16	4.52	5.20
20	1.00	1.10	1.25	1.40	1.50	1.85

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

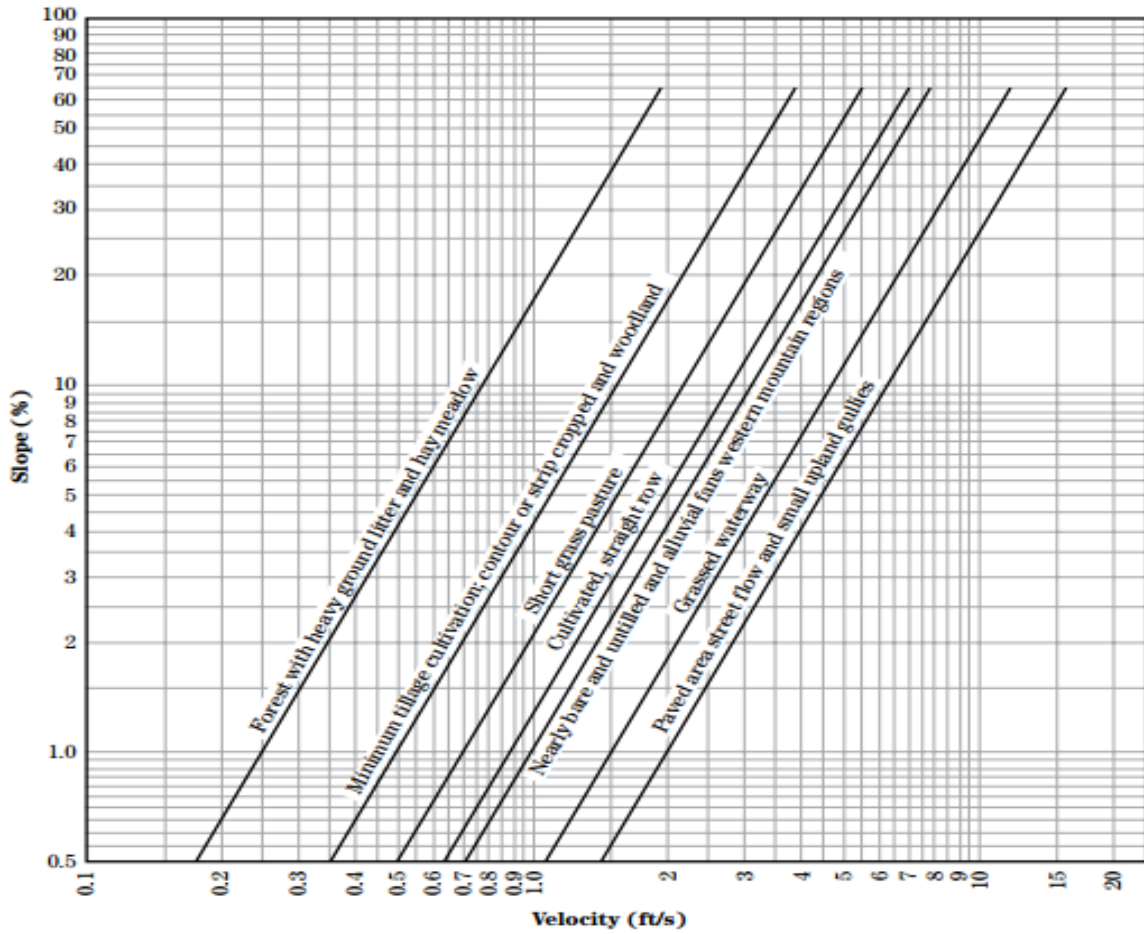


Figure B.6: Velocity versus slope for shallow concentrated flow

APPENDIX C: Generated hydrographs from each watershed along the railway infrastructure

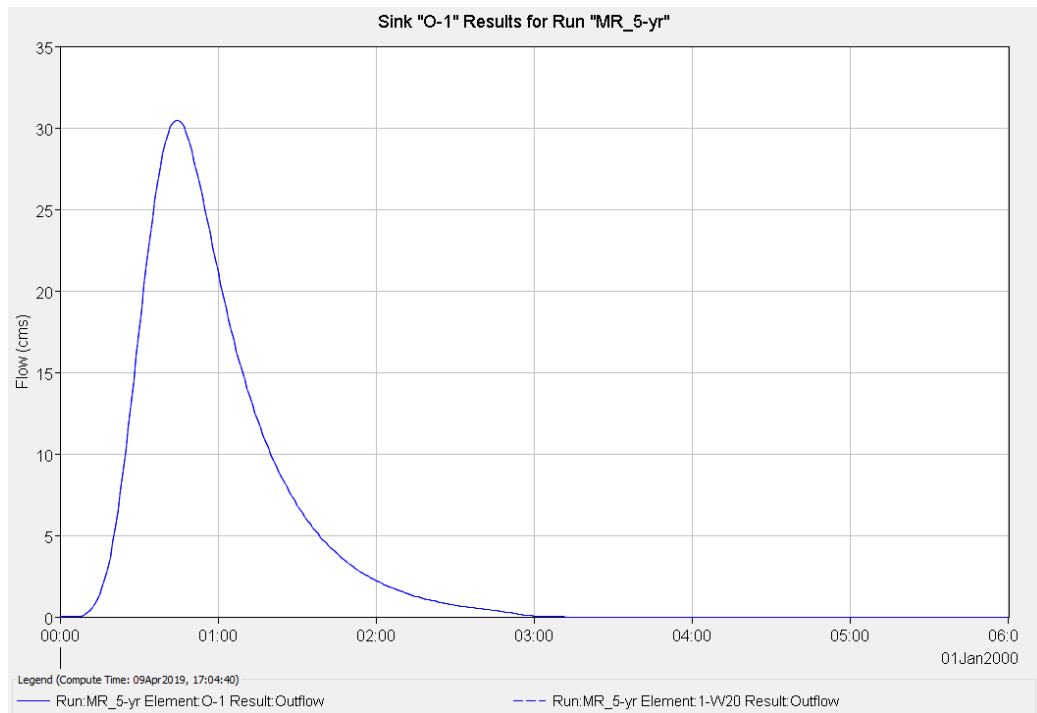


Figure C.1: 5-yr Hydrograph for drainage point 1

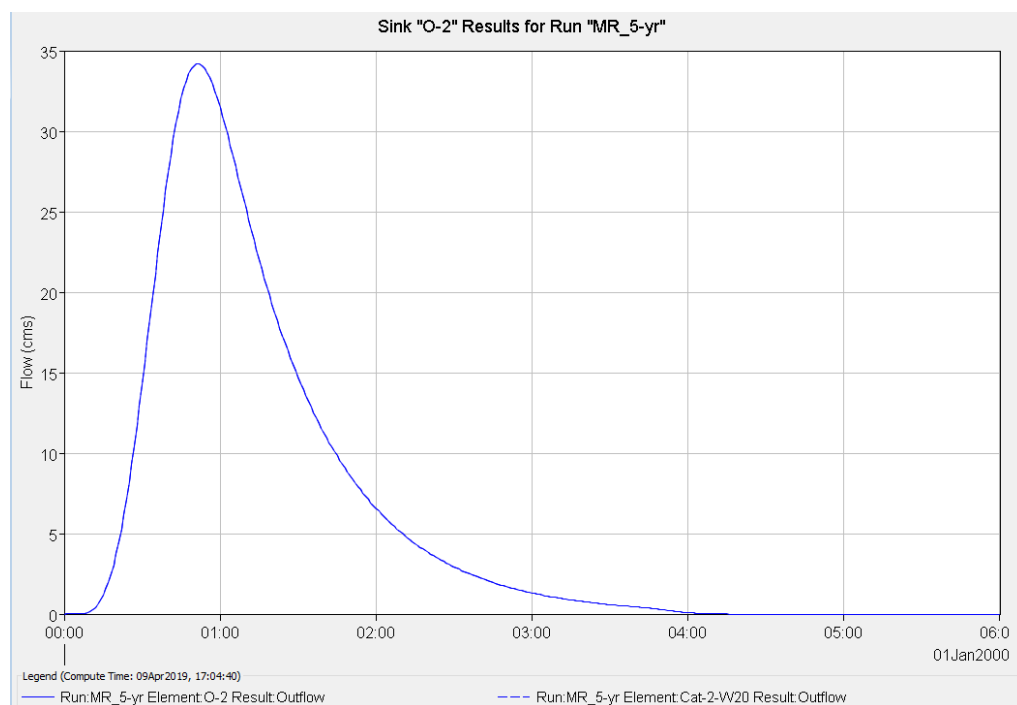


Figure C.2: 5-yr Hydrograph for drainage point 2

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

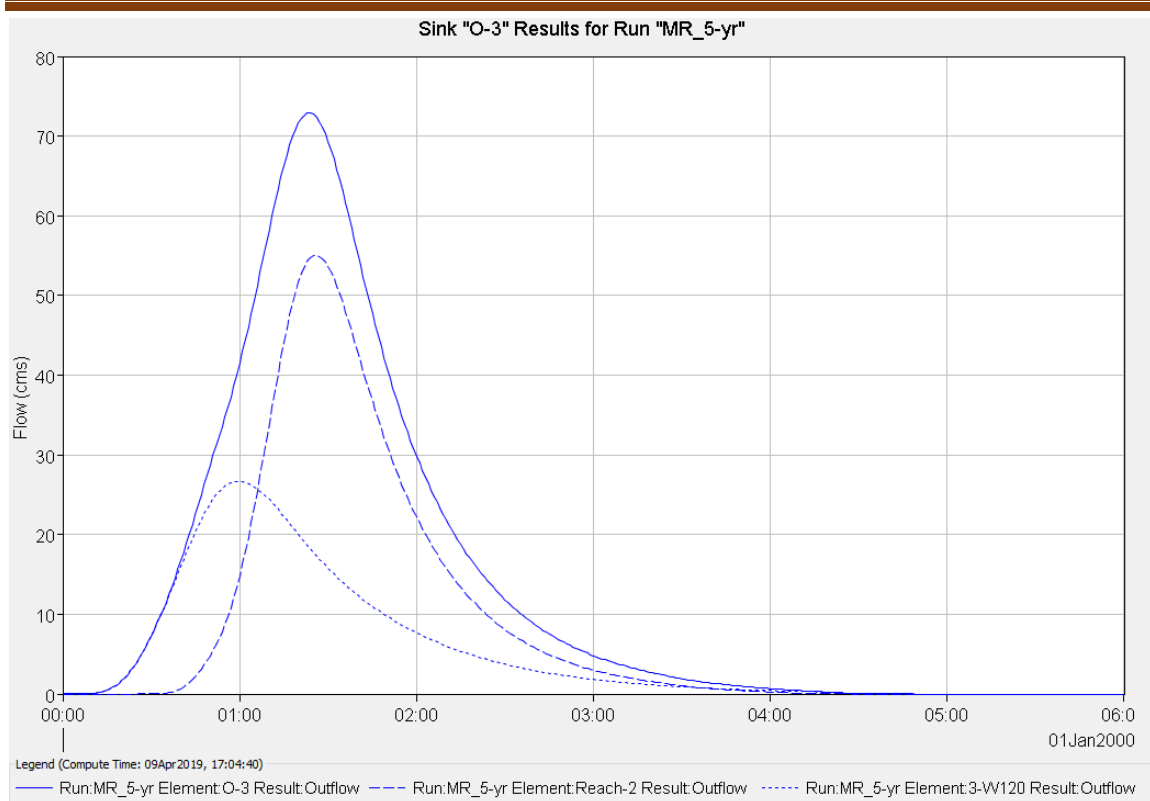


Figure C.3: 5-yr Hydrograph for drainage point 3

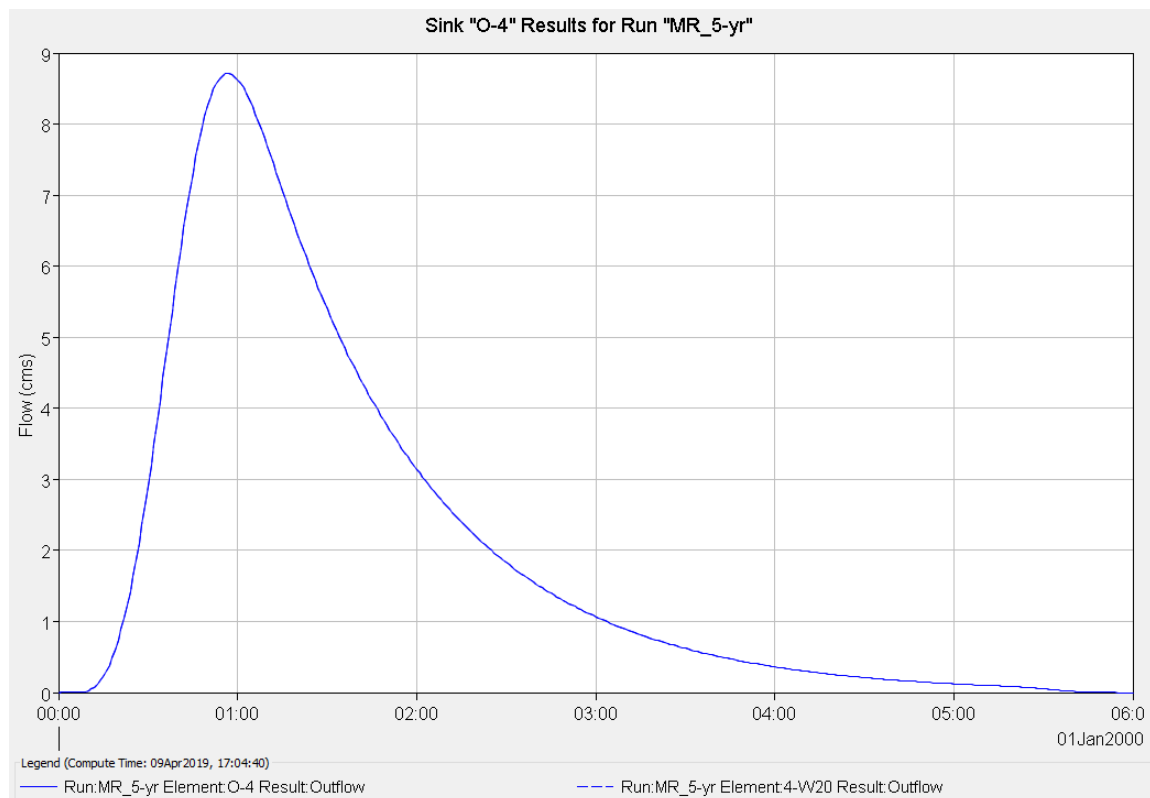


Figure C.4: 5-yr Hydrograph for drainage point 4

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

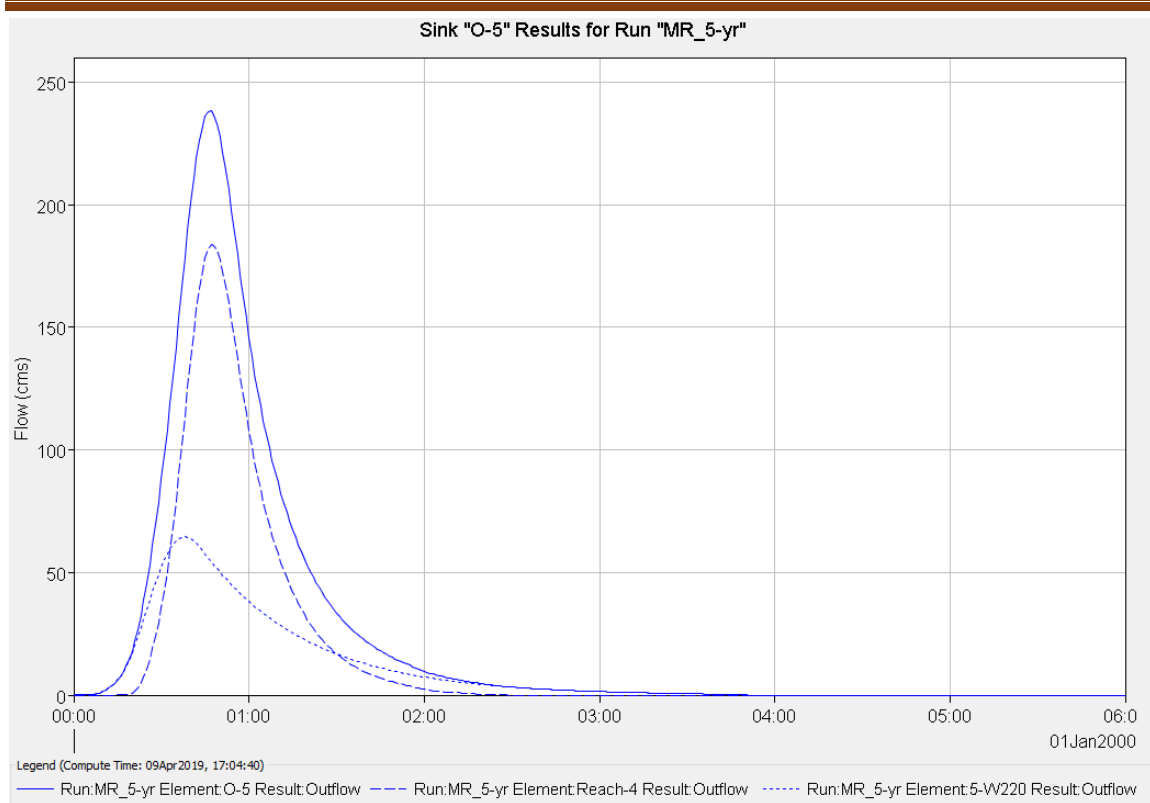


Figure C.5: 5-yr Hydrograph for drainage point 5

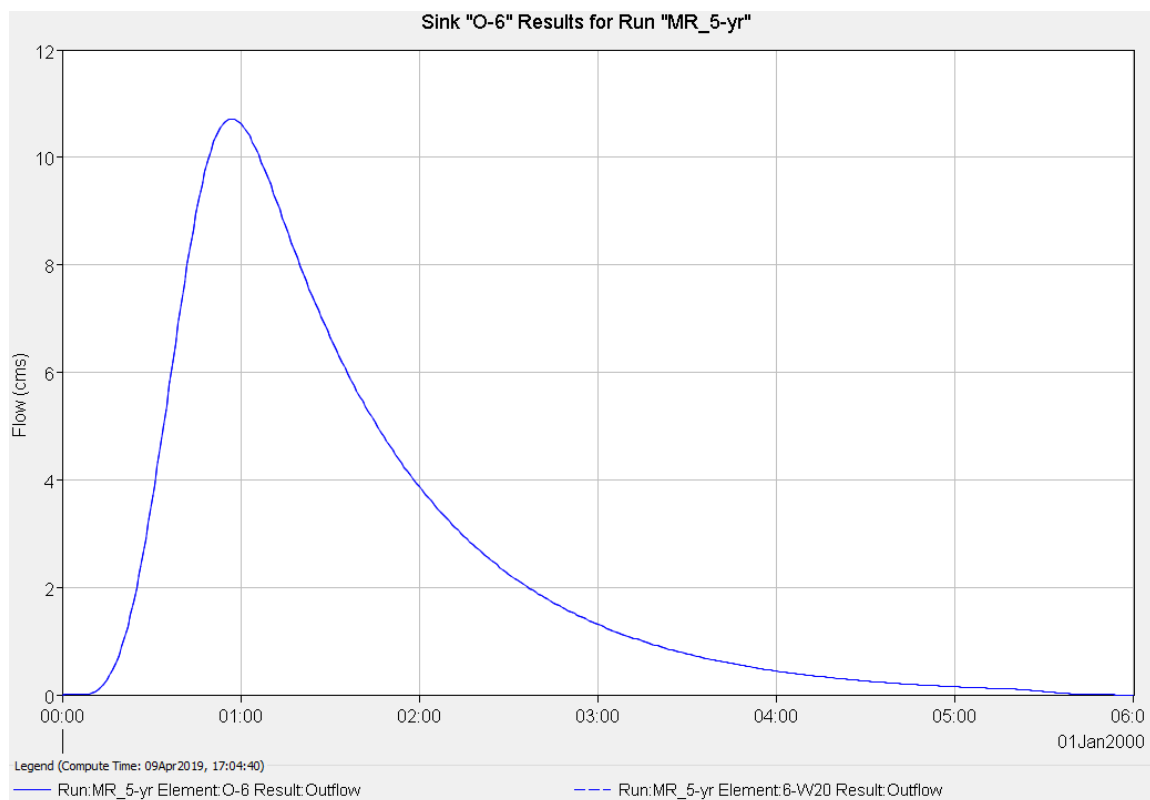


Figure C.6: 5-yr Hydrograph for drainage point 6

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

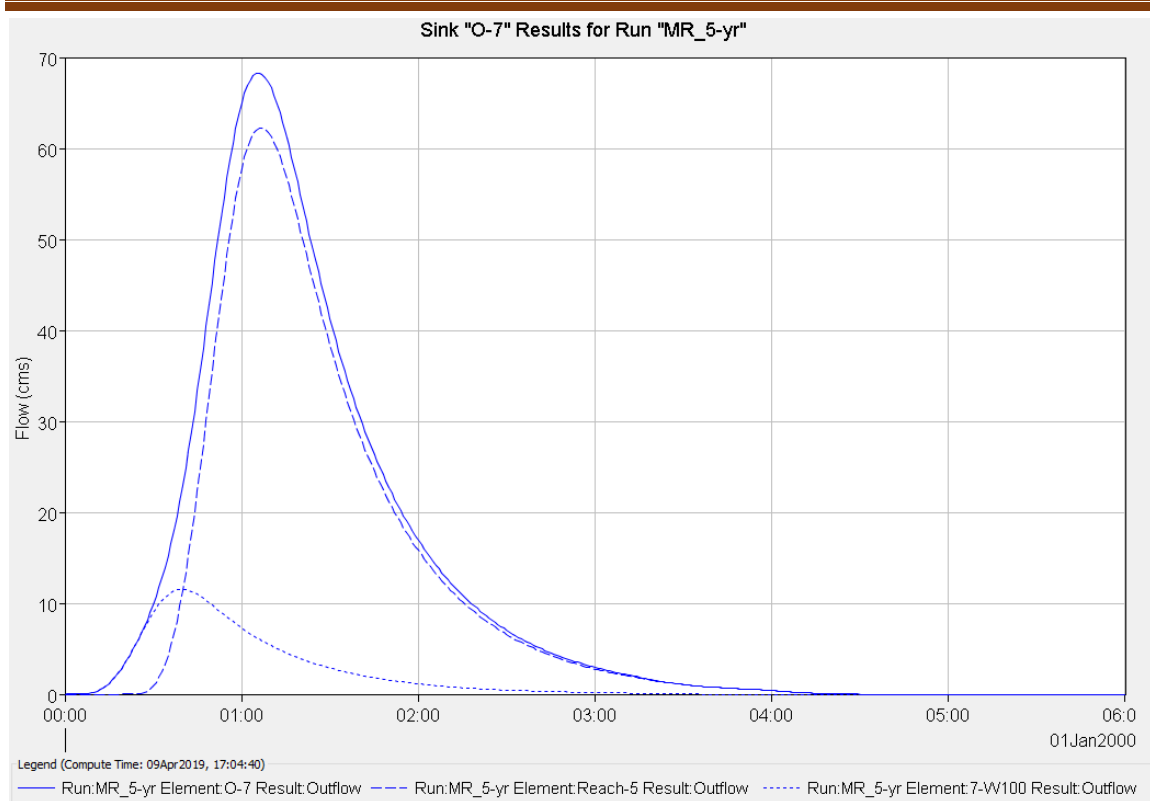


Figure C.7: 5-yr Hydrograph for drainage point 7

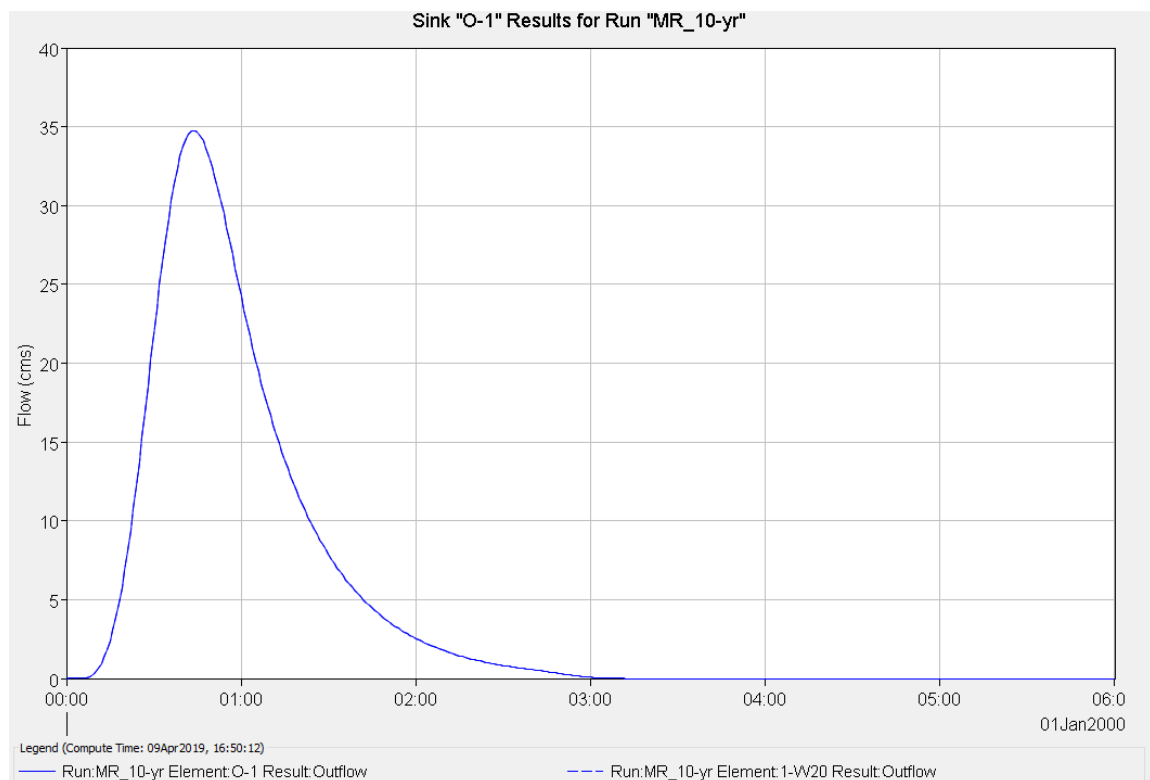


Figure C.8: 10-yr Hydrograph for drainage point 1

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

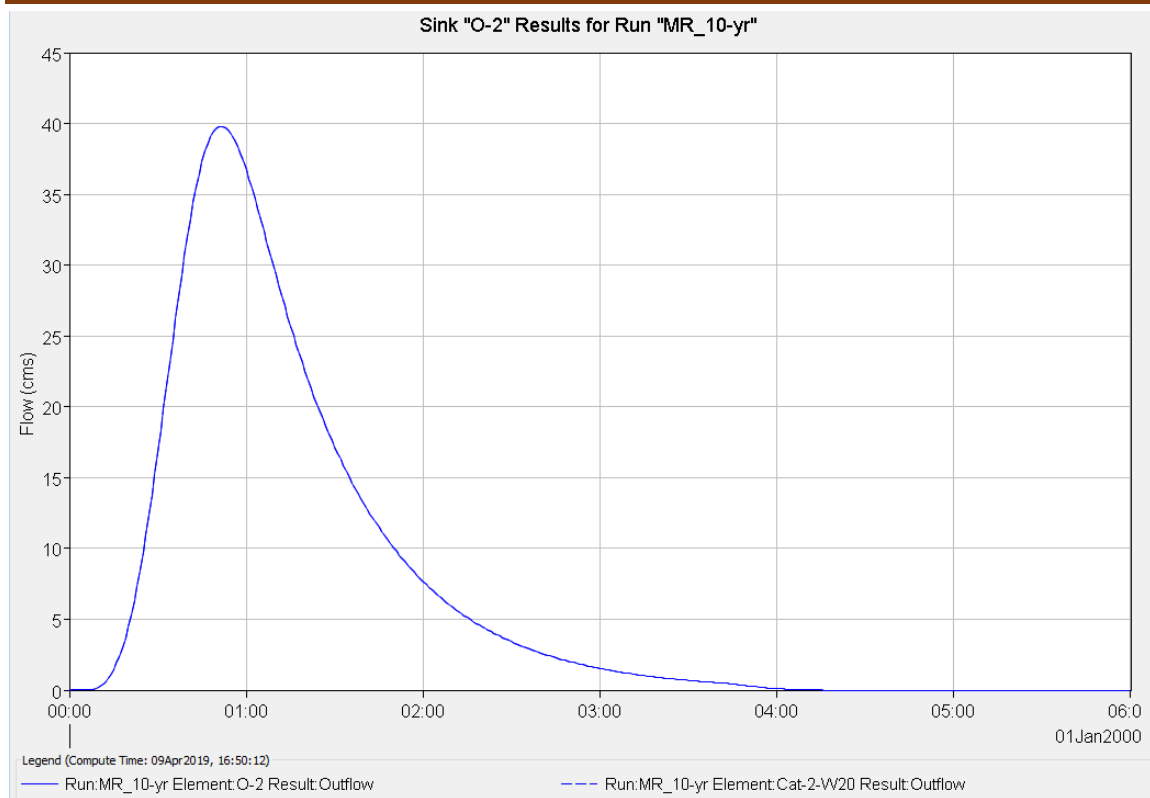


Figure C.9: 10-yr Hydrograph for drainage point 2

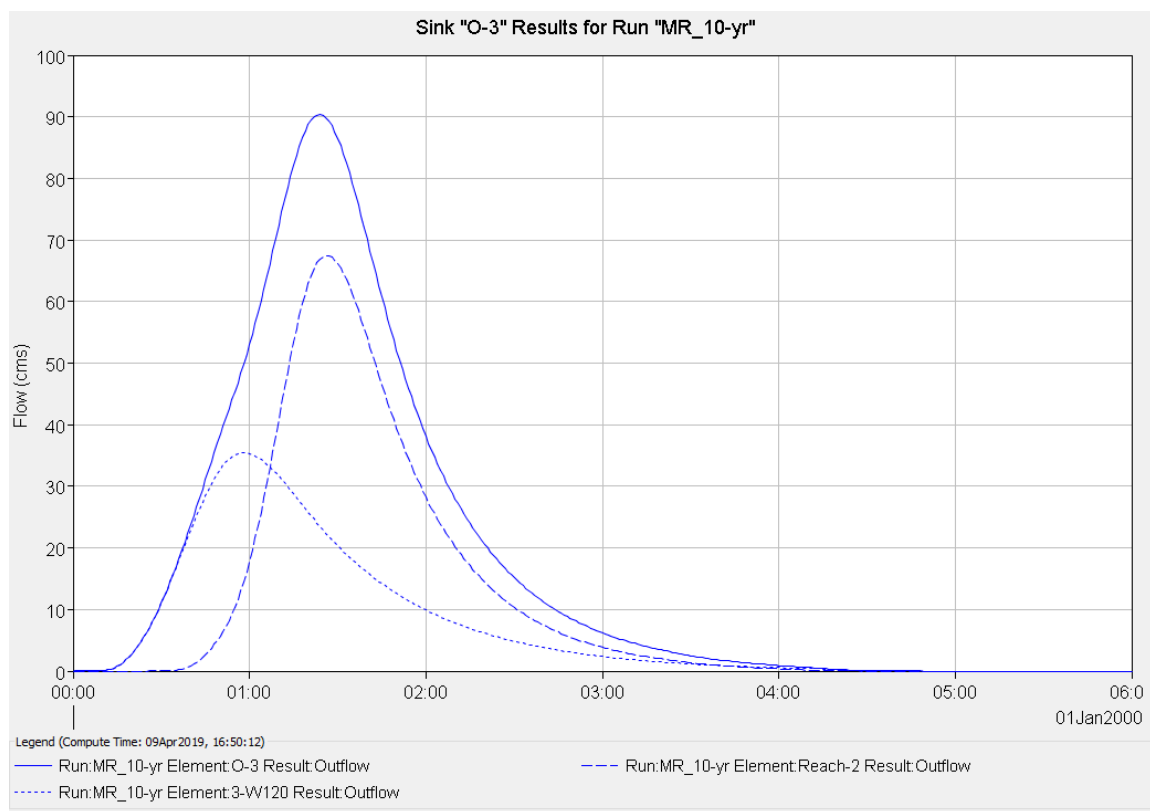


Figure C.10: 10-yr Hydrograph for drainage point 3

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

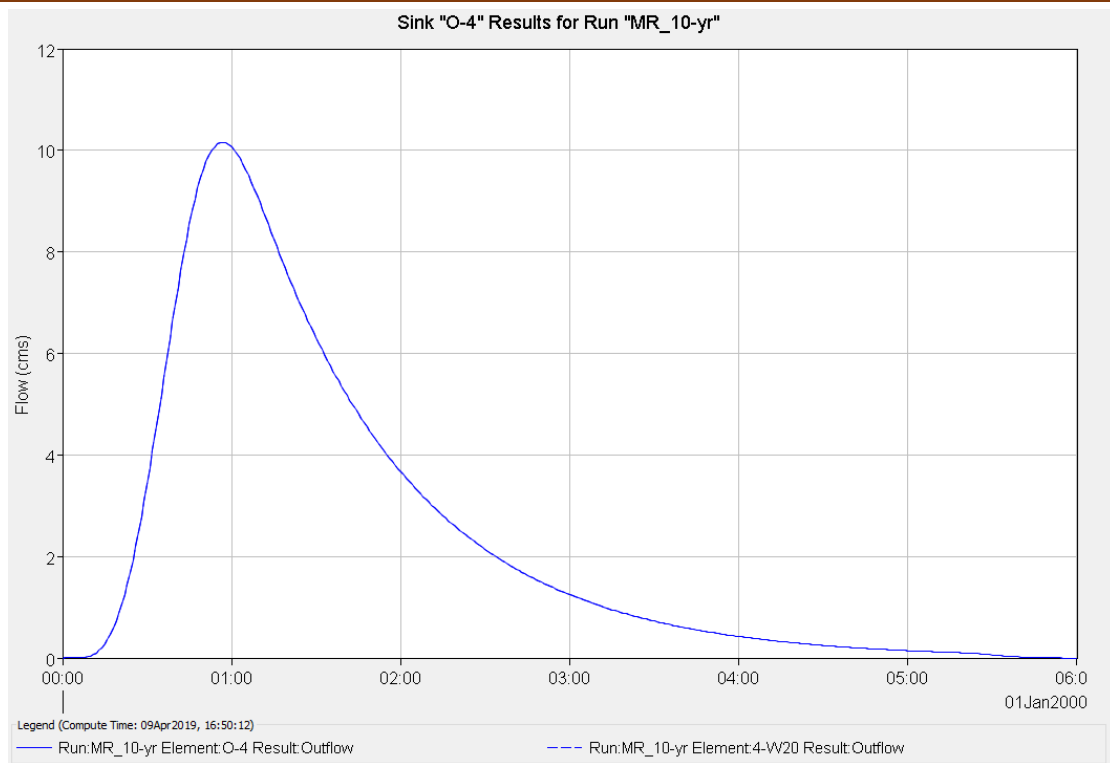


Figure C. 11: 10-yr hydrograph for drainage point 4

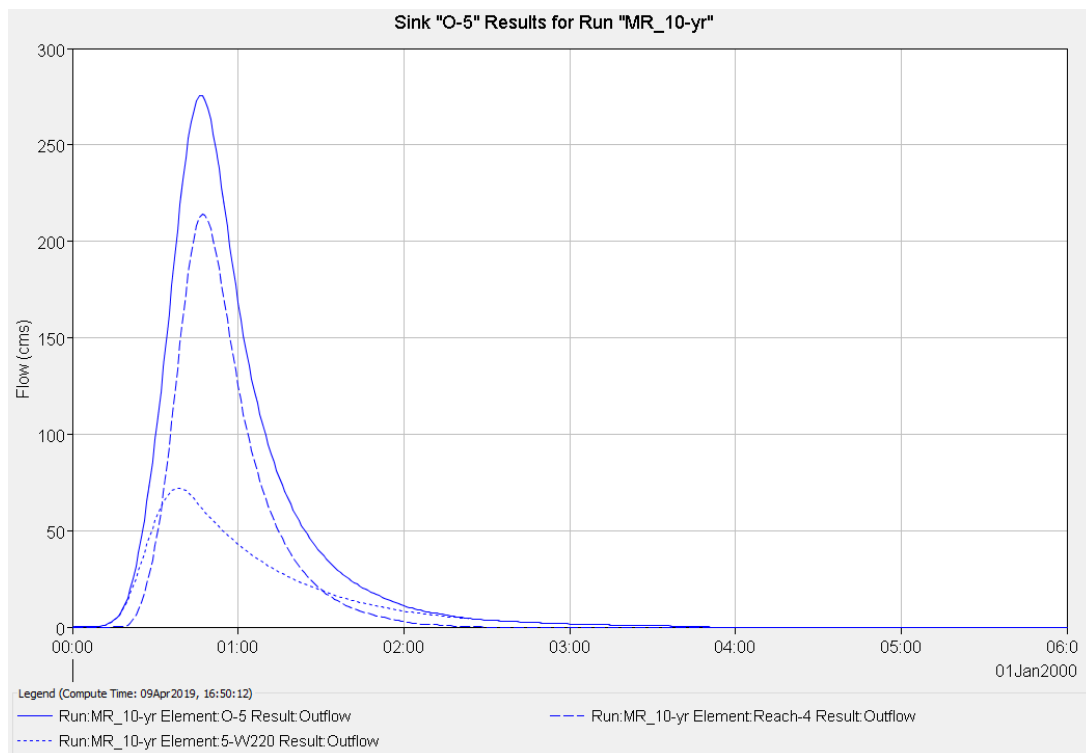


Figure C.12: 10-yr hydrograph for drainage point 5

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

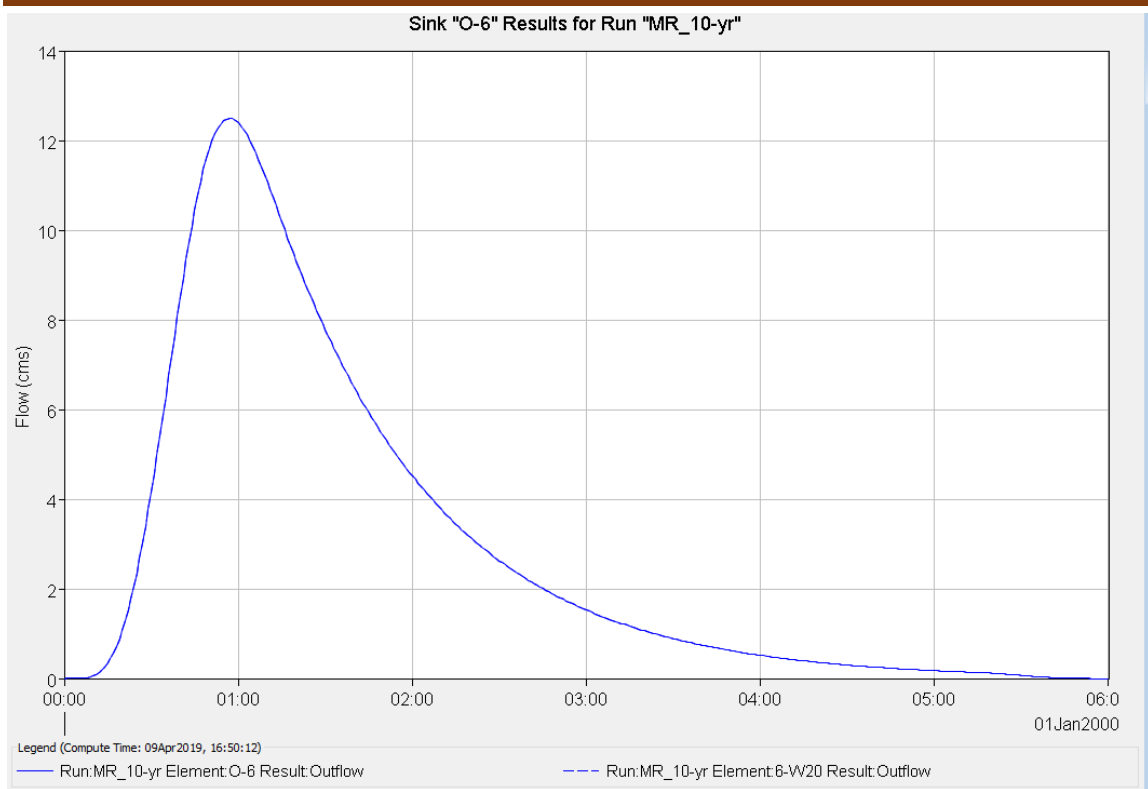


Figure C. 13: 10-yr hydrograph for drainage point 6

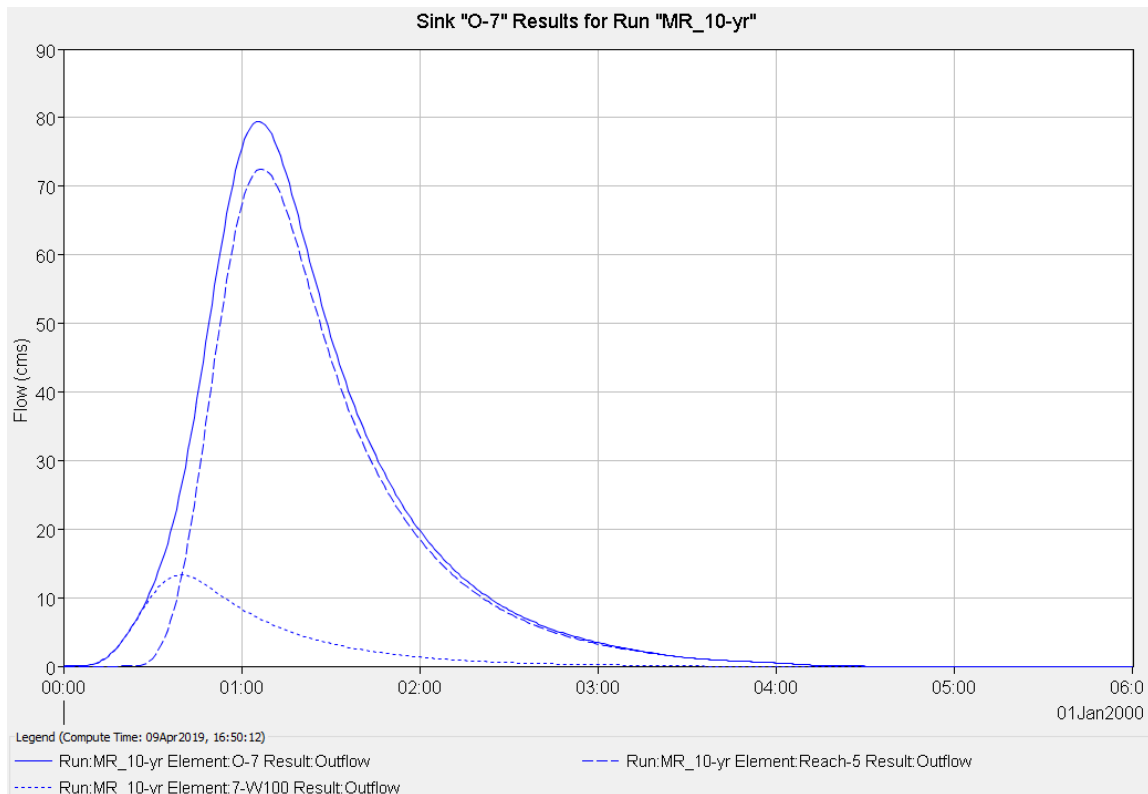


Figure C.14: 10-yr hydrograph for drainage point 7

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

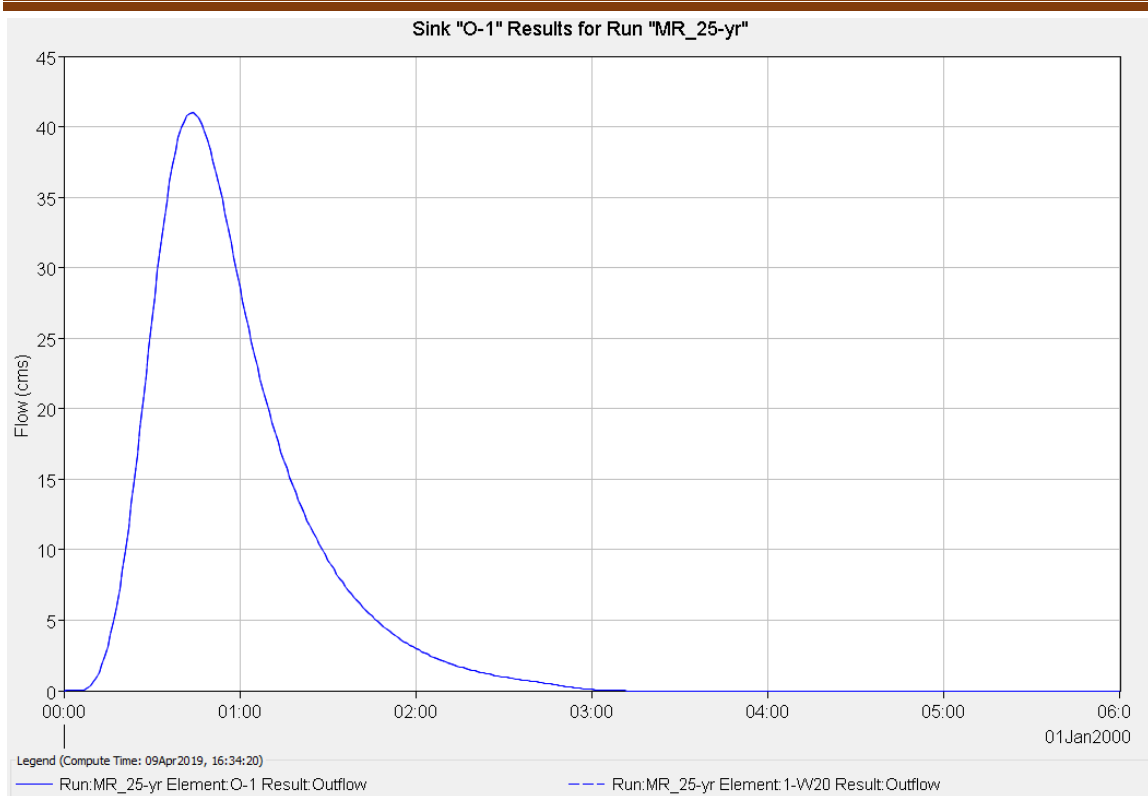


Figure C.15: 25-yr hydrograph for drainage point 1

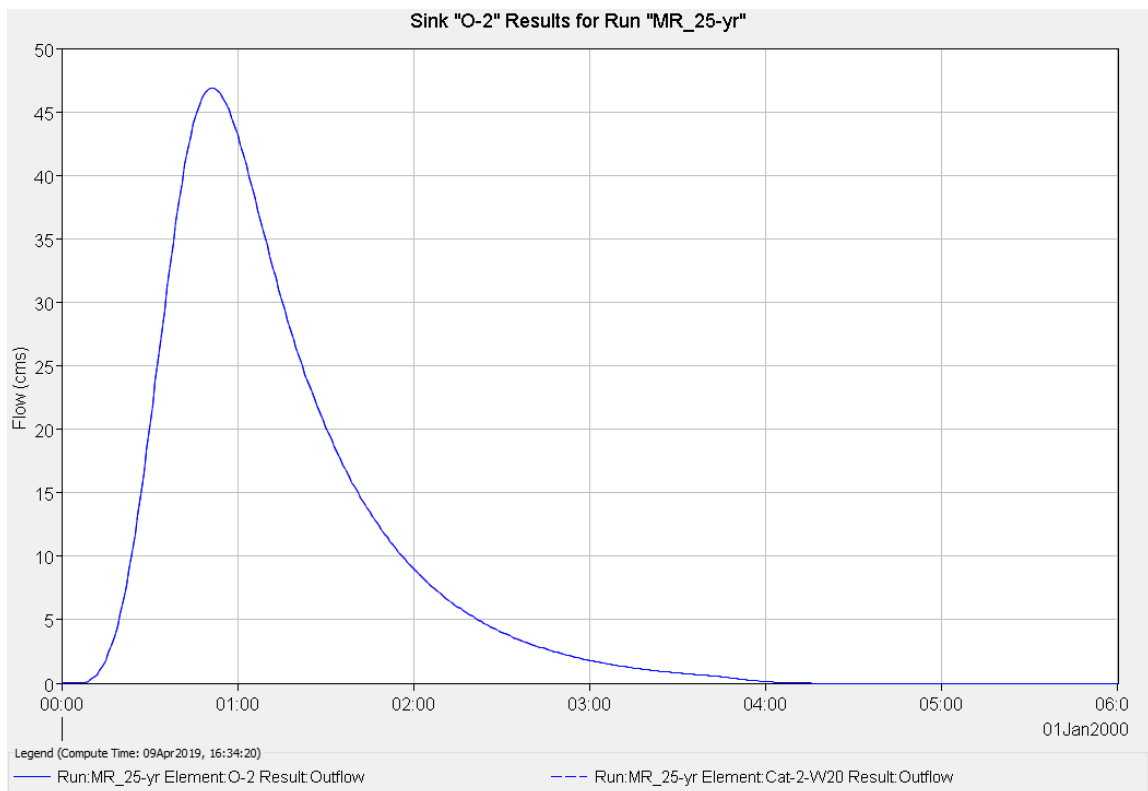


Figure C.16: 25-yr hydrograph for drainage point 2

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

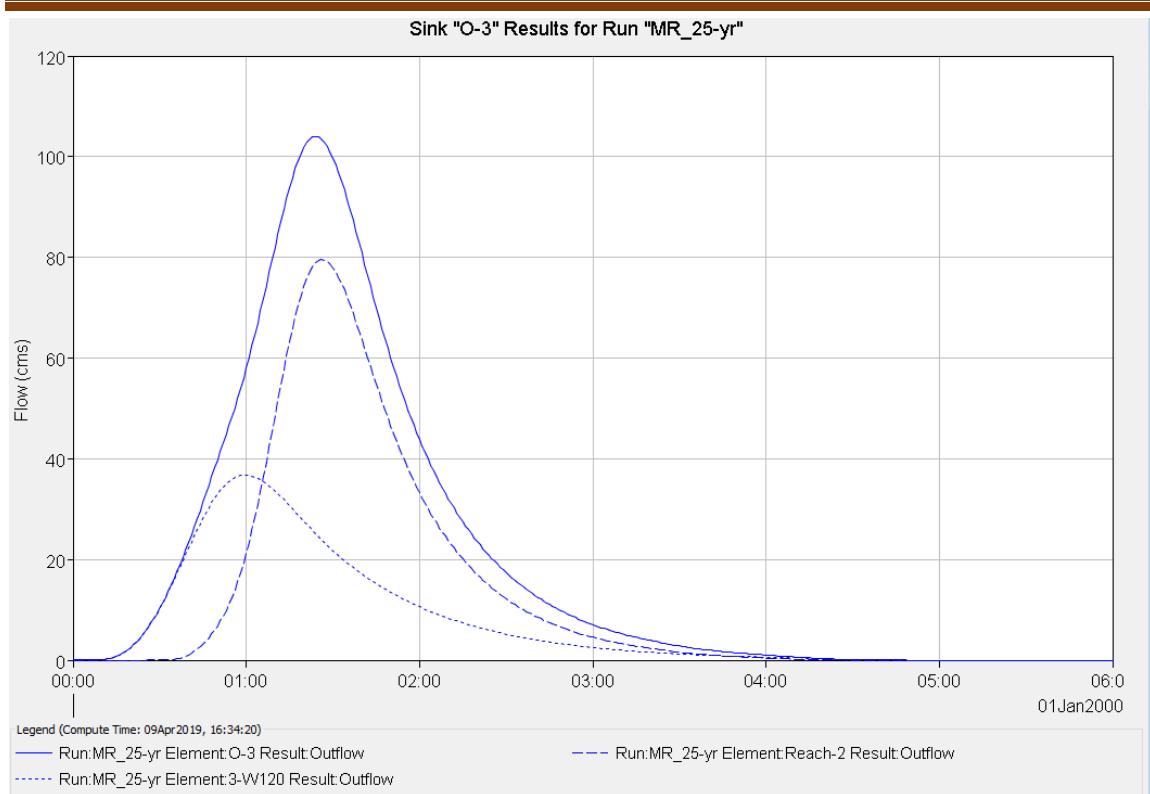


Figure C.17: 25-yr hydrograph for drainage point 3

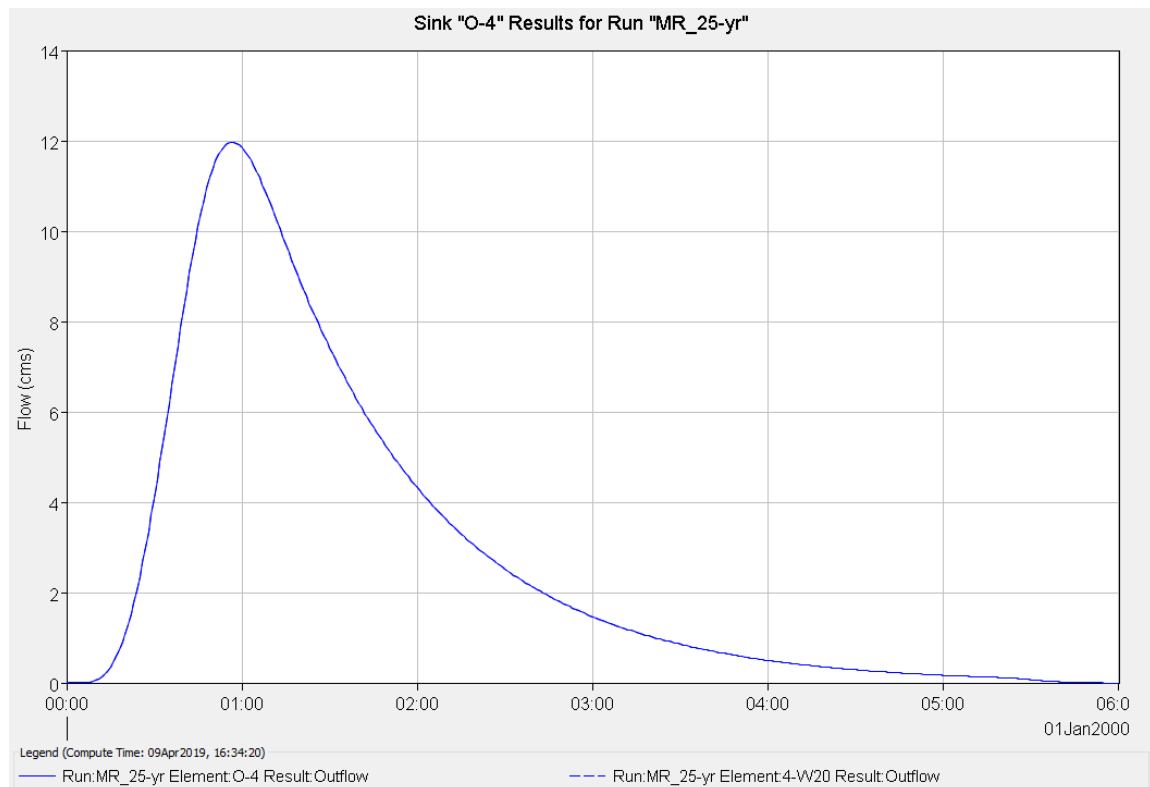


Figure C.18: 25-yr hydrograph for drainage point 4

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

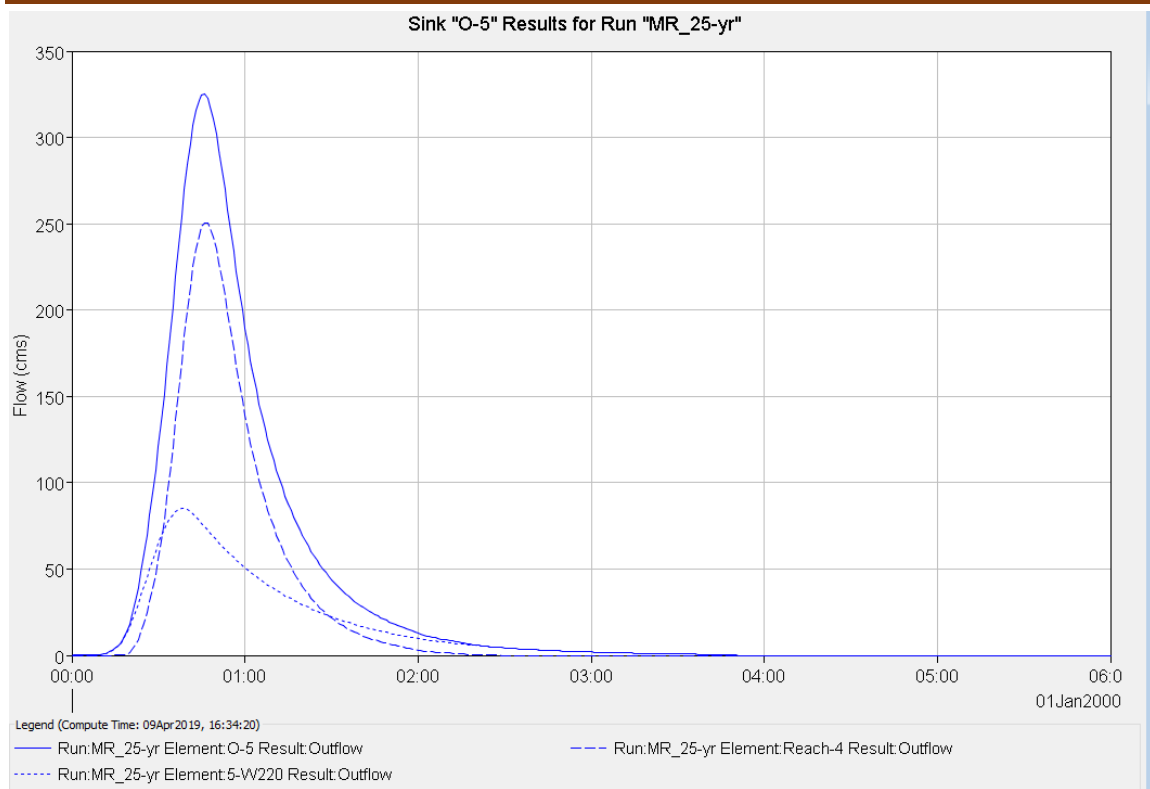


Figure C.19: 25-yr hydrograph for drainage point 5

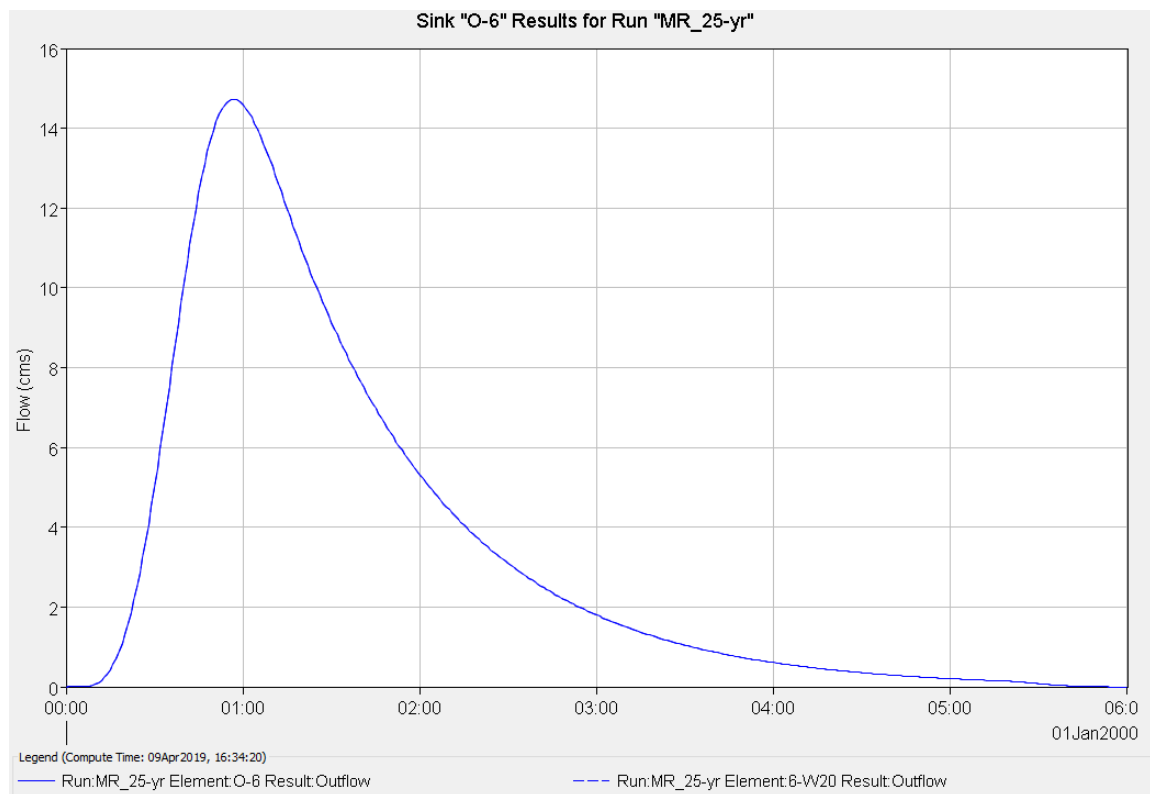


Figure C.20: 25-yr hydrograph for drainage point 6

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

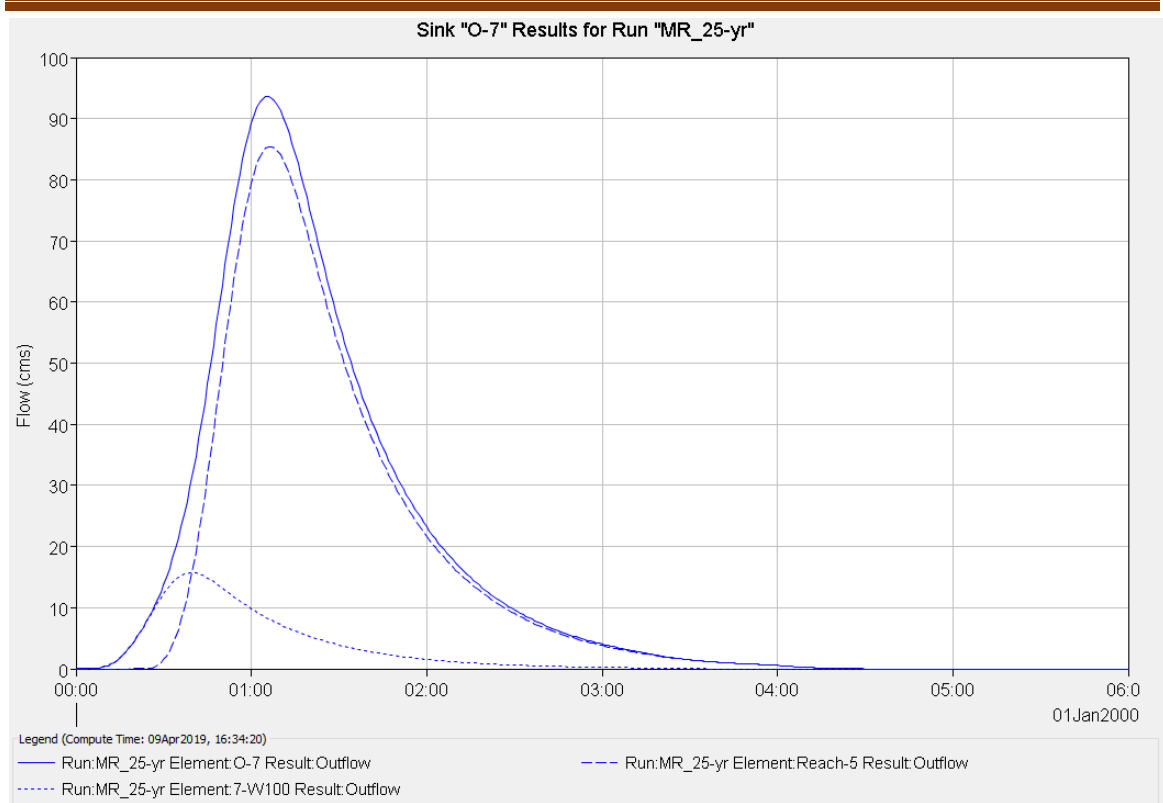


Figure C.21: 25-yr hydrograph for drainage point 7

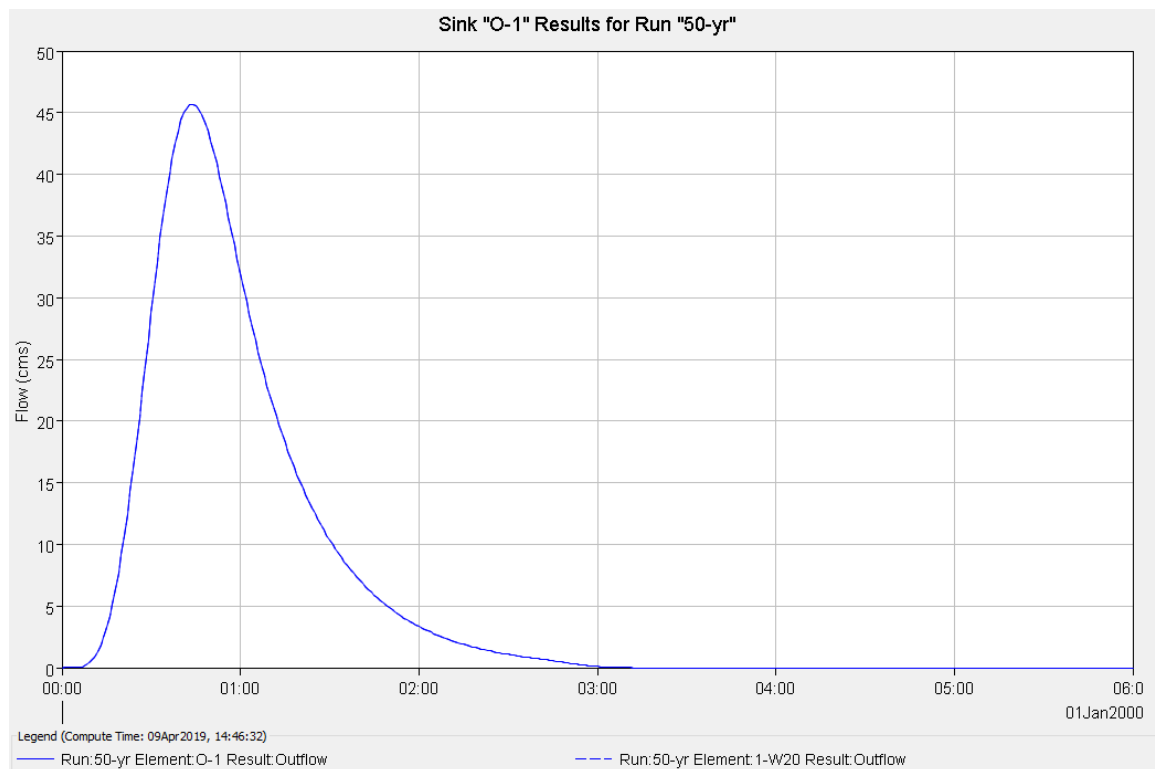


Figure C.22: 50-yr hydrograph for drainage point 1

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

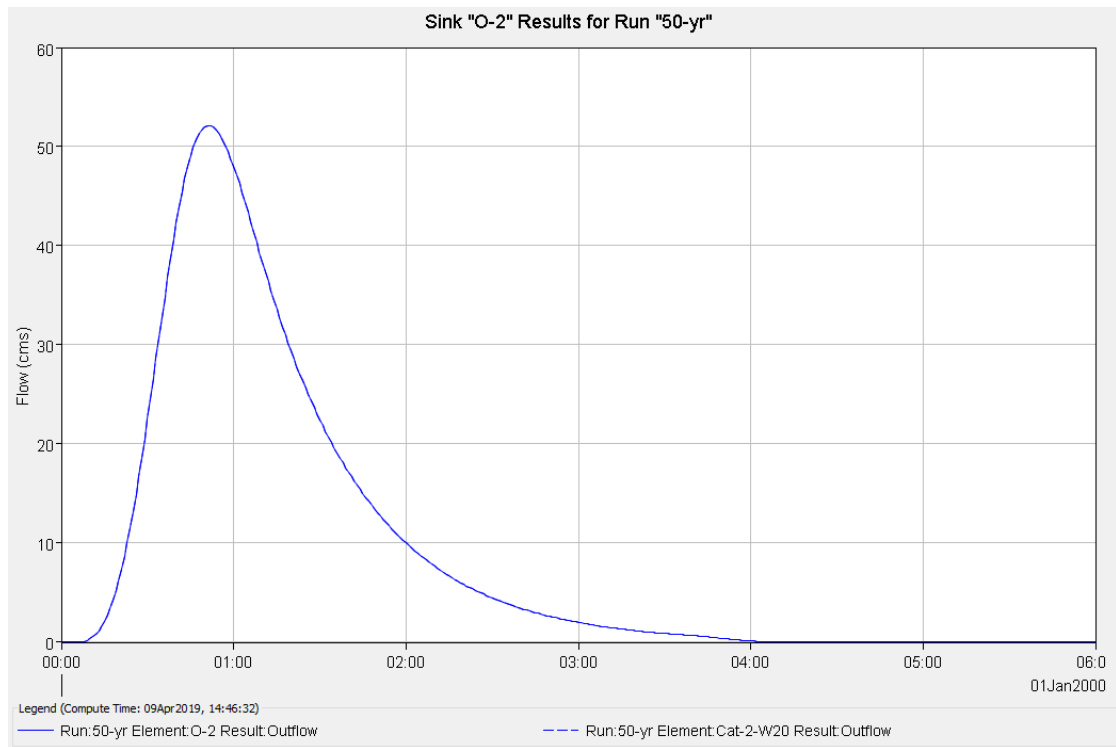


Figure C.23: 50-yr hydrograph for drainage point 2

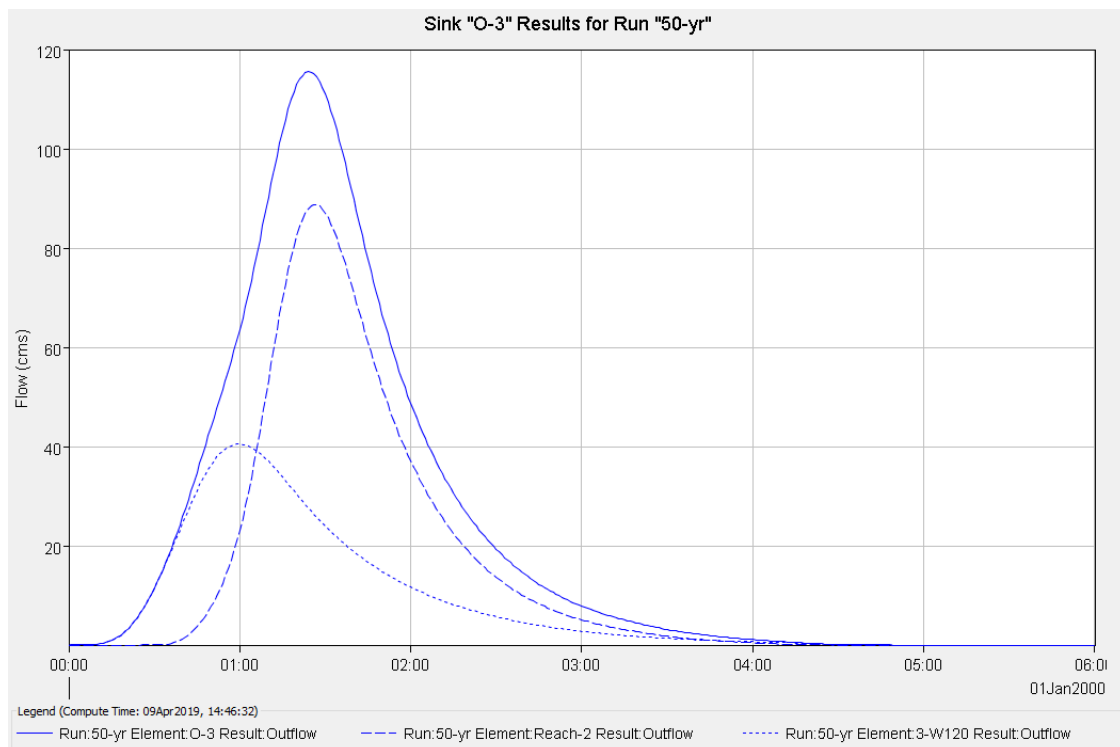


Figure C.24: 50-yr hydrograph for drainage point 3

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

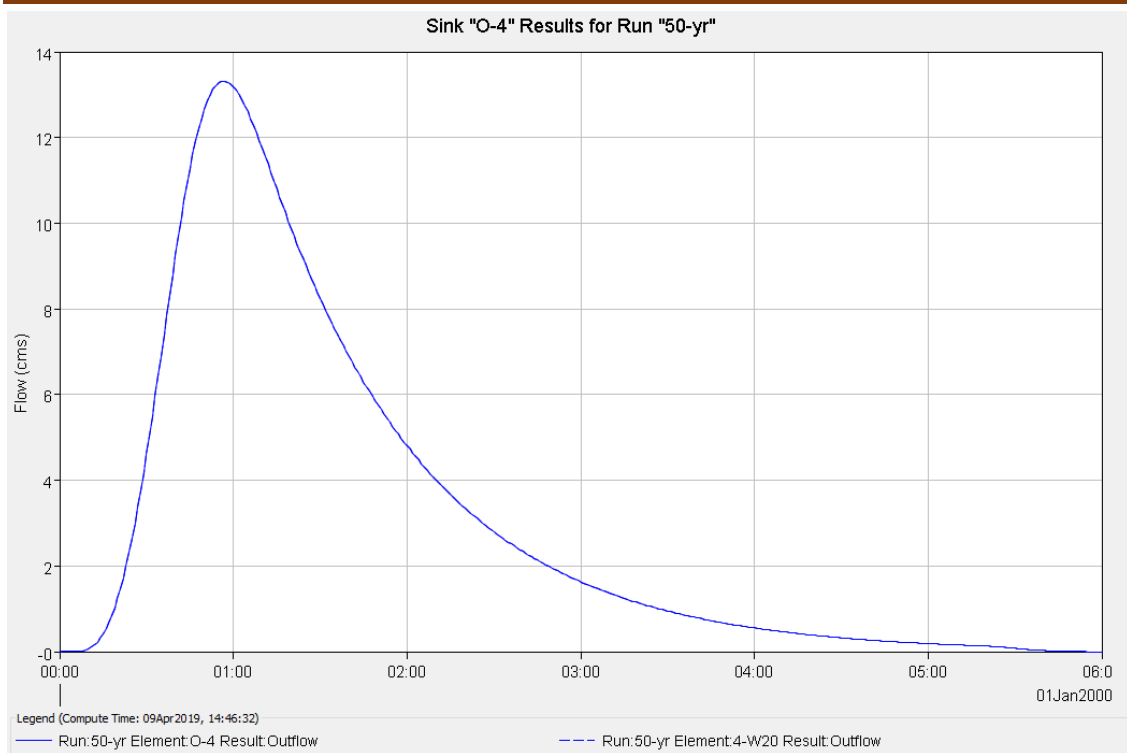


Figure C.25: 50-yr hydrograph for drainage point 4

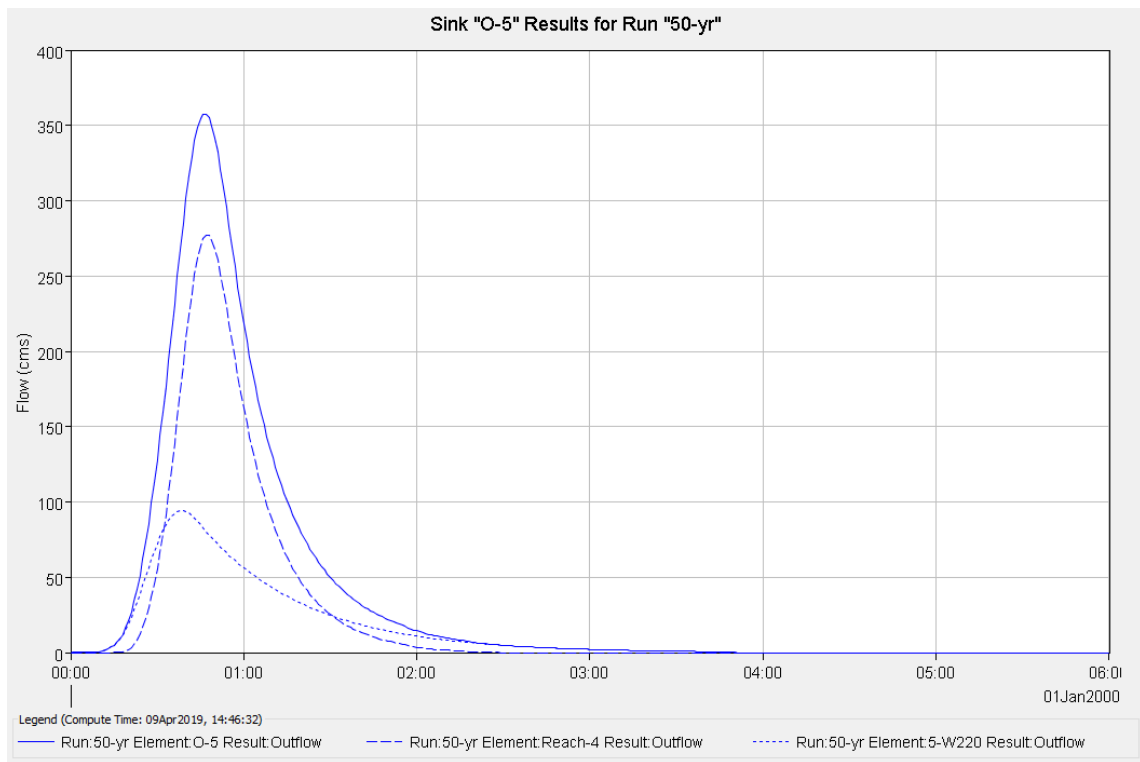


Figure C.26: 50-yr hydrograph for drainage point 5

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

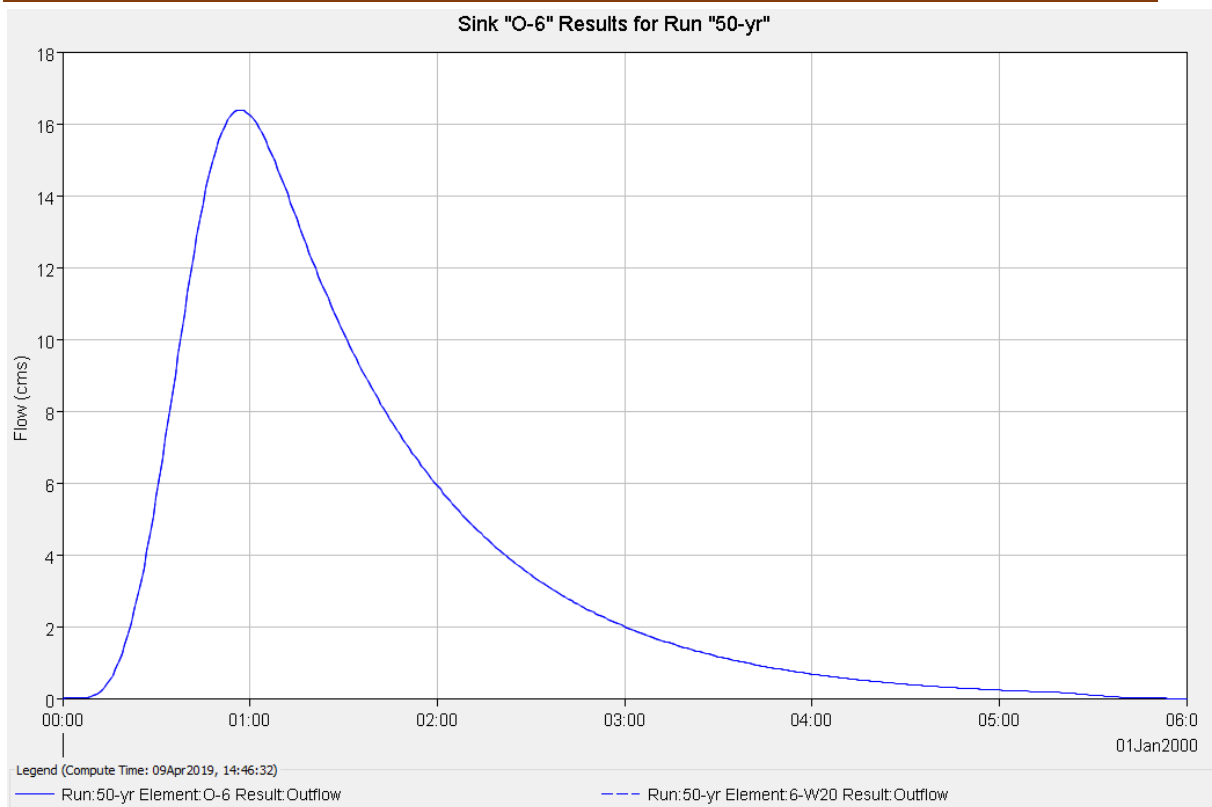


Figure C.27: 50-yr hydrograph for drainage point 6

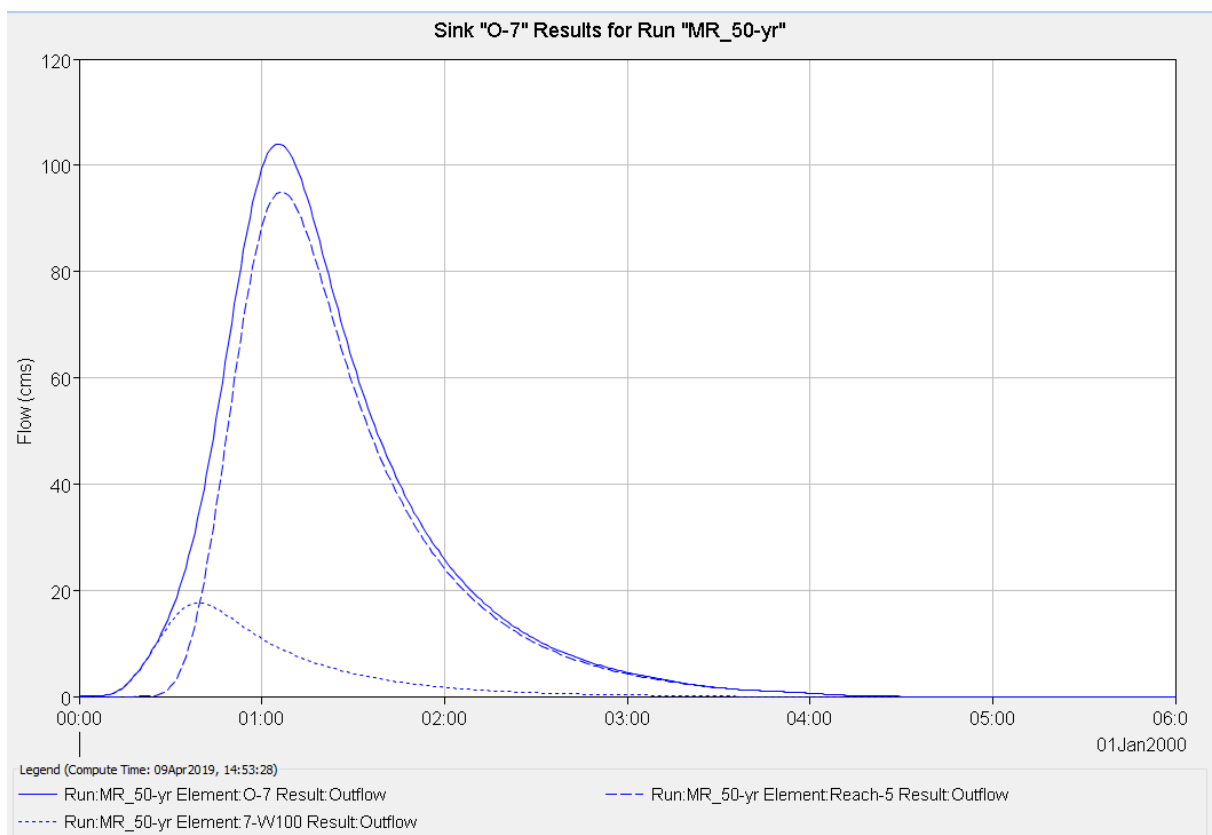


Figure C.28: 50-yr hydrograph for drainage point 7

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

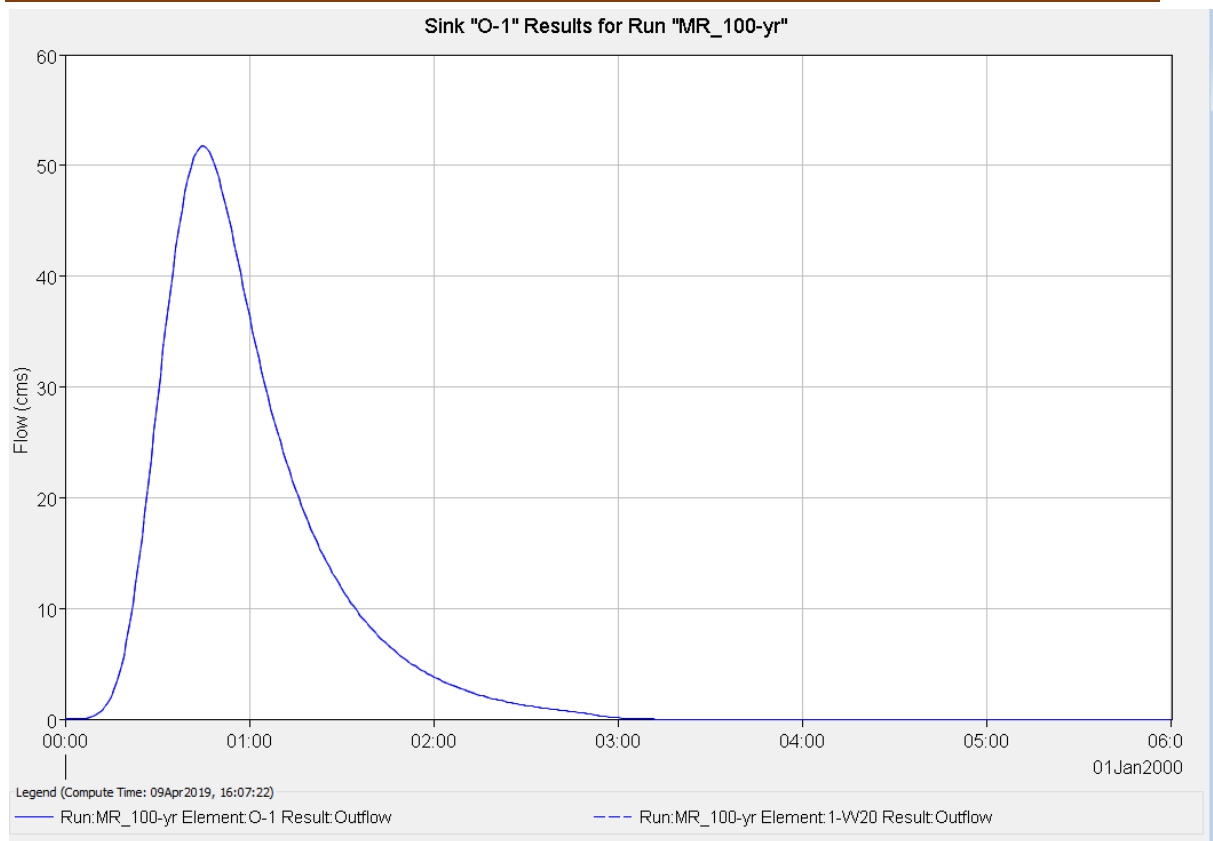


Figure C.29: 100-yr hydrograph for drainage point 1

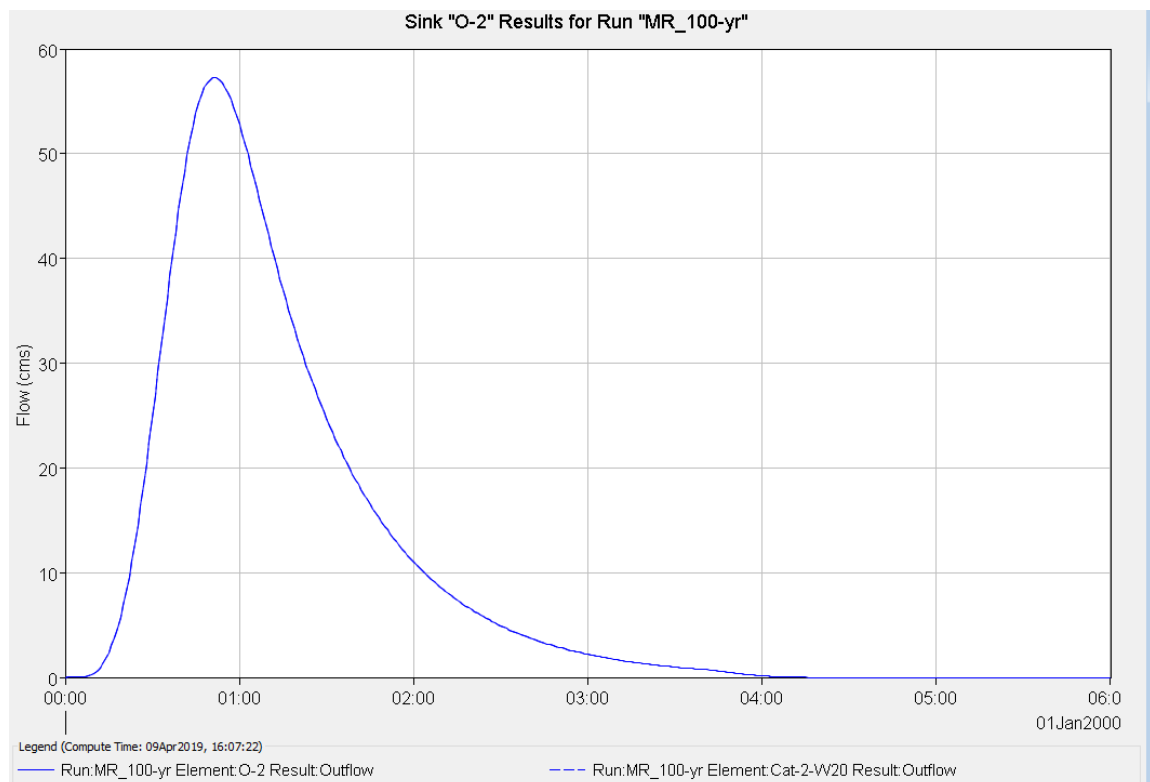


Figure C.30: 100-yr hydrograph for drainage point 2

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

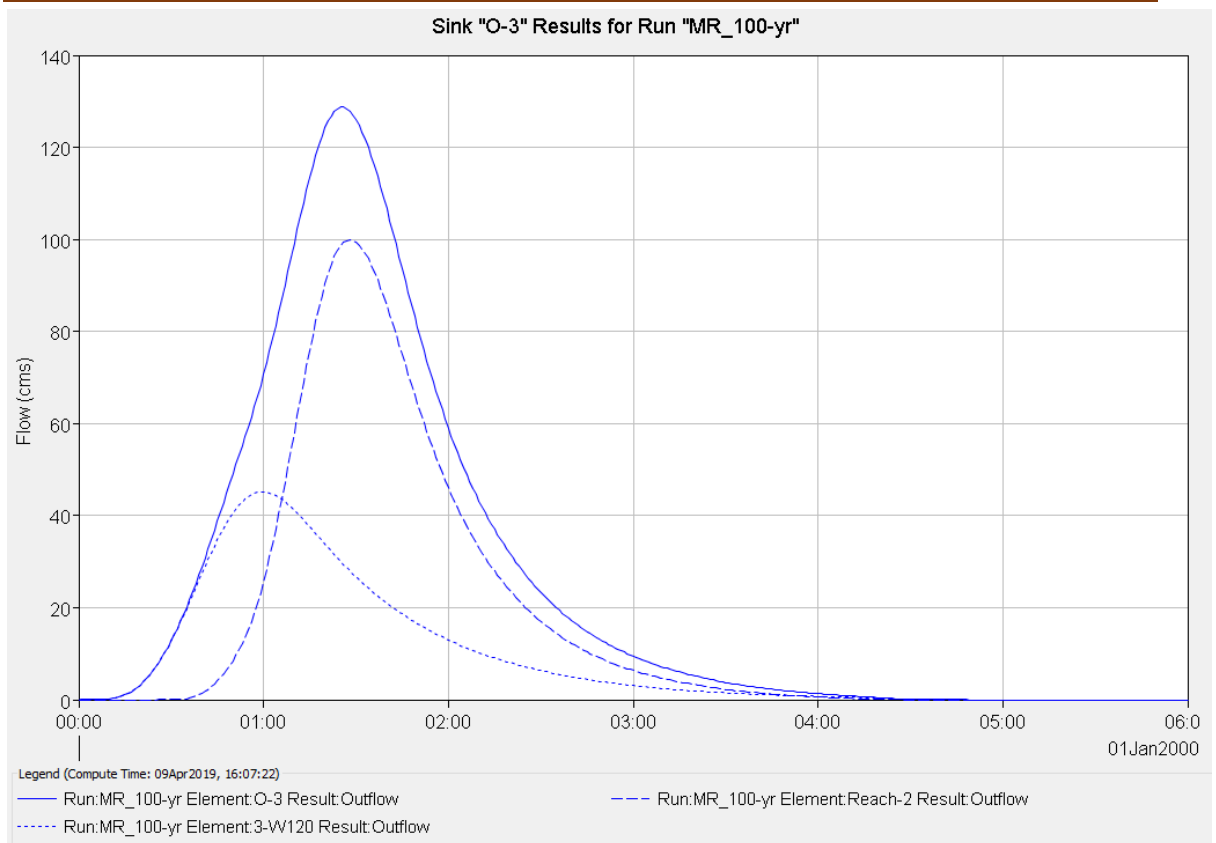


Figure C.31: 100-yr hydrograph for drainage point 3

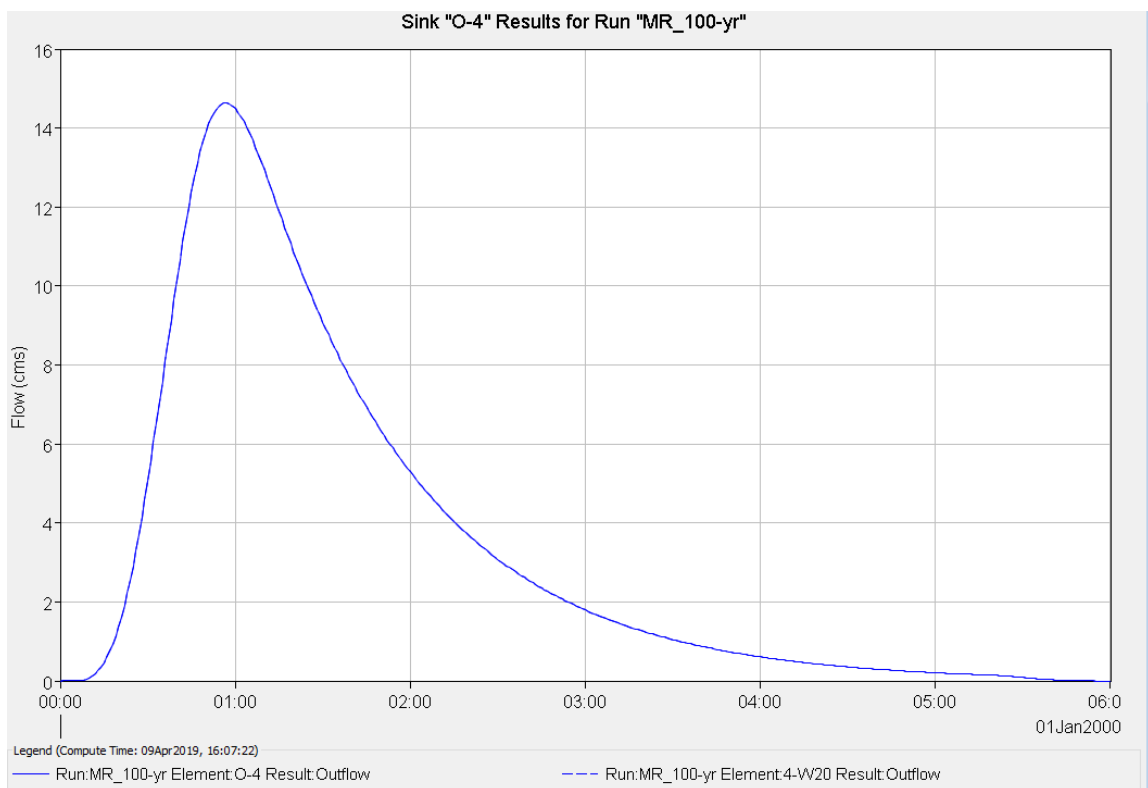


Figure C.32: 100-yr hydrograph for drainage point 4

FLOOD ANALYSIS AND HYDRAULIC COMPETENCE ASSESSMENT OF RAILWAY INFRASTRUCTURES. A CASE OF MEGANAGNA-AYAT LINE

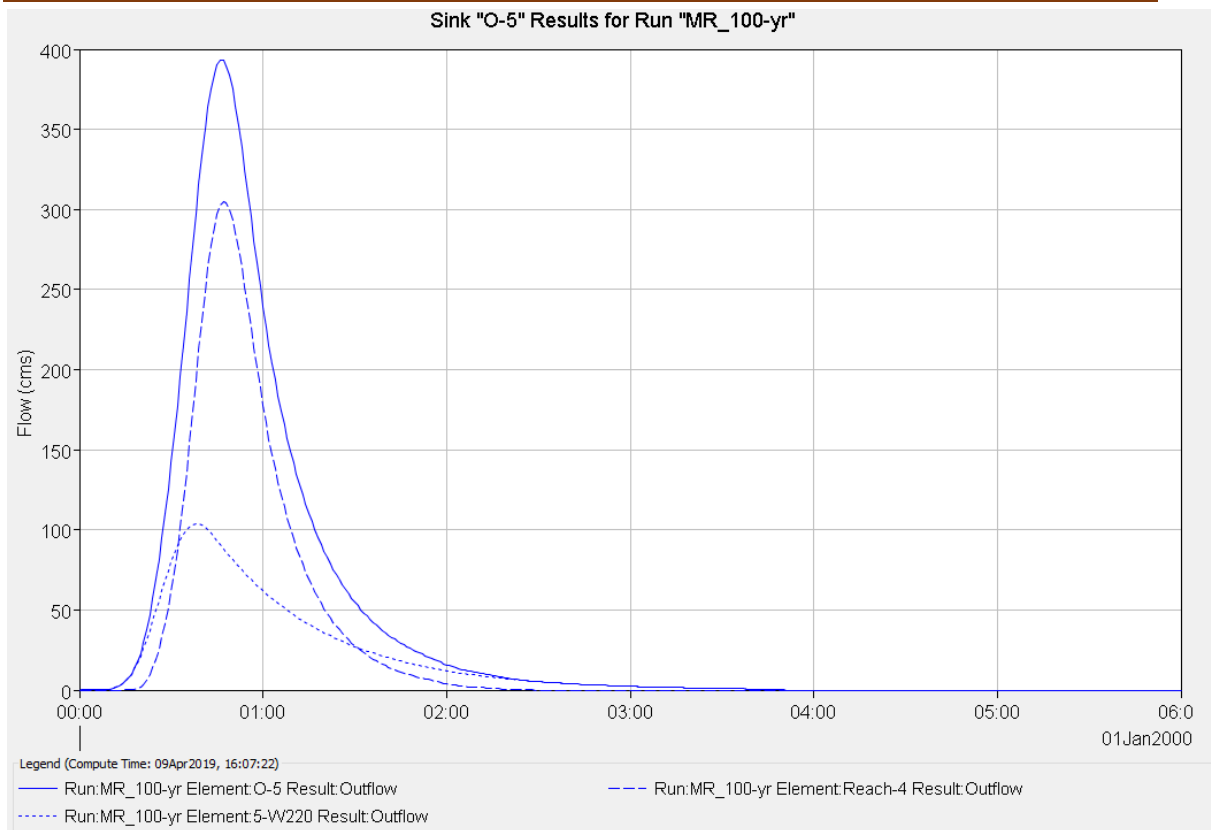


Figure C.33: 100-yr hydrograph for drainage point 5

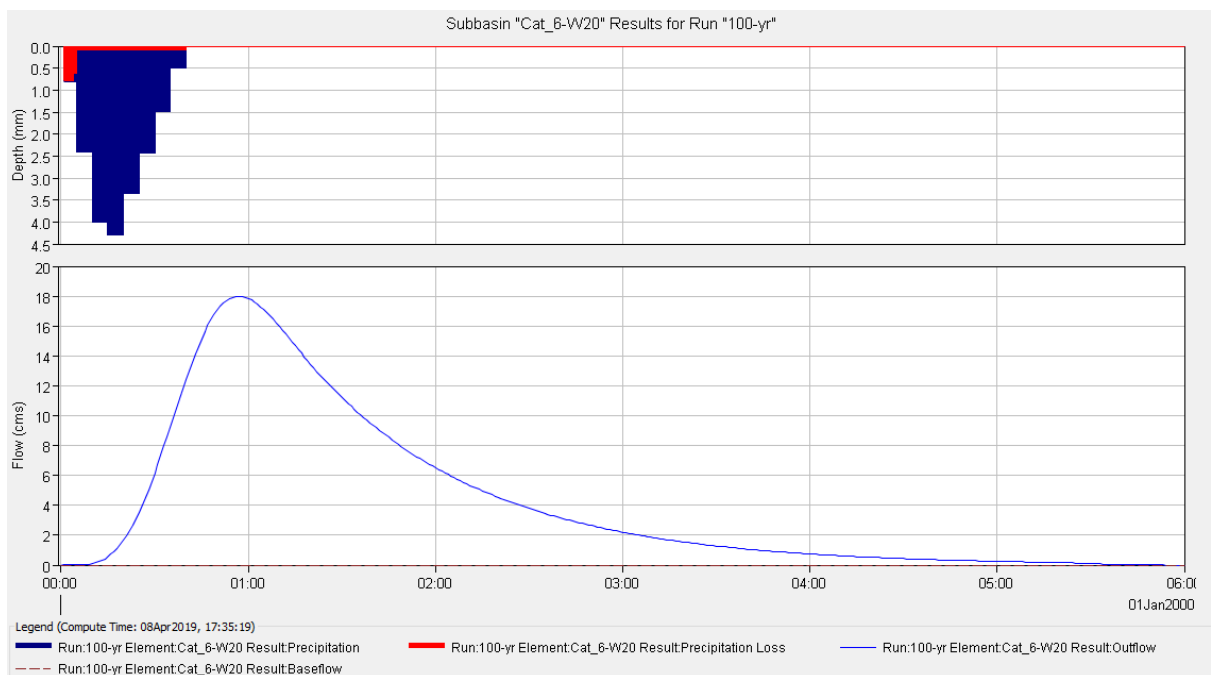


Figure C.34: 100-yr hydrograph for drainage point 6