University of Southern Queensland

Faculty of Health, Engineering and Sciences

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AQUAPLANING: AN INVESTIGATION OF SURFACE FLOW CALCULATION

A dissertation submitted by

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Abstract

This research project will numerically analyse current methods used for calculating surface flow depth and the accuracy of different models. It will model the surface flow build up over the duration of a design storm event using the standards values which are determined from the following research and documentation.

This research project compares the accuracy and reliability of surface flow calculation methods including the Gallaway Equation, Manning's Equation and a kinematic wave equation model. The research reviews current design rainfall intensity values as well as other input variables such as texture depth, acceptable flow depth and driver behaviour and determines if they are suitable for study of aquaplaning analysis.

Current standards outline procedure for choosing input variable based on the conditions. These have been based on historical studies and still seem applicable to today. A design rainfall intensity of the 1 year ARI, 5 minute duration or 50mm/h, whichever is the lesser, is chosen to account t for driver behaviour and time of concentration. The standard texture depth should be chosen depending on the specified pavement type or determined by on site testing if available.

The Gallaway equation provides a fast a simple method to calculate depth however in areas of particular concern or risk a more extensive hydraulic analysis with the use of the kinematic wave equations may be warranted. The RRL method produce high depths of flow and is therefore no recommended for use in Australia.

This research investigates the time of concentration and surface drainage of the flow path to assess the aquaplaning risk over time. The results suggest the maximum flow depth conditions will be reached for surface drainage catchments after approximately 5 minutes and the depth will subside to below critical depth within 5 minutes of the cessation of the rainfall.

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Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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(Signed)

30/10/14 **(Date)**

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1. Introduction to aquaplaning

1.1 Background

The phenomenon of aquaplaning is very complex and our understanding of how and why it occurs is limited. Essentially aquaplaning can be described as the separation of a tyre from the road surface due to a build-up of water underneath the tyre. This separation is often the cause of drivers losing total control as braking and steering can no longer manoeuvre the vehicle. This often results in a crash unless there is a sufficient increase in the contact between road and vehicle to enable the driver to regain control of the car.

Opinions of aquaplaning vary greatly throughout the road industry with some believing that true aquaplaning does not exist at the speeds we travel at on our roadways whilst other believe the problem to be very common and occurs at mid to low speeds. In reality both extremes would be hard to prove and a more conservative middle ground is probably more accurate (Gallaway et al., 1979). The likely assumption of aquaplaning is that it is a rare event due to the compound circumstances required for it to occur, the most influential being rainfall of a high intensity. As high intensity rainfall in itself is quite rare, it follows that aquaplaning is quite rare. There is also the general misconception between true aquaplaning and skidding, with many assuming they are the same thing. This however, is not the case as skidding is related to a loss of friction force due to inconsistent rotation of the tyre on the pavement. Skidding may also occur in dry conditions whilst aquaplaning is purely concerned with a water film build up beneath the tyre.

The studies of Horne (1968), which were performed by NASA at the Langley Research Centre were primarily concerned with aircraft tyres, however it is also applicable to highways and the terminology used to describe the phenomenon of aquaplaning in this paper has been in use ever since. The study has broken the phenomenon of aquaplaning into 3 categories, of which only 2 are relevant to roads and the studies of this research paper. The two main types of aquaplaning are viscous and dynamic aquaplaning.

Viscous aquaplaning can occur at low speeds usually with smooth roads and with limited tire tread during braking at an intersection when the viscosity of the water prevents it from escaping under the tyre footprint.

Dynamic aquaplaning occurs once a vehicle exceeds a critical speed. It could consist of partial or full separation of the tyre with the road surface due to a wedge of surface water in front of the tyre which causes some degree on contact loss (Staughton and Williams, 1970).

Aquaplaning can also be described by different but similar terminology by the terms full aquaplaning and partial aquaplaning. These are approximately the same as dynamic and viscous aquaplaning however, they refer to the degree of loss of frictional forces between the tyre and the road surface.

Key factors which influence (or cause) the occurrences of aquaplaning are:

- Road geometry
- Road surface texture, porosity and rutting
- Operating speed
- Rainfall intensity
- Water film depth
- Tyre tread depth, vertical load, width of tyres and tyre pressure
- Driver behaviour

(Austroads Part 5A, 2013)

Aquaplaning needs to be considered throughout the road design process to provide a safe network to road users. This is to ensure that unsafe areas do not result as a result from surface water reducing the ability for the vehicle to maintain contact with the road. The aquaplaning phenomenon must also be considered in road maintenance, as the road surface wears and rutting occurs, build-up of water is more likely to occur and therefore the situation could be less safe than originally designed. Road authorities have methods in place to identify, analyse and ameliorate aquaplaning locations. These methods are primarily focused on the initial design of a road but must also take into account the long term use of the road. An issue might not be present initially but may develop over time as the network changes and separate designs compound each other. For instance as one project upgrade joins into an existing project.

This study will mainly focus on the areas of film depth, rainfall intensity, texture and driver behaviour. This is due to the large variables and unknown to do with tyres and tyre pressures. There are also laws in place that govern tread depth and tyre dimensions, which ensure the vehicle is road worthy. As a design engineer, tyre properties are beyond your control and therefore investigation should be limited to factors that directly influence the road.

1.2 Objectives

The project specific objectives are outlined below:

1. Compare the accuracy and reliability of surface flow calculation methods including the Gallaway Equation, Manning's Equation and a kinematic wave equation model.
2. Review current design rainfall intensity values and determine if they are suitable for study of aquaplaning analysis.
3. Investigate if and how driver behaviour should be included in models. For instance, during large intensity events drivers will slow down considerably.
4. Determine how standard values, such as texture depth, acceptable flow depth etc., used in current methods were adopted from historical studies. Investigate if these values are relevant to road conditions today.

5. Determine if the time of concentration for the flow path should be taken into account in the modelling. Analyse a design storm for a determined intensity and duration to calculate the water flow build up and the time taken to fully drain the surface.

This research project will numerically analyse current methods used for calculating surface flow depth and the accuracy of different models. It will model the surface flow build up over the duration of a design storm event using the standards values which are determined from the following research and documentation.

This project will investigate the current methods and standards used by road authorities internationally and throughout Australia. These methods will be compared for consistency and accuracy. Flow depth for aquaplaning is influenced by rainfall intensity, texture depth, slope and length of the flow path. This report will analyse the effect of these variables with three models and comment on the reliability of the results from each model. Many authorities have adopted standard values for these variables and this report will discover the origins of these assumptions and the limitations on their use.

Road safety is a major concern throughout the world and there is a major push to reduce the road toll from all major government bodies. The design elements of a road should put the safety of the driver as a paramount concern. However project budgets and on a wider scale organisation funding is not finite, therefore this suggests that road safety measures should be both warranted and relatively cheap. Current road standards give guidance on the calculation of water depth on the road surface and the allowable depth before it becomes a hazard to road users. During both the design and maintenance phases of the road project, considerable time and resources are expended on highlighting and alleviating problem areas for aquaplaning.

This research project aims to assess the current guidelines and calculation methods for flow depth on the road surface. Often in engineering standards there is a level of conservatism that allows for a factor of safety. However, the level of this conservatism is not obvious for the calculation of surface flow depth for aquaplaning. This makes it difficult to quantify the benefits of the conservative approach. I.e. does the cost of over designing to meet standards provide value for money benefits? This could essentially be explained by a small cost investment associated with designing out aquaplaning issues resulting in significant reductions in crashes. Many standards and technologies have been updated in the world since they were first established, therefore it should be analysed whether the standards used for this element of road design should also be updated.

Design standards do not only play a part in design but also in maintenance and assessing existing road conditions. Many roads experience some settlement after construction; they will also experience some polishing of the pavements surface over long term use. This settlement can reduce the cross falls and the ability of the road surface to naturally drain itself. If the analysis is too conservative for design, it may result in the assessment of the road having a larger depth and therefore require corrective action to be taken. The works required to alleviate an existing aquaplaning issues are often quite extensive and funding cannot be directly sourced from a project budget, funds would have to be reallocated from another project.

If this research finds that current methods of calculation are overly conservative and are producing calculated depths that are higher than would actually be experienced, there would be an opportunity to re-evaluate the standard method of calculating the depth. This would result in lower depths universally and would hence reduce the number of existing locations that require attention or action to address aquaplaning. If these are in design, the time and design resources can be spent elsewhere whilst the additional construction costs are avoided. If the location were an existing or maintenance location, the lower calculated depth would prove that the issue is not evident and therefore would not need to be addressed.

Conversely, this research project may show that current methods are not conservative enough and the standard method of calculation results in depth that are too shallow. This would pose a road safety risk and would highlight more areas where surface water may be a problem to road users. There would be a considerable cost involved in ensuring that the risk of aquaplaning is appropriately considered and actioned for road users.

Care should be taken when recommending changes to standards to avoid adopting a standard that underestimates the likelihood and risk of accidents due to aquaplaning. Therefore, if there is doubt as to whether the standards should be lowered, then a more conservative approach should always be taken.

1.3 Report Organisation

This document has 8 chapters. They are organised into the following topics as follows:

- Chapter 1 (this section) – defines the purpose of the document and provides background information on aquaplaning and road design engineering
- Chapter 2 – Literature review of standards and published works
- Chapter 3 – defines the research design and methodology
- Chapter 4 – Results of calculated flow depths
- Chapter 5 – Discusses the results on a numerical level to compare accuracy and the values produced.
- Chapter 6 – Draws conclusions from the results and suggests recommended actions based on the content of this work
- Chapter 7 – Discusses how the work contain in this document can be extended by future work and investigations

2. Literature Review

This chapter investigates the existing literature on the topic of aquaplaning. This documents the extensive research performed to model the depth of flow on the surface of the road as well as methods to account for the risk associated with the likelihood of aquaplaning occurring. The literature review will establish parameters that will be further investigated as part of this research paper.

This chapter will be broken up into the following sections:

- Introduction
- Factors affecting aquaplaning
- Aquaplaning equations for flow depth calculations
- Kinematic wave model
- Rainfall intensity
- Visibility and driver behaviour
- Texture depth standard values
- Time of concentration – sheet flow
- Allowable surface water film depth

2.1 Introduction

As the water depth flowing across a roadway surfaces increases, the potential for aquaplaning increases. Aquaplaning occurs when the drainage capacity of the tyre and the road surface is exceeded and water builds up in front of the tyre. Aquaplaning may occur at speeds of 89km/h with a water depth of 2mm. However depending on a variety of factors influencing the conditions, aquaplaning may occur at speeds and depths with less values for both speed and water film depth (FHWA, HEC-22, 2009).

Aquaplaning occurs when a tyre is separated from the road surface by a film of water which causes loss of control. While aquaplaning the vehicle rides on top of the water and can completely lose contact with the road surface. This loss of contact puts road users into immediate danger of sliding out of the lane (Andren and Jolkin, 2003). Aquaplaning can be described in two different types which are full aquaplaning and partial aquaplaning (Oliver, 1979).

Full aquaplaning occurs when a tyre is completely separated from the road surface by a film of water resulting in a loss of control. Oliver (1979) has indicated that for vehicles travelling within speed limits and with tyres in good condition, full aquaplaning is likely to be a rare event.

Partial aquaplaning occurs when the intrusion of water results in a reduced tyre contact area as speed increases. This will result in reduced longitudinal friction coefficient between the tyre and the road surface. While reasonable control of the vehicle may apparently remain under conditions of constant speed and direction, it could become critical in locations where relatively high demands may be placed on either longitudinal or lateral friction. These situations could be described as areas of braking to slow the vehicle or changing the direction of the vehicle to change lanes (Oliver, 1979).

When entering surface water, the surface of thee tyre must move the water out of the way in order for the tyre to maintain contact with the road surface. The tyre will move some out the water away from the contact area around the sides of the tyre. The remaining water must be forced underneath the tyre through the treads on the tyre surface. On a smooth polished road surface in moderate rain at 90km/h, each tyre has to displace about 4 litres of water per second from beneath a contact area which is about the same size as the palm of your hand (Andren and Jolkin, 2003).

Accidents on wet roads may be influenced by general reduced visibility, glare, invisibility of pavement markings and reduction of tyre-road surface forces. This document will investigate the causal effects which create conditions which are more likely to cause accidents on the road.

Skidding is the phenomenon which occurs when frictional demands on the vehicle wheels exceed that available. Such loss results in an increased stopping distance, loss of directional stability and loss of operator control. This is therefore a considerably dangerous situation to the occupants of the skidding vehicle as well as other people or property which might be impacted by the skidding vehicle (Gallaway et al., 1971).

Aquaplaning is a function of water depth, roadway geometrics, vehicle speed, tread depth, tyre inflation pressure and conditions of the pavement surface. Research papers and design manuals have investigated aquaplaning and the conditions that make it more likely to occur. The following literature review will investigate research into the water film depth, rainfall intensity, texture depth and the limit at which aquaplaning is accepted to occur.

2.2 Factors affecting aquaplaning

The factors affecting aquaplaning were stated in Section 1. These factors are both interconnected and very complex. This research will consider the hydraulics and hydrology of water on the road surface that increases the risk of aquaplaning. For the purposes of this study, the following factors affecting aquaplaning will be investigated:

- Road surface texture
- Rainfall intensity
- Water film depth
- Driver behaviour

The effect of road surface texture on aquaplaning is twofold. The texture of a pavement can be described by two different properties that affect aquaplaning potential. These are called microtexture and macrotexture (Austroads part 5A, 2013).

Microtexture relates to the irregularities in the aggregate in the pavement surface and provides the friction force in the tyre/road surface relationship. This will affect the friction values which is applied to the tyre from the pavement. The value of friction between the tyre and the road surface decreases as the water film depth increase. The partial aquaplaning condition is initiation by the water on the surface of the pavement interrupting the contact between the tyre and the particles in the pavement surface (Staughton and Williams, 1970).

Macrotexture relates to the height difference between the top asperities of the aggregate in the pavement and the bulk matrix of the pavement. For instance the stones in an asphalt pavement will protrude above the bulk mass level of the bitumen binder. The macrotexutre of a pavement creates voids which in turn provide drainage channels for water displaced by the tyre. Adequate channels reduce the water film layer that is built up above the pavement and reduce the pressure that builds up in the water layer. This is particularly important at high speeds if full or partial aquaplaning is to be avoided (NAASRA, 1986).

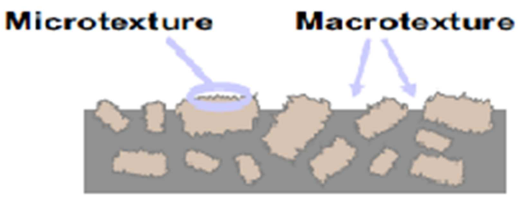

Figure 2.1 - Texture elements of pavement surfaces

(Source: Austroads Part 5A, 2013)

Rainfall intensity is defined as the mean point rainfall intensity assumed to occur uniformly over a catchment. It is a function of both time of concentration to the point being considered, and the recurrence interval of the design storm (NAASRA, 1986). The rainfall intensity is measured by the unit depth of water which falls over a $1m^2$ area over a specified time. The usual units of measurement are mm/h which signify a mm depth over the unit area over a 1 hour time period (BoM, 2014).

When rain falls on a sloped pavement surface, it forms a thin film of water that increases in thickness as it flows to the edge of the pavement. Factors which influence the depth of water on the pavement are the length of flow path, surface texture, surface slope, and rainfall intensity. As the depth of water on the pavement increases, the potential for vehicular aquaplaning increases. (FHWA, HEC-22, 2009)

In real world situations the length of the flow path is quite simple to determine from contours or from more sophisticated 3d design programs. Unfortunately the slope of a flow path is less easy to determine as the slope will very rarely be a simple planar surface for the entire length of the flow. It is more likely to consist of various sub-lengths of slope, all of which vary with their singular point to point slope. Therefore, a method has to be determined to define the average slope over the entire flow path length. Two methods of doing this are the ‘point-to-point slope’ also called the ‘average slope’, which measures a direct grade from first point to last point on the flow path. The other method is called the ‘equal area (EA) slope (Austroads part 5A, 2013).

Austroads Part 5A (2013) outlines the best ‘single slope’ representation of a flow path is the EA slope method. This method ensures that if the flow path is relatively flat, but contains a few short lengths of steeper grade, the resulting equal area slope will be relatively flat. Conversely if the flow path is predominantly steep the resulting EA slope will be steep. The method of finding the EA slope involves plotting a long section of the flow path for the entire length and working out the area under the slope for the true grades. A single flat grade is then drawn to a point at the end of the flow path so that the area under the single slope is equal to the area under the true long section of the flow path.

It should be noted that the method outline above for slope is necessary for the calculation of aquaplaning water film depth as the variable for slope is a single grade for the entire flow path. This will be investigated further in the following sections.

Wheel spin down is defined as the reduction in speed of the rotation of a wheel. It is an indication of a loss of in the tyre/ground frictional force and can indicate the manifestation of aquaplaning occurring (Stoker and Lewis, 1972). This property is used by many researchers, including Staughton and Williams (1970), to determine the speed and water film depth which initiates full or partial aquaplaning.

The driver behaviour aspects that this research will investigate will be limited to the visibility of the road and the road surface during storm events and the degree to which the driver will slow down during these events. It will not investigate any other actions a driver may take which may include manoeuvring around puddled surface water once a storm has ceased and the visibility to the road has improved.

2.3 Aquaplaning equations for flow depth calculation

The problem of aquaplaning was investigated heavily during the late 1960s and through the 1970s. The first step in the process was to derive an equation for flow depth along a specified surface. Two independent methods were determined from studies in both the UK and in the USA. Many authorities worldwide still commonly use these methods today.

The two accepted methods are known as the Road Research Laboratory (RRL) method from the UK and the Texas Department of Transport (TxDOT) method or Gallaway equation from the USA. These are outlined below and the adopted methods for Australian and New Zealand authorities are stated.

When calculating the WFD, Gallaway's equation uses the same parameters of flow path, slope and rainfall intensity as the RRL method, but with significantly different indices applied to each, resulting in radically different results. Gallaway also takes into account the texture depth of the pavement, which further reduces the predicted WFD (NZ transport, 2014)

Research and studies have also been conducted to investigate the use of other methods to calculate sheet flow depth on pavement surfaces, including the kinematic wave model. Since these are not approved methods of calculating aquaplaning flow depth, these will be further discussed in detail in section 2.4

2.3.1 United Kingdom – Road Research Laboratory method

Research performed on behalf of the UK Ministry of Transport at the Road Research Laboratory (RRL) by Ross and Russam (1968) investigated the depth of rain water on road surfaces.

The work of Ross and Russam (1968) involved constructing a test flow path to simulate rainfall situations. The equipment included a rainfall simulator which was 30m long and could control the rate of rainfall between 1 cm/h and 20 cm/h. A tilting platform which was 11m long and 5.5m wide could be tilted to change the grade of the flow path up to a 1 in 20 slope. Water as to run-off the surface and be collected by a tank at the lower end which was used a measurement device to automatically measure the discharge rate and correlate between the known rainfall intensity.

During the testing procedure, the platform was adjusted to the required slope and the rainfall simulator and water level recorder were switched on. Flow was allowed to run for a number of minutes to reach equilibrium. Measurements of the water depth were taken at various locations along the flow path by placing a steel measuring rod into the flow (Ross and Russam, 1968).

The method of measuring the flow depth was repeated with several slopes and several rainfall intensities to give a broad range of results. The test platform surface was also covered with two different surfaces, which were a rolled asphalt and rolled concrete (Ross and Russam, 1968).

An assumed relationship for the flow depth was adopted for the research which related length, rainfall intensity and slope in the form of:

$$\boldsymbol{d = Constant\frac{(L\ x\ I)^m}{S^n}} \qquad \textbf{2.1}$$

The experimentation gathered data for the depth with various slope and rainfall intensities. The vast amounts of data were analysed using a multiple regression computer program to provide the best of data to the above equation. This regression was then used to determine the constant, m and n above (Ross and Russam, 1968).

The UK research conducted at the Road Research Laboratory produced a regression relationship for water film thickness which is related to the drainage path length, rainfall intensity and flow path slope as follows:

$$\boldsymbol{d = 0.015\ (L\ x\ I)^{0.5}\ x\ S^{-0.2}} \qquad \textbf{2.2}$$

Where

d = water film depth above top of texture (cm)

L = drainage path length (m)

I = rainfall intensity (cm/h)

S = flow path slope (m/m)

(Ross and Russam, 1968)

The equation and method has since been referred to as the UK RRL method and will be describe as such throughout the rest of this report.

The method as outlined above was tested with experiments varying the slope and length of path. The tests also varied the type of pavement texture, however, the equation does not take texture depth into account. The regression program used to fit the constant in the equation did so taking into account the two surfaces tested. Therefore the equation is not specified for any one texture type but a mix of the asphalt and concrete. The equations could therefore be limited in its accuracy over a range of different pavement types.

It should also be noted that the flow path length was only tested to 11m. Lengths over 11m would be experienced in a large number of areas on the road. The use of the RRL equation has not been studied beyond these lengths but it is assumed to hold for greater lengths (Ross and Russam, 1968)

The results were obtained using surfaces whose texture depths were in the range 1.5mm to 2.5mm. The relationship is considered to hold well for texture depths below 1.5mm, but for surface whose textures depths are greater than 2.5mm, the water depths estimated may be excessive (NAASRA, 1986)

2.3.2 United States Federal Highway Administration – Gallaway Equation

The United States research for surface flow depth was undertaken at Texas A & M University over a number of years in the 1970s. A number of draft reports were released and subsequently built upon with later research. The final report of 'Pavement and geometric design criteria for minimizing aquaplaning' was released in December 1979 (Gallaway et al, 1979).

The draft reports built research upon which the 1979 guide to minimising aquaplaning (Gallaway, 1979) was based. Gallaway et al. (1971) investigated the effects of rainfall intensity, pavement cross slope, surface texture and drainage length on pavement water depths. The findings of this research paper have been used as the Gallaway equation since published (Gallaway et al. 1971).

The test method was similar to that outlined for the RRL method previously, with rainfall simulated to fall on a test surface with measurements taken of the depth of flow. The surface could be tilted to alter the slope and the rainfall intensity also manipulated through the flow rate. Nine different surfaces were tested which were chosen to contain a range of texture found on Texas Highway pavements. The surfaces were placed on individual 28-foot (8.53m) long by 4 foot (1.21m) wide concrete beams which were chosen to represent the width of a typical highway of 2 lanes wide with a unit segment length long the highway (Gallaway et al. , 1971).

A uniform rainfall intensity was applied to the surface. This was performed by nozzles installed above the test surface and positioned to provide a uniform simulated rainfall onto the test surface.

Water depth measurements were taken at several drainage lengths for various combinations of rainfall intensities and cross slope. Multiple regression analyses were used to determine the best fit of the relationships. (Gallaway et al., 1971)

The report derived an empirical relationship for the surface flow depth on pavement surfaces. The equation linked the same variables as that of the RRL method, being drainage path length, rainfall intensity and flow path slope, but also accounted for the texture depth of the pavement material being used. This made it far more accurate than previous methods.

The equation derived by Gallaway et al. (1971) is as follows:

$$\boldsymbol{d = \left[0.00338(T)^{0.11}(L)^{0.43}(I)^{0.59}(1/S)^{0.42}\right] - T} \quad \textbf{2.3}$$

Where

d = water depth above the texture (in.)

T = average texture depth (in.)

L = drainage-path length (ft)

I = rainfall intensity (in/h)

S = slope of pavement (ft/ft)

(Gallaway et al, 1971)

This research concluded that greater drainage lengths increased water depths, however the rate of increase in water depth became smaller as the flow path length increased. It also concluded that increasing the surface texture resulted in a decrease in water film depth for any given conditions of slope, length and rainfall intensity. This effect was more pronounced on flatter grades and lower rainfall intensities (Gallaway et al., 1971).

The Gallaway et al. (1979) research also predicted the critical speed for aquaplaning based on tyre characteristics such a tread and pressure however this model will not be considered as part of this report.

The Gallaway formula is an empirical formula based on conditions that are only evident in the laboratory. The experimental parameters upon which the formula was based are as follows:

- Drainage lengths up to 14.6m
- Rainfall intensities up to 50.8mm/h
- Slopes up to 8%
- Testing was performed on several surface textures including sprayed seals, asphalt and concrete

(Austroads Part 5A, 2013)

Gallaway concluded that water depth as a function of cross slope, texture depth and rainfall intensity can be reliably predicted for drainage lengths up to 15m and probably considerable beyond (Gallaway et al., 1971). This however was not modelled therefore the accuracy of the model as the flow path increases is not known. While it is suggested that the formula can be used for flow path lengths greater than 15m, no evidence proving or disproving the use of the formula over longer paths has been found. Therefore, the Gallaway formula is still considered appropriate (Austroads Part 5A, 2013)

Other limitations of the Gallaway model are that the flow path tested was over a simple planar surface and therefore the formula does not contain a term for hydraulic resistance of the pavement. The Gallaway model is one dimensional and only assesses depth of flow along a zero width flow path. The model does not assess flow velocity or width of flow on the pavement.

Some situations can occur where water run-off from off the road surface can flow onto the road and/or where run off from one flow path crosses a boundary and joins another flow path. The Gallaway formula is unable to assess these situations properly and cases such as these should be referred to hydraulic specialists (Austroads, 2013). It should be noted that all the current methods used for aquaplaning analysis are not able to model these situations.

The work of Welleman (1978) compares of the results of a number of formulae for calculating water-film thickness and gives preference for that of Gallaway et al. (1971). However, it provides a caveat that the value of such a formula should not be overrated. The production of the formula is based on conditions only achievable in a laboratory, and to limits that are often exceeded in real world situations. It should be borne in mind that differences are likely as regards traffic intensity and composition, wind effects and the existence of (thermoplastic) markings or rutting (Welleman, 1978).

2.3.3 Australia

Austroads is the Association of Australian and New Zealand Road Transport and Traffic Authorities. Their aim is to provide consistency and guidance through standards and documentation across all road authorities in Australia and New Zealand.

The standard method for calculating aquaplaning flow depth in Australia has change throughout time. The NAASRA (1974) document '*Design of wide flat pavements*' referenced the RRL method as the calculation method for flow depth. Although the research which derived the Gallaway equation was performed in 1971 (Gallaway et al., 1971), the final report was not released until 1979. This suggests that Australian authorities did not adopt the Gallaway equation as soon as it was released and the RRL method remained the approved method for some time.

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The 1986 NAASRA document, 'Guide to the design of road surface drainage', contained both the Gallaway and RRL methods and provided commentary on the results produced by each method. These will be discussed further in Section 5 of this report. The report suggest that the Gallaway equation is a more reliable method and since this time this has been the adopted method in Australia (NAASRA Road surface drainage, 1986). The Gallaway method has been documented in subsequent design manuals, the latest of which is the current Austroads Part 5A, which outlines the method for calculating aquaplaning water film depth

The following is an extract from the Austroads Guide to Road Design Part 5A, section 4.9 and outlines the preferred method of assessment for water film depth:

Several theoretical and empirical methods and formula exist to predict the depth or thickness of the water film over the surface.

The method provided in this guide is not considered appropriate for New Zealand conditions as its suitability for use in New Zealand has not been fully demonstrated. Practitioners in New Zealand and/or designing for New Zealand conditions are referred to the NZ Transport Agency website for further advice.

The approved method for New Zealand will be discussed further below.

The adopted method was developed by Gallaway et al. (1979) for the USA Federal Highway Administration U.S. Department of Transportation.

The metric version of the formula is given below:

$$d = \frac{0.103\ x\ T^{0.11} x L^{0.42} x I^{0.59}}{S^{0.42}} - T \qquad \textbf{2.4}$$

Where

d = water film depth above the top of the pavement texture (mm)

T = Average pavement texture depth (mm)

L = Length of drainage path (m)

I = Rainfall intensity (mm/h)

S = Slope of drainage path (%)

Note: several versions of this formula have been published however the key difference is generally the units used for the slope variable.

(Austroads Part 5A, 2013)

The Austroads guide further expands on the variable used in the formula and gives direction on values to select or methods to use to calculate the variables. As the extract shows the method adopted may not be appropriate everywhere and all of the literature is accepted as best practice until further research can make better predictions of surface flow. The approved methods from Austroads Part 5A (2013) for rainfall intensity and texture depth will be explored in the following sections.

Roads and Maritime Services, the current road authority in New South Wales, adopts the Gallaway equation to measure water film depth. The process is taken exactly as it is documented in the Austroads guide without alteration or supplementation.

Queensland Department of Transport and Main Roads played a large role in producing the Austroads document. The method adopted by the department is the one developed by Gallaway et al (1979) for the Federal Highway Administration. The limitations with the Gallaway equation regarding the length of flow and a simple planar surface which were discussed above are also repeated in the Queensland documentation (Queensland Road Drainage Manual, 2010). Slight differences exist for standard values of rainfall and texture depth however, these will be discussed later.

2.3.4 New Zealand

Since 1977 the aquaplaning potential of new roads in New Zealand has been calculated using the method published in the Ministry of Works and Development ‘Highway Surface Drainage Design Guide for Highways with a Positive Collection System’ (Oakden, 1977). This manual was based on a formula developed in 1968 by the Road Research Laboratory (RRL) for the UK Ministry of Transport.

In more recent years, additional research has been undertaken to better predict water film depth on the road surface. These studies show that the method that has previously been adopted by Transit New Zealand yields rather conservative results, overestimating the flow depths for a given pavement slope and length of flow path (NZ Transport Agency, 2014). This conservatism creates difficulties for geometric design and adds unnecessary cost to New Zealand’s road projects as designers attempt to manipulate the road geometry and materials to minimise water depths.

The work of Chesterton et al (2006) investigated the use of the Gallaway equation in New Zealand by the use of a case study. The used a current motorway design project to model key aquaplaning locations using both methods and the design actions that were needed to be taken to lower the aquaplaning risk. The conclusions of the report suggest that the RRL method used in New Zealand calculates higher water film depths than does the Gallaway equation. This coupled with the excess cost of reducing the risk in these areas of aquaplaning lead the design team to recommend and use the Gallaway equation. Despite this research, the New Zealand Transport agency still recommends the UK RRL method but gives allowances to check the design with the Gallaway as a deviation from standards if the calculation with RRL method produces results that suggest a high aquaplaning risk and all feasible design options have been considered to safely reduce the risk (NZ Transport, 2014)

The New Zealand Transport agency release a technical memorandum (TM – 2505) in 2014 to remove any discussion on the relevant method for use on new road projects in New Zealand. The technical memorandum outlines the RRL method as the accepted method. It contains the following commentary on depth of flow calculation:

'In the absence of more definitive research and/or evidence as to which is the better prediction for the NZ environment, the RRL method of estimating WFD should be used.'

'The Gallaway method should only be used to assess the WFD in areas that have been identified as predicting unacceptably high values using the RRL method. The Gallaway equations should not be used as the default analysis method for any NZ Road Projects.'

The formula shown in the document is:

$$\boldsymbol{d} = \frac{\mathbf{0.46}(\boldsymbol{L\ x\ I})^{\mathbf{0.5}}}{\boldsymbol{S}^{\mathbf{0.2}}} \qquad \mathbf{2.5}$$

Where

d = depth of flow (mm) at the end of the flow path

L = Length of flow path (m)

I = Rainfall intensity (mm/h)

S = flow path slope (m/m)

(NZ Transport Agency, 2014)

Modifying the design of the pavement to compensate, and therefore reduce this theoretical over-estimation, could lead to undesirable pavement shape. Rates of change in superelevation, vertical profiles and crown positions are each adjusted and the combination of these effects assessed in order to minimise the lengths of the flow paths and therefore the WFD. While these adjustments are usually accommodated within acceptable and safe limits, there have been occasions when the design modifications became excessively complex, producing an unpredictable and therefore unsafe environment for the motorist. If constructed, this safety risk would be ever-present, compared to the risks associated with the design-year event that precipitates the unacceptable WFD.

(NZ Transport, 2014)

The Gallaway method should only be used to assess the WFD in areas that have been identified as predicting unacceptably high values using the RRL method. The Gallaway equations should not be used as the default analysis method for any NZ Road Projects.

(NZ Transport, 2014)

2.4 Kinematic wave model

As previously outlined the approved methods to calculate aquaplaning flow depth are empirical formulas which were statistically determined to fit a range of measured results. Other hydraulic methods can be used to numerically calculate the flow depth on an impervious surface. The method discussed here will be the kinematic wave model.

The mass continuity equation and the momentum equation are commonly referred to as the Saint Venant (SV) system of equations. In the case of pavement sheet flow, the kinematic wave has been shown to be an appropriate momentum model of the wave. The system of full equation can be reduced to the kinematic equation based on the assumption that terms are either small or negligible (Cristina and Sansalone, 2003). Consequently, the momentum equation can be reduced to:

$$\boldsymbol{S_f = S_0} \qquad \textbf{2.6}$$

Where:

S_f = friction slope (m/m)

S_0 = bed slope (m/m)

And the continuity equation is:

$$\boldsymbol{\frac{\vartheta A}{\vartheta t} + \frac{\vartheta Q}{\vartheta x} = q} \qquad \textbf{2.7}$$

Where:

A = cross sectional area of flow (m^2)

t = time (s)

Q = volume of sheet flow (m^3/s)

x = spatial coordinate along the length of flow path (m)

q = distributed inflow (m^2/s)

These two equations together are referred to as the kinematic equations (Stephenson and Meadows, 1986).

The works of Cristina and Sansalone (2003) investigated the use of the kinematic wave model for urban pavement rainfall run-off that was subjected to traffic loading.

The kinematic wave model was also used to compute the depth of flow across the pavement section. For the eleven observed storms, the depth of flow never exceeded 4 mm at the downstream edge of the paved shoulder even though the discharge associated with this 300-m2 drainage area approaches 400 L min21. The maximum depth of the plane is directly related to rainfall intensity as predicted by the kinematic wave model. No correlation was found between total depth of rainfall and depth of flow on the plane. The depths predicted by the kinematic wave model were verified by field observation at the downstream edge of the pavement during rainfall-runoff events.

The research concluded that the kinematic wave model accurately captures the significant aspects of rainfall-runoff events such as time to peak, total volume of flow, and to a lesser degree, peak discharge for the range of Manning's n applicable to the pavement area under study. This finding indicates that for small, asphalt-paved single land use watersheds subject to traffic loadings, the kinematic wave model appears to be a reasonable approximation to the measure results (Cristina and Sansalone, 2003).

The kinematic wave theory used by Cristina and Sansalone (2003) also gave predictions of the time of concentration that were at least as accurate as other, more commonly used runoff prediction methods. This will be discussed further in the following sections.

Tisdale, Hamrick and Yu (1999) performed a study of the analysis of the kinematic wave method for large sheet flow catchments. The research produced a mathematical derivation considering the relationship between the kinematic wave flow equations and the runoff surface topography. The results from observed and simulated discharge and depths demonstrated reasonable agreement for the calculation method. The research recommended that further testing is required to validate the use of the model for sheet flow, this was due to the small sample of textures used in sheet flow. The results produced were considered accurate however the limited data should be extended to ensure the wide use of the method is more appropriate. The results suggested that the model correctly simulated the measured physical properties of the flow, however, the conditions modelled were a very small sample size and therefore the study recommended more detailed analysis and simulation.

Shultz et al. (2008) investigated the use of the kinematic wave technique to the hydrological modelling of storm events. This research was conducted over large synthetic impervious catchment areas and the results compared with measured hydrographs. The research considered the use of both the kinematic wave technique and the full dynamic or diffusion wave technique. As per the kinematic wave technique, dynamic wave model are a one-dimensional model based on the continuity and momentum equations. The dynamic model takes into account the full version of the momentum equation, i.e. it does not simplify the values assumed to be small and cancel each other out as done for the kinematic wave model to produce Equation 2.6.

Shultz et al (2008), highlighted that the kinematic wave model considers only gravity and friction by assuming that acceleration and pressure are negligible and therefore zero. Making these assumptions makes the calculations and model production much more simple, however they do place limitations on the use of the kinematic wave simulation technique.

Jeong (2008) and Jeong and Charbeneau (2010) extended the use of the kinematic wave model to the full diffusion or dynamic wave model to simulate storm run-off on highway pavements at superelevation transitions. The modelling used for this study is a more complex 2-D model that is not used by any other the other methods discussed. The two-dimensional rainfall-runoff model predicts the spatial and temporal variations of sheet flow on the geometrically complex surfaces found at superelevation transitions. This research was performed at the University of Texas with both authors extending on previous research for a number of years.

The NCHRP document, ‘Improved surface drainage of pavements’ (1998), used a one-dimensional kinematic model as the preferred model for predicting water film thickness. This one-dimensional steady state form of the model was used in developing the surface drainage guidelines and used in building the PAVDRN program. PAVDRN is a computer model for predicting water film depth and potential for aquaplaning on both new and existing road surfaces. This program can be used in conjunction with 3d civil design tools to analyse the topography and determine the longest flow path of a section before applying the kinematic wave equations to solve for depth, velocity and volume (NCHRP, 1998).

2.5 Rainfall intensity

Intensity, frequency and duration are three characteristics that define rainfall events. Intensity is a measure of the volume of water that falls as precipitation. This is usually expressed in the units of mm/h and represents a uniform depth of water over a $1m^2$ area. The frequency defines the likelihood or recurrence of the event. It can be expressed in a number of ways with the most common being Average Recurrence Interval (ARI), a 1 in X years probability or as Annual Exceedance Probability (AEP), a percentage of occurrence in any given year. The duration defines the time the storm lasts and is expressed in minutes.

As there is an increased risk of aquaplaning in intense rainfall, it is necessary to make assumptions of the Average Recurrence Interval (ARI), rainfall intensity and duration. The ARI and rainfall intensity will be discussed in more detail in this section and section 2.5 whilst the duration will be discussed in section 2.7.

The works of Gallaway et al. (1979) and Ivey (1975) studied the probability of certain rainfall intensities occurring. They linked the rainfall intensity values to the equation derived for water film depth but did not recommended standard values for use. The recommendation was for users to select rainfall based on site characteristics and geographic location.

The commentary from Ivey (1975) tells of the rare occurrence of high intensity rainfall in Texas, USA. The research suggests that if highway engineers design for 6mm/h rainfall intensity the design would be adequate 99.6% of the time. If the design rainfall of 25mm/h is selected there will be less intense rainfall 99.95% of the time, or more intense rainfall for 1.2 hours in every 100 days. It should be noted here that the rainfall data used for this study was from the United States and therefore this conclusion could be quite different for rainfall data based on that from Queensland or New South Wales.

Since these studies occurred, extensive data collection and correlation has been done across Australia. The Australian Bureau of Meteorology (BoM) website contains extensive data of rainfall intensity and duration data. This data is freely available to all users and comes in the form of an Intensity-Frequency-Duration (IFD) chart or table. Users can choose the required frequency from the ARI and duration of the storm event. An assumption for rainfall intensity is needed before the water film depth can be calculated.

The 1974 NAASRA research paper titled “Drainage of Wide Flat Pavements” recommended an ARI of 1 year as the design frequency with a time of concentration (or storm duration) of no less than 5 minutes. This figure seems to be the standard adopted from this point in time with the intensity reduced if necessary due to driver behavior.

A subsequent paper, ‘guide to the design of road surface drainage’ (NAASRA, 1986) gives advice on the selection of design ARI for a variety of design elements. It comments on the factors that influence the choice of a design ARI as follows:

In terms of aquaplaning for example, it becomes increasingly difficult to drive in rainfall intensities greater than 100mm/hr. Hence it would be inappropriate to assume that average vehicle speeds will remain constant at higher intensities, and the hydroplaning risk would drop accordingly;

The recommended ARI from this document for Road Surface (aquaplaning) is 0.5 to 2 years (NAASRA, 1986). This suggests that a balance needs to be taken between the high intensity storms which will result in an increased surface flow depth and an intensity which is considered too high for drivers to operate at normal conditions. This will be discussed further in the following section.

The current Austroads outlines the following process for rainfall intensity.

> *The rainfall intensity to be used for the determination of water film depth is the lesser intensity determined using a site-specific IFD chart (ARI 1 year/5 minute duration) and 50 mm/h.*

Austroads, 2013

The above is consistent with literature in the Queensland Road Drainage Manual 2010, which states:

> *'The department has adopted and used the rainfall intensity of 50 mm/h to determine water film depths for some time now and it is considered appropriate to continue to use this intensity until further research / review supports change.'*

(QRDM, 2010)

In Queensland, it is assumed that the ARI 1 year / 5 minute duration storm will always have an intensity higher than 50mm/h. The ambiguity between which method to use is removed to aid the designer and simplify the process. The statement above does leave the situation open for further research.

In New Zealand, the standard design storm event for aquaplaning risk is the 2 year ARI and 5 minute duration event (Oakden, 1977). This will appear to have the effect of increasing the design storm intensity from that of the standard used in Australia. However rainfall intensity in New Zealand may be lower than those found in Australia and the 2 year, 5 minute storm could be justified as a more cost effective design storm to minimise risk.

2.6 Visibility and driver behaviour

Observations and experience tell you that drivers reduce speed in wet weather conditions. However, driver behaviour is dictated by what they perceive to be a hazardous situation. There are a number of factors that influence drivers in wet weather, they include visibility and the slowing down of the vehicles around you as the network capacity reduces amongst others. The difficulty arises in defining when and to what degree a driver will slow down in rain or on a wet pavement.

The studies of Ivey et al. (1975) set out to determine the effect of different intensities on driver visibility. The research developed an approximate equation for driver visibility based on rainfall intensity, vehicle speed and the cyclic frequency of the windshield wipers. Dash (2006) stated that windscreen wiper speeds are usually in the range of 40 to 60 cycles/minute. The research of Ivey et al. (1975) concluded that as rainfall intensity increases, drivers will usually reduce speed. The research also showed visibility at precipitation rates exceeding 50mm/h decreased at an abrupt rate. Given the likelihood of drivers reducing speed, this figure has been adopted in NSW, Qld and by Austroads as the design rainfall intensity (Dash, 2006).

The findings of the research outlined the low probability of high frequency rainfall events, they also concluded that passing manoeuvres become a hazard when traffic speeds are in excess of 45mph (70km/h) and are performed during rainfall higher than 25mm/h. Another conclusion from the research is that for high speeds, the derived equations do not predict that the stopping sight distance criteria is breached due to reduced visibility until rainfall intensities reach approximately 55mm/h. There is however, a caveat on these values as testing did not allow verification of this value and it is therefore a prediction only.

Current Australia documentation including Austroads 2013, and Queensland's Road Drainage Manual all contain the following exert on the effect of rainfall intensity of driver behaviour.

> *However, research and other design documentation (Yeager 1974, NAASRA 1986, Ibrahim & Hall 1994, HCM 2000, Dash 2006) suggest that drivers tend to slow as rainfall intensity increases and visibility decreases. This 'slowing' typically occurs at about 50 mm/h however some drivers start to reduce speed at rainfall intensities as low as 25 mm/h. As speed decreases, the potential for aquaplaning also decreases.*
>
> (DMRT, RDM, 2010)

The work of Bryant (1979) suggest that the optical characteristics of the pavement surface are influenced by moisture layer thicknesses far less than the 2-4mm range which is critical for loss of friction or aquaplaning. The study concludes that the design storm approach to pavement drainage design which is based on the flow depth of water on the surface not exceeding a certain depth, is not adequate if other factors than skidding, such as surface reflectivity or visibility to pavement marking are taken into account (Bryant, 1979). This research implies that visibility to the pavement surface will be reduced far before the visibility due to the direct rainfall landing on the windscreen impairs vision due to the build-up of water on the windscreen. The paper does not attempt to quantify the degree to which these conditions slow the driver however it should be noted that if this does influence drivers to slow it would occur before the 50mm/h rainfall intensity which is currently used as the design storm intensity.

Other factors associated with storm events can lead to reduced visibility of the road and the surrounding road environment. The work of Welleman (1978) discussed the road safety issues associated with surface water and rainfall events. The paper highlighted a number of general issues which increase the risk associated with accidents in the wet and specifically outlines some visibility issues which impact on the road environment during wet weather.

Reduced general visibility can be attributed to the falling raindrops or other forms of precipitation directly reducing visibility for road users. These are more greatly experienced during night time or at dusk where the light on the roadway is already at a reduced level. Ways that precipitation directly affects the drivers' visibility are the water directly on the windshield, sprays from other vehicles which splash surface water up and into the path of the following vehicle. This increases the demand on the wipers to clear the screen sufficiently. Steam on the windscreen, fog, glare due to water and artificial lighting and visibility to pavement markings are also factors which can decrease the visibility of the road environment and lead to an increased likelihood of a crash (Welleman, 1978).

Research on behalf of Florida Department of Transportation investigated driver behaviour in response to aquaplaning conditions and rainfall events with the use of a computer driver simulation program. The work by Villiers et al. (2012) used a driver simulator to investigate patterns of driver behaviour during various rainfall events using different roadway geometries.

The work of Villiers et al. (2012) analysed extensive field data of major highways in Florida which was used to build a driving simulator which would be considered similar to many driving computer games which are currently on the market. In the driver simulation, 30 participants took part and were placed in a video graphics type simulator console and various conditions were replicated in the simulation to check the reaction and travel speeds. The computer generated model of the roadway was also filled with storm events ranging from light rain for rainfall intensities from 0.25mm/h to 6.1mm/h and heavy rain for rainfall intensities greater than 6.1mm/h.

On average, in dry conditions, drivers tend to drive to the posted speed limits. Based on this research, light rainfall events had little or no effect on drivers' behaviour. Heavy rainfall events had a significant impact on behaviour, leading to a reduction in speed. On average drivers reduced their speed by 10-19km/h in these heavy rainfall events (Villiers et al., 2012).

The simulator appears to provide identical results to the field data analysis, leading credence to the validity of using driving simulators to investigate the pattern of drivers behaviour during a rainfall event (Villiers et al., 2012).

2.7 Texture depth standard values

The texture depth of a pavement represents the distance between the raised most portion of the aggregate and the bulk of the material matrix. For instance, asphalts with large aggregate and lower base will have a larger texture depth whilst a homogenous material such as finished concrete will have a much less value of texture depth.

The pavement surface types tested by Gallaway et al (1971) when deriving the Gallaway equation varied in their texture depth. In all, nine texture types were tested. The texture depth used in the equations was determined using the sand method (Gallaway et al., 1971). In this method a unit area of pavement is taken as the testing area. Sand is then used to pour over the pavement and fill the voids in the macrotexture. The known volume of sand which is required to fill the pavement to the top of the aggregate can be used to determine the uniform depth over the unit area to which the sands fills. This depth of sand required is the average texture depth of the pavement surface (Gallaway et al, 1971). This method is still considered to be accurate and is used in determining the texture depths of pavements in laboratories today.

The standards values of texture depth have not varied greatly over time. Many different documents have reference or re-issued values similar to each other. The following list, which was first part of RTA (Roads and Traffic Authority of NSW) research in 1994 and is now referenced from Austroads, provides the most extensive texture depth values for a variety of different pavement materials.

Table 2.1 - texture depth of various pavement surfaces

Wearing Course Surface	Texture depth[1] (mm)
Dense graded asphalt 10mm or larger	0.4-0.8
Dense graded asphalt, 7mm	0.3-0.5
Open Grade Asphalt[2]	>0.9
Stone Mastic Asphalt	>0.7
Fine Gap Graded Asphalt	0.2-0.4
Slurry Surfacing	0.4-0.8
Spray seals,10mm or larger	>1.5
Spray seals, 7mm	0.6-1.0
Grooved Concrete	1.2
Exposed aggregate concrete	>0.9
Tyned concrete	0.4-0.6
Hessian dragged concrete	0.3-0.5
Broomed concrete	0.2-0.4

(1) Texture depth is usually measured by the sand patch test using either sand or glass beads.

(2) As high as 2mm when new, but clogs up and needs cleaning.

Source: Donald (1994), and Dash (1977), cited in DTMR (2010)

(Reproduced from Austroads, 2013)

This list however, does not account for the wearing of pavement course over long-term use. This has implications in the texture depth selection for aquaplaning analysis on existing roads on which the pavement has worn; the results given may vary to those experienced in the real world due to the different in texture depth. This will require further research to investigate in situ values of texture depth and surface friction.

2.8 Time of concentration – sheet flow

Hydrological studies and urban drainage networks use the time of concentration method to define the time taken for water to travel from the furthest point in the catchment to the outlet. This means that when rainfall lands on the highest point in the catchment it will slowly travel downhill to the lowest point.

Sheet flow is a shallow mass of runoff on a plane surface with the depth varying along the sloping surface. Typically, flow depths will not exceed 50mm. Such flow occurs over relatively short distances, rarely more than about 100m, but most likely less than 25m. (AASHTO, 2005). In the context of the road environment the flow paths lengths in a superelevation transition are typically less than 100m and are generally kept approximately 50m in length. The flow paths lengths found in urban situation around intersection would generally be around 25m. These lengths of flow paths could have implications on the braking and manoeuvrability through the intersection as the depth of flow increases.

Various methods can be used to estimate the time of concentration for a catchment based on the type of flow likely to occur. Here we are studying sheet flow, which is typically experienced in the uppermost portions of the catchment before concentrated flow paths can form. Since the catchments we will be studying will consist of flow from the high side of a paved roadway to the outlet on the low side, and lengths are typically less than 100m, it is considered to be sheet flow.

According to McCuen (1984) who studied numerous equations for the time of concentration for a catchment, the rainfall intensity is the most important input variable. This suggests that any model used to calculate the time of concentration should include a variable to account for the rainfall intensity. This study by McCuen, modelled the time of concentration over large catchment areas for 11 different equations or models. These were compared with experimental data measurements from actual catchments. One method used in the study was the kinematic wave approximation for sheet flow, which has since been used by many authorities. The kinematic wave model is commonly used to model surface flow to calculate time of concentration for drainage design. Other common methods are attributed to Friend (1954) and Oakden (1977). These methods will be discussed in further detail below however it is important to note that neither of these formula contain a variable to account for rainfall intensity.

The kinematic wave formula as documented by McCuen (1984) is:

$$t_c = 0.01567 L^{0.6} n^{0.6} I^{-0.4} S^{-0.3} \quad \textbf{2.8}$$

Where:

tc = time of concentration (hours)

L = flow length (ft)

n = Manning's roughness coefficient

I = excess rainfall rate (in./h)

S = slope of the surface (ft/ft)

2.8.1 United States

The United States have numerous state bodies, which contain standards for road and highway design. However, most are slight adjustments of the national standard American Association of State Highway and Transportation Officials (AASHTO). The AASHTO model drainage manual 2005 has the following method for time of concentration for sheet flow. This method is an adaptation of the kinematic wave equation method outlined previously.

AASHTO kinematic wave time of concentration is:

$$t_c = \frac{6.92}{I^{0.4}}\left(\frac{nL}{\sqrt{S}}\right)^{0.6} \qquad \textbf{2.9}$$

Where:

t_c = time of concentration (minutes)

L = flow length (m)

n = roughness coefficient

I = Rainfall intensity for a storm that has a return period T and duration of tc (minutes)

S = slope of the surface (m/m)

Values of n can be obtained from Table 2.2 on the following page:

Table 2.2 - Roughness Coefficients (Manning's n) for sheet flow

Surface description	n
Smooth surfaces (concrete, asphalt, gravel, bare soil)	0.011
Fallow (no residue)	0.5
Cultivated Soils:	
Residue cover ≤ 20%	0.06
Residue cover > 20%	0.17
Grasses:	
Short grass prairie	0.15
Dense grasses	0.24
Bermuda grass	0.41
Range (natural)	0.13
Woods:	
Light underbrush	0.40
Dense underbrush	0.80

(Source: AASHTO model drainage manual, 2005)

Some hydrologic design methods, such as the Rational method, assume that the storm duration equals the time of concentration. Thus, the time of concentration is entered into the *IDF* curve to find the design intensity. However, for the kinematic wave equation, I depends on tc and tc is not initially known. Therefore, the computation of tc is an iterative process. An initial estimate of tc is assumed and used to obtain i from the intensity-duration-frequency curve for the locality. The tc is computed from Equation 7.9 and used to check the initial value of i. If they are not the same, then the process is repeated until two successive tc estimates are the same (AASHTO model drainage manual, 2005).

The kinematic wave method outlined above is also recommended by the Federal Highway Administration (FHWA) and is reproduced in the Hydraulic Engineering Circular (HEC-22) Urban Drainage Manual 2009. It is also recommended by various other United States documentation including the 'HEC-21 Design of Bridge Deck Drainage, (1993)'

2.8.2 Australia and New Zealand

Literature in Australia consists of three methods to calculate sheet flow time of concentration. These consist of the kinematic wave equation, Friend's formula and the Oakden formula (Austroads Part 5, 2013).

The kinematic wave equation for approximating time of concentration is attributed to Ragan and Duru (1972). The method should only be applied to planes of sheet flow that are homogeneous in slope and roughness (QUDM, 2007). The equation is similar in form to the reference in the manuals from the United States.

Ragan and Duru (1972) Kinematic Wave equation:

$$\boldsymbol{t_c = 6.94\frac{Ln^{0.6}}{I^{0.4}S^{0.3}}} \qquad \textbf{2.10}$$

Where:

t_c = time of overland flow (minutes)

L = overland flow path length (m)

n = Manning's roughness value

I = Rainfall intensity from the design ARI event (mm/h)

S = slope of overland flow path (m/m)

Experience both in Australia and as quoted by McCuen (1984) indicates that the Kinematic Wave Equation tends to result in excessively long overland sheet flow travel time (QUDM, 2007). Kinematic wave model gave estimates of time of concentration that were much higher than measured with experiments. This was due to the varied nature of the flow and the research concluded that the kinematic wave model was applicable to overland flow over short distances (McCuen, 1984). This formula cannot be applied to large heterogeneous catchments. The kinematic wave equation is best applied to large paved areas such as car parks and airports (QUDM, 2007).

The real world conditions of sheet flow would mean that the kinematic wave model would experience some errors in predicting time of concentration. However since this study is analysing a plane drainage surface of uniform texture the method is deemed appropriate.

The Oakden (1977) formula was based on research from New Zealand and contained in the 'Highway Surface Drainage Design Guide for highways with a positive collection system'. This manual is the standard use document in New Zealand and therefore the use of the Oakden formula is recommended above the kinematic wave equation and Friend's formula. The formula attributed to Oakden (1977) is:

$$\boldsymbol{t_c = 500nL^{2/3}S^{-1/3}} \qquad \textbf{2.11}$$

Where:

t_c = time of concentration (seconds)

L = length (m)

S = slope (m/m)

n = Manning's roughness value

The formula shown below is attributed to Friend (1954) may be used for determination of sheet flow times. The formula was derived from previous work in the form of a nomograph for shallow sheet flow times over a plane surface (QUDM, 2007). The Queensland Urban Drainage manual recommends this formula for use instead of the kinematic wave equation (QUDM, 2007).

Friend's Equation:

$$\boldsymbol{t_c = (107nL^{0.333})/S^{0.2}} \qquad \textbf{2.12}$$

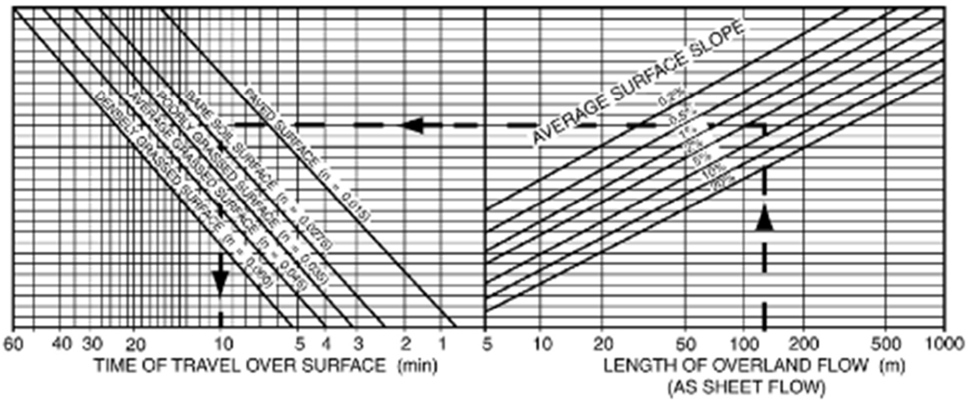
Where:

t_c = overland sheet flow time (minutes)

L = overland sheet flow path length (m)

n = Horton's surface roughness factor

S = slope of surface (%)



Source: (QRDM, 2010)

Figure 2.2 - Overland sheet flow times - shallow sheet flow only

Table 2.3 - Horton's surface roughness values

Surface Type	Horton's Roughness coefficient n
Concrete or Asphalt	0.010 - 0.013
Bare Sand	0.010 - 0.016
Gravelled Surface	0.012 - 0.030
Bare Clay-Loam Soil (eroded)	0.012 - 0.033
Sparse Vegetation	0.053 - 0.130
Short Grass Paddock	0.100 - 0.200
Lawns	0.170 - 0.480

Source: (QUDM, 2007)

2.9 Allowable surface water film depth

The allowable surface water film depth is determined to provide adequate safety against the likelihood of aquaplaning occurring. Various research papers have been produced to recommend allowable values of depth. These have since been documented in design standards around the world however the documentation of how the values have been derived have often been lost. Below is the guidance from various transport authorities and a summary of the research from which these standards have been based.

Concentrations of sheet flow across roadways are to be avoided. According to the California department of transport (Caltrans), as a general rule, no more than $0.003m^3/s$ should be allowed to concentrate and flow across a roadway (Caltrans, HDM, 2001).

The current Austroads Guide to drainage gives the following guidelines for considering the aquaplaning potential. Road surface geometry should be such that drainage paths lengths are less than about 60m (Austroads Part 5, 2013). This suggests that for flow paths which exceed 60m in length, the water film depth will increase to a depth that is sufficient to considerably increase the aquaplaning potential.

A maximum water film depth of 2.5mm (desirable) to 4.0mm (absolute) applies to a section where the operating speed is greater than or equal to 80km/h. This standard is also applicable to many common road areas with an increased risk of a crash occurring, such as, intersections and roundabouts (including approaches), steep downhill sections, merge and diverge areas for ramps/overtaking lanes/climbing lanes etc. and superelevated curves. A maximum water film depth of 5.0mm (desirable and absolute) applies to all other situations (Austroads Part 5, 2013).

These standards will be explored further below but essentially they reflect that full or dynamic aquaplaning is unlikely to occur. Partial aquaplaning is likely to occur at lower depths of flow from around 2.5mm and it is much more likely that the tyre/road surface forces will experience a minimum when there is a combination of surface water and the driver attempting to manoeuvre the vehicle. I.e. braking, changing lanes or direction.

When considering the geometry of the road surface the designer must employ every effort to comply with these length and flow depth requirements. On high speed, wide flat pavements, it can be nearly impossible to achieve the 2.5mm desirable limit, however experience has shown that depths of about 3.25mm are achievable. The 3.25mm flow depth is often accepted by road authorities provided the risks to road users at the site are low and the expected aged or deteriorated pavement conditions are unlikely to result in a flow depth exceeding 4.0mm absolute minimum limit (Austroads Part 5, 2013).

According the New Zealand Surface Drainage Manual (1977), rougher pavement surfaces textures are desirable because more ponding can occur before water level rises above the texture. The text implies an insignificant amount of water actually flows below the top of the texture and the water is generally stored here stationary. It is therefore concluded that surface roughness has a negligible effect in the hydraulics of rainwater flow (NZ, surface drainage manual, Oakden, 1977).

The critical depth for aquaplaning ranges from 4mm to 10mm depending on the tyre and pavement surface. The surface water depth therefore, should be restricted to 4mm for all but special situations where superelevation produces long, curved flow paths. Higher depths may be accepted over limited areas (NZ, surface drainage manual, Oakden, 1977).

The small flow depth associated with aquaplaning, relative to the larger flows taken by a pit and pipe network, requires the return period for surface water depth to be less than that for the longitudinal drainage system (NZ, surface drainage manual, Oakden, 1977). Some risk must be accepted as conditions conducive to aquaplaning may only occur but only for a relatively short time during minor storm events. In the event of larger events the major drainage systems may fail meaning the pavement surface is no longer required to be free from water.

As per the above discussion, a complete prevention of aquaplaning risk may not be possible when considering the longitudinal and transverse drainage networks. A design solution could also involve excessive time and money as the relevant factors are very difficult to control to the extent of restricting surface water depth. Consequently, New Zealand Surface Drainage Manual (1977), recommends a two year return period for surface water depth is sufficient. In addition a minimum time of concentration of 5 minutes should be used to allow flow to build up above the texture of the pavement.

Aquaplaning depends on a range of vehicle speeds, tyre tread patterns, tyre pressure and pavement surface texture and therefore the research reports investigated do not clearly define a depth of water which will cause aquaplaning. However, there is considerable agreement on the water depth required to produce when ‘spin down’ without actually aquaplaning but with sufficient loss of tyre friction to present a major driving hazard. This condition is considered the partial aquaplaning condition where the surface water has reduce the forces that can act between the tyre and the road. The partial aquaplaning depth is in the range 2.5mm to 5mm (NAASRA, drainage of wide flat pavements, 1974). Further, the critical depth to cause full aquaplaning seems to range from 4mm to 10mm depending on the character of the tyre pavement surface. There are many situations, produced by common and accepted design principles, where the above depths of flow may occur under normal rainfall conditions through inadequate drainage, road deformation or where the flow path is extended due to the contours of the road.

From the work of Staughton and Williams (1970), it is possible to infer that for vehicles travelling below about 80-100km/h with tyres in good condition, full aquaplaning is not likely to occur. Welleman (1978) produced very similar results. Increasing water depth reduced friction coefficient, with the greatest reduction occurring up to a depth of 4mm. Beyond 4mm, full aquaplaning may result, depending on tyre condition and vehicle speed. Consequently, surface treatment should be chosen so that under the design conditions, water depths in wheel path locations should be kept below about 4mm (NAASRA, road surface drainage, 1986). This further adds to the literature concluding that the critical depth of flow is in the range of 4 to 10mm however, no further research has been cited in some documents and they restate the work of others. The critical depths of aquaplaning are therefore accepted until further research can prove or disprove the currently accepted values.

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Staughton and Williams (1970), performed extensive research and drew many conclusions on the occurrence of aquaplaning. The documentation was built on research based on the results of an investigation of the tyre/road adhesion of a single wheel towed through various depths of water. These tests were performed with both a free rolling tyre and under braking force, with different tyres and different flow depth ranging up to 10mm. The free rolling wheel test was used to simulate conditions required to make full or dynamic aquaplaning occur. The results showed that for water film depths below 3mm it was difficult to attain a speed sufficient to induce wheel spin down, even with a very worn tyre.

The Staughton and Williams (1970) research also concluded that at water depths above 4mm the freely rolling wheel tended to spin down and this occurred at lower speeds as the tyre inflation pressure was reduced. When the wheel was locked, the test signifying braking, the tyre/road adhesion also reduced at the lower inflation pressures. The greatest loss in adhesion occurred between the dry surface and the lightly wetted surface, with increasing reduction in adhesion as the water depth was increased to 4mm; at depths greater than this the adhesion value were already close to the minimum. The adhesion also decreased with speed, for example, a drop of 0.3 braking force co-efficient occurred on the smooth concrete surface as the speed was increased from 50 to 120 km/h for a 4mm water depth with a patterned tyre. Stopping distances for this water depth can be at least double those for a just wet surface. Some further tests showed that adhesion on a rough harsh textured surface was also affected by water depth (Staughton and Williams, 1970).

Studies from Stoker and Lewis (1972), investigate the variables associated with tyre aquaplaning. The research suggests that many factors must be considered in determining safe wet weather speeds. However from an aquaplaning perspective, for sections of highway where water can accumulate to depths of 0.1 inch (2.54mm) or greater consideration should be given to reducing speed to 50 mph (80km/h).

Welleman (1978) investigated the road safety issues of surface water. Testing was performed to measure the combined effect of forces between the tyre and the road surface with the presence of water. The combined effect of these being termed braking force coefficient. The likely occurrence of aquaplaning occurring was determined from the test results by minima being experienced in the longitudinal braking force coefficient. The locations of these minima were variable depending on the type of pavement surface used. For untextured Epoxy Bitumen the minimum occurred at 66 km/h and a water film depth of about 0.5mm. For open-textured asphaltic concrete, the minimum occurred at about 4 to 5mm at 88 km/h and 2mm at 102 km/h. Porous asphaltic concrete with an apparent texture depth of 2 to 3mm experienced a minimum in braking force coefficient at 5 to 6mm at 120 km/h (Welleman, 1978).

Welleman (1978) also suggested there is no point in ascertaining the precise speed and water film thickness at which aquaplaning will occur. The reason for this assumption is that long before the critical aquaplaning water depth and speed the available longitudinal forces are so low that the road user is already in a dangerous situation. Once the 2 to 3 mm level of water film thickness is exceeded, the depth hardly has any more influence on the measured longitudinal force. This means that measures to limit water-film thicknesses can only have a favourable influence on transmissible tyre/road-surface forces if they reduce the water-film thickness to levels under the 2 to 3mm range.

3. Research design and methodology

3.1 Introduction

This chapter outlines the methodology used in the research paper. It establishes the mathematical models to be used and the analyses that will be performed.

This chapter will be broken up into the following sections:

- Introduction (this section)
- Aquaplaning equations for flow depth calculations
- Application of the three approaches
- Rainfall intensity
- Texture depth standard values
- Time of concentration – sheet flow
- Design storm simulation

This methodology relies on comparing three different methods used for calculating the aquaplaning surface water film depth. Once three model are established the effect of the input variables into the models will be investigated in more depth. The analysis will then investigate the time duration aspects of storm events.

3.2 Equations of flow depth calculation

The analysis of the water film depth will involve three different methods of calculation. The three methods outlined in the literature review section of this report are the Gallaway equation, RRL method and the kinematic wave model. The Gallaway equation and the RRL method are widely accepted around the world as methods of calculating the aquaplaning flow depth. The kinematic wave model is a complex hydraulics model which will model the sheet flow as a kinematic wave and solve the continuity equations to find the velocity, volume and depth of flow.

A number of assumptions and model set up parameters were established to provide consistency between the three methods. The first assumption is that the surface of the flow path would be continuous grade for the entire length of the slope. As discussed previously this would not necessarily be the case in real world situations due to variance in the pavement surface and geometric changes to the roadway, however, methods such as the Equal Area (EA) slope as define in section 1, can be used to represent the slope as a continuous plane. It is assumed here that a method such as Equal Area has been used to create surfaces of continuous grade. This assumption allows for a more simplistic calculation as the methods do not handle changes in grade and it also give a set base to allow for direct comparison between the results.

The road surface must be given an arbitrary length of flow. For this analysis, the depth of flow was along the flow path was calculated up to a length of 90m. This value was chosen due to the literature suggesting sheet flow rarely exceeds lengths of 100m (AASHTO, 2005). It is also a convenient length as the design principles recommend that the flow path length be limited to around 60m (Austroads Part 5, 2013). The justification for testing considerably beyond this 60m length is to allow for testing of the recommendation and allows the critical length for flow depth depths exceeding aquaplaning criteria to be determined. The depth was calculated at 1m increments along the flow path for all 3 models to allow the most accurate trends to be determined along the flow path.

The three methods used for flow depth calculations and comparisons are the Gallaway equation, the RRL method and the Kinematic wave model.

3.2.1 Gallaway Equation

The Gallaway equation will be used to establish a simulation regime to calculate the depth of flow for combinations of flow path length and slope.

The Gallaway (1971) Equation:

$$\boldsymbol{d} = \frac{\mathbf{0.103}\ \boldsymbol{x}\ \boldsymbol{T}^{\mathbf{0.11}}\boldsymbol{x}\boldsymbol{L}^{\mathbf{0.42}}\boldsymbol{x}\boldsymbol{I}^{\mathbf{0.59}}}{\boldsymbol{S}^{\mathbf{0.42}}} - \boldsymbol{T} \qquad \textbf{3.1}$$

Where

d = water film depth above the top of the pavement texture (mm)

T = Average pavement texture depth (mm)

L = Length of drainage path (m)

I = Rainfall intensity (mm/h)

S = Slope of drainage path (%)

(Austroads Part 5A, 2013)

3.2.2 RRL method

The RRL method will be used to establish a simulation regime to calculate the depth of flow for combinations of flow path length and slope.

The RRL method (Note: the metric version from New Zealand Literature is used):

$$d = \frac{\mathbf{0.46}(\boldsymbol{L}\ \boldsymbol{x}\ \boldsymbol{I})^{\mathbf{0.5}}}{\boldsymbol{S}^{\mathbf{0.2}}} \qquad \textbf{3.2}$$

Where

d = depth of flow (mm) at the end of the flow path

L = Length of flow path (m)

I = Rainfall intensity (mm/h)

S = flow path slope (m/m)

(NZ Transport Agency, 2014)

3.2.3 Kinematic Wave Model

The kinematic wave model is more complex than a single equation and therefore the production of the model will be explained in further detail. The derivation of the model is outlined below.

The road pavement surface problem can be simplified by representing the flow path of the surface water as a one-dimensional hydraulic model. Essentially this reduces the flow path to a unit width of flow down the predominant slope. The kinematic wave approximation was deemed to be appropriate for the task at hand as it will produce sufficiently accurate results with the complexity of the calculations reduced dramatically with respect to the full diffusion wave model discussed in the literature review. The method full dynamic wave equations was considered for use however, this makes the calculation more strenuous, this method will be recommended for further investigation as part of further research.

The first step in producing the kinematic wave model for the road surface problem is to visualise the solution space. The model will be set up in a way to analyse the flow depth (y), velocity (v) and volumes of the flow (q) at a point in time and space along the flow path (Figure 3.1). The distance and time variables need to be divided into equal intervals in order to find values of y, v and q along the length of the slope and over a sufficient duration of time. For this study the time-space matrix solution space is divided into increments of 1m in the x-axis, or distance along the flow path, and into increments of 1 second along the t-axis or duration of storm event. The distance (x-axis) and time (t-axis) coordinates can be used to label each point on the slope at a given point in time denoted by P(x,t). The solutions space can be used to systematically solve for all the required values at each point P(x,t). The process starts at the first time interval and moves along in the spatial dimension (from left to right in figure 3.1) until it reaches the downstream boundary or the end of the flow path is reached. The time step is then increased to the next step and x returns to zero. Again, the calculations follow the length of the slope until the downstream boundary is reached. The time step is increase by another interval and the process repeated until calculations for a sufficient time duration are reached.

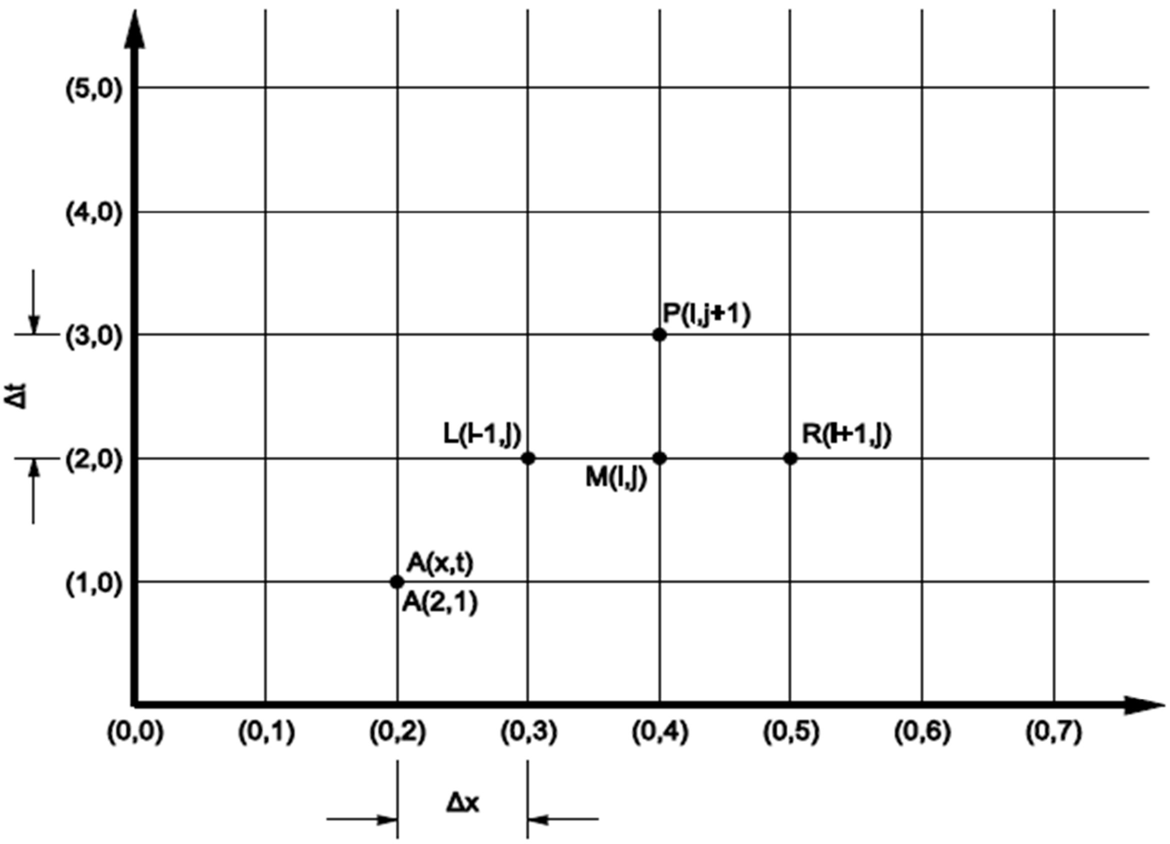

Figure 3.1 - The x - t solution space for point P

The next step in the process of forming an explicit numerical solution to the kinematic wave equation for sheet flow runoff is to develop the formulae to solve for the Depth of flow (y), Discharge (q) and Velocity (v).

The solutions to the kinematic wave problem are based on the continuity equation, which relate volumes and depth. The continuity equation is as follows;

$$\frac{dq}{dx} + \frac{dy}{dt} = I \qquad \textbf{3.3}$$

Where:

I = rainfall intensity (mm/h)

y = depth of flow (m)

q = flow per unit width (m^2/s)

x = distance along the flow path (m)

t = time (s)

The Kinematic wave model is also based of the momentum equations, where in this case most of the terms are assumed to be small and are cancelled out which reduced the momentum equation to:

$$S_f = S_0 \qquad \textbf{3.4}$$

Where:

S_f = friction slope (m/m)

S_0 = bed slope (m/m)

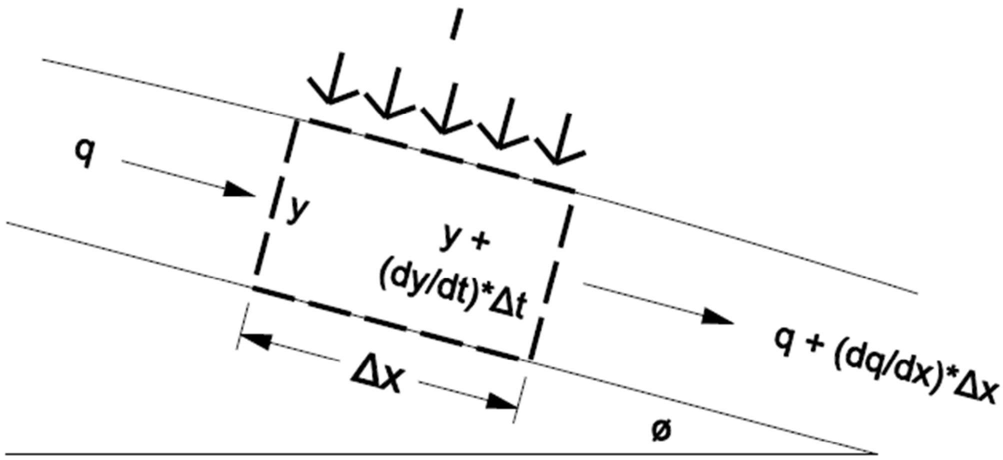

Figure 3.2 - development of the continuity equation

The continuity equation is developed for a finite element along the flow path. The element in Figure 3.2 has the dimensions of Δx, which is a representation of the increment along the x-axis. Across the element there will be an increase in flow depth, flow velocity and flow volume which is produced by the inflow provided by the rainfall on the surface.

The use of Equation 3.3 is based on knowing the initial conditions of flow and some other information at the boundary locations. In this case, before the rainfall commences there will be no water of the pavement surface. This translates to no depth of flow and no volume of flow along the entire length of the flow path. Numerically this is:

When t = 0, q=0 and y=0 for all distance x

At the upstream boundary there will be no inflow from finite elements above this point. The rainfall that falls on the first 1m increment of flow path will contribute to the volume at the second x increment of the flow path. Therefore the volume of flow at the upstream boundary is zero for the entire length of the storm duration. Numerically this is:

When x=0, q=0 for all time t

We now consider the main body of the solution space in Figure 3.1. To solve for values at a point P(i,j) we can use approximations for the derivatives in the continuity equation. To develop the equations for the main body approximations for both dq/dx and dy/dt need to be found. These approximations can be made over the x-t solutions space. As described above this solutions space is divided into specific time and distance intervals. Since the dx and dt values are defined as 1m and 1s respectively the dq and dy terms can be found by using differences between values that have been previously found.

Using backward differences in the x direction the dq/dx derivative can be derived as:

$$\frac{dq}{dx} \approx \frac{q_{(i,j)} - q_{(i-1,j)}}{\Delta x} \qquad \textbf{3.5}$$

Using the forward differences in the time direction the dy/dt derivative can be derived as:

$$\frac{dy}{dt} \approx \frac{y_{(i,j+1)} - y_{(i,j)}}{\Delta t} \qquad 3.6$$

Now substituting Equations 3.5 and 3.6 into the continuity equation, Equation 3.3, and rearranging, the depth of flow (y) at any point, P(i,j+1) from Figure 3.1, can be found using the following formula over the x-t solution space.

$$\frac{y_{(i,j+1)} - y_{(i,j)}}{\Delta t} + \frac{q_{(i,j)} - q_{(i-1,j)}}{\Delta x} = I \qquad 3.7$$

$$y_{(i,j+1)} = \Delta t\left(I - \left(\frac{q_{(i,j)} - q_{(i-1,j)}}{\Delta x}\right)\right) + y_{(i,j)} \qquad 3.8$$

Equation 3.8 is also applicable at the downstream boundary of the car park slope as the differences used are still defined at this limiting point. At the upstream boundary, however this equation is not applicable. The approximation for the dq/dx term is not defined here, as the backward difference cannot be performed. However according to the initial conditions outlined above, at the x = 0 boundary the discharge, q, is also equal to zero. Since there is zero discharge it is appropriate to assume that the depth, y, is also equal to zero as it becomes negligibly small. Since q = v x y throughout the model it is determined that the velocity is zero for all time interval at the x = 0 boundary. The equations at the upstream boundary point P(0,t) are then;

$$y_P = 0 \qquad 3.9$$

$$v_P = 0 \qquad 3.10$$

$$q_P = 0 \qquad 3.11$$

The velocity, V_p, of the flow at the point P(i,j+1) is found using the manning equation, which is;

$$v_P = \frac{1}{n} S_0^{1/2} y_P^{2/3} \qquad 3.12$$

Where

v = velocity of flow (m/s)

n = Manning's roughness

S_0 = flow path slope (m/m)

y_P = depth of flow (m)

The Manning’s value used for this study is n = 0.011.

The chosen value was selected from Table 2.2, for smooth surfaces (concrete, asphalt, gravel, bare soil), as this is predominantly the pavement types found on road way surfaces (AASHTO model drainage manual, 2005)

The discharge at point P(i,j+1) is then found by;

$$q_P = v_P y_P \qquad 3.13$$

By systematically moving point P along the solution space and solving for y, v and q the model simulating the pavement slope runoff can be fully formed and all the required values can be determined. An arbitrary modelling time of 30 minutes was chosen, however the analysis was modelled for a sufficient time to ensure that steady equilibrium conditions were reached.

3.3 Application of the three approaches

The road surface was analysed for different longitudinal slopes or grades. To replicate the situations that are common on road surfaces the minimum slope to be tested will be 0.5%. Surfaces will always need to have some form of slope to drain the surface. Longitudinal grades of roads are also kept below certain values to allow for trucks travelling up hill and pedestrians in urban areas. For these reasons, an upper limit of grade for this study was chosen to be 7%. The water film depth for each of the three methods was calculated between 0.5% and 7% slope at increments of 0.5%.

Comparisons of the water film depth were made at standard positions along the flow path. Although the calculations were made at 1m intervals, the results will be compared at 20m, 40m, 60m and 80m distances from the start of the flow path.

3.3.1 Matlab coding

The analysis requires the use of MATLAB coding to produce tables of the computed water film depth values. Files were created to compute the flow depth with all the different combinations of variables and the data exported to spreadsheets. Below is a list of the files that were produced as part of the project. A brief description of each file and the order they run is also included. The files used for the analysis are attached in their entirety as Appendix B.

The MATLAB coding for the project used in project is as follows:

- gallaway_intensity_aquaplaning.m
- gallaway_texture_aquaplaning.m
- RRL_intensity_aquaplaning.m
- Time_of_concentration_1.m
- Time_of_concentration_2.m
- Time_of_concentration_3.m
- Kinematic_wave_index.m
- slope_matrices.m
- intensity_data.m
- Kinematic_wave_intensity_15.m
- Kinematic_wave_intensity_25.m
- Kinematic_wave_intensity_35.m
- Kinematic_wave_intensity_50.m
- Kinematic_wave_intensity_75.m
- Kinematic_wave_intensity_100.m
- Kinematic_wave_design_storm.m

gallaway_intensity_aquaplaning.m

This file was created to run the simulations for flow depth using the Gallaway Equation. This file:

- Specifies the standard texture depth for comparison is to be 0.5mm.
- Sets up the range of rainfall intensities 15, 25, 35, 50, 75 and 100mm per hour.
- Sets up the slope intervals at 0.5% increments from 0.5% to 7%
- Set up the length of the flow path from 0 to 90m in 1m increments
- Calculates the depth of flow for all combinations of intensity, length of flow and grade of slope.
- Exports the data to spreadsheets

gallaway_texture_aquaplaning.m

This file was created to run the simulations for flow depth using the Gallaway Equation. This file:

- Sets up the range of texture depths from 0.2mm to 1.2mm in 0.1mm increments.
- Specifies the standard rainfall intensity for comparison is to be 50mm/h.
- Sets up the slope intervals at 0.5% increments from 0.5% to 7%
- Set up the length of the flow path from 0 to 90m in 1m increments
- Calculates the depth of flow for all combinations of texture depth, length of flow and grade of slope.
- Exports the data to spreadsheets

RRL_intensity_aquaplaning.m

This file was created to run the simulations for flow depth using the RRL method Equation. This file:

- Specifies the standard texture depth for comparison is to be 0.5mm.
- Sets up the range of rainfall intensities 15, 25, 35, 50, 75 and 100mm per hour.
- Sets up the slope intervals at 0.5% increments from 0.5% to 7%
- Set up the length of the flow path from 0 to 90m in 1m increments
- Calculates the depth of flow for all combinations of intensity, length of flow and grade of slope.
- Exports the data to spreadsheets

Time_of_concentration_1.m

This file was created to run the simulations for the catchment time of concentration using the kinematic wave approximation. This file:

- Sets up the range of rainfall intensities 15, 25, 35, 50, 75 and 100mm per hour.
- Specifies Manning’s roughness coefficient as 0.011

- Sets up the slope intervals at 0.5% increments from 0.5% to 7%
- Set up the length of the flow path from 0 to 90m in 1m increments
- Calculates the time of concentration for all the combinations of rainfall intensity, length of flow and grade of slope.
- Exports the data to spreadsheets

Time_of_concentration_2.m

This file was created to run the simulations for the catchment time of concentration using the Oakden formula. This file:

- Specifies Manning's roughness coefficient as 0.011
- Sets up the slope intervals at 0.5% increments from 0.5% to 7%
- Set up the length of the flow path from 0 to 90m in 1m increments
- Calculates the time of concentration for all the combinations of length of flow and grade of slope.
- Exports the data to spreadsheets

Time_of_concentration_3.m

This file was created to run the simulations for the catchment time of concentration using Friend's formula. This file:

- Specifies Horton's roughness coefficient as 0.011
- Sets up the slope intervals at 0.5% increments from 0.5% to 7%
- Set up the length of the flow path from 0 to 90m in 1m increments
- Calculates the time of concentration for all the combinations of length of flow and grade of slope.
- Exports the data to spreadsheets

Kinematic_wave_index.m

The file was created as the master file for simulating the kinematic wave model of calculating the surface flow depth. This file:

- Set up the length of the flow path from 0 to 90m in 1m increments

- Sets up the time axis for the solution space at 1 seconds interval for a duration of 30 minutes.
- Specifies Manning's roughness coefficient as 0.011

This file is then the master file for inputting the reference input files in the following order:

- slope_matrices.m
- intensity_data.m
- Kinematic_wave_intensity_15.m
- Kinematic_wave_intensity_25.m
- Kinematic_wave_intensity_35.m
- Kinematic_wave_intensity_50.m
- Kinematic_wave_intensity_75.m
- Kinematic_wave_intensity_100.m

slope_matrices.m

This file was created to establish the slope matrix used in the simulation. It creates the slope variables in increments of 1%

intensity_data.m

This file was created to establish the rainfall intensity data for defining the storm events. It creates rainfall intensity variables at 15, 25, 35, 50, 75 and 100mm per hour.

Kinematic_wave_intensity_15.m

This file was created to perform the flow depth calculation for the 15mm/h rainfall intensity event. The file:

- Specifies the 15mm/h event
- Creates the solution space matrices.
- Solves for the flow depth at 1% grade and export to a spreadsheet
- Repeats the previous step for grade increments up to 7%

Kinematic_wave_intensity_25.m

This file was created to perform the flow depth calculation for the 25mm/h rainfall intensity event. The file:

- Specifies the 25mm/h event
- Creates the solution space matrices.
- Solves for the flow depth at 1% grade and export to a spreadsheet
- Repeats the previous step for grade increments up to 7%

Kinematic_wave_intensity_35.m

This file was created to perform the flow depth calculation for the 35mm/h rainfall intensity event. The file:

- Specifies the 35mm/h event
- Creates the solution space matrices.
- Solves for the flow depth at 1% grade and export to a spreadsheet
- Repeats the previous step for grade increments up to 7%

Kinematic_wave_intensity_50.m

This file was created to perform the flow depth calculation for the 50mm/h rainfall intensity event. The file:

- Specifies the 50mm/h event
- Creates the solution space matrices.
- Solves for the flow depth at 1% grade and export to a spreadsheet
- Repeats the previous step for grade increments up to 7%

Kinematic_wave_intensity_75.m

This file was created to perform the flow depth calculation for the 75mm/h rainfall intensity event. The file:

- Specifies the 75mm/h event
- Creates the solution space matrices.

- Solves for the flow depth at 1% grade and export to a spreadsheet
- Repeats the previous step for grade increments up to 7%

Kinematic_wave_intensity_100.m

This file was created to perform the flow depth calculation for the 100mm/h rainfall intensity event. The file:

- Specifies the 100mm/h event
- Creates the solution space matrices.
- Solves for the flow depth at 1% grade and export to a spreadsheet
- Repeats the previous step for grade increments up to 7%

Kinematic_wave_design_storm.m

This file was created as a user input design storm simulation. It provides the user a fast way to run a design storm simulation as specify the input parameters as needed. While running the file will:

- Prompt the user to enter a flow path length (default 90m)
- Prompt the user to enter the time for simulation (default 30 minutes)
- Prompt the user to enter the storm duration (default 30 minutes. I.e. the length of simulation. If this is entered at a lower value it specifies the end of rainfall)
- Prompt the user to enter the rainfall intensity (default 50mm/h)
- Prompt the user to enter a Manning's value (default 0.11)
- Prompt the user to enter a longitudinal grade (default 0.03 or 3%)
- Perform the kinematic wave model simulation using the specified input variable
- Export the results to a spreadsheet

3.4 Rainfall Intensity

The Australian Bureau of Meteorology (BoM) website contains extensive data of rainfall intensity and duration data. This data is freely available to all users and come in the form of an Intensity-Frequency-Duration or IFD chart or table. From this data, it is easy to choose the rainfall intensity for a specified likelihood and duration.

As outlined in the literature review, the standard value for rainfall intensity used in modelling of surface water depth is the lesser of the 1 Year ARI, 5-minute duration event and 50mm/h. This however, has been linked with the driver slowing down due to visibility issues associated with water build up on the windscreen. Initial investigation appears that the 50mm/h intensity is greatly exceeded for the 1 year ARI 5 minute design storm for the majority of locations in New South Wales for which data was obtained.

Table 3.1 - Design rainfall intensities across New South Wales (BoM, 2014)

Location	1 year ARI 5 min storm (mm/h)	Design storm intensity (mm/h)
Bega	86.1	50
Broken Hill	49.8	49.8
Byron Bay	128	50
Deniliquin	48	48
Grafton	103	50
Newcastle	87.6	50
Parkes	64.2	50
Parramatta	83.7	50
Port Macquarie	103	50
Sydney	101	50
Tamworth	69.3	50
Wagga Wagga	54.6	50
Walgett	66.9	50
Wollongong	111	50

As can be seen in Table 3.1, the magnitude of the rainfall intensity for the 1 year 5-minute duration event is quite often above the 50mm/h value. From the locations chosen, the value was above the 50mm/h value for all but two of the locations, these being Broken Hill and Deniliquin with intensities of 49.8 and 48 mm/h respectively. The maximum value of rainfall intensity reported in Table 3.1 is 128mm/h in Byron Bay, which suggests geographically the coastal areas in NSW experience far higher rainfall intensities than the drier inland areas such as Broken Hill. Table 3.1 also highlights the spread of rainfall intensities that could be used in aquaplaning calculations if the intensity was not limited to driver behaviour. This means that across the state various depths of flow would be calculated for identical geometrical conditions.

A sensitivity analysis will be performed to analyse the effect the rainfall intensity will have on the calculated depth of water on the road surface. A range of rainfall intensities values will be used with each of the described methods of calculation, Gallaway equation, RRL method and kinematic wave model. From initial modelling the intensity has a large impact on the depth.

The simulations will be performed with rainfall intensities 15, 25, 35, 50, 75 and 100mm/h. these values were chosen as they give a spread with the deign values of 50mm/h in the middle. The values also present a good spread, as the upper limit of 100mm/h is the approximate maximum of the values in Table 3.1. The lower limit values of 15 and 25 mm/h have also been suggested as intensities that would result in the driver slowing down.

It should be noted that this analysis is to be used to justify the design storm rainfall intensity and to investigate dropping or raising the adopted value.

Some literature outlined above gave the range of rainfall intensity to be considered as heavy rain to be in the region greater than 6.5mm/h. This value is from Florida therefore it may not be applicable to the conditions of Australia. The rainfall intensities produced from the BoM specify the conditions in Australia and therefore these will be used. It should be noted however that the 6.5mm/h intensity should be investigated in driver behaviour if this intensity will result in the driver slowing down. As a likelihood of rainfall and surface drainage, the ARI method will be used.

IFD data for locations around NSW is attached as Appendix C.

3.5 Texture depth standard values

Current standard values are outlined in various texts cited in the literature review. These have a wide range of origins and more literature will be needed in order to determine if these are applicable to future studies and are in line with advances in pavement materials.

The Gallaway equation model that has been established to calculate flow depth will be used to investigate the effect of the texture depth on the depth of water film produced with the calculation.

As outlined previously a larger texture depth will allow more water to infiltrate the macrotexture of the pavement before it becomes surface sheet flow. Therefore, larger macrotexture produces lower calculated surface water film depths. A sensitivity analysis will be performed by using various values of texture depths to represent the range of pavement surface commonly used on the roads today. This study will be more useful in a maintenance type study where the surface texture might have degraded over time. Another effect of texture will be a polishing of the aggregate, which would raise the risk of viscous aquaplaning. This effect will not be investigated as part of this study.

The Gallaway equation will be used to calculated the flow depth for lengths and grade as per the previous methodology. The texture depth will be tested at incremental steps of 0.1mm starting from 0.2mm, representing a relatively smooth surface type such as broomed concrete or fine gap graded asphalt. The upper limit of the testing will be 1.2mm, which represents a course or open grade pavement type such as a large aggregate spray seal or a concrete surface that has been treated with grooves to increase water storage in the pavement. Texture depths above this value will not be tested as the likelihood of pavement maintaining a texture depth above this is assumed to be small once the macrotexture is filled with grit and silt and other contaminants.

Texture depth will also have an impact on the value of manning's roughness used in the kinematic wave model. As previously discussed the manning's value chosen is used to compare the models. The manning's value chosen will significantly affect the depths calculated if they are small like the values produced by the kinematic wave model in this study. The effect of manning's roughness will not be assessed as part of this research, however it should be investigated if the use of the kinematic wave model for calculating the aquaplaning depth becomes more widespread.

3.6 Time of concentration – sheet flow

The time of concentration (tc) for the surface flow runoff catchment will be calculated with three methods outlined in the literature review. These models are the kinematic wave approximation, Oakden's formula and Friend's formula.

Ragan and Duru (1972) Kinematic Wave approximation equation:

$$t_c = 6.94 \frac{Ln^{0.6}}{I^{0.4} S^{0.3}} \qquad \textbf{3.14}$$

Where:

t_c = time of overland flow (minutes)

L = overland flow path length (m)

n = Manning's roughness value

I = Rainfall intensity from the design ARI event (mm/h)

S = slope of overland flow path (m/m)

Oakden's (1977) Formula

$$t_c = 500nL^{2/3}S^{-1/3} \qquad \textbf{3.15}$$

Where:

t_c = time of concentration (seconds)

L = length (m)

S = slope (m/m)

n = Manning's roughness value

Friend's Equation:

$$t_c = (107nL^{0.333})/S^{0.2} \qquad \textbf{3.16}$$

Where:

t_c = overland sheet flow time (minutes)

L = overland sheet flow path length (m)

n = Horton's surface roughness factor

S = slope of surface (%)

As per the previous calculations, the time of concentration will be calculated along the length of the flow path at 1m intervals. The (tc) will be calculated at various grades of the flow path. To provide consistency with the previous methods, these will be calculated at 0.5% intervals in the range 0.5% to 7% slope.

It should be noted that the Oakden formula and Friend's formula do not contain a variable for rainfall intensity. The kinematic wave approximation formula does however contain the rainfall intensity variable so it therefore will have some effect on the time of flow through the catchment. The kinematic wave approximation will be used to determine how the rainfall intensity w=either increases or decreases the time of concentration.

The kinematic wave model data produced as part of Section 3.2.3 will be used to investigate the time of saturation of the catchment. The depth along the flow path will continue to rise with respect to time until the depth reaches an upper limit at which the water does not rise any further. This point in time is considered to be where the flow has reached an equilibrium between inflow and outflow for the finite elements of the model. The analysis will produce graphs for depth of flow over time for the end of the flow path to determine the time in minutes until the point of maximum depth is reached.

A comparison will be made between the calculated tc from the three methods above in equations 3.14 to 3.16 and the time of saturation/equilibrium for the full kinematic wave model of Section 3.1. The time of concentration is study as part of the drainage analysis as it is assumed that this duration will give the catchment time to reach its maximum depth. The time of concentration is similar to the time of saturation however they may not exactly correlate. The values obtained will be compared to test whether the calculated time of concentration is sufficient enough to record the maximum depth of the flow or if the water will continue to build up after this time.

3.7 Design storm simulation

The kinematic wave model was used to simulate a number of design storm events. The model was used to determine how long sheet flow is likely to remain on the surface of a roadway. The time of concentration equations from Section 3.4 were also used as a check on sheet flow travel times.

The storm duration is chosen as an indication of the time of concentration for the catchment area of surface runoff from a roadway surface. However, the analysis does not allow for a time for the storm event to cease and the catchment to drain. Therefore, the probability of the depth reaching the critical level during large intensity storms may be high, but the time for which the water film depth is above critical level may be considerably lower due to the catchment draining quickly. The combined effect of likelihood of storm event and draining away of the flow could lower the overall probability of aquaplaning occurring.

The design storm events simulate rainfall for a specified time duration. The rainfall was then turned off to represent the end of the storm event and the model continued to run with no further inflow until the surface was drained away.

The design storm rainfall intensities were a 50mm/h intensity, as well as the worst case 100mm/h storm event. These represented the current design standard as well as an upper limit, which is assumed that drivers will not be able to drive in due to loss in visibility. From a hydrology point of view, the 100mm/h storm event is not unlikely to occur and therefore this storm event can be used to assess to risk involved in such events.

The 5-minute storm duration was the standard duration to be tested. The analysis also tested a 10-minute duration storm to assess whether the duration of the storm affects the time needed for draining away the surface water or if the surface will drain after a certain amount of time for a storm of any given duration.

For consistency throughout the project the depth of flow was be calculated at 1m intervals along the flow path and reported at 20m, 40m, 60m and 80m lengths. As explained previously these represent common lengths of flow for road surface conditions.

The design storm simulations were performed at a number of various grades. As the higher values of flow depths were experienced on flatter grades, the simulations were restricted to these. The design storms were modelled on grades of 1%, 2%, and 3%.

Comparisons of a number of the design storms allowed results to be obtained to analyse the time period it takes to fully drain the surface and how long the depth will remain above a critical value of depth.

4. Results of depth flow calculations

Results for the above analysis were created in the form of spread sheets containing data on the flow depth for different combinations of the input variables to the three chosen models of aquaplaning flow depth.

Where appropriate the data has been presented in the form of tables and graphs to allow for clearer representation and to allow for observations to be made and for trends to emerge. As per the outline in the methodology, the results presented here will follow the following format:

- Gallaway equation
- RRL Method
- Kinematic wave model
- Comparisons of the three models
- Rainfall intensity analysis
- Texture depth analysis
- Time of concentration analysis
- Design storm simulation

4.1 Gallaway Equation

The results for flow depth calculated using the Gallaway equation allowed for some general trends to be observed across the specified study range. As will be seen in the results below the Gallaway Equation calculation revealed that for all grades, the water film depth increase along the length of the flow path. It also showed that low or flat grades produced the greatest depths of flow. This is explainable by the reduced gravity force for the flat grade which will not let the pavement drain and leave water to build up on the surface.

The calculated water film depths for higher grades (i.e. 4-7%) have less variation in the calculated depths while the flatter grades have higher variation in calculated depth. For instance the difference in flow depth calculated at 1% and 2% will be a greater difference than for the when the values are calculated at 6% and 7%. This suggests that the critical slopes for producing high water film depths are those under 3 % and more specifically those under 2%. The flatter the grade the higher the variation in calculated depth. At flat grades a slight decrease in grade leads to a magnitude of increase in depth.

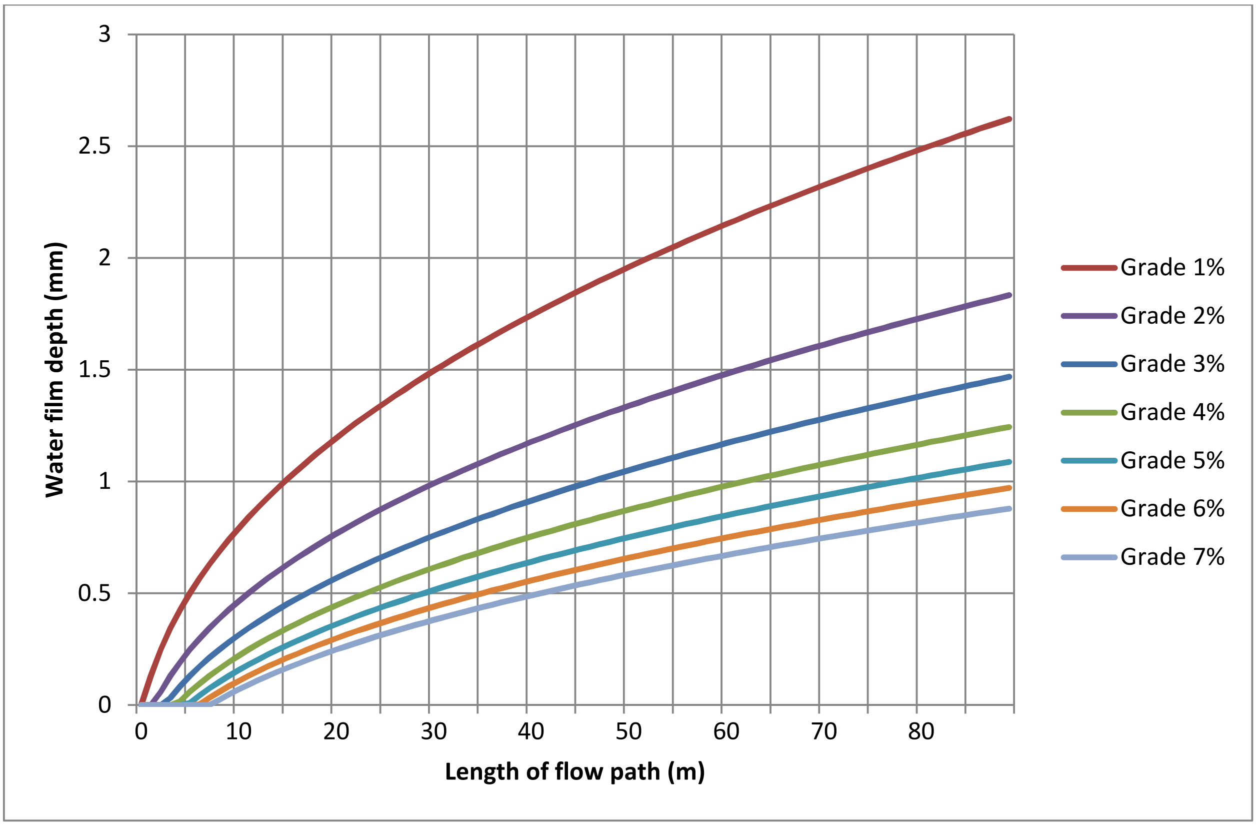

Figure 4.1 - Water film depth using Gallaway @ 15mm/h rainfall intensity

Figure 4.1 and Table 4.1 express the data obtained for the 15mm/h intensity rainfall event. The worst case depth for the 15mm/h intensity is found at the end of the 1% flow path grade. This value is just below the 2.5mm critical value which is documented as likely to induce partial aquaplaning.

The aquaplaning depths for the 15mm/h intensity rainfall do not pose significant aquaplaning issues despite the flow being for long grades. This rainfall would be consistent with common rainfall recurrence intervals typically less than 1 year ARI or rainfall over prolonged time giving the catchment time to drain away. Therefore, it could be concluded that road geometry and conditions do not pose surface drainage risks for rainfall intensities of 15mm/h or below.

Table 4.1 - Water film depth using Gallaway @ 15mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	1.16	0.74	0.55	0.43	0.34	0.28	0.23
40	1.72	1.16	0.90	0.74	0.63	0.55	0.48
60	2.13	1.47	1.16	0.97	0.84	0.74	0.66
80	2.47	1.72	1.37	1.16	1.01	0.90	0.81

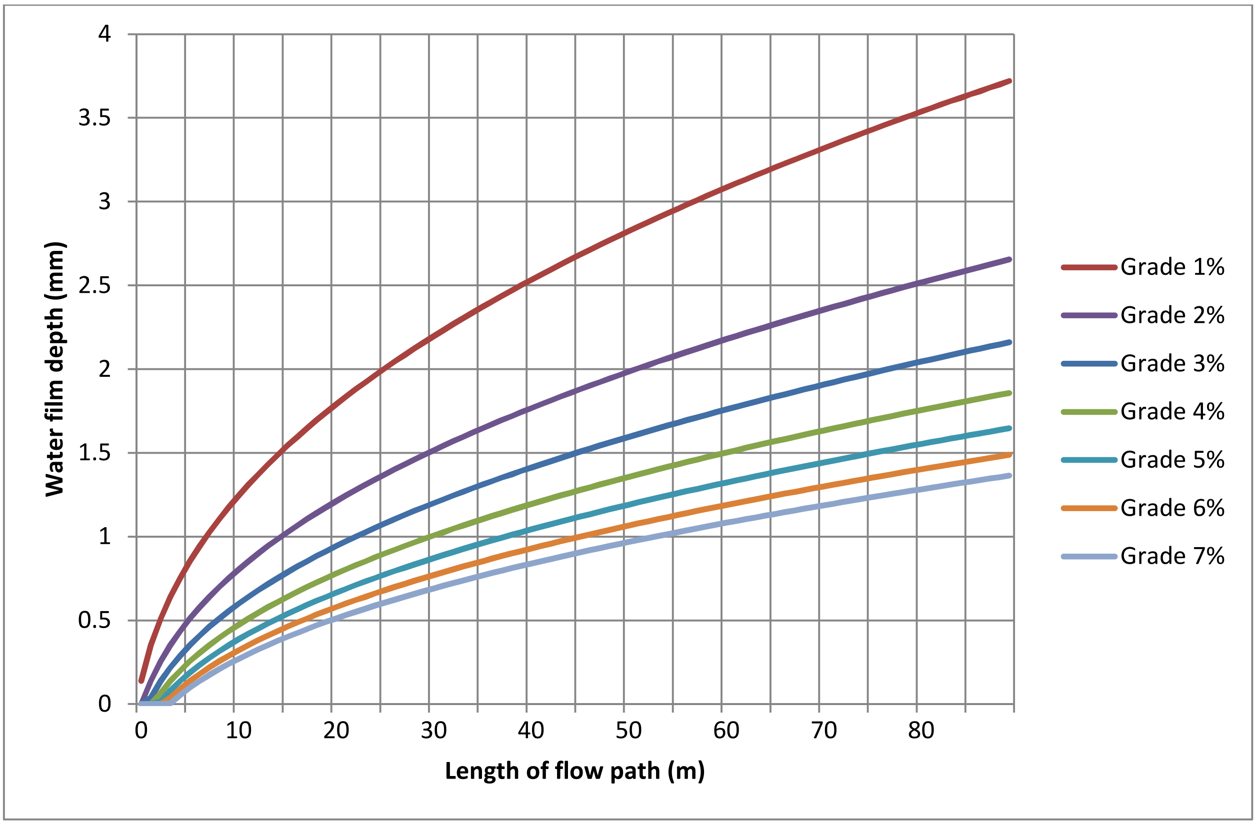

Figure 4.2 - Water film depth using Gallaway @ 25mm/h rainfall intensity

Figure 4.2 and Table 4.2 express the data obtained for the 25mm/h intensity rainfall event. The depth for the 25mm/h rainfall intensity does not rise above the 4mm critical depth value for the tested flow length on any grade. The 2.5mm desirable level however is breached for low grades. The 1% grade rises above the critical level at 40m length and the 2% grade at 80m. The maximum depth experienced at this rainfall intensity is the 80m length at 1% grade which gives 3.52mm depth of flow on the road surface.

Table 4.2 - Water film depth using Gallaway @ 25mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	1.74	1.18	0.91	0.75	0.64	0.56	0.49
40	2.50	1.74	1.39	1.18	1.03	0.91	0.83
60	3.06	2.16	1.74	1.49	1.31	1.18	1.07
80	3.52	2.50	2.03	1.74	1.54	1.39	1.27

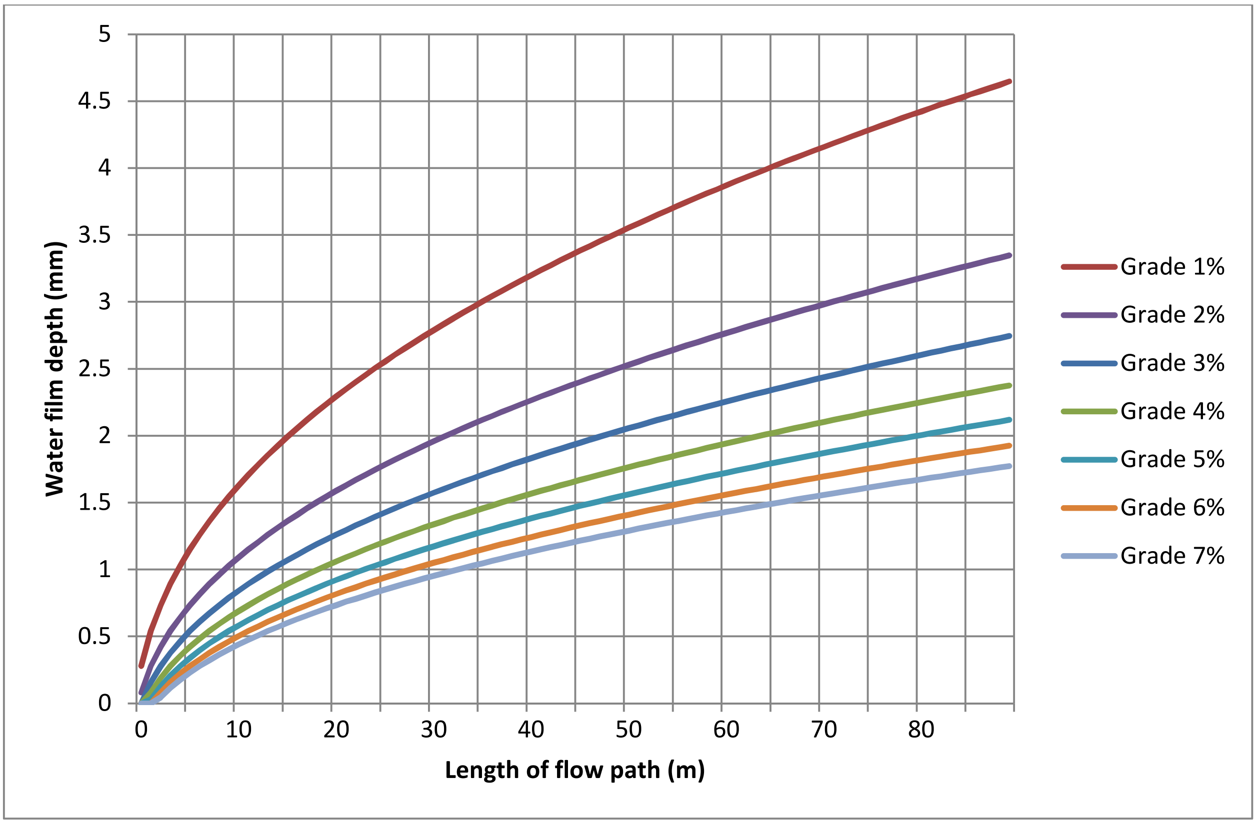

Figure 4.3 - Water film depth using Gallaway @ 35mm/h rainfall intensity

Figure 4.3 and Table 4.3 express the data obtained for the 35mm/h intensity rainfall event. The flow exceeds both the 2.5mm desirable and the 4mm absolute level for aquaplaning depth as some combinations of slope length and grade.

The flow exceeds the 4mm critical level for the 1% grade at 65m along the flow path. The 1% grade exceeds the 2.5mm level at 25m along the flow path.

For the 2% grade the depth of flow exceeds the 2.5mm value at a length of 50m along the flow path.

For the 3% grade the depth of flow exceeds the 2.5mm value at a length of 75m along the flow path.

Table 4.3 - Water film depth using Gallaway @ 35mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.24	1.55	1.22	1.03	0.89	0.79	0.71
40	3.16	2.24	1.81	1.55	1.36	1.22	1.12
60	3.84	2.74	2.24	1.92	1.71	1.55	1.42
80	4.40	3.16	2.59	2.24	1.99	1.81	1.66

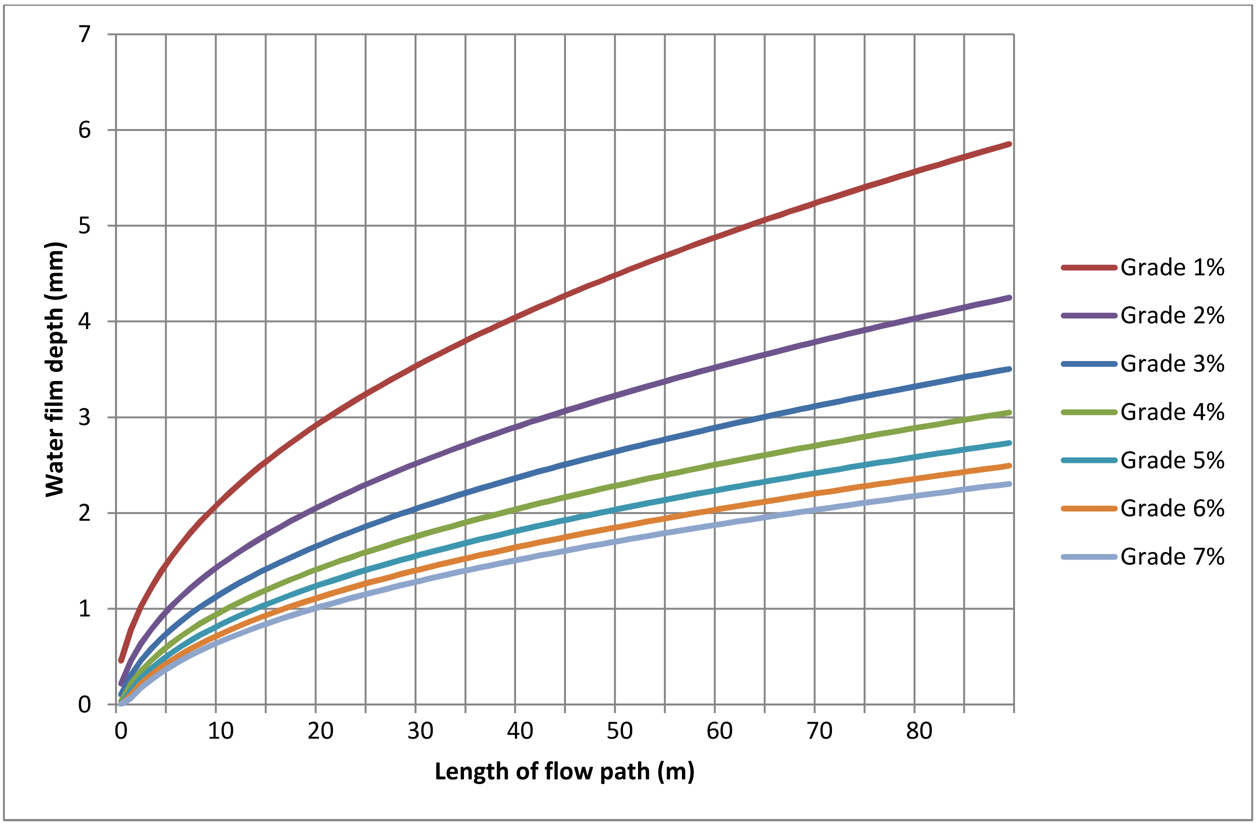

Figure 4.4 - Water film depth using Gallaway @ 50mm/h rainfall intensity

Figure 4.4 and Table 4.4 express the data obtained for the 50mm/h intensity rainfall event. The 50mm intensity rainfall analysis calculated the flow depth would exceed aquaplaning limits for numerous combinations of flow path length and grade.

The 1% grade breaches the 4mm level at 40m along the flow path and the 2.5mm level at approximately 15m along the flow path. Such short paths as this would be experienced at intersections in urban environments.

The 2% grade exceeds the 4mm level at 80m along the flow path and the 2.5mm level at 30m along the flow path.

The 3% grade exceeds 2.5mm level at 50m along the flow path.

The 4% grade exceeds 2.5mm level at 60m along the flow path.

The 50mm/h rainfall intensity sees a marked increase in the grade that will produce at risk depths as well as a reduction in the lengths on which they occur from lesser rainfall intensities.

Table 4.4 - Water film depth using Gallaway @ 50mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.88	2.02	1.63	1.39	1.22	1.09	0.99
40	4.02	2.88	2.35	2.02	1.80	1.63	1.50
60	4.86	3.50	2.88	2.49	2.23	2.02	1.87
80	5.55	4.02	3.31	2.88	2.58	2.35	2.17

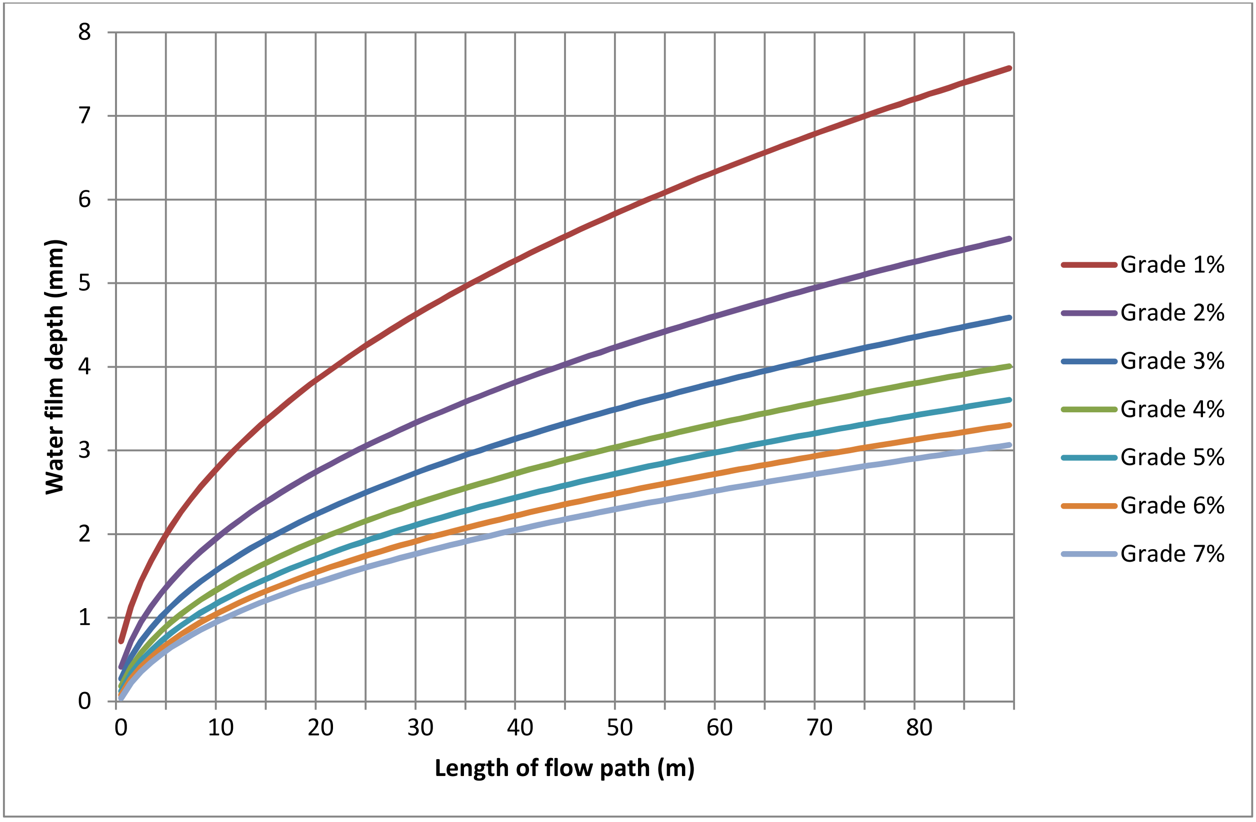

Figure 4.5 - Water film depth using Gallaway @ 75mm/h rainfall intensity

Table 4.5 - Water film depth using Gallaway @ 75mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.79	2.71	2.20	1.90	1.68	1.52	1.39
40	5.24	3.79	3.12	2.71	2.42	2.20	2.03
60	6.31	4.59	3.79	3.30	2.96	2.71	2.51
80	7.18	5.24	4.34	3.79	3.41	3.12	2.89

Figures 4.5 and 4.6 and Tables 4.5 and 4.6 express the data obtained for the 75mm/h and 100mm/h intensity rainfall events. They will be discussed here together as they are both large intensity storms and the results are similar in both cases. These rainfall intensities experience large amounts of depth that would be considered an aquaplaning risk. They are experienced at steeper grades and shorter depths than the lesser rainfall intensities. The maximum depths experienced on the 75mm/h and the 100mm/h rainfall events are 7mm and 9mm respectively. The 4mm depth is exceeds for grades up to 4% and under lengths of 60m.

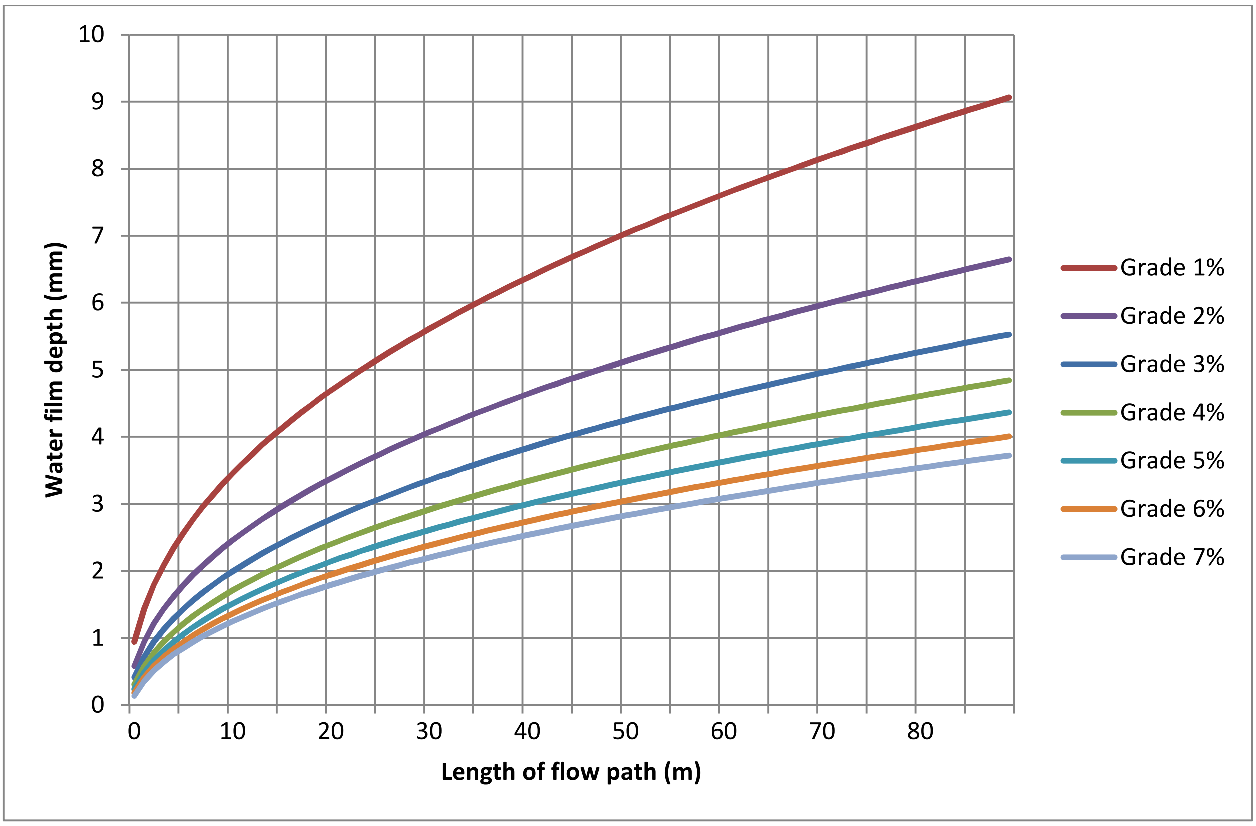

Figure 4.6 - Water film depth using Gallaway @ 100mm/h rainfall intensity

Table 4.6 - Water film depth using Gallaway @ 100mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	4.58	3.30	2.70	2.34	2.09	1.90	1.74
40	6.30	4.58	3.79	3.30	2.96	2.70	2.50
60	7.56	5.53	4.58	4.00	3.60	3.30	3.06
80	8.60	6.30	5.24	4.58	4.13	3.79	3.52

4.2 Road Research Laboratory method

The results for flow depth calculated using the RRL Method allowed for some general trends to be observed across the specified study range. As will be seen in the results below the RRL Method, the general trends in respect to grades and the water film depth increasing along the length of the flow path are similar to that of the Gallaway Equation. It should be noted that the variance between the grades is not as pronounced in the RRL method as the Gallaway method, with the results seeming to follow the same trends for each grade.

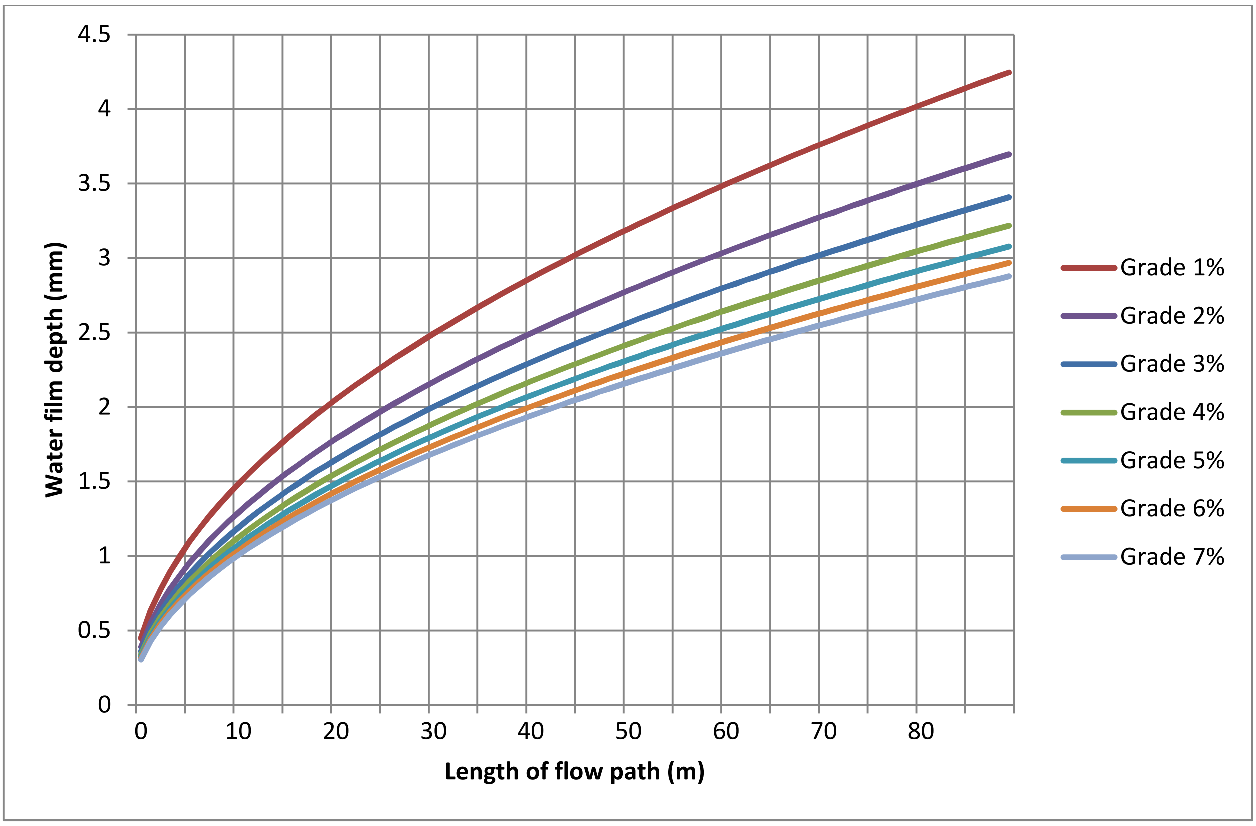

Figure 4.7- Water film depth using RRL method @ 15mm/h rainfall intensity

Figure 4.7 and Table 4.7 express the data obtained for the 15mm/h intensity rainfall event.

The max depth of flow here is 4mm on the 1% grade at 80m. This indicates that the flow depth exceeds the 4mm critical value at 80m on 1% grade.

All other grades experience depths of flow that exceed the 2.5mm level at some length along the flow path. For the 3% grade, the 2.5mm critical depth is exceeded at 50m length and for the 7% grade it is exceeded at 70m along the flow path.

Table 4.7 - Water film depth using RRL method @ 15mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.00	1.74	1.61	1.52	1.45	1.40	1.36
40	2.83	2.46	2.27	2.14	2.05	1.98	1.92
60	3.47	3.02	2.78	2.63	2.51	2.42	2.35
80	4.00	3.48	3.21	3.03	2.90	2.80	2.71

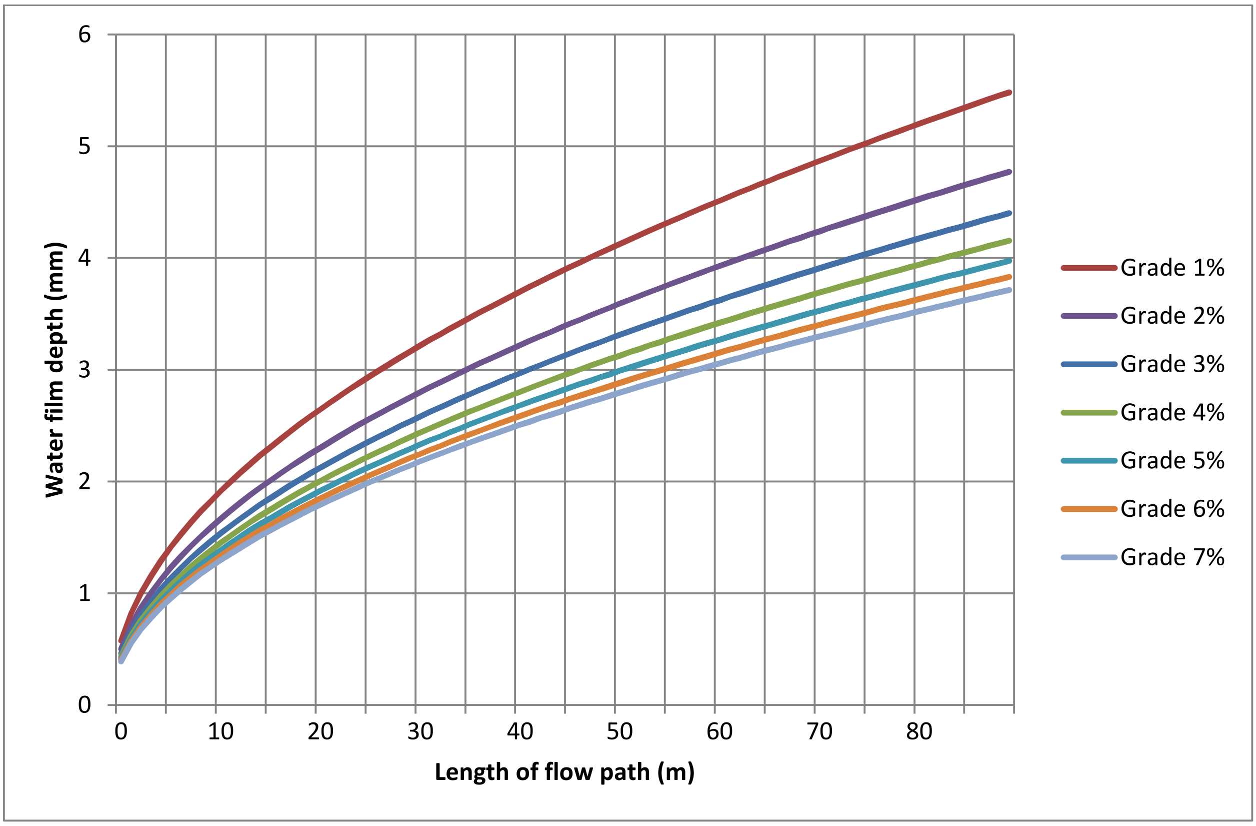

Figure 4.8 - Water film depth using RRL @ 25mm/h rainfall intensity

Figure 4.8 and Table 4.8 express the data obtained for the 25mm/h intensity rainfall event. The 25mm/h rainfall intensity starts to produce high values of flow depth. The maximum depth calculated in this simulation is over 5mm.

As per the 15mm/h intensity, all grades for the 25mm/h intensity exceed 2.5mm of flow depth at some length flow path. The 7% grade exceeds the 2.5mm value at 40m flow path length which means that for all lengths shorter than this on any grade the depth of flow will be at a level considered a risk to partial aquaplaning. There is a significant amount of areas on the road network that would be considered a risk using this criteria.

The 4mm depth is exceeded on the 1% grade at 47m length of flow with this value being exceeded on the 2% and 3% grades at 65m and 75m along the flow path respectively.

Table 4.8 - Water film depth using RRL method @ 25mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.58	2.25	2.07	1.96	1.87	1.81	1.75
40	3.65	3.18	2.93	2.77	2.65	2.55	2.48
60	4.48	3.90	3.59	3.39	3.24	3.13	3.03
80	5.17	4.50	4.15	3.92	3.75	3.61	3.50

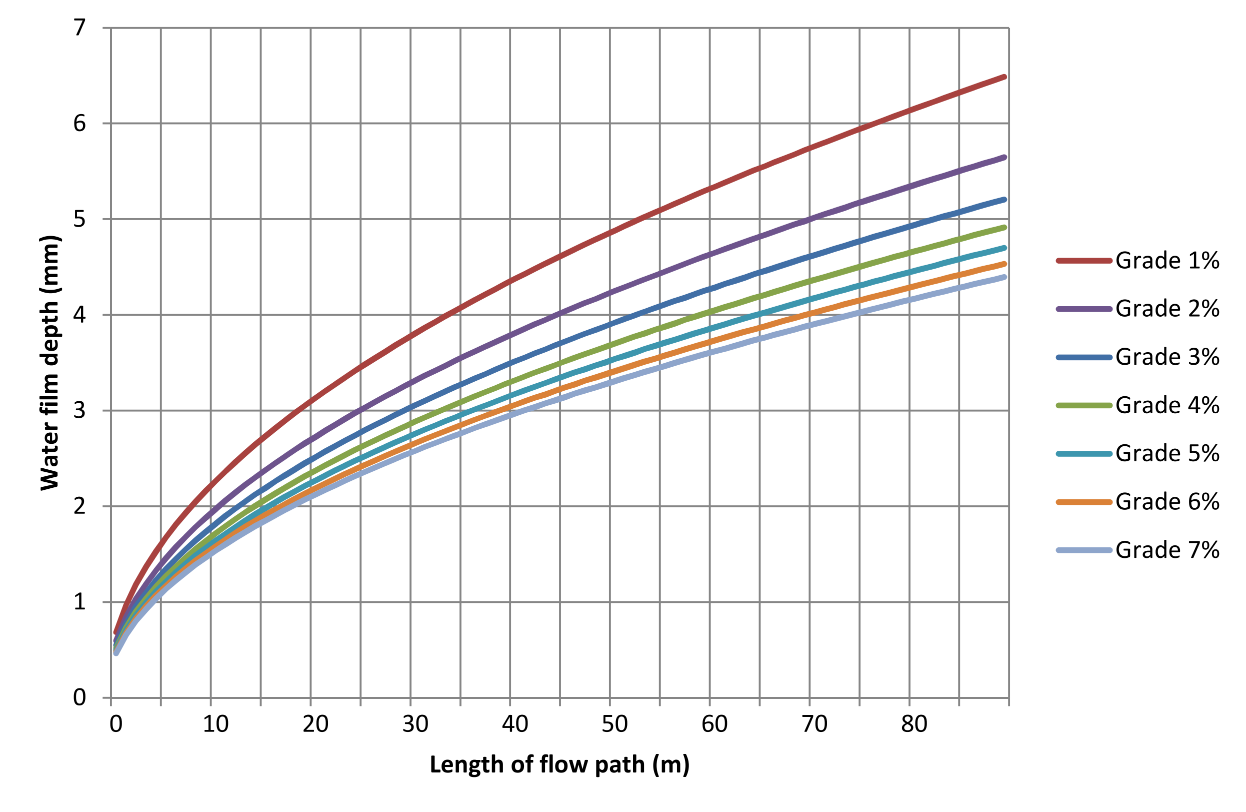

Figure 4.9 - Water film depth using RRL method @ 35mm/h rainfall intensity

Figure 4.9 and Table 4.9 express the data obtained for the 35mm/h intensity rainfall event. Again all grades exceed the 2.5mm criteria. This includes the 7% grade at a length of 30m. The flatter grades experience this depth of flow at lengths which are far less than this and far more common on the road network.

The 4mm depth criteria is exceeded between 35m for 1% and 75m for 7%.

The maximum depth at this rainfall intensity is over 6mm.

Table 4.9 - Water film depth using RRL method @ 35mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.06	2.66	2.45	2.32	2.22	2.14	2.07
40	4.32	3.76	3.47	3.28	3.13	3.02	2.93
60	5.30	4.61	4.25	4.01	3.84	3.70	3.59
80	6.11	5.32	4.91	4.63	4.43	4.27	4.14

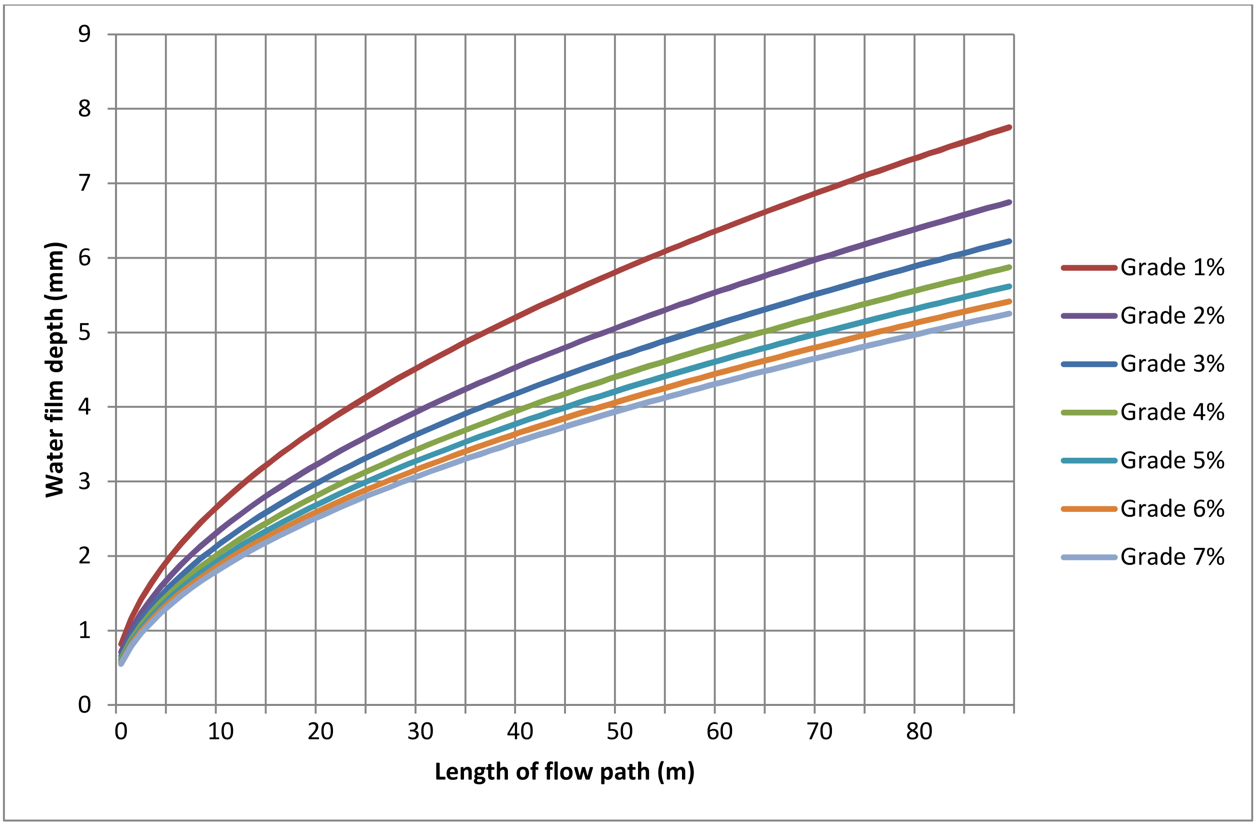

Figure 4.10 - Water film depth using RRL method @ 50mm/h rainfall intensity

Figure 4.10 and Table 4.10 express the data obtained for the 50mm/h intensity rainfall event.

The 4mm depth is exceeded for all grades form between 25m for 1% to 55m at 7%. This represents very high aquaplaning risk for all common types of road surfaces.

The 2.5mm depth is exceeded for all lengths over 25m on any grade. The value is exceeded after approximately 10m on the 1% grade. Again this analysis would highlight many common road situations as a high aquaplaning risk.

Table 4.10 - Water film depth using RRL method @ 50mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.65	3.18	2.93	2.77	2.65	2.55	2.48
40	5.17	4.50	4.15	3.92	3.75	3.61	3.50
60	6.33	5.51	5.08	4.80	4.59	4.42	4.29
80	7.31	6.36	5.87	5.54	5.30	5.11	4.95

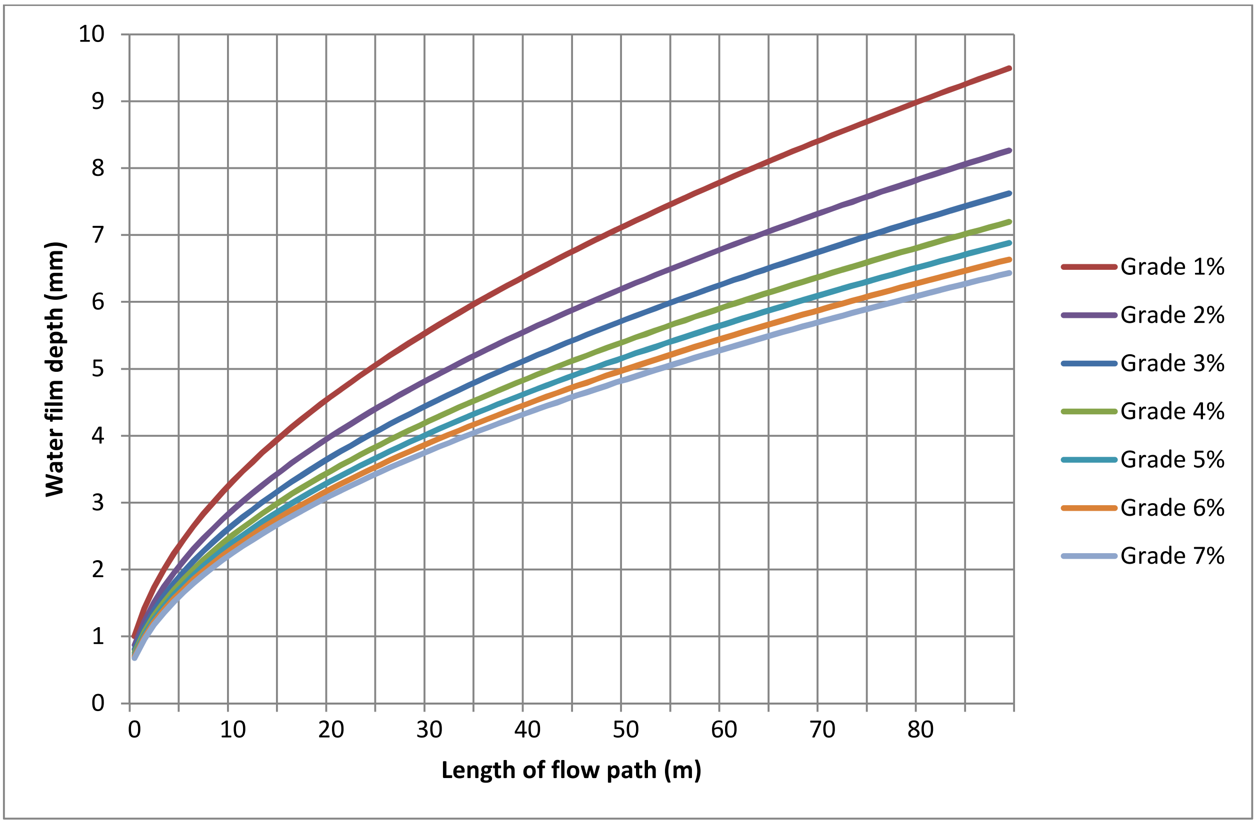

Figure 4.11 - Water film depth using RRL method @ 75mm/h rainfall intensity

Table 4.11 - Water film depth using RRL method @ 75mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	4.48	3.90	3.59	3.39	3.24	3.13	3.03
40	6.33	5.51	5.08	4.80	4.59	4.42	4.29
60	7.75	6.75	6.22	5.87	5.62	5.42	5.25
80	8.95	7.79	7.18	6.78	6.49	6.25	6.06

Figures 4.11 and 4.12 and Tables 4.11 and 4.12 express the data obtained for the 75mm/h and 100mm/h intensity rainfall events. These two rainfall intensities have been shown for consistency, however the depth of flow exceeds 9mm and 10mm in the worst cases. This represents high aquaplaning risk for all grades. All grades experience flow depths that exceeds both the 2.5mm and 4mm criteria for short lengths of grade under 20m

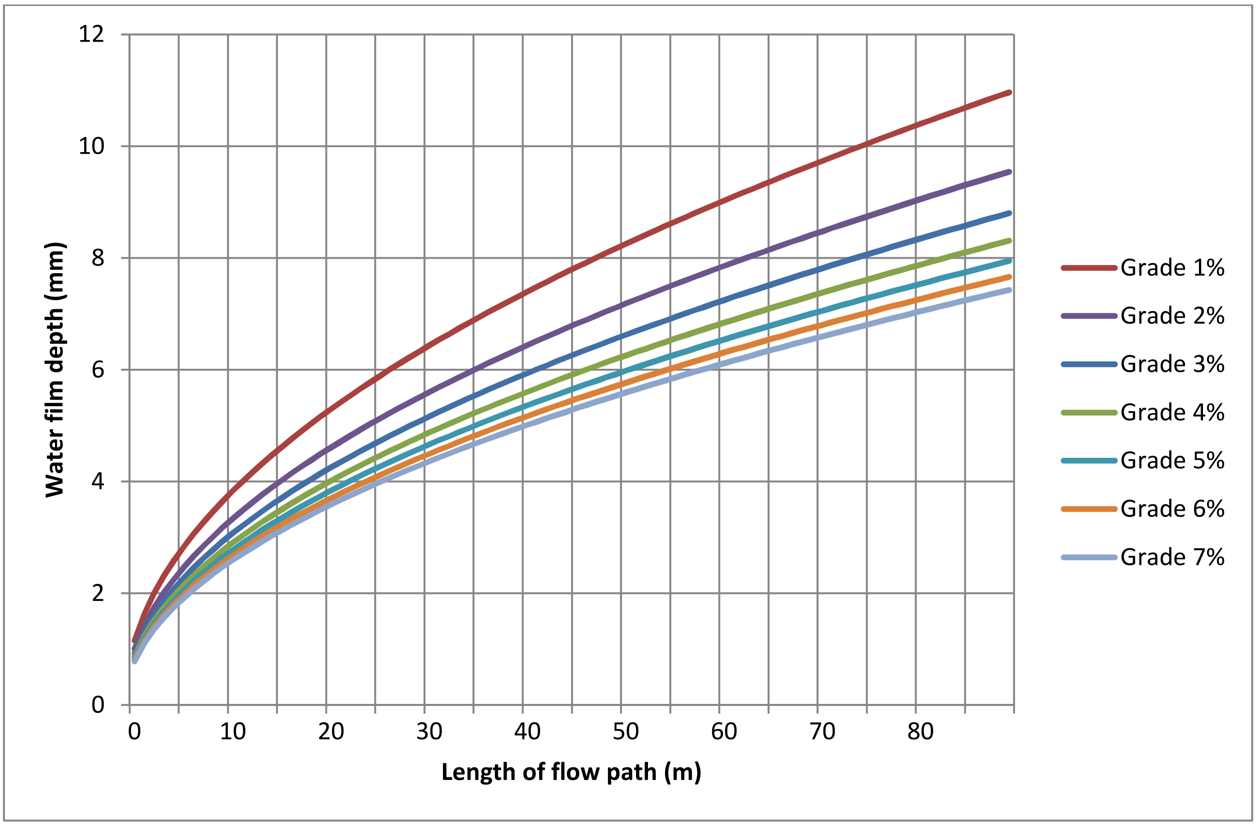

Figure 4.12 - Water film depth using RRL Method @ 100mm/h rainfall intensity

Table 4.12 - Water film depth using RRL method @ 100mm/h rainfall intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	5.17	4.50	4.15	3.92	3.75	3.61	3.50
40	7.31	6.36	5.87	5.54	5.30	5.11	4.95
60	8.95	7.79	7.18	6.78	6.49	6.25	6.06
80	10.33	9.00	8.30	7.83	7.49	7.22	7.00

4.3 Kinematic Wave Equations

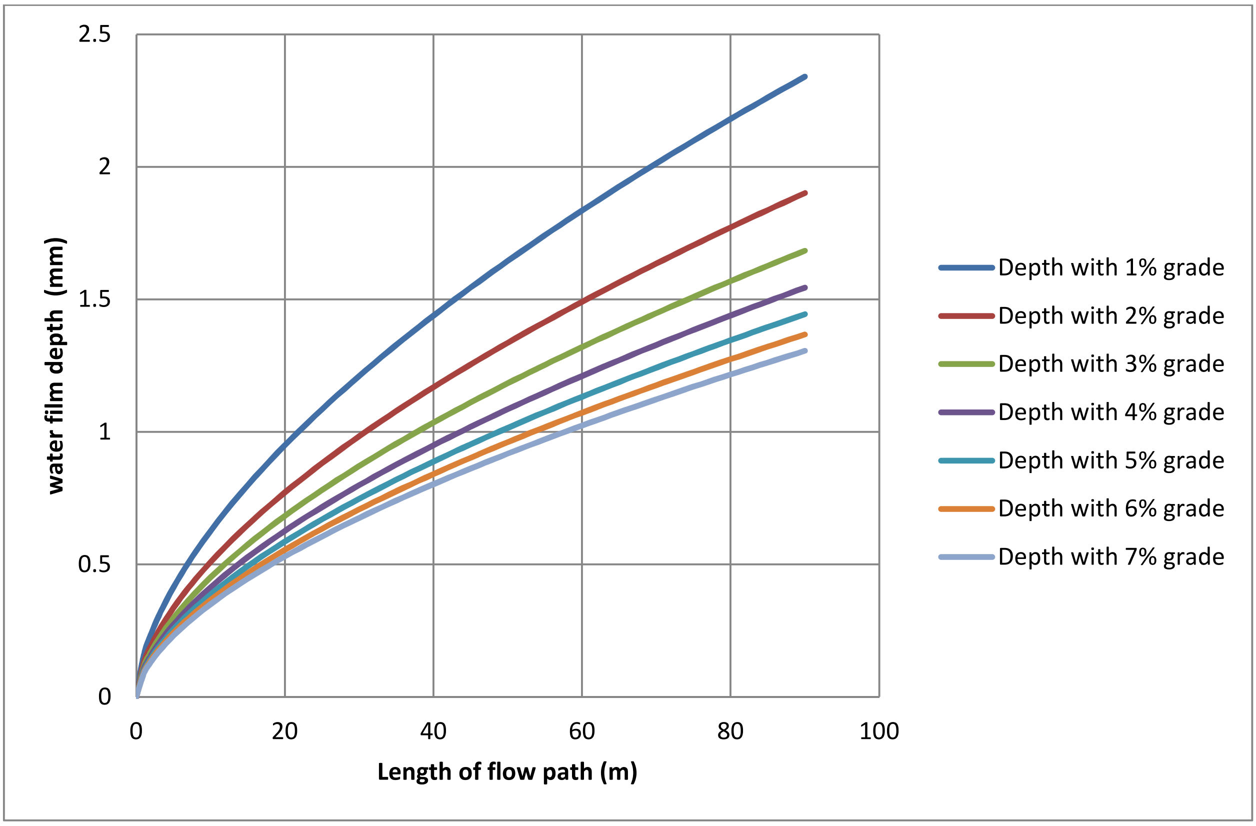

Figure 4.13 - Kinematic wave equation - depth @15mm/h intensity

Figure 4.13 and Table 4.13 express the data obtained for the 15mm/h intensity rainfall event. All calculated depths of flow are below the aquaplaning risk criteria.

The max depth experienced is 2.18mm at 8m length of flow path on the 1% grade.

Table 4.13 - Kinematic wave equation - depth @15mm/h intensity

Distance along flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	0.95	0.77	0.68	0.63	0.59	0.55	0.53
40	1.44	1.17	1.03	0.95	0.89	0.84	0.80
60	1.83	1.49	1.32	1.21	1.13	1.07	1.02
80	2.18	1.77	1.57	1.44	1.35	1.27	1.22

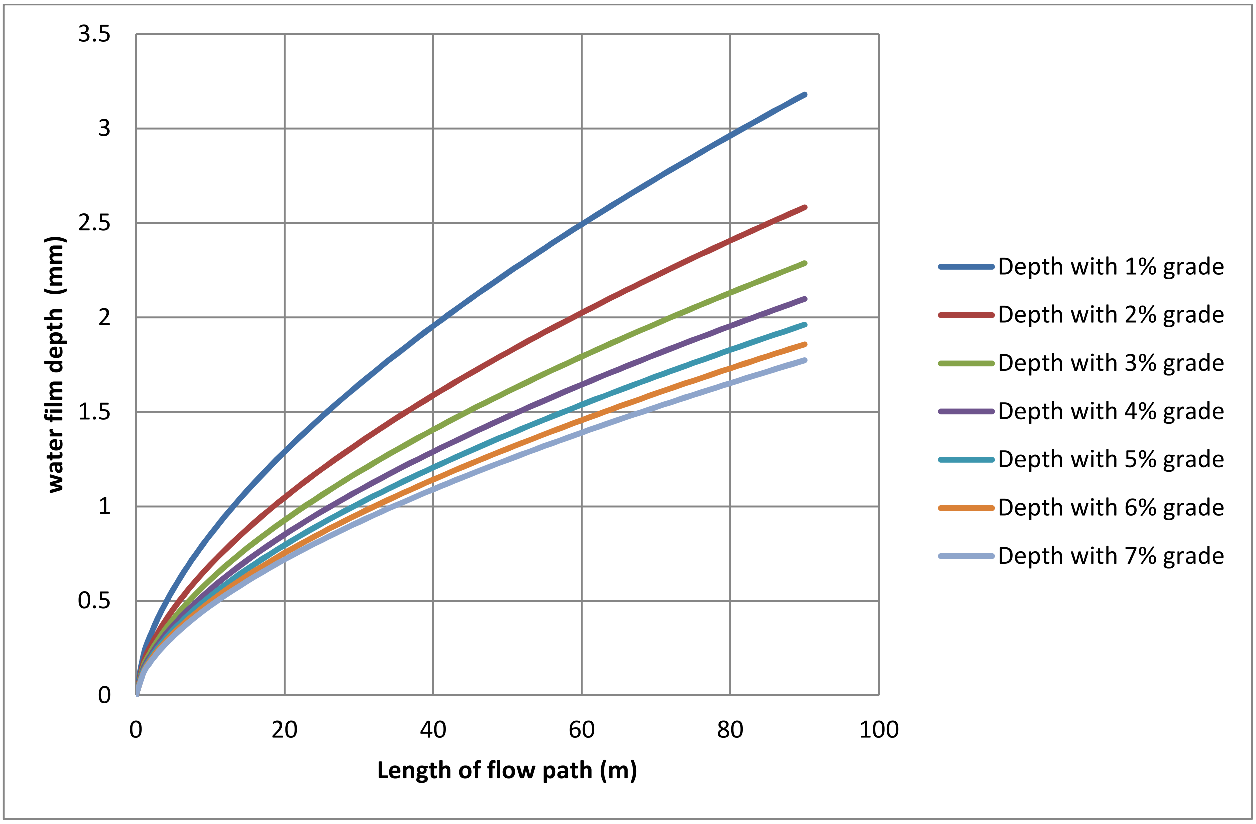

Figure 4.14 - Kinematic wave equation - depth @ 25mm/h intensity

Figure 4.14 and Table 4.14 express the data obtained for the 25mm/h intensity rainfall event. All calculated depths are below the 4mm criteria for all the grades and lengths of flow path.

The maximum depth calculated is 2.96mm at 80m length of flow on the 1% grade

The 1% grade exceeds the 2.5mm criteria at 60m length along the flow path

Table 4.14 - Kinematic wave equation - depth @ 25mm/h intensity

Distance along flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	1.29	1.05	0.93	0.85	0.80	0.75	0.72
40	1.95	1.59	1.41	1.29	1.21	1.14	1.09
60	2.49	2.02	1.79	1.64	1.54	1.46	1.39
80	2.96	2.41	2.13	1.95	1.83	1.73	1.65

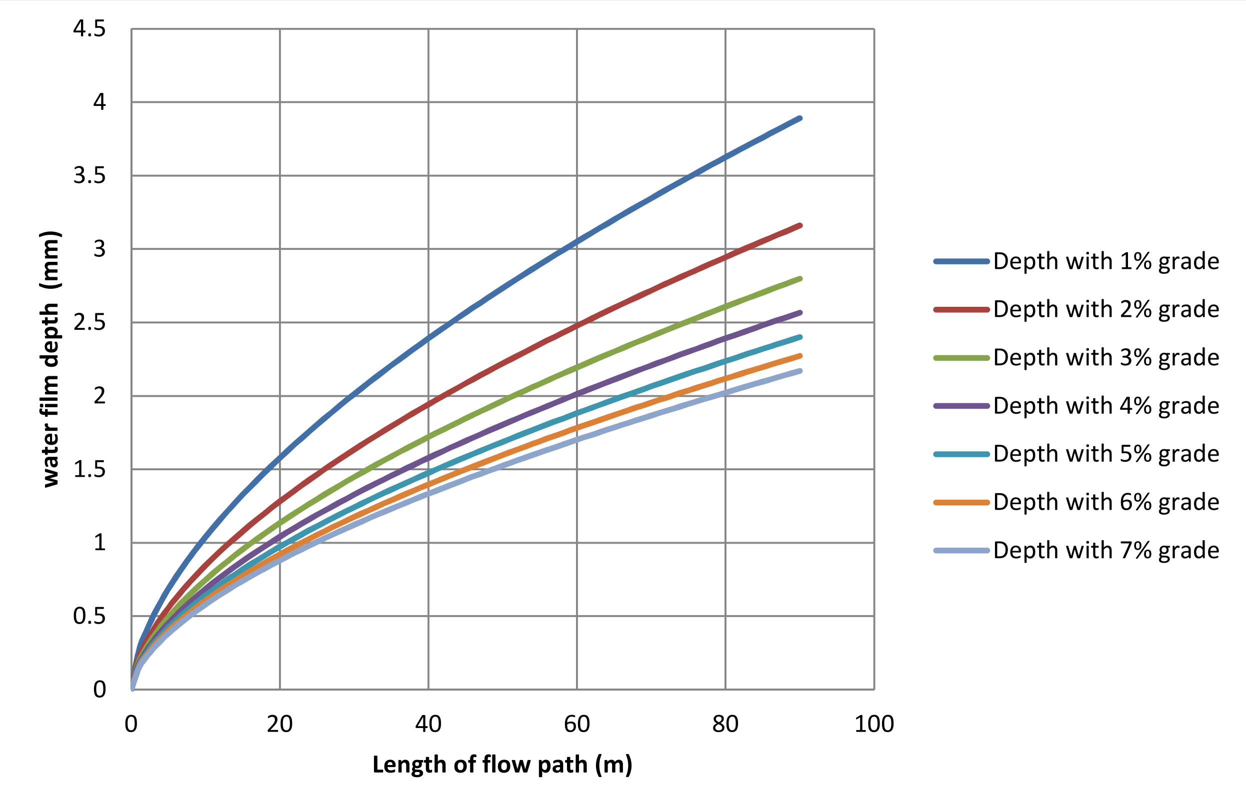

Figure 4.15 - Kinematic wave equation - depth @ 35mm/h intensity

Figure 4.15 and Table 4.15 express the data obtained for the 35mm/h intensity rainfall event.

All calculated depths are below the 4mm criteria for all the grades and lengths

The maximum depth calculated is 3.63mm at 80m length of flow on the 1% grade

The 1% grade exceeds the 2.5mm criteria at 43m length along the flow path

Table 4.15 - Kinematic wave equation - depth @ 35mm/h intensity

Distance along flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	1.58	1.28	1.13	1.04	0.97	0.92	0.88
40	2.39	1.94	1.72	1.58	1.48	1.40	1.33
60	3.05	2.48	2.19	2.01	1.88	1.78	1.70
80	3.63	2.94	2.61	2.39	2.24	2.12	2.02

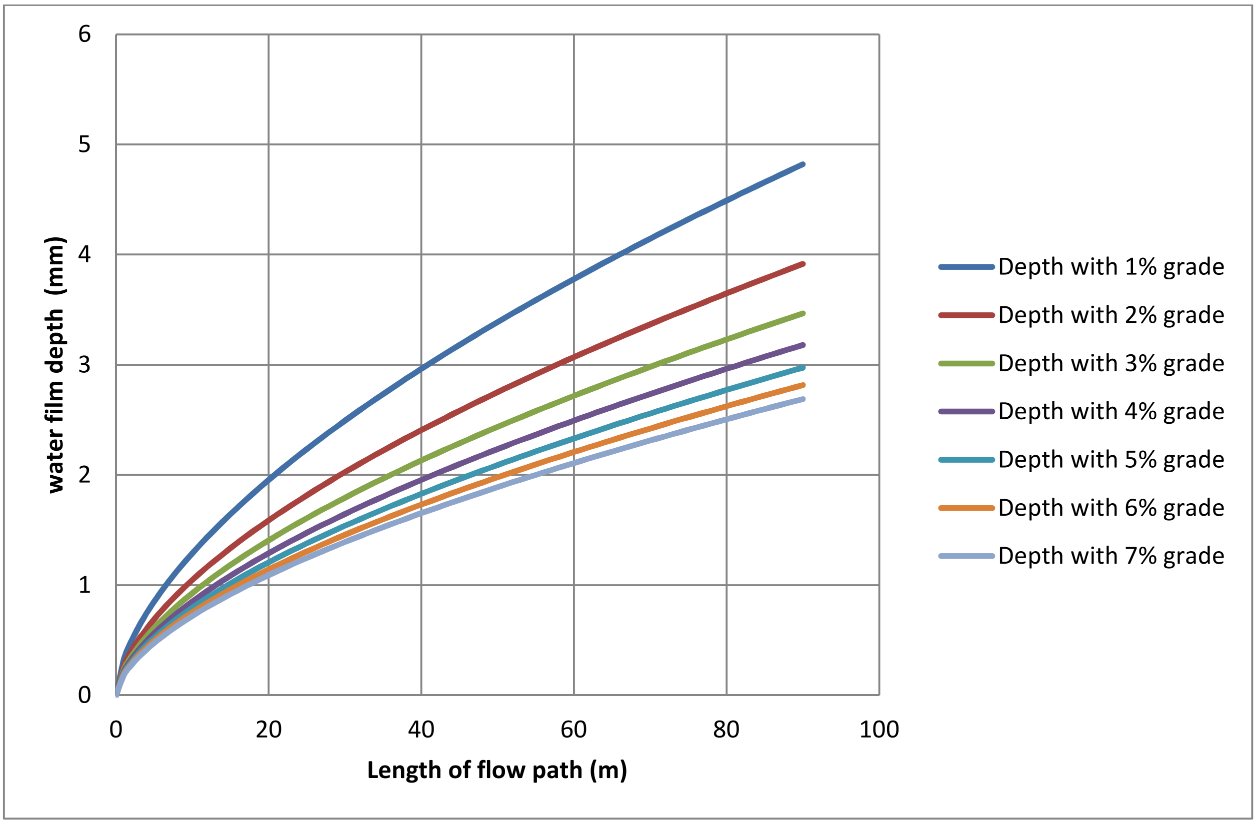

Figure 4.16 - Kinematic wave equation - depth @ 50mm/h intensity

Figure 4.16 and Table 4.16 express the data obtained for the 50mm/h intensity rainfall event.

The maximum calculated depth of flow is 4.5mm at over 80m length along the flow path for the 1% grade.

The 4mm criteria is exceeded for the 1% grade at a length of 65m along the flow path.

The 2.5mm criteria is exceeded for grades flatter than 5% at lengths along the flow path varying from 30m for 1% to 70m for 5%

Table 4.16 - Kinematic wave equation - depth @ 50mm/h intensity

Distance along flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	1.95	1.59	1.41	1.29	1.21	1.14	1.09
40	2.96	2.41	2.13	1.95	1.83	1.73	1.65
60	3.78	3.07	2.72	2.49	2.33	2.21	2.11
80	4.49	3.65	3.23	2.96	2.77	2.62	2.50

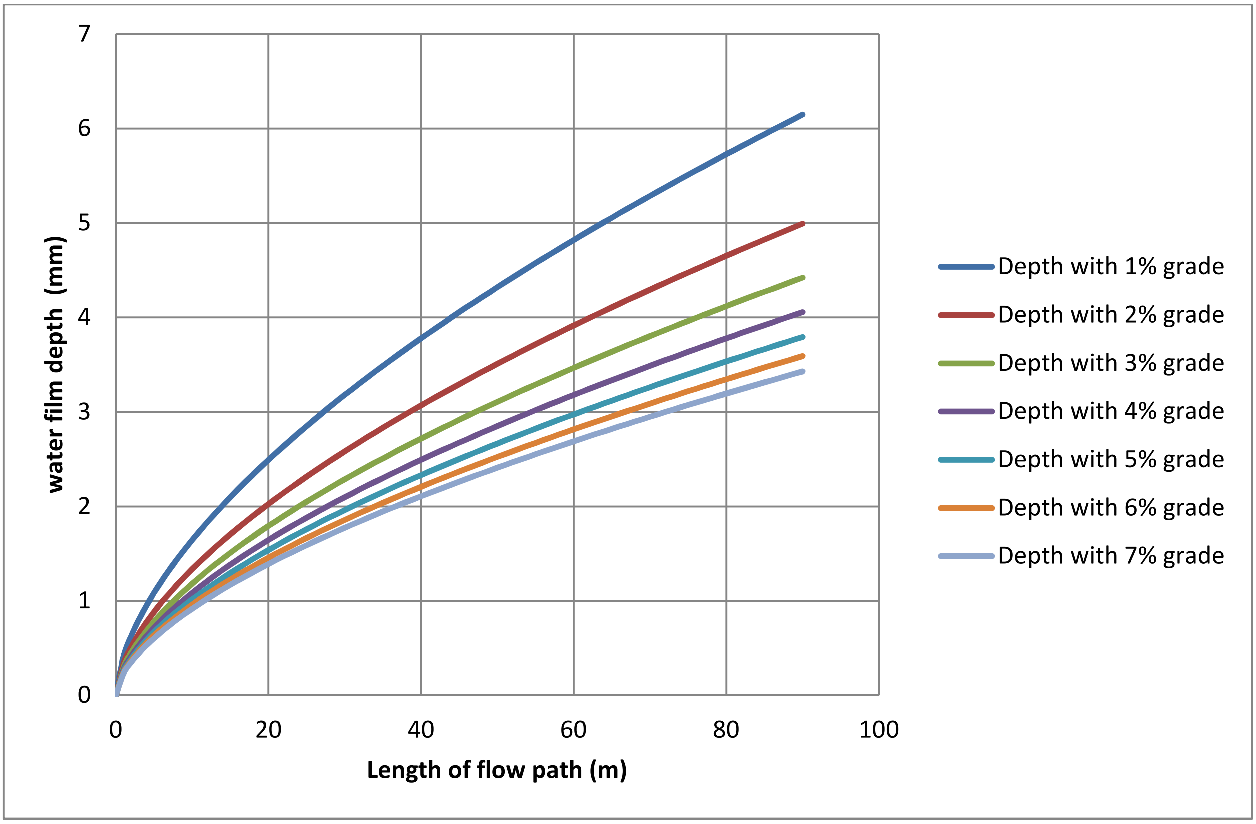

Figure 4.17 - Kinematic wave equation - depth @ 75mm/h intensity

Table 4.17 - Kinematic wave equation - depth @ 75mm/h intensity

Distance along flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.49	2.02	1.79	1.64	1.54	1.46	1.39
40	3.78	3.07	2.72	2.49	2.33	2.21	2.11
60	4.82	3.91	3.47	3.18	2.97	2.82	2.69
80	5.73	4.65	4.12	3.78	3.53	3.35	3.19

Figures 4.17 and 4.18 and Tables 4.17 and 4.18 express the data obtained for the 75mm/h and 100mm/h intensity rainfall events.

The 4mm criteria is exceeded for all grades flatter than 5% at lengths along the flow path varying from 25m for 1% to 75m for 5%.

The 2.5mm criteria is exceeded for all grades flatter than 7% at lengths along the flow path varying from 20m for 1% to 55m for 5%

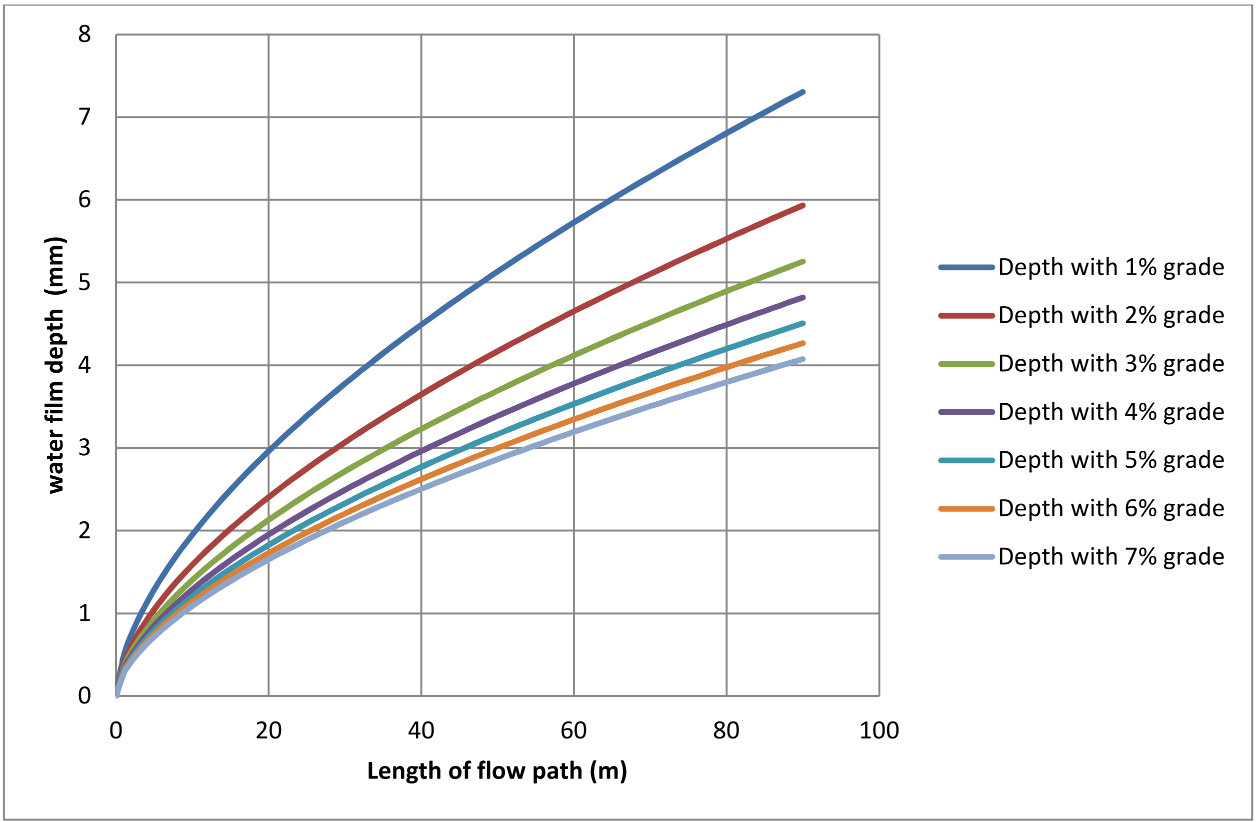

Figure 4.18 - Kinematic wave equation - depth @ 100mm/h intensity

Table 4.18 - Kinematic wave equation - depth @ 100mm/h intensity

Distance along flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.96	2.41	2.13	1.95	1.83	1.73	1.65
40	4.49	3.65	3.23	2.96	2.77	2.62	2.50
60	5.73	4.65	4.12	3.78	3.53	3.35	3.19
80	6.81	5.53	4.90	4.49	4.20	3.98	3.80

4.4 Comparisons of methods

To perform a comparison of the three models used to calculate the flow depth, the values for corresponding values of intensity, slope and grade are compared. The following graphs provide a summary of the comparison results. General trends emerge from the results and can be seen in the graphs below. Generally the RRL produces much higher calculated values of flow depth than both the Gallaway method and the Kinematic wave model. There is however, a more complex relationship between the values produced by the Gallaway method and the kinematic wave model. This will be explored below.

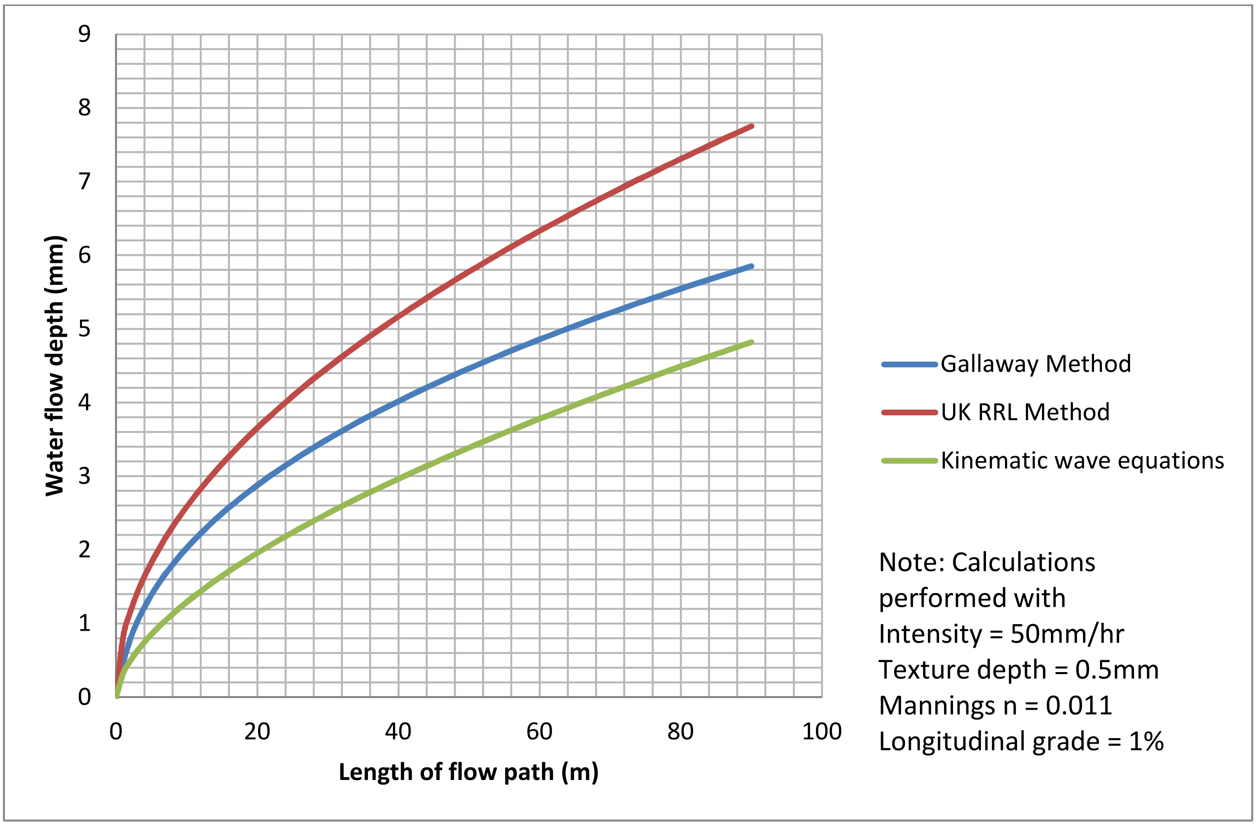

Figure 4.19 - Comparisons of depth calculation methods (1% grade)

The above Figure 4.19 shows the comparisons of the models on a flat grade at the 50mm/h design rainfall intensity. The trends provided here are also evident in all values of rainfall intensity used. The RRL method is shown as a much higher depth of flow. The Kinematic wave produces depth which are small than the Gallaway equation for this grade. As can be seen in Table 4.19, at the 60m length along the flow path, the kinematic wave model calculates water film depth approximately 1mm less than the Gallaway equation. As will be shown below, this trends does not continue for all grades of slope.

Table 4.19 - Comparisons of depth calculation methods (1% grade)

Distance along flow path (m)	Gallaway Method	UK RRL Method	Kinematic wave equations
20	2.88	3.65	1.95
40	4.02	5.17	2.96
60	4.86	6.33	3.78
80	5.55	7.31	4.49

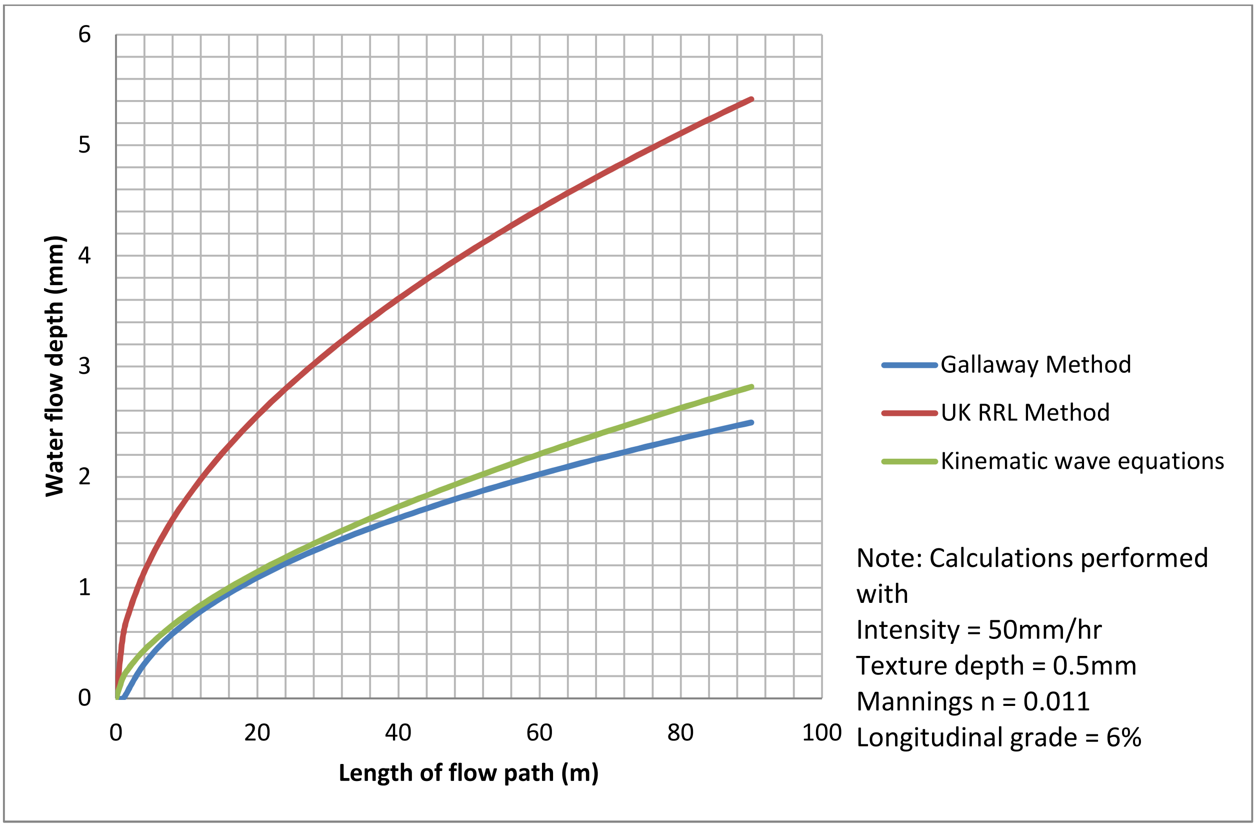

Figure 4.20 - Comparisons of depth calculation methods (6% grade)

Figure 42.0 represents the comparisons of the model where the grade has been increased to 6%. Unlike the previous graph, this shows that the Gallaway equation produces the lowest depth calculation. Here the only input variable has been the grade of the longitudinal grade, this change has altered the results produced from all the models. Table 4.20 shows that at the 60m length along the flow path, the Gallaway equation calculates water film depth approximately 0.15mm less than the kinematic wave model.

Table 4.20 - Comparisons of depth calculation methods (6% grade)

Distance along flow path (m)	Gallaway Method	UK RRL Method	Kinematic wave equations
20	0.99	2.35	1.04
40	1.56	3.47	1.65
60	1.97	4.31	2.14
80	2.30	5.01	2.56

From the above results the trend could be describes as the kinematic wave model will calculate lower flows of depths on flat grades when compared to the Gallaway equation. However, for steep grades the kinematic wave model calculates higher values of flow depth than the Gallaway equation.

The full range of graphs produced for the comparison of models analysis are attached as Appendix D.

4.5 Rainfall intensity

The rainfall intensity has a large impact on the calculated flow depth. The range of rainfall intensities tested as part of the simulation represents a large charge in the storm intensity. The values are spread around the design rainfall intensity of 50mm/h.

Figure 4.21 below shows the degree to which the rainfall intensity will impact the on the value of water film depth calculated. The figures show that the larger the intensity the larger the water film depth, with the 100mm/h storm producing depths of flow which are considerably larger that the corresponding values when calculated with the 15mm/h storm.

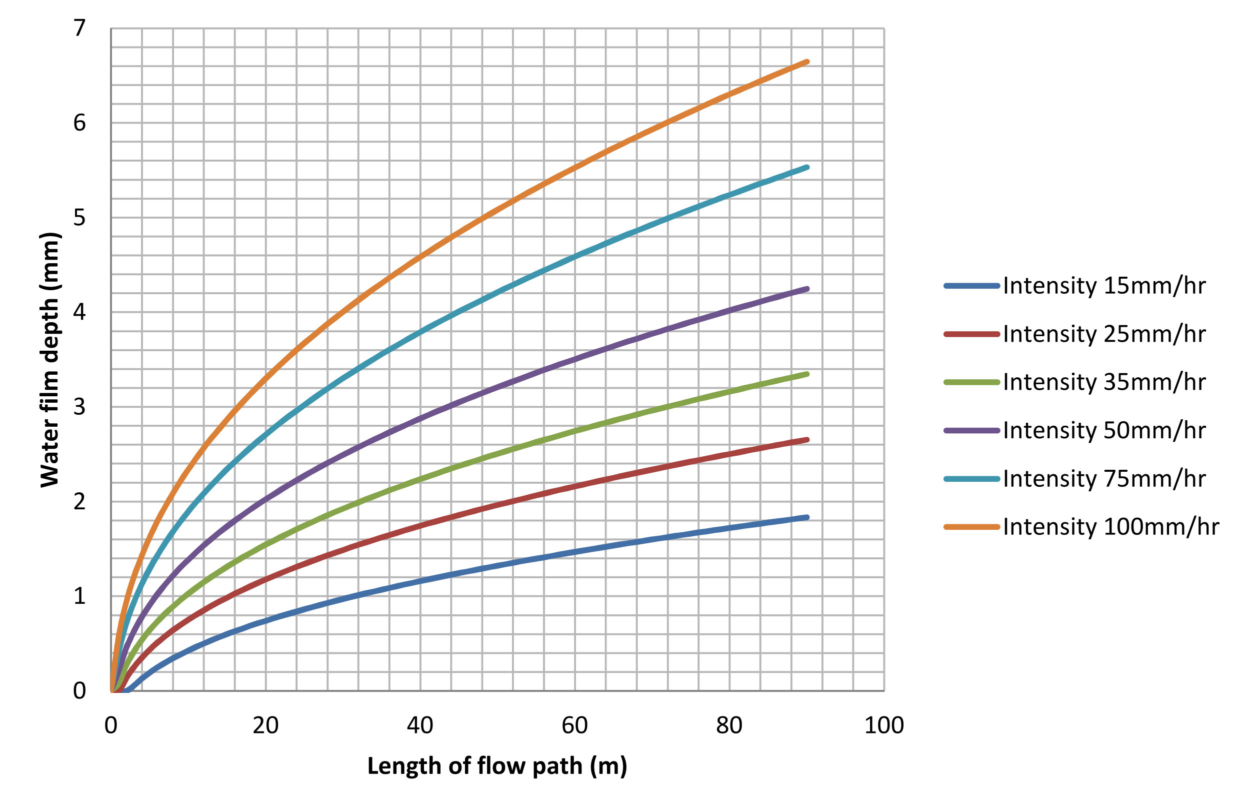

Figure 4.21 - Rainfall Intensity analysis - with 2% grade and 0.5mm texture depth

The 2% grade shown here shows a relatively flat grade however the trend of increased intensity increasing the depth is valid for all slopes and flow path length combinations. As can be seen in Table 4.21 below, the depth of flow calculated at the 60m length along the flow path can alter between 1.5mm for the lower intensity and up to 5.5 for the larger, 100mm/h intensity. This shows a 4mm depth of flow difference which is attributed to the rainfall intensity.

Table 4.21 - Rainfall intensity analysis at 2% grade and 0.5mm texture depth

Distance along the flow path (m)	Intensity (mm/h)					
	15	25	35	50	75	100
20	0.741	1.177	1.545	2.024	2.706	3.299
40	1.160	1.744	2.236	2.877	3.790	4.583
60	1.468	2.160	2.744	3.504	4.586	5.527

80	1.721	2.502	3.161	4.018	5.240	6.301

The full range of graphs produced for the rainfall intensity analysis are attached as Appendix G.

4.6 Texture depth

Texture depth is assumed by the Gallaway equation to have a bearing on the depth of flow calculation. The analysis with the texture depth variable showed that the chosen value does alter the depth value calculated; however, it is difficult to derive or observe any obvious trends from the analysis. Over the length of the flow path, different texture depths have different effects on the depth. It is assumed that the larger texture depths give a greater water storage volume and will therefore give a reduced water film depth. This is seen for the calculation on the short length of flow path under approximately 30m. However, above this value the results seem to vary with smaller texture depth generating smaller flow depths. There appears to be a median value of texture depth that gives the largest flow depths. As stated previously it is hard to quantify the relationship for texture depth however, the ratio of depth to texture depth is not even. For instance, a 1mm increase in texture depth from 0.2mm to 1.2mm does not result in a 1mm reduction in the water film depth.

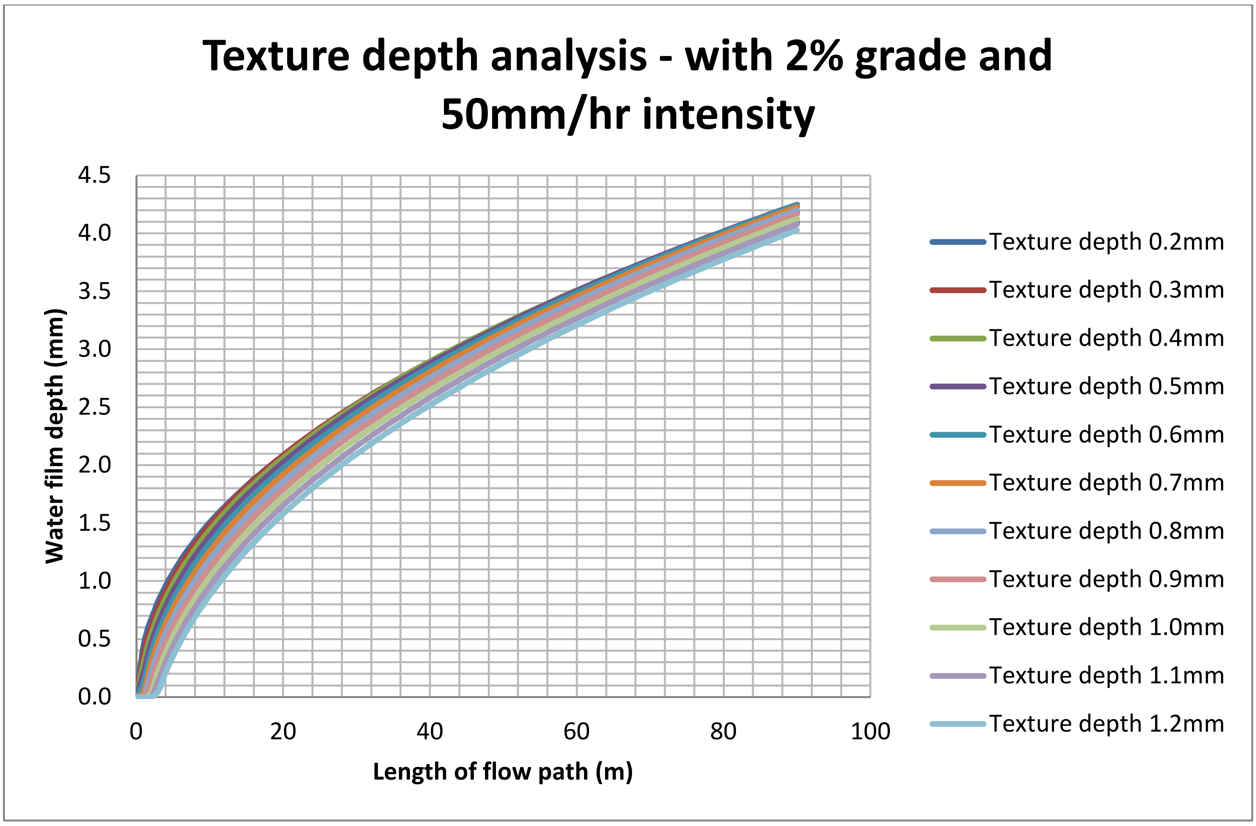

Figure 4.22 - Depth of flow with variation in texture depth

Table 4.22 - Depth of flow with variation in texture depth

Distance along flow path (m)	Texture depth (mm)										
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2
20	2.08	2.09	2.06	2.02	1.98	1.92	1.86	1.79	1.72	1.65	1.58
40	2.85	2.89	2.90	2.88	2.85	2.80	2.76	2.70	2.64	2.58	2.52
60	3.42	3.49	3.51	3.50	3.49	3.46	3.42	3.37	3.32	3.27	3.21
80	3.89	3.97	4.01	4.02	4.01	3.99	3.96	3.92	3.88	3.83	3.78

4.7 Time of concentration

The time of concentration of a road surface catchment is used as a guide to determine the time necessary for maximum depth of flow to be reached. The three methods used in the calculations show the difference in the times calculated for each method. The kinematic wave approximation is the only formula used which contains a variable for rainfall intensity. Therefore it will be used to determine the effect of the rainfall intensity. General trends from all the calculations suggest that flat grades lead to longer time of concentration. Longer flow paths also lead to longer times of concentration which is explained by the water particles having to travel a further distance at the same speed. The kinematic wave approximation method shows that and an increase in intensity leads to a decrease in time of concentration. This would be due to the increase volume of water on the surface having more gravity force to travel down the slope at a higher speed.

Table 4.23 - Time of concentration (minutes) using kinematic wave @ 15mm/h intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.77	3.06	2.71	2.49	2.33	2.20	2.10
40	5.71	4.64	4.11	3.77	3.53	3.34	3.19
60	7.29	5.92	5.24	4.81	4.50	4.26	4.07
80	8.66	7.04	6.23	5.71	5.34	5.06	4.83

Table 4.22 shows the worst case for the time of concentration. This was evident on the 1% slope for a length of 80m with the 15mm/h rainfall intensity for a time of concentration of 8.66 minutes.

Table 4.24 - Time of concentration (minutes) using kinematic wave @ 25mm/h intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.07	2.50	2.21	2.03	1.90	1.80	1.71
40	4.66	3.78	3.35	3.07	2.87	2.72	2.60
60	5.94	4.83	4.27	3.92	3.67	3.47	3.31
80	7.06	5.74	5.08	4.66	4.36	4.13	3.94

Table 4.23 shows a decrease in all values from table 4.22 which is attributed to the increased rainfall.

Table 4.25 - Time of concentration (minutes) using kinematic wave @ 50mm/h intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	2.33	1.89	1.68	1.54	1.44	1.36	1.30
40	3.53	2.87	2.54	2.33	2.18	2.06	1.97
60	4.50	3.66	3.24	2.97	2.78	2.63	2.51
80	5.35	4.35	3.85	3.53	3.30	3.13	2.98

Table 4.24 again shows a decrease in all time of concentration times with the increase in intensity. The max time of concentration here is just over 5 minutes for the 80m flow path length. It should be noted that the design storm duration for aquaplaning analysis is the 50mm/h with 5 minute duration, which is close to what is calculated with the kinematic wave approximation.

Figure 4.22 can be compared with Table 4.24 to determine is the results calculated with the full kinematic wave simulation model correlate with the kinematic wave approximation formula for time of concentration. The graph shows the 1% slope values of depth over time. As can be seen the equilibrium conditions is reach at approximately 2 minutes, 3.5 minutes, 4.5 minutes and 5.5 minutes for the 20, 40, 60 and 80m length of flow respectively. These values show a close correlation and therefore justify the accuracy of the two models.

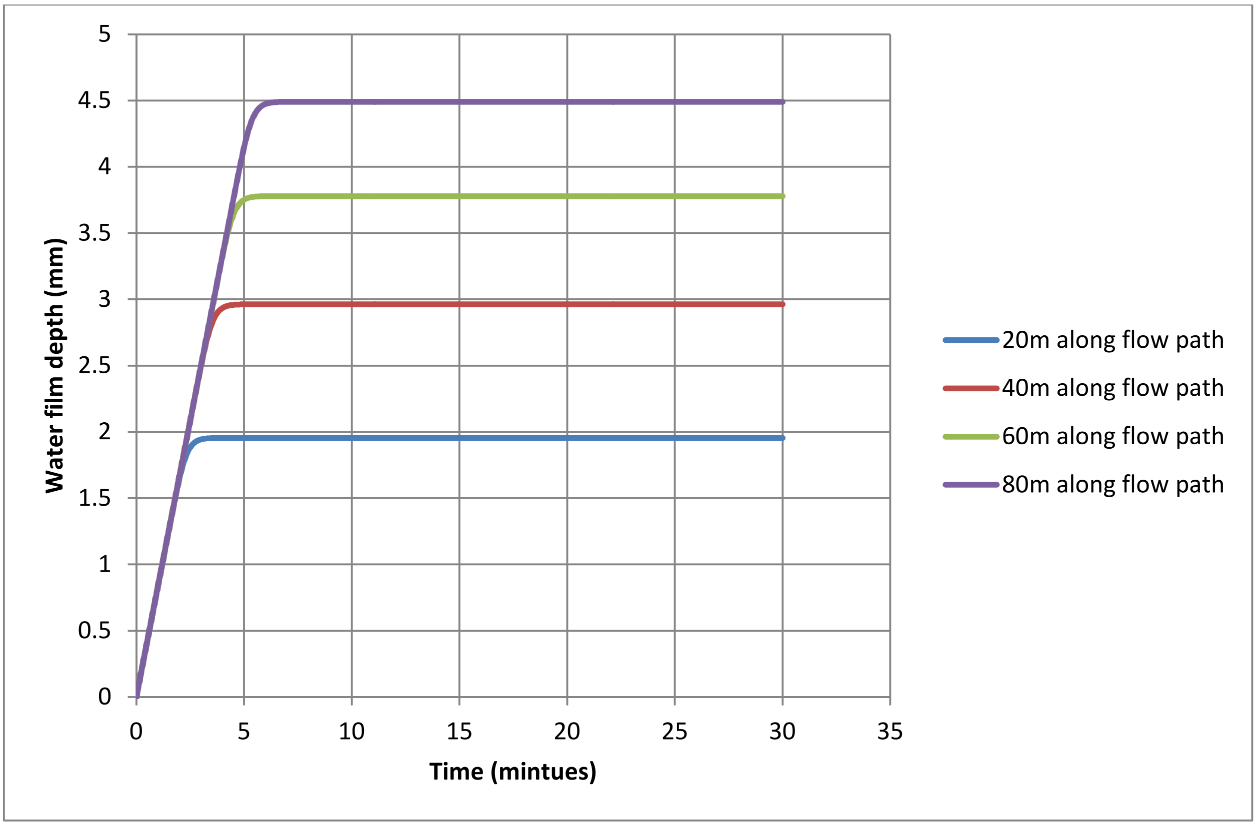

Figure 4.23 - Kinematic wave simulation @ 50mm/h intensity and 1% slope

Table 4.26 - Time of concentration (minutes) using kinematic wave @ 100mm/h intensity

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	1.77	1.43	1.27	1.16	1.09	1.03	0.98
40	2.68	2.17	1.92	1.77	1.65	1.56	1.49
60	3.41	2.77	2.45	2.25	2.11	1.99	1.90
80	4.06	3.29	2.92	2.68	2.50	2.37	2.26

Table 4.27 - Time of concentration (minutes) using Oakden formula

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.13	2.49	2.17	1.97	1.83	1.73	1.64
40	4.98	3.95	3.45	3.13	2.91	2.74	2.60
60	6.52	5.18	4.52	4.11	3.81	3.59	3.41
80	7.90	6.27	5.48	4.98	4.62	4.35	4.13

The Oakden Formula values shown in table 4.26 give higher reading than those calculated with Friends formula in table 4.27. the friend formula values seem to closely match those of a 50mm/h intensity rainfall in the kinematic approximation whilst the Oakden values seem to match a rainfall intensity closer the 25mm/h modelled with the kinematic wave approximation.

Table 4.28 - Time of concentration (minutes) using Friend's formula

Distance along the flow path (m)	Grade (%)						
	1	2	3	4	5	6	7
20	3.19	2.78	2.56	2.42	2.31	2.23	2.16
40	4.02	3.50	3.23	3.05	2.91	2.81	2.72
60	4.60	4.01	3.69	3.49	3.34	3.22	3.12
80	5.06	4.41	4.07	3.84	3.67	3.54	3.43

The calculated results show that the time of concentration within the study ranges between a couple of minutes for high grades to 8 minutes for the worst case flat grades.

4.8 Design storm simulation

The design storm simulations were run for the purpose of determining the time that the surface flow depth remained above the critical values. In the following graphs a design storm was simulated over the pavement surface for a duration of 5 minutes and then 10 minutes to determine the time necessary to reach maximum flow depth.

Once the duration of the design storm was exceeded that rainfall was ceased and the simulation allowed to run to simulated the draining of the surface.

Below is a sample of the graphs produced to show the worst case storms on the flattest grade. These graphs represent the longest time to saturation or equilibrium and the largest surface flow depths. Even in these worst cases the road surface begins to drain immediately after the cessation of rain and subsides to a low depth of flow within 5 minutes. The full range of design storm analysed can be seen in Appendix E.

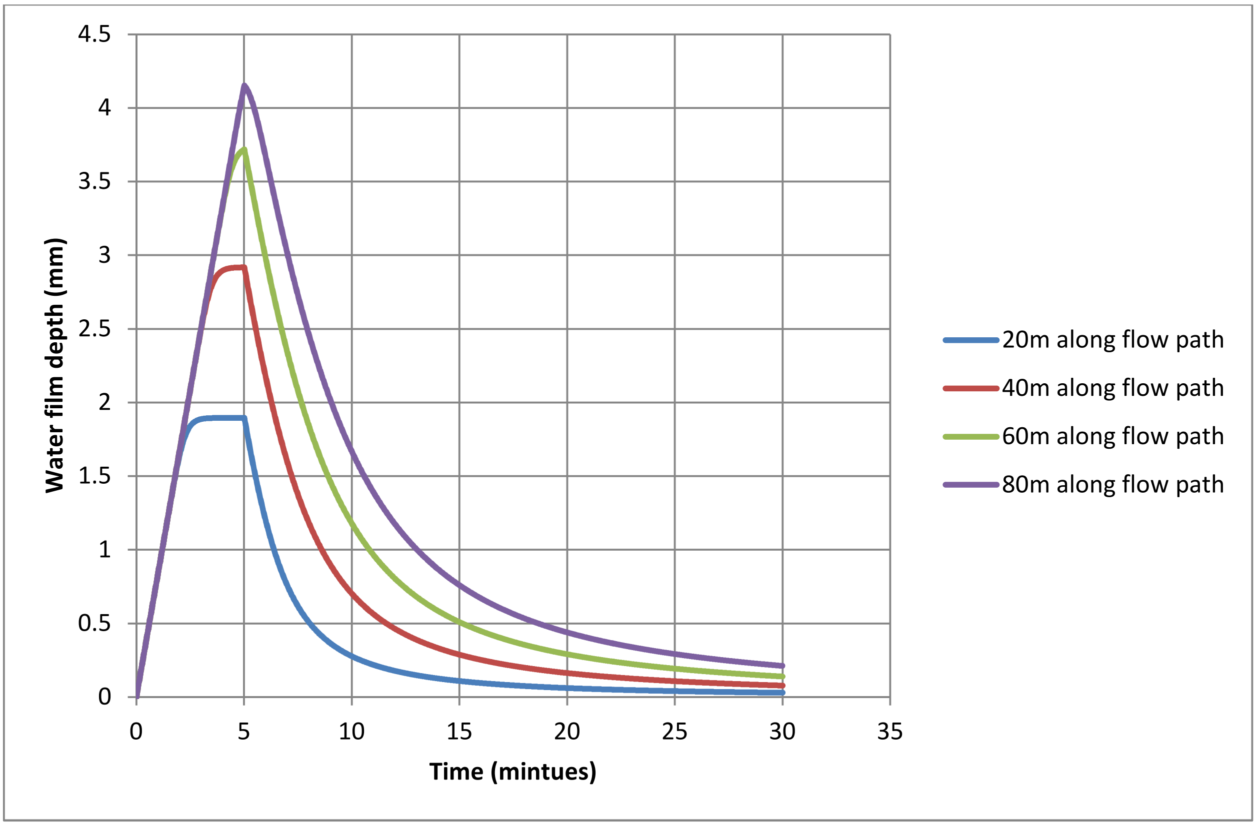

Figure 4.24 - Design storm simulation @ 1% for 50mm/h, 5 minutes

Figure 4.23 shows the design storm for a 50mm/h intensity storm event on a 1% grade with a 5 minute duration. As can be seen in the graph, the flow depth reaches a value just over the critical 4mm value for the 80m flow path length. It should be noted here that the storm duration of 5 minutes does not allow for equilibrium to be reached before the storm is stopped. However, after the storm stops, the flow depth quickly drops below the 4mm value and is under the 2.5mm criteria for partial aquaplaning within approximately 3 minutes (total time 8 minutes).

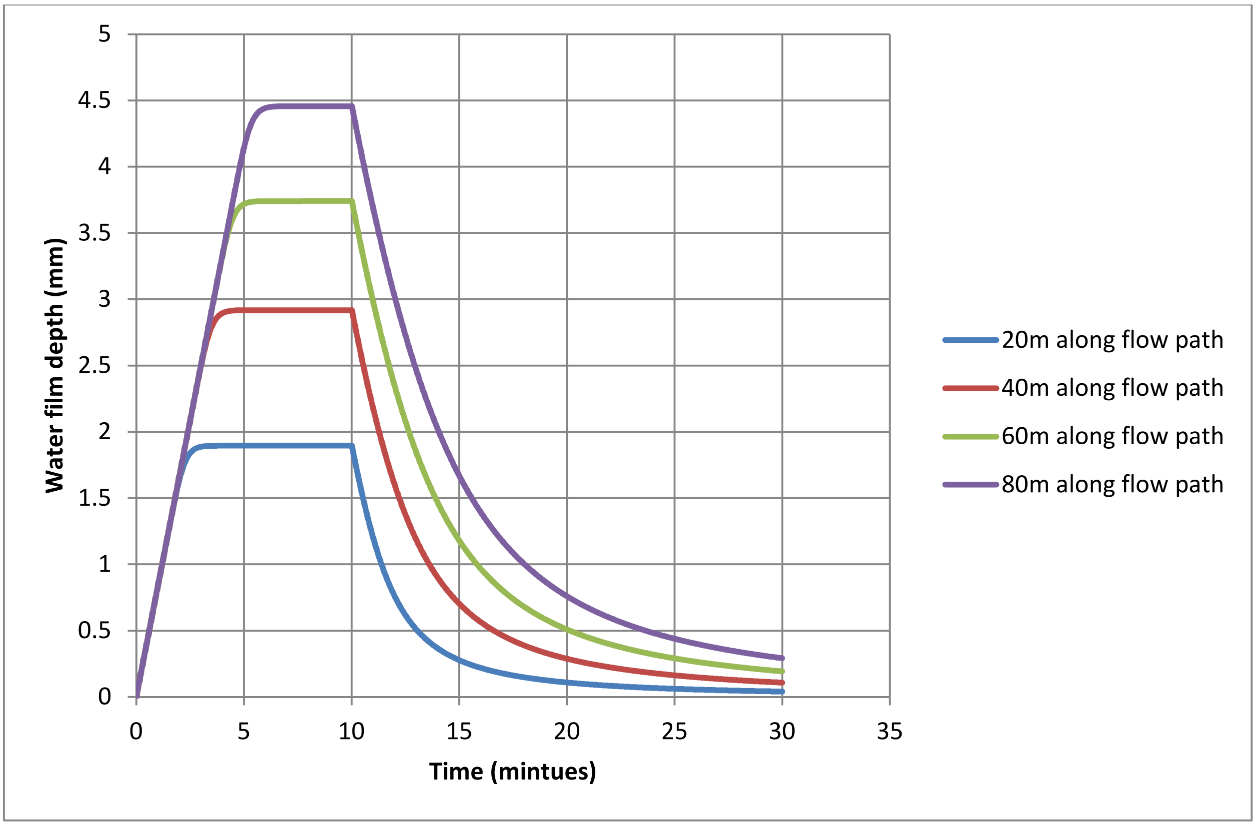

Figure 4.25 - Design storm simulation @ 1% for 50mm/h, 10 minutes

Figure 4.24 shows the same design storm intensity as figure 4.23 however the duration of the storm has been extended to 10 minutes. As can be seen in the graph, the flow depth reaches a value just under 4.5mm for the 80m flow path length. It should be noted here that the storm duration of 10 minutes is sufficient for the equilibrium conditions to be reached. Likewise when the storm stops in this simulation, the flow depth quickly drops below the 4mm value and is under the 2.5mm criteria for partial aquaplaning within approximately 3 minutes (total time 13 minutes).

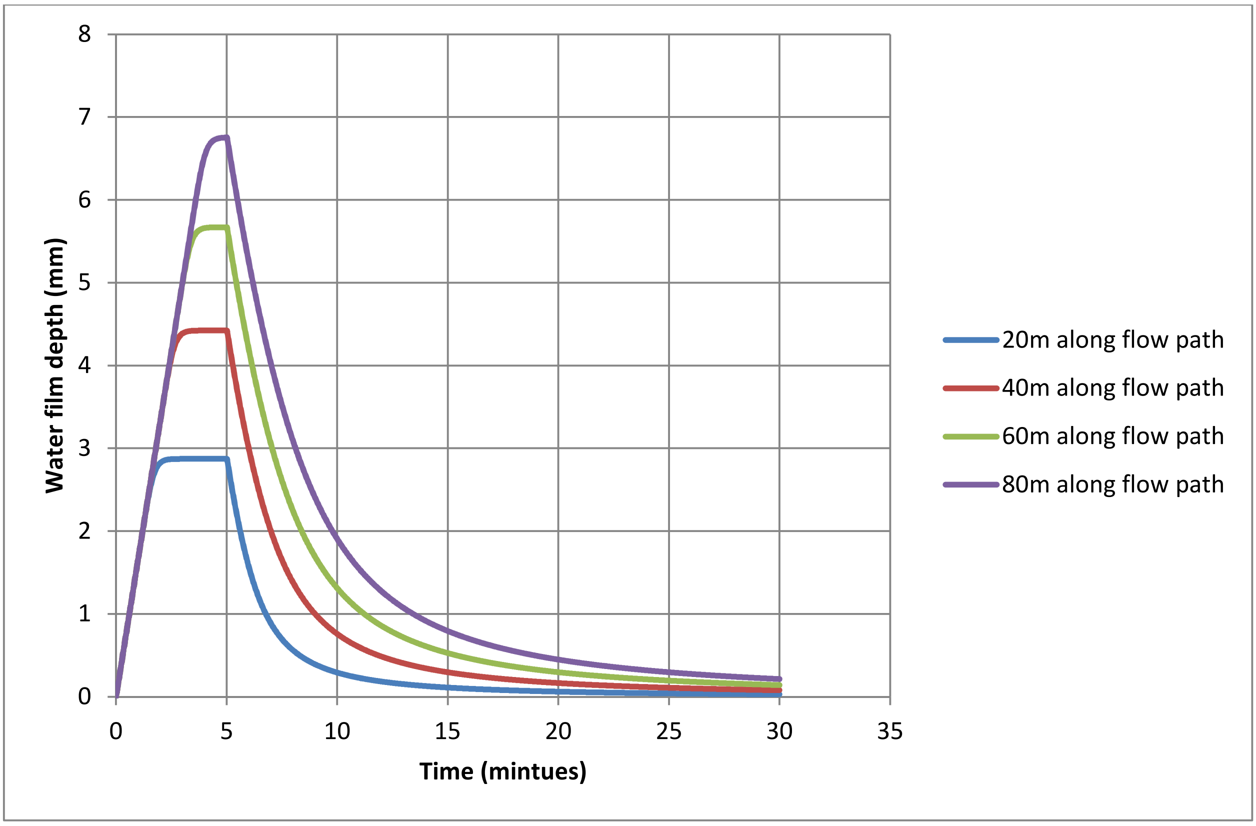

Figure 4.26 - Design storm simulation @ 1% for 100mm/h, 5 minutes

Figure 4.25 shows the design storm for a 100mm/h intensity storm event on a 1% grade with a 5 minute duration. This shows the effect of a higher intensity on the flow depth as the maximum value of flow depth is approximately 6.7mm. The higher intensity does not affect the time necessary for the equilibrium conditions, this is shown by the 80m flow path still not reaching equilibrium before 5 minutes. Once the storm stops, the draining action of the surface is still relatively fast, although due to the increased volume of water the time is slightly longer. The depth drops below 4mm in approximately 3 minutes and to continues to fall to 2mm after 5 minutes (total time 10 minutes).

5. Discussions

The common acceptance of the Gallaway (1979) formula by transportation authorities from both Australia and the United States shows this formula to be the widely accepted method for calculating the water film depth. As explained in the literature, the flow path depth is related to slope length, grade, rainfall intensity and pavement texture depth. The results produce confirmed this with the trends holding true for all three methods tested.

The results from all three models show that the depth of flow will continue to rise for the length of the flow path; however, the rate of increase becomes smaller as the length increased. All the models were sensitive to slope values, with low slope values providing the most sensitivity in the results.

The Gallaway Equation is least sensitive to texture depth as it does not show a great deal of variance in the results as the texture depth increases.

For the Gallaway equation the calculated water film depths for higher grades (i.e. 4-7%) have less variation in the calculated depths while the flatter grades have higher variation in calculated depth. The flatter the grade the higher the variation in calculated depth. At flat grades a slight decrease in grade leads to a magnitude of increase in depth.

This trend was also evident in the RRL method although it should be noted that the variance between the grades is not as pronounced in the RRL method as the Gallaway method. The results seem to follow the same trends for each grade.

The RRL method for calculating surface water depth on pavements is conservative when compared to the Gallaway equation. The RRL consistently gave higher calculations for depth of flow, the consequences of which would be to imply a higher risk of aquaplaning and possibly result in costly redesign measures. This conservatism creates difficulties for geometric design and adds unnecessary cost to road projects. It is for this reason that many road authorities recommend that the Gallaway equation be used to calculate the surface water film depth associated with aquaplaning.

At the 15mm/h rainfall intensity the Gallaway equation did not produce any depths over the 2.5mm desirable maximum, however the RRL method produced this flow depth at all values of grade and even for lengths as short as 30m for flat 1% grades. This would pose many issues for the design as this rainfall intensity would be considered common, as would the geometric conditions described. It would therefore follow that the RRL method would highlight an aquaplaning issue where the Gallaway equation does not.

The designer should consider the length and also the location of the flow path as this will influence the drivers behaviour. The literature suggested that designers should limit flow path length to below 60m, but this does not remove the aquaplaning risk entirely as there could still be high depth of flow on lengths shorter than this. The calculations show that the depth of flow can be exceeded at shorter length than this recommended value. Therefore the combination of both lengths and grade of the flow path must be considered simultaneously. There may also be a risk to the location of the flow path. For instance, vehicles will brake on approach to an intersection. Therefore flow paths in this location should limit flow depth below the 2.5mm criteria. However, a straight long section of road where the driver will continue at a constant speed may be able to experience 4mm depth of flow without increasing the risk of aquaplaning occurring.

The Gallaway equation evaluates more variables and shows more sensitivity than the RRL. The kinematic wave model evaluates more variables and it more complex than both of the other two methods do.

The results from all models tested showed that the intensity had a large impact on the calculated flow depth. Greater surface film depths were associated with higher intensities for all three of the models used. The Gallaway equation is most sensitive to the rainfall intensity at high values of intensity. The results showed that the larger the intensity the large the calculated flow depth especially when considering the 100mm/h intensity which produce flow depths up to 4mm larger than the 15mm/h intensity.

It is not completely possible to define the water film depth when aquaplaning will occur however the literature indicates the critical depth are 4mm for full aquaplaning and 2.5mm for partial aquaplaning. This project has shown that the 2.5mm criteria is exceeded on many combinations of length of flow path and grade. these situation would be common on the existing road network and therefore many existing areas would be highlighted as risks for aquaplaning.

Visibility and driver behaviour will also have an impact on the modelling. As outlined in the literature review, current standards suggests that driver will slow down due to visibility at rainfall intensities greater than 50mm/h, with some suggesting this figure could be lowered to 25mm/h. Current models take into account the driver slowing down in rainfall events. They only use the values of rainfall intensity that will result in loss of visibility for over talking manoeuvres due to a build up of water on the windscreen. They do not take into account the other visibility issues that could cause a driver to slow down much sooner. More review of drivers slowing down will be looked at with recommendations into more extensive data collection which will not be part of this research.

Texture depth is an important variable however does not have a significant impact on the calculated flow. The texture depth analysis performed with the Gallaway equation showed that there may be some limitations with the Gallaway equation. The results showed some inconsistent trends throughout the data set . This may be due to the equation being derived with the length being below 15m. At longer lengths above 60m there seems to be some inconsistent trends.

Research suggests that above 6mm/h is heavy rainfall from driver simulation testing and drivers would slow down up to 10-19km/h, however if this is an urban environment this is a considerable drop in speed, if this was on a high speed highway environment, even with the reduction in speed, the vehicle may be above critical aquaplaning speed.

Time of concentration is currently taken into account of aquaplaning depth modelling with the use of the design storm event duration. The 5 minute duration is to allow for surface flow to build up to maximum depth. Time of concentration is often under 5 minute. The modelling in NSW and QLD does not technically account for tc as the 50mm/h design storm intensity is longer a specified duration event. The provision is to allow for full depth of flow. This will most likely occur within 5 minutes however even if the storm event is more likely to last longer at this intensity.

The calculated tc values ranged around 5-10 minutes with the flat grades or lower intensities leading to a longer time of concentration. The modelling showed that for some combinations of slope length and grade the time of concentration would be longer than 5 minutes. The kinematic wave approximations of tc correlated very accurately with the kinematic wave simulation for flow depth.

The analysis of the design storm events and time of concentration highlighted that the depth of flow would continue to rise along the flow path until the equilibrium conditions are reached. This duration was typically in the region of 5 minutes, however the worst case for the study parameters was approximately 8 minutes. The design storm also highlighted that the road surface drains away relatively quickly past the critical criteria. Although the surface takes some time to fully drain the initial drop in surface depth reduced the depth below critical levels therefore reducing the aquaplaning potential.

6. Conclusions and recommendations

The RRL method produces consistently higher values of water film depth when compared to the Gallaway Equation and the Kinematic wave simulation model. The Gallaway Equation and Kinematic wave model give very close correlation on results with similar values produced for corresponding grades and lengths. The kinematic wave model will calculated depths less than the Gallaway equation for flat grades, however will produce higher depths at steep grades.

The kinematic wave model could be used if or when necessary as dictated by the risk involved. For instance, if the flow depth is close to critical levels and a more extensive investigation is required. Gallaway is a simple method to use for flow depth approximation however if the depth is close to critical more extensive methods should be used. Hydraulic analysis can be a useful and accurate tool for designers, however the high cost and difficulty is establishing models would not warrant an analysis in all situations.

The high values calculated from the RRL method, as well as the terrain and rainfall intensities experienced in NSW and QLD make the use of the RRL method high in cost to ensure designs meet standard depths for water film depth. Therefore it should not be used, as per the current Austroads standards which state the Gallaway method to be used and the RRL in NZ which would also experience less intense rainfall events that Australia.

The kinematic wave model is assumed to be more accurate as it is used in many computer applications. Transportation authorities should invest into sophisticated mathematical programming to perform calculations of the flow depth.

Texture depths used in producing the Gallaway and RRL methods were determined using the sand patch method. Current pavement texture depths are still determined with the same method, which is an appropriate lab test whose validity is accepted. The texture depth values presented from the standards are also measured using the same laboratory testing. The designer must select an appropriate texture depth for the surface type in question whether in the initial design phase or the maintenance analysis stage. If in the initial design stages, the proposed pavement surface type should be selected to allow for calculation to contain an accurate texture depth value. The texture depth for maintenance projects should be determined by on site testing for accuracy.

Rainfall intensity values are given as 1 year ARI and 5 min duration, or 50mm/h whichever is the lesser. Although the 50mm/h intensity is often exceeded in the 5 min, 1-year event, the adopted value represents a balance of cost and risk. The results show that design for 100mm/h intensities would be almost impossible as critical depth would be exceeded at very short lengths of flow. Therefore the design standard to adopt the maximum rainfall intensity at 50mm/h seems to be appropriate. Consideration could be given to special circumstances to further lower the intensity value, however this must take on considerable risk to alter the approach.

Driver behaviour is considered in the modelling of aquaplaning by the 50mm/h design rainfall intensity. This represents the upper limit of driver behaviour as research suggests that drivers could start slowing down at much lower rainfall intensities. There needs to be a balance between risk and cost for design to high standards. Currently this design rainfall intensity provides that balance. Drivers may slow down at intensities lower than this value however this is not guaranteed and the rainfall experienced in Australia can exceed this design rainfall intensity at numerous times throughout the year. If there is considerable risk involved in the likelihood of aquaplaning due to water film depth a more detailed analysis into how the risk has been calculated should be performed.

Critical depths of aquaplaning are widely accepted as 2.5mm for partial aquaplaning and 4mm for full aquaplaning. These are documented in Austroads Part 5A (2013) as the depths for which the flow should be kept under. Until further research is performed to either prove or disprove existing critical depths as documented in previous research, these values should be used as the critical aquaplaning depths.

Time of concentration is currently taken into account of aquaplaning depth modelling with the use of the design storm event duration. The 5 minute duration is to allow for surface flow to build up to maximum depth. This research performed an analysis performed calculations into the time of concentration for the road surface catchments. The calculated tc values ranged around 5 minutes with the flat grades or lower intensities leading to a longer time of concentration. The modelling showed that for some combinations of slope length and grade the time of concentration would be longer than 5 minutes.

The kinematic wave approximations of tc correlated very accurately with the kinematic wave simulation for flow depth. It is therefore appropriate to model the drainage of the surface flow with the design storm analysis. The design storm analysis showed time of equilibrium in the region of 5 minutes for each situation and the surface drained quickly after rainfall. On each of the occasions modelled the flow depth subsided below the critical levels within 5 minutes of the cessation of the rainfall event. This suggests time of concentration and surface drainage should be calculated in the analysis to fully appreciate the risks involved. The time of concentration analysis is specifically recommended where numerous storm events are expected to breach critical depth levels but the depth are not maintain on the surface for a considerable time. It would be necessary to find the time per year that super critical depth will be experience to assess the full risk associated with surface flow depths

7. Future works

This research project has investigated the aquaplaning risk on the road network by analysing the numerical models used to calculate the flow depth. It modelled the surface flow build up over the duration of a design storm event. The phenomenon of aquaplaning is very complex and this research focuses on a small portion of that topic. This work could be extended in the future by analysing different areas and improving the clarity around these areas.

With regard to this research, there are three main areas which could be improved and a higher level of validity placed on the results. These three areas are computer modelling, Manning's n for texture depth roughness and testing driver behaviour in wet weather.

As briefly discuss in the body of this report, some existing computer programs are in use to help designers calculate the aquaplaning depth of surface flow using the 3d terrain model. However, the mechanisms behind these programs were not investigated to the full degree. The internal workings of the computer program may be built around the Gallaway Equation or they may employ a more complex hydraulic wave model. A thorough investigation into existing programs, how they work and the accuracy of the results they produce may lead to a faster and more efficient method for designers to perform calculations and design checks. An investigation as to whether the existing market software applications are sophisticated enough to use for complex computation should be performed. This may lead to the Gallaway equation being replaced by a hydraulics model.

Manning's value in the kinematic wave model is used to calculate the velocity of flow. The value adopted for this study was appropriate for a typical road surface type. This study did not however perform a sensitivity analysis on the values of Manning's chosen to gauge the effect of the Manning's value on the flow depth. There was also no link made between an increase in texture depth and an increase in Manning's value. Both of these aspects could be further explored to investigate the models in greater depth.

This report presented the finding of research with regard to driver behaviour and slowing down in wet weather. This research was not performed in Australia and therefore the results may not be applicable to conditions here. More detailed research into testing and modelling of vehicle reduction in speed during wet weather would allow greater emphasis to be placed on reducing the design storm intensity. Other factors which may impact on the lowering of vehicle speeds would be the overall network congestion (i.e. other vehicles slowing down), visibility, night/dark and surface water.

Other areas which may be investigated further which are related to the surface flow depth calculation would be:

Perform a road safety statistics analysis to analyse crash data at known aquaplaning black spots and compare with data for various other wet weather crashes. Test whether crashes could be more accurately assigned to loss of friction due to a wet surface rather than aquaplaning.

Analyse the increased technology available in vehicles to combat loss of friction/driving force. For instance stability control may provide vehicles with a reduced likelihood of aquaplaning.

Surface water will have an effect of reducing friction. Analyse the road design principles and curve radii formula to determine if this could have an impact on the crash rate. Study the effect friction factor has on existing curve radii using the road design formula with respect to design speed. Assess the impact these factors have on road safety.

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Appendix A - Project Specification

University of Southern Queensland
Faculty of Health, Engineering and Science

ENG4111/4112 Research Project
Project Specification

FOR: CHRIS SNOOK
TOPIC: AQUAPLANING: AN INVESTIGATION OF SURFACE FLOW CALCULATION
SUPERVISOR: Dr. Malcolm Gillies
ENROLMENT: ENG4111 – S1, 2014
ENG4112 – S2, 2014
PROJECT AIM: This research project will numerically analyse current methods used for calculating surface flow depth and the accuracy of different models. It will model the surface flow build up over the duration of a design storm event.

PROGRAMME: Issue C, 6th October 2014

1. Compare the accuracy and reliability of surface flow calculation methods including the Gallaway Equation, Manning's Equation and a kinematic wave equation model.
2. Review current design rainfall intensity values and determine if they are suitable for study of aquaplaning analysis.
3. Investigate if and how driver behaviour should be included in models. For instance, during large intensity events drivers will slow down considerably.
4. Determine how standard values, such as texture depth, acceptable flow depth etc, used in current methods were adopted from historical studies. Investigate if these values are relevant to road conditions today.
5. Determine if the time of concentration for the flow path should be taken into account in the modelling. Analyse a design storm for a determined intensity and duration to calculate the water flow build up and the time taken to fully drain the surface.

AS TIME PERMITS:

6. Analyse crash data at known aquaplaning black spots and compare with data for various other wet weather crashes. Test whether crashes could be more accurately assigned to loss of friction due to a wet surface rather than aquaplaning.
7. Analyse the increased technology available in vehicles to combat loss of friction/driving force. For instance stability control may provide vehicles with a reduced likelihood of aquaplaning.
8. Investigate whether existing market software applications are sophisticated enough to use for complex computation.

AGREED:

_______________ (Student) _______________ (Supervisor)
____/____/_____ ____/____/____

Appendix B – Matlab coding

gallaway_intensity_aquaplaning.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])


%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');


T = 0.5; % Average pavement texture depth in mm
I15 = 15; % rainfall intensity in mm/h
I25 = 25; % rainfall intensity in mm/h
I35 = 35; % rainfall intensity in mm/h
I50 = 50; % rainfall intensity in mm/h
I75 = 75; % rainfall intensity in mm/h
I100 = 100; % rainfall intensity in mm/h

S = [0.5:0.5:7]; % slope gradient in steps of 0.25

Length = [1:1:90]; % length of flow path in 0.5m intervals

L = Length'; % change dimension of length

m = length(S);
n = length(L);
% D = (0.103*(T^0.11)*(L^0.42)*(I^0.59))/(S^0.42)-T;
D = zeros(n,m);
D25 = zeros(n,m);
D15 = zeros(n,m);
D35 = zeros(n,m);
D50 = zeros(n,m);
D75 = zeros(n,m);
D100 = zeros(n,m);

for j=1:m % loop for each time
for i = 1:n % loop for each x
D15(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I15^0.59))/(S(:,j)^0.42)-T;

D15 = max(D,D15);
end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
D25(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I25^0.59))/(S(:,j)^0.42)-T;
```

```
D25 = max(D,D25);
end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
D35(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I35^0.59))/(S(:,j)^0.42)-T;

D35 = max(D,D35);
end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
D50(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I50^0.59))/(S(:,j)^0.42)-T;

D50 = max(D,D50);
end
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
D75(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I75^0.59))/(S(:,j)^0.42)-T;

D75 = max(D,D75);
end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
D100(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I100^0.59))/(S(:,j)^0.42)-T;

D100 = max(D,D100);

end
end
xlswrite('Gallaway_intensity.xlsx', D15, 'A15');
xlswrite('Gallaway_intensity.xlsx', D25, 'A25');
xlswrite('Gallaway_intensity.xlsx', D35, 'A35');
xlswrite('Gallaway_intensity.xlsx', D50, 'A50');
xlswrite('Gallaway_intensity.xlsx', D75, 'A75');
xlswrite('Gallaway_intensity.xlsx', D100, 'A100');

%-------------------------------------------------------------------------
%-------------------------------------------------------------------------




%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISH--------\n');
```

gallaway_texture_aquaplaning.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])


%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');

% Average pavement texture depth in mm
T_02 = 0.2;
T_03 = 0.3;
T_04 = 0.4;
T_05 = 0.5;
T_06 = 0.6;
T_07 = 0.7;
T_08 = 0.8;
T_09 = 0.9;
T_10 = 1.0;
T_11 = 1.1;
T_12 = 1.2;


I = 50; % rainfall intensity in mm/h

S = [0.5:0.5:7]; % slope gradient in steps of 0.25

Length = [1:1:90]; % length of flow path in 0.5m intervals

L = Length'; % change dimension of length

m = length(S);
n = length(L);
% D = (0.103*(T^0.11)*(L^0.42)*(I^0.59))/(S^0.42)-T;
D = zeros(n,m);
D_T_02 = zeros(n,m);
D_T_03 = zeros(n,m);
D_T_04 = zeros(n,m);
D_T_05 = zeros(n,m);
D_T_06 = zeros(n,m);
D_T_07 = zeros(n,m);
D_T_08 = zeros(n,m);
D_T_09 = zeros(n,m);
D_T_10 = zeros(n,m);
D_T_11 = zeros(n,m);
D_T_12 = zeros(n,m);
```

```
T = T_02;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_02(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_02 = max(D,D_T_02);
end
end

T = T_03;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_03(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_03 = max(D,D_T_03);
end
end

T = T_04;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_04(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_04 = max(D,D_T_04);
end
end
T = T_05;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_05(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_05 = max(D,D_T_05);
end
end
T = T_06;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_06(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_06 = max(D,D_T_06);
end
end
T = T_07;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_07(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_07 = max(D,D_T_07);
end
end

T = T_08;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_08(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_08 = max(D,D_T_08);
end
```

```
end
T = T_09;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_09(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_09 = max(D,D_T_09);
end
end
T = T_10;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_10(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_10 = max(D,D_T_10);
end
end
T = T_11;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_11(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_11 = max(D,D_T_11);
end
end

T = T_12;
for j=1:m % loop for each time
for i = 1:n % loop for each x
D_T_12(i,j)= (0.103*(T^0.11)*(L(i,:)^0.42)*(I^0.59))/(S(:,j)^0.42)-T;

D_T_12 = max(D,D_T_12);
end
end



xlswrite('Gallaway_texture.xlsx', D_T_02, 'D_T_02');
xlswrite('Gallaway_texture.xlsx', D_T_03, 'D_T_03');
xlswrite('Gallaway_texture.xlsx', D_T_04, 'D_T_04');
xlswrite('Gallaway_texture.xlsx', D_T_05, 'D_T_05');
xlswrite('Gallaway_texture.xlsx', D_T_06, 'D_T_06');
xlswrite('Gallaway_texture.xlsx', D_T_07, 'D_T_07');
xlswrite('Gallaway_texture.xlsx', D_T_08, 'D_T_08');
xlswrite('Gallaway_texture.xlsx', D_T_09, 'D_T_09');
xlswrite('Gallaway_texture.xlsx', D_T_10, 'D_T_10');
xlswrite('Gallaway_texture.xlsx', D_T_11, 'D_T_11');
xlswrite('Gallaway_texture.xlsx', D_T_12, 'D_T_12');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------




%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISH--------\n');
```

RRL_intensity_aquaplaning.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp([' RRL AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])


%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');


I15 = 15; % rainfall intensity in mm/h
I25 = 25; % rainfall intensity in mm/h
I35 = 35; % rainfall intensity in mm/h
I50 = 50; % rainfall intensity in mm/h
I75 = 75; % rainfall intensity in mm/h
I100 = 100; % rainfall intensity in mm/h

S = [0.5:0.5:7]; % slope gradient in steps of 0.25
S = S/100;

Length = [1:1:90]; % length of flow path in 0.5m intervals

L = Length'; % change dimension of length

m = length(S);
n = length(L);
% D = (0.103*(T^0.11)*(L^0.42)*(I^0.59))/(S^0.42)-T;
D = zeros(n,m);
D25 = zeros(n,m);
D15 = zeros(n,m);
D35 = zeros(n,m);
D50 = zeros(n,m);
D75 = zeros(n,m);
D100 = zeros(n,m);

for j=1:m % loop for each time
for i = 1:n % loop for each x
D15(i,j)= (0.046*(L(i,:)*I15)^0.5)/(S(:,j)^(0.2));

D15 = max(D,D15);
end
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
D25(i,j)= (0.046*(L(i,:)*I25)^0.5)/(S(:,j)^(0.2));

D25 = max(D,D25);
```

```
end
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
D35(i,j)= (0.046*(L(i,:)*I35)^0.5)/(S(:,j)^(0.2));

D35 = max(D,D35);
end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
D50(i,j)= (0.046*(L(i,:)*I50)^0.5)/(S(:,j)^(0.2));

D50 = max(D,D50);
end
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
D75(i,j)= (0.046*(L(i,:)*I75)^0.5)/(S(:,j)^(0.2));

D75 = max(D,D75);
end
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
D100(i,j)= (0.046*(L(i,:)*I100)^0.5)/(S(:,j)^(0.2));

D100 = max(D,D100);
end
end



xlswrite('RRL_intensity.xlsx', D15, 'D15');
xlswrite('RRL_intensity.xlsx', D25, 'D25');
xlswrite('RRL_intensity.xlsx', D35, 'D35');
xlswrite('RRL_intensity.xlsx', D50, 'D50');
xlswrite('RRL_intensity.xlsx', D75, 'D75');
xlswrite('RRL_intensity.xlsx', D100, 'D100');




%-----------------------------------------------------------------------
%-----------------------------------------------------------------------




%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISH--------\n');
```

Time_of_concentration_1.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])


%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');


I15 = 15; % rainfall intensity in mm/h
I25 = 25; % rainfall intensity in mm/h
I35 = 35; % rainfall intensity in mm/h
I50 = 50; % rainfall intensity in mm/h
I75 = 75; % rainfall intensity in mm/h
I100 = 100; % rainfall intensity in mm/h
mannings = 0.011;
S = [0.5:0.5:7]; % slope gradient in steps of 0.25
S = S/100;

Length = [1:1:90]; % length of flow path in 0.5m intervals

L = Length'; % change dimension of length

m = length(S);
n = length(L);
% D = (0.103*(T^0.11)*(L^0.42)*(I^0.59))/(S^0.42)-T;
Tc = zeros(n,m);
Tc25 = zeros(n,m);
Tc15 = zeros(n,m);
Tc35 = zeros(n,m);
Tc50 = zeros(n,m);
Tc75 = zeros(n,m);
Tc100 = zeros(n,m);

for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc15(i,j)= (6.94/I15^0.4)*(((mannings*(L(i,:)))/(S(:,j)^0.5))^0.6);

end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc25(i,j)= (6.94/I25^0.4)*(((mannings*(L(i,:)))/(S(:,j)^0.5))^0.6);

end
```

```
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc35(i,j)= (6.94/I35^0.4)*(((mannings*(L(i,:)))/(S(:,j)^0.5))^0.6);

end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc50(i,j)= (6.94/I50^0.4)*(((mannings*(L(i,:)))/(S(:,j)^0.5))^0.6);

end
end

for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc75(i,j)= (6.94/I75^0.4)*(((mannings*(L(i,:)))/(S(:,j)^0.5))^0.6);

end
end
for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc100(i,j)= (6.94/I100^0.4)*(((mannings*(L(i,:)))/(S(:,j)^0.5))^0.6);

end
end


xlswrite('Time_of_concentration.xlsx', Tc15, 'Tc_I15');
xlswrite('Time_of_concentration.xlsx', Tc25, 'Tc_I25');
xlswrite('Time_of_concentration.xlsx', Tc35, 'Tc_I35');
xlswrite('Time_of_concentration.xlsx', Tc50, 'Tc_I50');
xlswrite('Time_of_concentration.xlsx', Tc75, 'Tc_I75');
xlswrite('Time_of_concentration.xlsx', Tc100, 'Tc_I110');


%---------------------------------------------------------------------------
%---------------------------------------------------------------------------




%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISH--------\n');
```

Time_of_concentration_2.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])


%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');


mannings = 0.011;
S = [0.5:0.5:7]; % slope gradient in steps of 0.5
S = S/100;
Length = [1:1:90]; % length of flow path in 1.0m intervals

L = Length'; % change dimension of length

m = length(S);
n = length(L);
% D = (0.103*(T^0.11)*(L^0.42)*(I^0.59))/(S^0.42)-T;
Tc_oakden = zeros(n,m);

for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc_oakden(i,j)= (500*mannings*L(i,:)^(2/3))*(S(:,j)^(-1/3));

end
end

Tc_oakden = Tc_oakden/60;

xlswrite('Time_of_concentration_oakden.xlsx', Tc_oakden, 'Tc_oakden');

%--------------------------------------------------------------------------
%--------------------------------------------------------------------------




%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISH--------\n');
```

Time_of_concentration_3.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])

 %%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');

 hortons = 0.011;
S = [0.5:0.5:7]; % slope gradient in steps of 0.5

Length = [1:1:90]; % length of flow path in 1.0m intervals

L = Length'; % change dimension of length

m = length(S);
n = length(L);
% D = (0.103*(T^0.11)*(L^0.42)*(I^0.59))/(S^0.42)-T;
Tc_friend = zeros(n,m);

for j=1:m % loop for each time
for i = 1:n % loop for each x
Tc_friend(i,j)= (107*hortons*(L(i,:)^0.333))/(S(:,j)^0.2);


end
end

%(107*hortons*L(i,:)^(2/3))/(S(:,j)^0.2);
%tc_test = (107*hortons*(L(i,:)^0.333))/(S(:,j)^0.2);


xlswrite('Time_of_concentration_friend.xlsx', Tc_friend, 'Tc_friend');

%-------------------------------------------------------------------------
%-------------------------------------------------------------------------




%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISH--------\n');
```

Kinematic_wave_index.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])


%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');


x_step = 1;
Length = [0:x_step:90]; % length of flow path in 1.0m intervals
L = Length'; % change dimension of length

t_step = 1;
minutes = 30;
seconds = minutes * 60;
Time = [0:t_step:seconds];
Time = Time';

Mn = 0.011;


m = length(L);
n = length(Time);

fprintf('\ninputting slope matrices\n');
slope_matrices

fprintf('\ninputting storm intensity data\n');
intensity_data

%---------------------------------------------------------------------------
%---------------------------------------------------------------------------
fprintf('\nrunning intensity 15mm/hr storm\n');
Kinematic_wave_intensity_15

fprintf('\nrunning intensity 15mm/hr storm\n');
Kinematic_wave_intensity_25

fprintf('\nrunning intensity 15mm/hr storm\n');
Kinematic_wave_intensity_35

fprintf('\nrunning intensity 50mm/hr storm\n');
Kinematic_wave_intensity_50
```

```
fprintf('\nrunning intensity 75mm/hr storm\n');
Kinematic_wave_intensity_75

fprintf('\nrunning intensity 100mm/hr storm\n');
Kinematic_wave_intensity_100
%



%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISHED CALCULATIONS--------\n');
fprintf('\n------END--------\n');
```

slope_matrices.m

```
%file to create slope matrices

grade1 = 0.01;
grade2 = 0.02;
grade3 = 0.03;
grade4 = 0.04;
grade5 = 0.05;
grade6 = 0.06;
grade7 = 0.07;

S1 = [1:m];
S1 = S1';
for i = 1:m
    S1(i,1) = grade1;
end
S2 = [1:m];
S2 = S2';
for i = 1:m
    S2(i,1) = grade2;
end
S3 = [1:m];
S3 = S3';
for i = 1:m
    S3(i,1) = grade3;
end
S4 = [1:m];
S4 = S4';
for i = 1:m
    S4(i,1) = grade4;
end
S5 = [1:m];
S5 = S5';
for i = 1:m
    S5(i,1) = grade5;
end
S6 = [1:m];
S6 = S6';
for i = 1:m
    S6(i,1) = grade6;
end
S7 = [1:m];
S7 = S7';
for i = 1:m
    S7(i,1) = grade7;
end
```

intensity_data.m

```
% file for storm intensity data

storm0 = 0;
storm15 = 15/60/60/1000; % rainfall intensity in m/s
storm25 = 25/60/60/1000; % rainfall intensity in m/s
storm35 = 35/60/60/1000; % rainfall intensity in m/s
storm50 = 50/60/60/1000; % rainfall intensity in m/s
storm75 = 75/60/60/1000; % rainfall intensity in m/s
storm100 = 100/60/60/1000; % rainfall intensity in m/s



I15 = [1:n];
for i = 1:n
    I15(1,i) = storm15;
end
I25 = [1:n];
for i = 1:n
    I25(1,i) = storm25;
end
I35 = [1:n];
for i = 1:n
    I35(1,i) = storm35;
end
I50 = [1:n];
for i = 1:n
    I50(1,i) = storm50;
end
I75 = [1:n];
for i = 1:n
    I75(1,i) = storm75;
end
I100 = [1:n];
for i = 1:n
    I100(1,i) = storm100;
end
```

Kinematic_wave_intensity_15.m

```
disp(' ')
disp(['RUNNING CALCULATIONS - INTENSITY 15MM/HR',])
disp(' ')


I = I15;% INTENSITY TO BE 15mm/hr
%--------------------------------------------------------------------------
%calculation to be run for 1% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S1(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth1 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth1, 'Depth with 1%
grade');
%--------------------------------------------------------------------------
%--------------------------------------------------------------------------
%calculation to be run for 2% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S2(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth2 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth2, 'Depth with 2%
grade');
%---------------------------------------------------------------------------
%---------------------------------------------------------------------------
%calculation to be run for 3% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S3(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth3 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth3, 'Depth with 3%
grade');
%---------------------------------------------------------------------------
%---------------------------------------------------------------------------
%calculation to be run for 4% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S4(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth4 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth4, 'Depth with 4%
grade');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------
%calculation to be run for 5% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S5(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth5 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth5, 'Depth with 5%
grade');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------
%calculation to be run for 6% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
```

```
Vp(i,j+1) = (1/Mn)*(S6(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth6 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth6, 'Depth with 6%
grade');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------
%calculation to be run for 7% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S7(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth7 = Yp*1000;

xlswrite('Kinematic_wave_intensity15mm.xlsx',flow_depth7, 'Depth with 7%
grade');
%-------------------------------------------------------------------------
disp(['finished running 15mm/hr storm',])
```

Kinematic_wave_intensity_25.m

```
disp(' ')
disp(['RUNNING CALCULATIONS - INTENSITY 25MM/HR',])
disp(' ')


I = I25;% INTENSITY TO BE 25mm/hr
%---------------------------------------------------------------------------
%calculation to be run for 1% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S1(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth1 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth1, 'Depth with 1%
grade');
%---------------------------------------------------------------------------
%---------------------------------------------------------------------------
%calculation to be run for 2% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S2(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth2 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth2, 'Depth with 2%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 3% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S3(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth3 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth3, 'Depth with 3%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 4% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S4(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth4 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth4, 'Depth with 4%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 5% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S5(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth5 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth5, 'Depth with 5%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 6% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
```

```
Vp(i,j+1) = (1/Mn)*(S6(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth6 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth6, 'Depth with 6%
grade');
%------------------------------------------------------------------------
%------------------------------------------------------------------------
%calculation to be run for 7% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S7(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth7 = Yp*1000;

xlswrite('Kinematic_wave_intensity25mm.xlsx',flow_depth7, 'Depth with 7%
grade');
%------------------------------------------------------------------------
disp(['finished running 25mm/hr storm',])
```

Kinematic_wave_intensity_35.m

```
disp(' ')
disp(['RUNNING CALCULATIONS - INTENSITY 35MM/HR',])
disp(' ')


I = I35;% INTENSITY TO BE 35mm/hr
%-----------------------------------------------------------------------
%calculation to be run for 1% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S1(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth1 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth1, 'Depth with 1%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 2% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S2(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth2 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth2, 'Depth with 2%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 3% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S3(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth3 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth3, 'Depth with 3%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 4% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S4(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth4 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth4, 'Depth with 4%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 5% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S5(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth5 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth5, 'Depth with 5%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 6% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
```

```
Vp(i,j+1) = (1/Mn)*(S6(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth6 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth6, 'Depth with 6%
grade');
%------------------------------------------------------------------------
%------------------------------------------------------------------------
%calculation to be run for 7% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S7(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth7 = Yp*1000;

xlswrite('Kinematic_wave_intensity35mm.xlsx',flow_depth7, 'Depth with 7%
grade');
%------------------------------------------------------------------------
disp(['finished running 35mm/hr storm',])
```

Kinematic_wave_intensity_50.m

```
disp(' ')
disp(['RUNNING CALCULATIONS - INTENSITY 50MM/HR',])
disp(' ')


I = I50;% INTENSITY TO BE 50mm/hr
%-----------------------------------------------------------------------
%calculation to be run for 1% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S1(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth1 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth1, 'Depth with 1%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 2% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S2(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth2 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth2, 'Depth with 2%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 3% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S3(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth3 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth3, 'Depth with 3%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 4% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S4(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth4 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth4, 'Depth with 4%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 5% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S5(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth5 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth5, 'Depth with 5%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 6% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
```

```
Vp(i,j+1) = (1/Mn)*(S6(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth6 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth6, 'Depth with 6%
grade');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------
%calculation to be run for 7% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S7(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth7 = Yp*1000;

xlswrite('Kinematic_wave_intensity50mm.xlsx',flow_depth7, 'Depth with 7%
grade');
%-------------------------------------------------------------------------
disp(['finished running 50mm/hr storm',])
```

Kinematic_wave_intensity_75.m

```
disp(' ')
disp(['RUNNING CALCULATIONS - INTENSITY 75MM/HR',])
disp(' ')


I = I75;% INTENSITY TO BE 75mm/hr
%--------------------------------------------------------------------------
%calculation to be run for 1% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S1(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth1 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth1, 'Depth with 1%
grade');
%--------------------------------------------------------------------------
%--------------------------------------------------------------------------
%calculation to be run for 2% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S2(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth2 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth2, 'Depth with 2%
grade');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------
%calculation to be run for 3% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S3(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth3 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth3, 'Depth with 3%
grade');
%-------------------------------------------------------------------------
%-------------------------------------------------------------------------
%calculation to be run for 4% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S4(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth4 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth4, 'Depth with 4%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 5% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S5(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth5 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth5, 'Depth with 5%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 6% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
```

```
Vp(i,j+1) = (1/Mn)*(S6(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth6 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth6, 'Depth with 6%
grade');
%--------------------------------------------------------------------------
%--------------------------------------------------------------------------
%calculation to be run for 7% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S7(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth7 = Yp*1000;

xlswrite('Kinematic_wave_intensity75mm.xlsx',flow_depth7, 'Depth with 7%
grade');
%--------------------------------------------------------------------------
disp(['finished running 75mm/hr storm',])
```

Kinematic_wave_intensity_100.m

```
disp(' ')
disp(['RUNNING CALCULATIONS - INTENSITY 100MM/HR',])
disp(' ')


I = I100;% INTENSITY TO BE 100mm/hr
%--------------------------------------------------------------------------
%calculation to be run for 1% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S1(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth1 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth1, 'Depth with 1%
grade');
%--------------------------------------------------------------------------
%--------------------------------------------------------------------------
%calculation to be run for 2% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S2(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth2 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth2, 'Depth with 2%
grade');
%------------------------------------------------------------------------
%------------------------------------------------------------------------
%calculation to be run for 3% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S3(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth3 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth3, 'Depth with 3%
grade');
%------------------------------------------------------------------------
%------------------------------------------------------------------------
%calculation to be run for 4% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S4(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);
```

```
Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth4 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth4, 'Depth with 4%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 5% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S5(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth5 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth5, 'Depth with 5%
grade');
%-----------------------------------------------------------------------------
%-----------------------------------------------------------------------------
%calculation to be run for 6% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
```

```
Vp(i,j+1) = (1/Mn)*(S6(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth6 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth6, 'Depth with 6%
grade');
%-----------------------------------------------------------------------
%-----------------------------------------------------------------------
%calculation to be run for 7% grade
Yp = zeros(m,n);
Vp = zeros(m,n);
Qp = zeros(m,n);
Cp = zeros(m,n);

for i=1:m
    for j=1:n+1
        Cp(i,j) = t_step;
    end
end


for i=2:m % loop for each time
for j = 1:n % loop for each x
Yp(i,j+1) = t_step*(I(1,j) - ((Qp(i,j)- Qp(i-1,j))/x_step)) +Yp(i,j);
Vp(i,j+1) = (1/Mn)*(S7(i,1)^0.5)*(Yp(i,j+1)^(2/3));
Qp(i,j+1) = Vp(i,j+1)*Yp(i,j+1);


Cp(i,j+1) = x_step/(Vp(i,j+1)+(9.81*Yp(i,j+1))^0.5);
end
end

flow_depth7 = Yp*1000;

xlswrite('Kinematic_wave_intensity100mm.xlsx',flow_depth7, 'Depth with 7%
grade');
%-----------------------------------------------------------------------
disp(['finished running 100mm/hr storm',])
```

Kinematic_wave_design_storm.m

```
%%
% Clear the workspace.
clc
clear all
close all
% insert header to the top of the command window
disp(' ')
disp(['==========================================',])
disp(' ')
disp(['AQUAPLANING CALCULATIONS - CREATED BY LIAM SHERIDAN',])
disp(' ')
disp(['==========================================',])



%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\nProcessing data please wait...\n');



% Allows user to choose whether to run with the standard inputs or select
% their own values
display('Please enter input values on the left hand menu')
display('for ease of simulation choose default values')

x_step = 1;
choice = menu('Choose a flow path length','Default 90 meters','Other');
if choice == 1;
    l = 90;
else choice = 2;
    l=input('Please enter flow path length in meters = ');%
end



Length = [0:x_step:l]; % length of flow path in 1.0m intervals
L = Length'; % change dimension of length



%%

choice = menu('Choose a time for analysis','Default 30 minutes','Other');
if choice == 1;
    minutes = 30;
else choice = 2;
    minutes=input('Please enter time for analysis in minutes ');%
end

choice = menu('Choose a storm duration','Default 30 minutes','Other');
if choice == 1;
    duration = 30;
else choice = 2;
    duration=input('Please enter storm duration in minutes ');%
end



t_step = 1;
minutes = 30;
```

```
seconds = minutes * 60;
Time = [0:t_step:seconds];
Time = Time';
duration = duration  *60;
storm_duration = [0:t_step:duration];
storm_duration = storm_duration';

m = length(L);
n = length(Time);
p = length(storm_duration);
choice = menu('Choose rainfall intensity','Default 50mm','Other');
if choice == 1;
    Intensity = 50;
else choice = 2;
    Intensity=input('Please enter rainfall intensity in mm/hr =  ');%
end

storm_I = Intensity/60/60/1000; % rainfall intensity in m/s

I = [1:n];
for i = 1:n
    I(1,i) = 0;
end

for i = 1:p
    I(1,i) = storm_I;
end


choice = menu('Choose a mannings value','Default 0.011','Other');
if choice == 1;
    Mn = 0.011;
else choice = 2;
    Mn=input('Please enter mannings value =  ');%
end

%file to create slope matrices

choice = menu('Choose a longitudinal grade','Default 0.03','Other');
if choice == 1;
    grade = 0.03;
else choice = 2;
    grade=input('Please enter longitudinal grade as a decimal ie m/m =  ');%
end

S = [1:m];
S = S';
for i = 1:m
    S(i,1) = grade;
end



%------------------------------------------------------------------------
%------------------------------------------------------------------------
fprintf('\nrunning design storm...\n');
fprintf('\nplease wait...\n');
Kinematic_wave_calculation
```

```
%%
% Calculate the depth of flow using the Gallaway method for vaying slope and
lengths.
fprintf('\n------FINISHED CALCULATIONS--------\n');
fprintf('\n------END--------\n');
```

Appendix C - Rainfall data

Intensity – Frequency – Duration tables for locations around NSW

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	101	129	163	183	209	243	269
6Mins	94.3	121	153	172	196	228	252
10Mins	77.2	99.1	127	142	164	191	212
20Mins	56.6	73.1	94.8	107	124	146	163
30Mins	46	59.7	78	88.8	103	122	136
1Hr	31.2	40.5	53.5	61.2	71.2	84.4	94.5
2Hrs	20.3	26.4	34.9	39.9	46.5	55.1	61.8
3Hrs	15.6	20.3	26.7	30.6	35.6	42.2	47.3
6Hrs	9.9	12.8	16.9	19.2	22.3	26.4	29.6
12Hrs	6.34	8.21	10.7	12.2	14.2	16.8	18.7
24Hrs	4.12	5.33	6.98	7.95	9.22	10.9	12.2
48Hrs	2.64	3.42	4.49	5.12	5.94	7.02	7.85
72Hrs	1.97	2.55	3.33	3.8	4.41	5.21	5.82

IFD table - Sydney NSW

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	83.7	107	136	152	174	203	224
6Mins	78.4	101	128	143	164	190	211
10Mins	64.2	82.2	104	117	134	156	173
20Mins	46.9	60	76.1	85.3	97.5	113	126
30Mins	38.1	48.9	61.9	69.4	79.3	92.3	102
1Hr	25.8	33.2	42.2	47.4	54.2	63.2	70
2Hrs	16.9	21.8	27.9	31.5	36.2	42.4	47.1
3Hrs	13.1	16.8	21.8	24.7	28.5	33.4	37.2
6Hrs	8.38	10.8	14.2	16.2	18.8	22.2	24.9
12Hrs	5.43	7.06	9.35	10.7	12.5	14.8	16.7
24Hrs	3.57	4.66	6.2	7.12	8.31	9.89	11.1
48Hrs	2.33	3.04	4.04	4.64	5.41	6.45	7.24
72Hrs	1.76	2.29	3.05	3.51	4.1	4.89	5.5

IFD table - Parramatta NSW

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	103	130	159	176	199	229	252
6Mins	95.9	122	149	165	186	215	236
10Mins	78.5	99.5	122	135	152	176	193
20Mins	57.6	72.9	89	98.1	111	127	140
30Mins	46.9	59.4	72.4	79.7	90	103	114
1Hr	31.5	39.9	48.9	54	61.1	70.4	77.5
2Hrs	20.1	25.6	31.9	35.5	40.5	47	52
3Hrs	15.2	19.4	24.5	27.5	31.6	36.9	41.1
6Hrs	9.33	12.1	15.6	17.8	20.6	24.4	27.4
12Hrs	5.83	7.6	10.1	11.6	13.5	16.2	18.3
24Hrs	3.74	4.9	6.54	7.56	8.89	10.7	12.1
48Hrs	2.39	3.13	4.19	4.85	5.72	6.89	7.81
72Hrs	1.77	2.32	3.13	3.63	4.29	5.19	5.91
IFD table - Grafton NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	87.6	112	142	159	181	211	233
6Mins	82	105	133	149	170	198	219
10Mins	67	85.9	109	122	139	162	179
20Mins	49	62.7	79.5	89	102	118	131
30Mins	39.9	51.1	64.7	72.5	82.9	96.6	107
1Hr	26.9	34.5	43.9	49.3	56.4	65.8	72.9
2Hrs	17.5	22.4	28.6	32.1	36.9	43.1	47.8
3Hrs	13.4	17.2	22	24.7	28.4	33.2	36.9
6Hrs	8.46	10.9	14	15.8	18.2	21.3	23.7
12Hrs	5.42	6.99	9.04	10.2	11.8	13.9	15.5
24Hrs	3.55	4.6	6.01	6.85	7.94	9.38	10.5
48Hrs	2.31	3.01	3.99	4.58	5.34	6.36	7.15
72Hrs	1.73	2.27	3.03	3.49	4.09	4.89	5.51
IFD table - Newcastle NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	128	161	195	213	239	272	296
6Mins	120	151	183	200	225	256	278
10Mins	98.3	124	151	165	186	212	231
20Mins	72	91	112	123	138	158	173
30Mins	58.7	74.3	91.5	101	114	131	143
1Hr	39.7	50.5	62.7	69.5	78.8	90.8	99.8
2Hrs	25.7	32.8	41.1	45.8	52	60.2	66.4
3Hrs	19.7	25.1	31.6	35.3	40.3	46.7	51.6
6Hrs	12.4	15.9	20.1	22.6	25.9	30.2	33.4
12Hrs	7.95	10.2	13.1	14.8	17	19.9	22.1
24Hrs	5.28	6.81	8.81	10	11.5	13.5	15.1
48Hrs	3.52	4.56	5.96	6.79	7.87	9.3	10.4
72Hrs	2.67	3.48	4.57	5.22	6.07	7.19	8.05
IFD table - Byron Bay NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	103	133	171	193	223	261	290
6Mins	96.9	125	161	181	209	245	273
10Mins	79.3	102	133	151	174	205	229
20Mins	57.6	75	99	113	132	157	176
30Mins	46.8	61	81.3	93.6	109	131	147
1Hr	31.8	41.6	56	64.8	76	91.1	103
2Hrs	21.1	27.7	37.2	43	50.5	60.5	68.3
3Hrs	16.6	21.7	29	33.5	39.2	46.9	52.9
6Hrs	10.9	14.2	18.9	21.7	25.3	30.1	33.8
12Hrs	7.15	9.3	12.3	14.1	16.4	19.4	21.8
24Hrs	4.59	5.98	7.94	9.13	10.7	12.7	14.3
48Hrs	2.83	3.71	5.01	5.8	6.81	8.17	9.23
72Hrs	2.08	2.74	3.71	4.3	5.06	6.09	6.89
IFD table - Port Macquarie NSW							

DURATION	**1 Year**	**2 years**	**5 years**	**10 years**	**20 years**	**50 years**	**100 years**
5Mins	69.3	89.9	116	132	154	185	210
6Mins	64.5	83.7	108	123	144	172	195
10Mins	52.7	68.2	87.1	99	115	138	156
20Mins	38.7	49.7	62.6	70.6	81.6	96.7	109
30Mins	31.4	40.2	50.3	56.5	65.1	76.8	86
1Hr	21	26.8	33.2	37	42.5	49.8	55.6
2Hrs	13.4	17.1	20.9	23.3	26.6	31.1	34.6
3Hrs	10.2	12.9	15.8	17.5	20	23.3	25.9
6Hrs	6.31	8	9.72	10.8	12.2	14.2	15.8
12Hrs	3.91	4.95	6.02	6.67	7.59	8.83	9.79
24Hrs	2.4	3.06	3.77	4.2	4.82	5.64	6.29
48Hrs	1.42	1.83	2.32	2.62	3.04	3.6	4.06
72Hrs	1.02	1.31	1.68	1.92	2.24	2.67	3.03
IFD table - Tamworth NSW							

DURATION	**1 Year**	**2 years**	**5 years**	**10 years**	**20 years**	**50 years**	**100 years**
5Mins	111	141	176	196	223	258	283
6Mins	104	132	166	185	210	243	267
10Mins	85.3	109	138	155	176	205	227
20Mins	62.5	80.5	104	117	135	158	176
30Mins	50.9	65.9	85.6	97.2	112	132	148
1Hr	34.8	45.3	59.8	68.5	79.7	94.6	106
2Hrs	23.2	30.3	40.6	46.9	54.9	65.6	73.9
3Hrs	18.1	23.8	32.2	37.3	43.8	52.6	59.4
6Hrs	11.9	15.7	21.5	25.1	29.7	35.8	40.6
12Hrs	7.85	10.4	14.3	16.8	19.9	24.1	27.4
24Hrs	5.18	6.85	9.43	11	13.1	15.8	18
48Hrs	3.35	4.41	6.02	7.01	8.28	10	11.3
72Hrs	2.53	3.32	4.51	5.24	6.18	7.43	8.41
IFD table - Wollongong NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	86.1	113	150	173	203	245	278
6Mins	80.7	106	141	162	191	230	261
10Mins	66.2	86.9	116	135	159	193	219
20Mins	48.4	63.9	86.7	101	120	147	168
30Mins	39.4	52.2	71.4	83.8	99.8	122	140
1Hr	26.9	35.8	49.3	58.2	69.6	85.6	98.4
2Hrs	17.9	23.8	32.9	38.9	46.5	57.2	65.8
3Hrs	14.1	18.7	25.7	30.3	36.3	44.6	51.2
6Hrs	9.27	12.3	16.8	19.8	23.6	28.9	33.2
12Hrs	6.09	8.07	11.1	13	15.5	19	21.8
24Hrs	3.97	5.27	7.31	8.63	10.4	12.7	14.7
48Hrs	2.51	3.36	4.74	5.66	6.85	8.51	9.87
72Hrs	1.87	2.51	3.57	4.28	5.19	6.48	7.55
IFD table - Bega NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	54.6	72.1	97.7	114	136	166	190
6Mins	50.9	67.1	90.7	106	126	154	176
10Mins	41.4	54.5	73.3	85.3	101	123	141
20Mins	30.1	39.5	52.7	61.1	72.2	87.5	99.7
30Mins	24.3	31.8	42.2	48.8	57.6	69.6	79.1
1Hr	16.1	21.1	27.7	31.8	37.3	44.8	50.8
2Hrs	10.3	13.4	17.4	19.8	23.1	27.5	31
3Hrs	7.89	10.2	13.1	14.8	17.2	20.4	22.9
6Hrs	4.94	6.33	7.98	8.96	10.3	12.1	13.5
12Hrs	3.07	3.91	4.86	5.42	6.2	7.23	8.03
24Hrs	1.88	2.39	2.94	3.27	3.73	4.33	4.8
48Hrs	1.1	1.4	1.72	1.91	2.18	2.53	2.8
72Hrs	0.781	0.99	1.22	1.35	1.53	1.78	1.97
IFD table - Wagga Wagga NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	64.2	84.3	112	130	154	187	214
6Mins	59.7	78.4	104	121	143	174	199
10Mins	48.6	63.8	84.8	98.3	116	141	161
20Mins	35.5	46.5	61.8	71.6	84.4	102	117
30Mins	28.7	37.6	49.9	57.7	68.1	82.5	94.1
1Hr	19	24.8	32.7	37.8	44.5	53.8	61.2
2Hrs	11.9	15.5	20.2	23.3	27.3	32.8	37.2
3Hrs	8.88	11.5	15	17.2	20.1	24.1	27.3
6Hrs	5.35	6.92	8.9	10.1	11.8	14	15.8
12Hrs	3.24	4.19	5.33	6.04	6.99	8.3	9.32
24Hrs	1.99	2.56	3.25	3.67	4.24	5.02	5.63
48Hrs	1.19	1.54	1.95	2.2	2.54	3.01	3.37
72Hrs	0.849	1.09	1.38	1.56	1.8	2.13	2.38
IFD table - Parkes NSW							

DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	49.8	66.2	92.5	109	130	159	181
6Mins	46.1	61.3	85.8	101	121	147	168
10Mins	37.3	49.6	69.3	81.7	97.4	119	135
20Mins	27.1	35.9	50	58.9	70.1	85.4	97.4
30Mins	21.7	28.8	40.1	47.2	56.2	68.4	78
1Hr	14.1	18.7	26.1	30.7	36.6	44.5	50.8
2Hrs	8.66	11.5	16.1	19	22.7	27.7	31.6
3Hrs	6.4	8.51	12	14.1	16.9	20.7	23.6
6Hrs	3.77	5.03	7.12	8.46	10.1	12.4	14.3
12Hrs	2.23	2.98	4.24	5.05	6.08	7.48	8.59
24Hrs	1.32	1.76	2.51	3	3.61	4.45	5.12
48Hrs	0.753	1	1.44	1.72	2.07	2.55	2.93
72Hrs	0.519	0.698	1	1.2	1.44	1.78	2.05
IFD table - Broken Hill NSW							

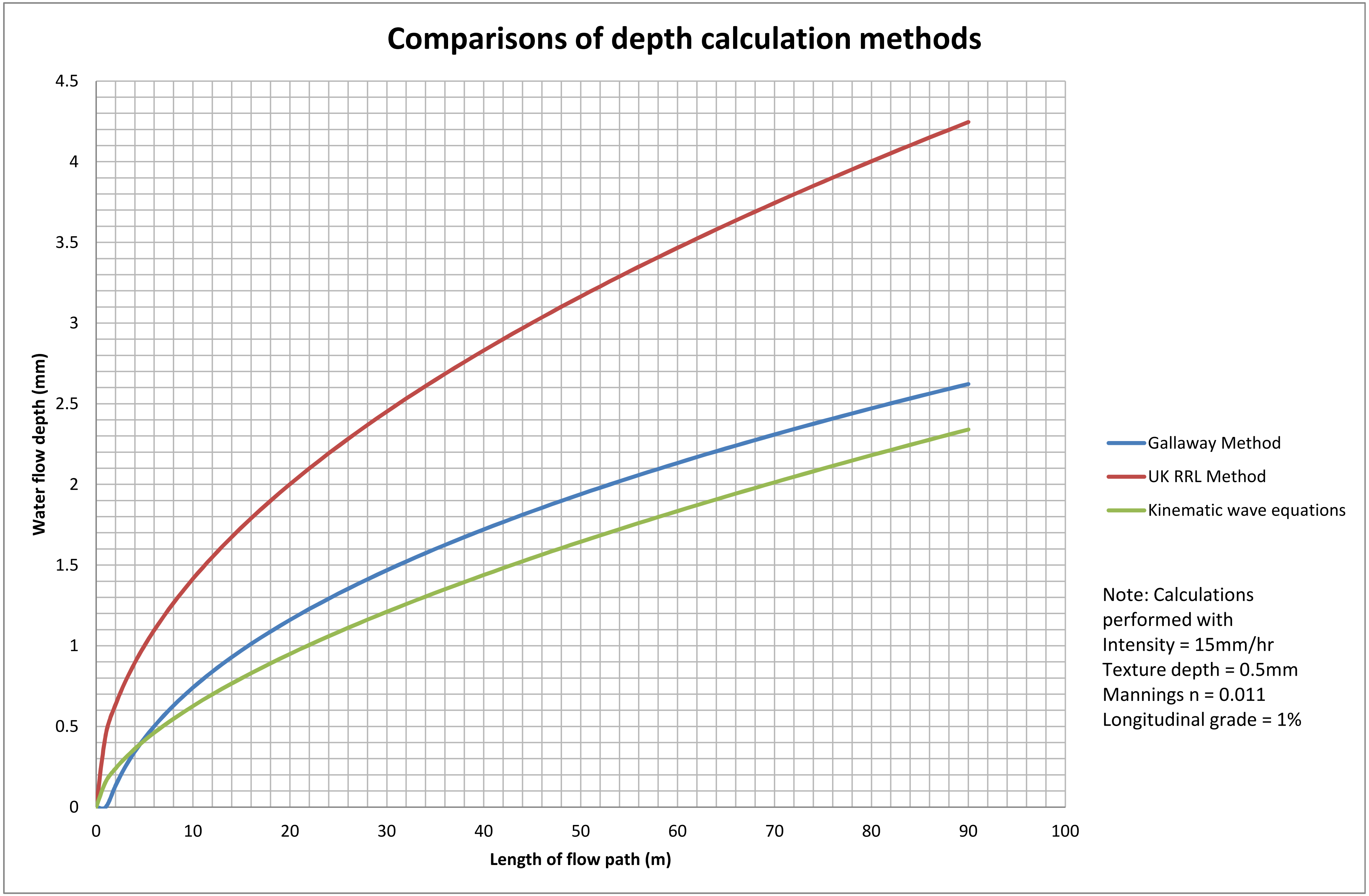
DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	66.9	88.4	120	141	168	207	238
6Mins	62.2	82.2	112	131	157	192	221
10Mins	50.7	67	91	107	128	157	181
20Mins	37.2	49.2	66.8	78.5	93.8	115	133
30Mins	30.1	39.9	54.2	63.7	76.1	93.6	108
1Hr	19.9	26.4	35.9	42.1	50.4	62	71.4
2Hrs	12.4	16.4	22.4	26.3	31.4	38.6	44.5
3Hrs	9.24	12.2	16.7	19.6	23.4	28.8	33.1
6Hrs	5.53	7.32	10	11.7	14	17.2	19.8
12Hrs	3.33	4.41	6	7.05	8.43	10.4	11.9
24Hrs	2.03	2.69	3.67	4.31	5.16	6.35	7.31
48Hrs	1.22	1.62	2.2	2.59	3.1	3.83	4.41
72Hrs	0.869	1.15	1.57	1.85	2.21	2.73	3.14

IFD Table - Walgett NSW

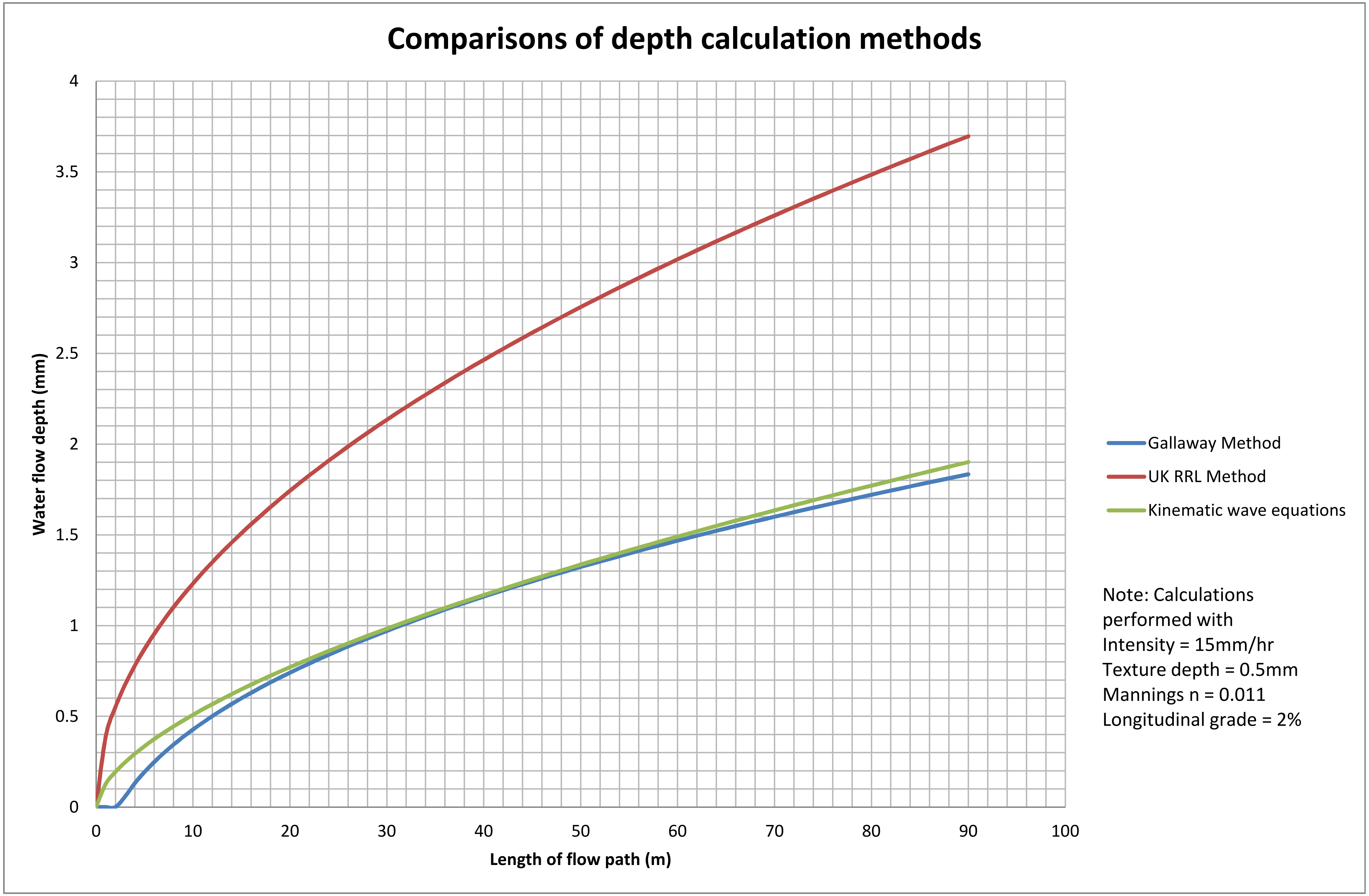
DURATION	1 Year	2 years	5 years	10 years	20 years	50 years	100 years
5Mins	48	63.7	88.9	105	125	153	176
6Mins	44.6	59.3	82.4	97.3	116	142	163
10Mins	36.1	47.9	66.4	78.2	93.2	114	130
20Mins	26	34.5	47.5	55.8	66.3	80.8	92.2
30Mins	20.9	27.6	38	44.5	52.8	64.2	73.2
1Hr	13.7	18.1	24.7	28.8	34.2	41.4	47.1
2Hrs	8.64	11.4	15.4	17.9	21.2	25.6	29
3Hrs	6.51	8.55	11.5	13.4	15.8	19.1	21.6
6Hrs	3.98	5.22	7	8.11	9.54	11.5	13
12Hrs	2.43	3.18	4.25	4.9	5.75	6.88	7.78
24Hrs	1.48	1.93	2.56	2.94	3.44	4.1	4.62
48Hrs	0.872	1.14	1.49	1.7	1.98	2.36	2.65
72Hrs	0.62	0.81	1.05	1.2	1.39	1.65	1.85

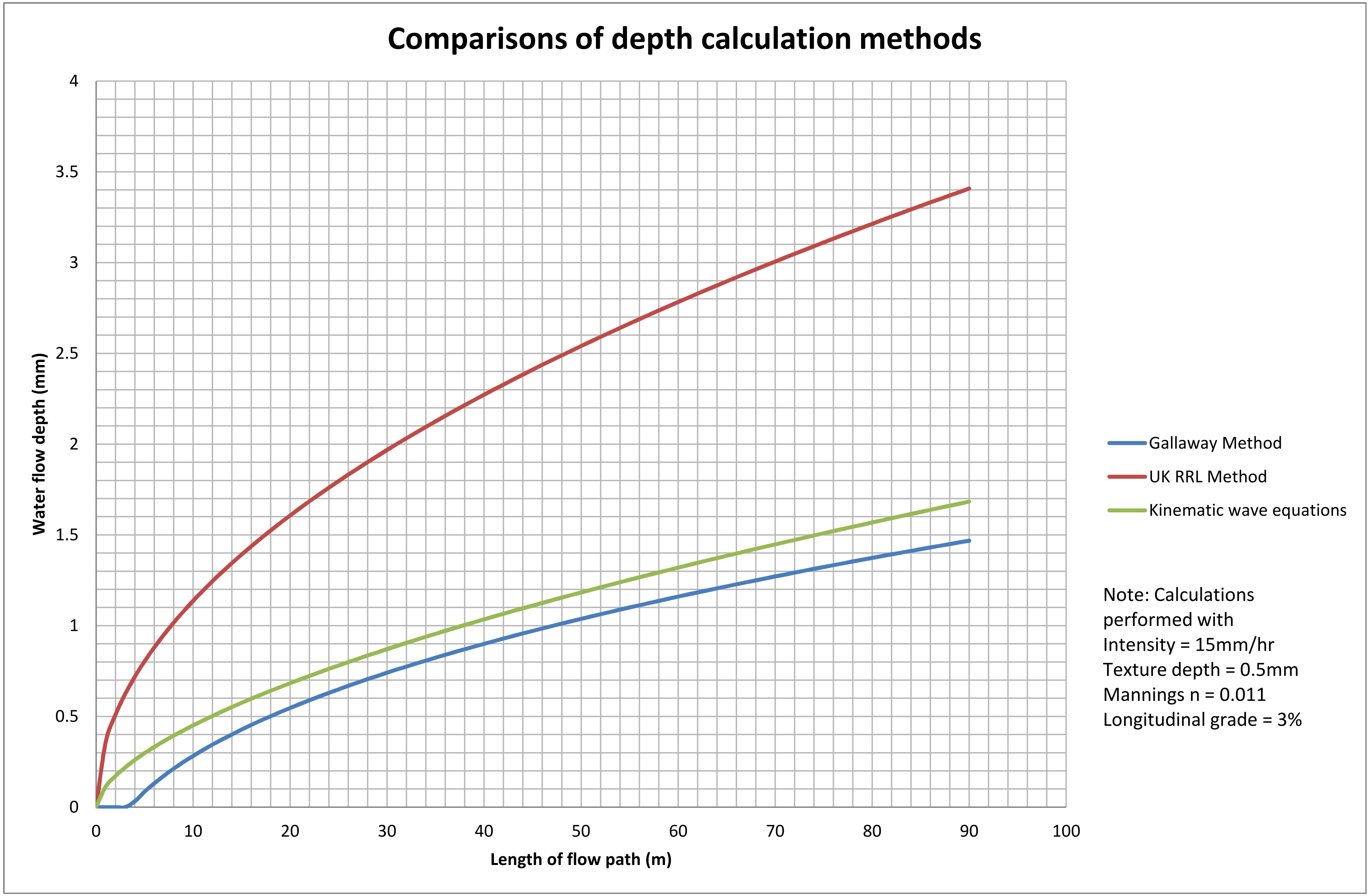
IFD table - Deniliquin NSW

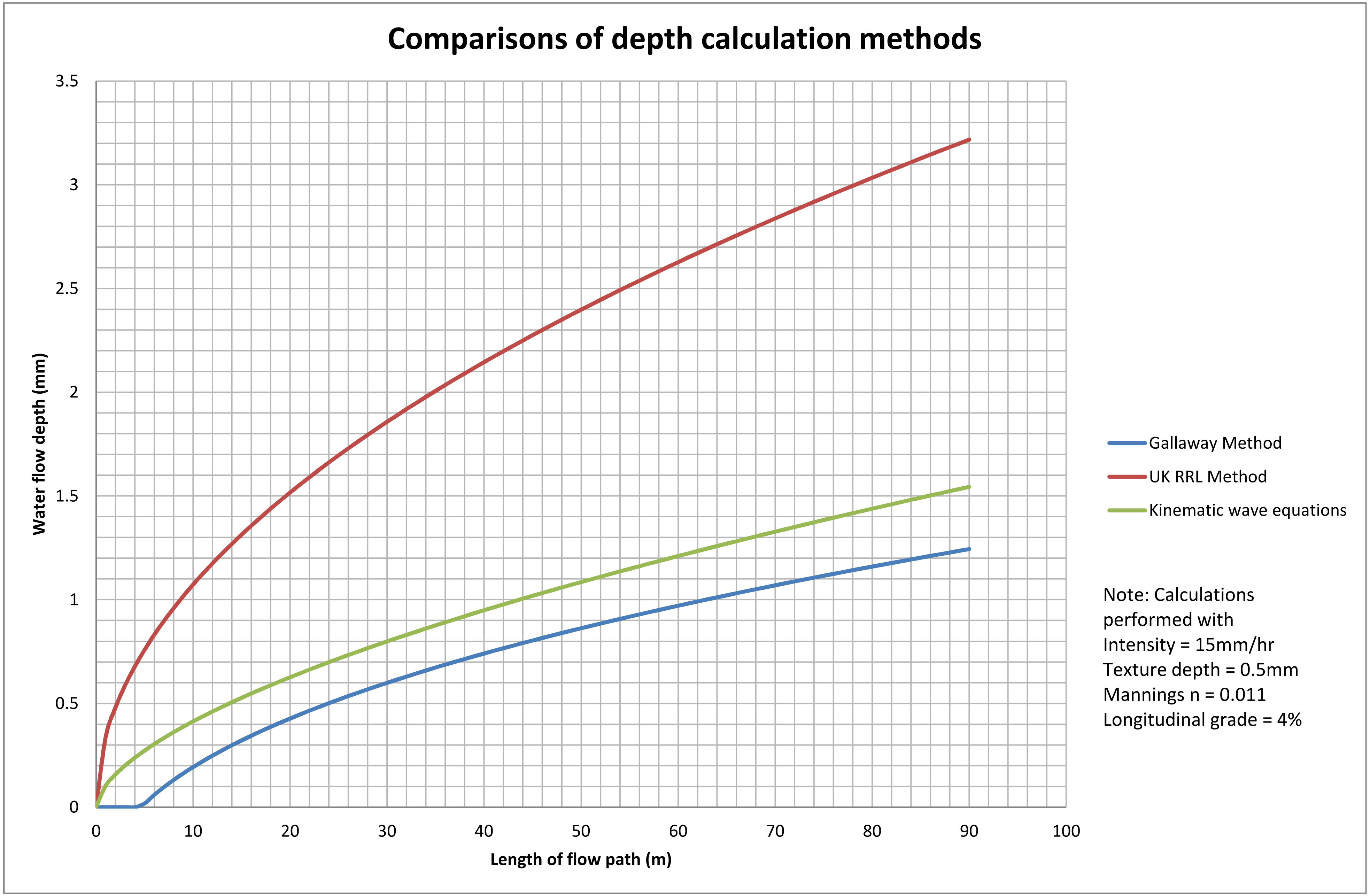
Appendix D - Comparisons of flow depth graphs



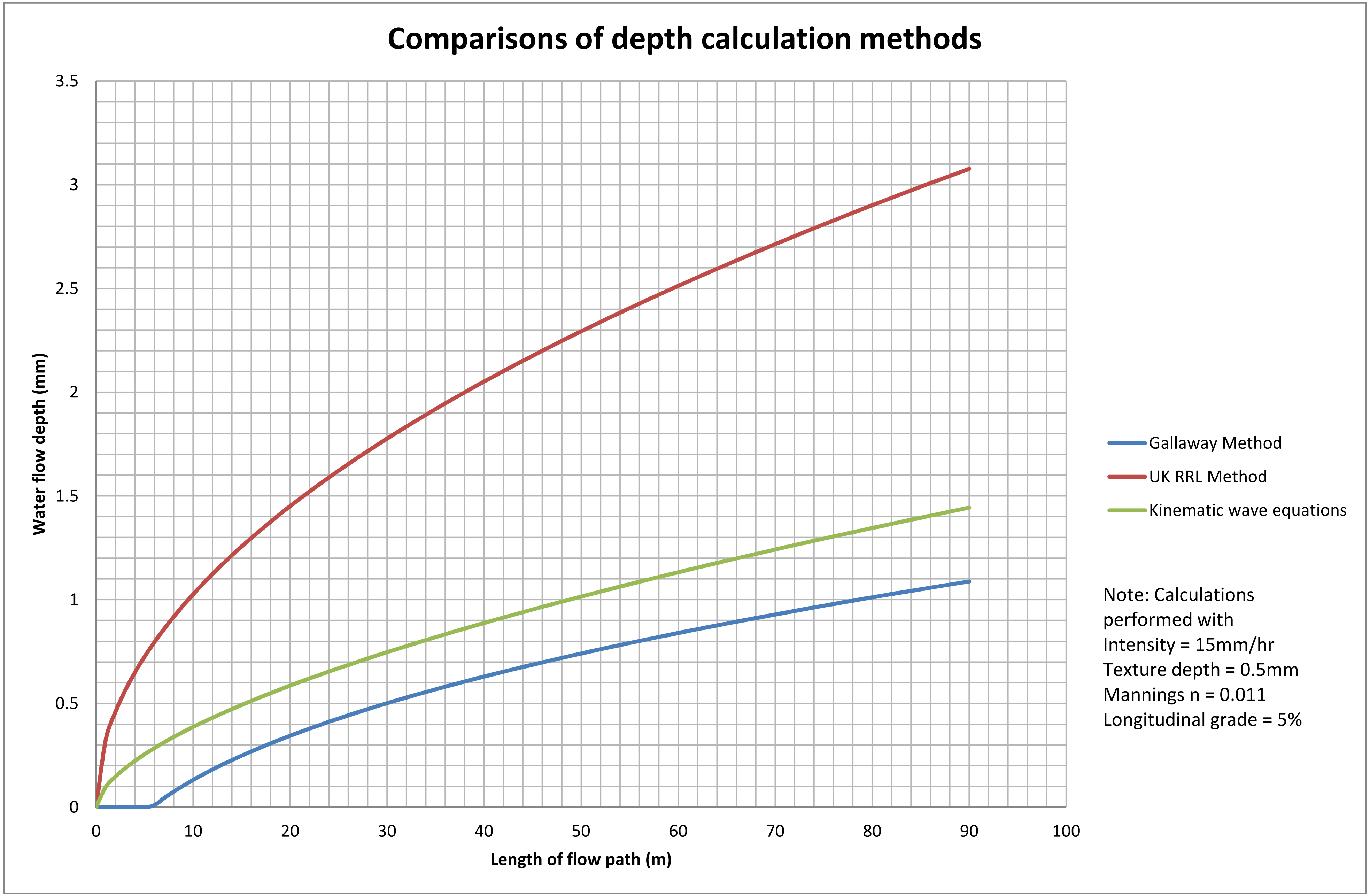
Comparisons of depth calculation methods
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Water flow depth (mm)
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations
performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 1%

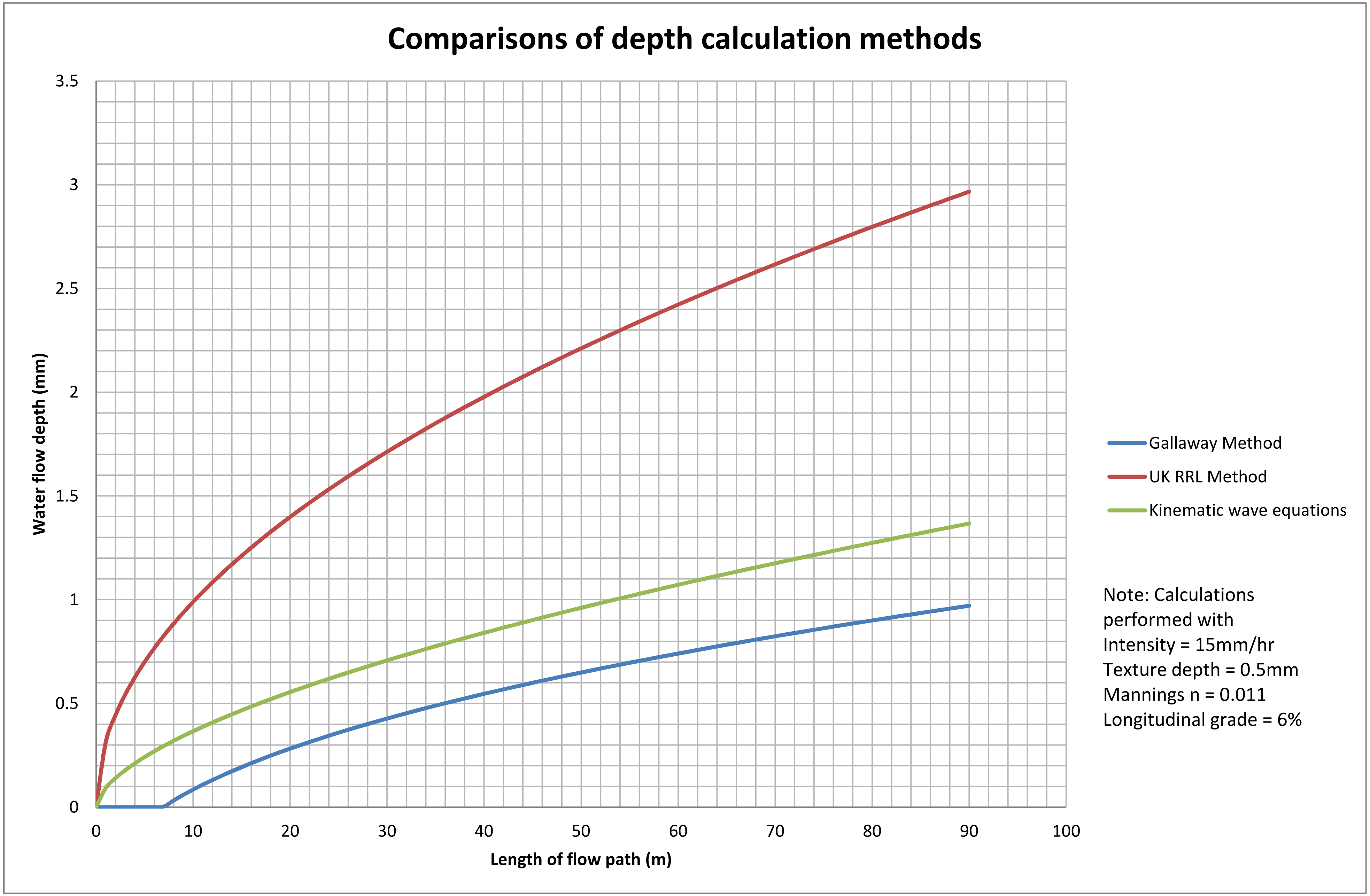

Comparisons of depth calculation methods
Water flow depth (mm)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 2%

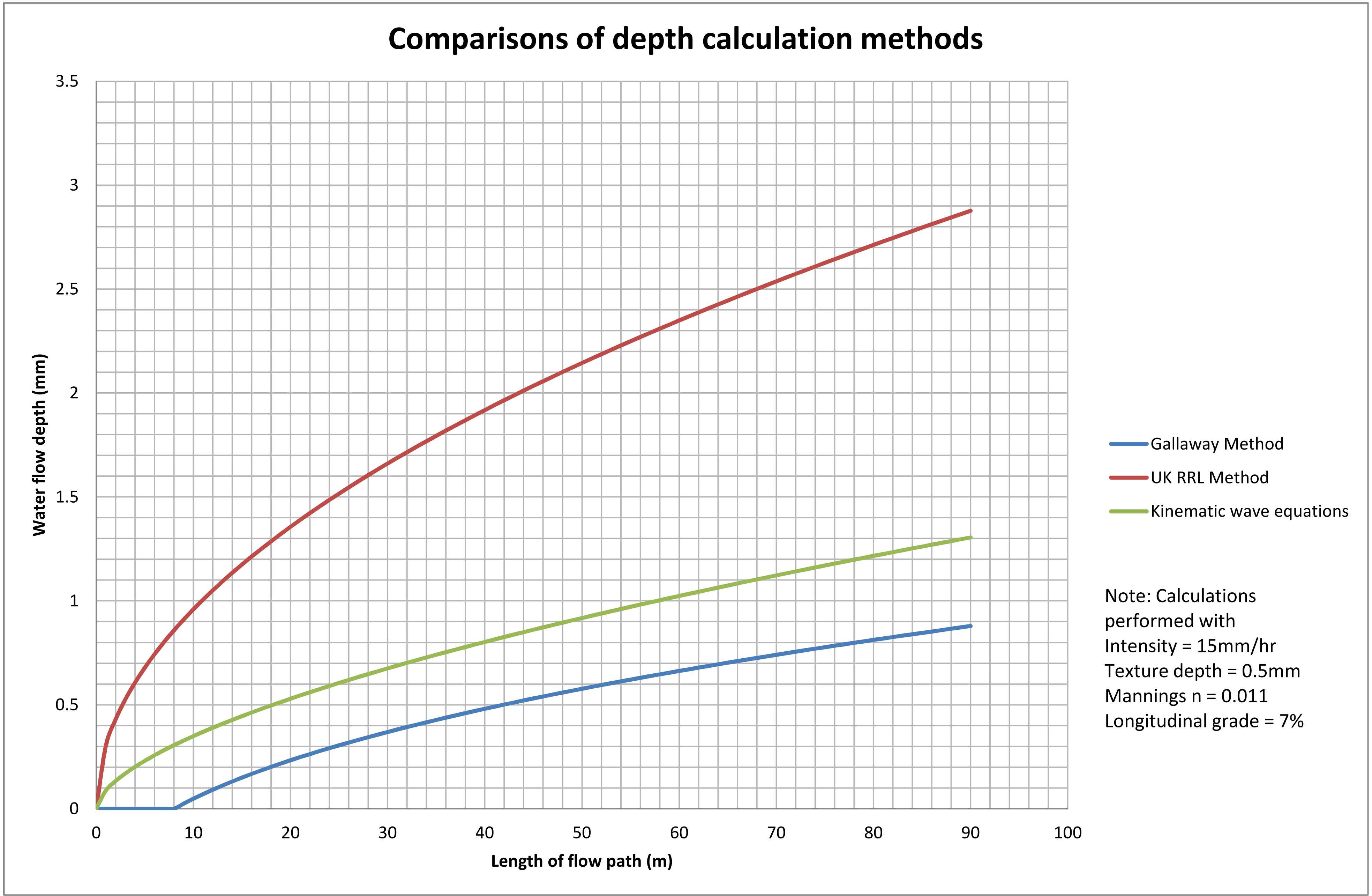

Comparisons of depth calculation methods
Water flow depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
Length of flow path (m)
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 3%

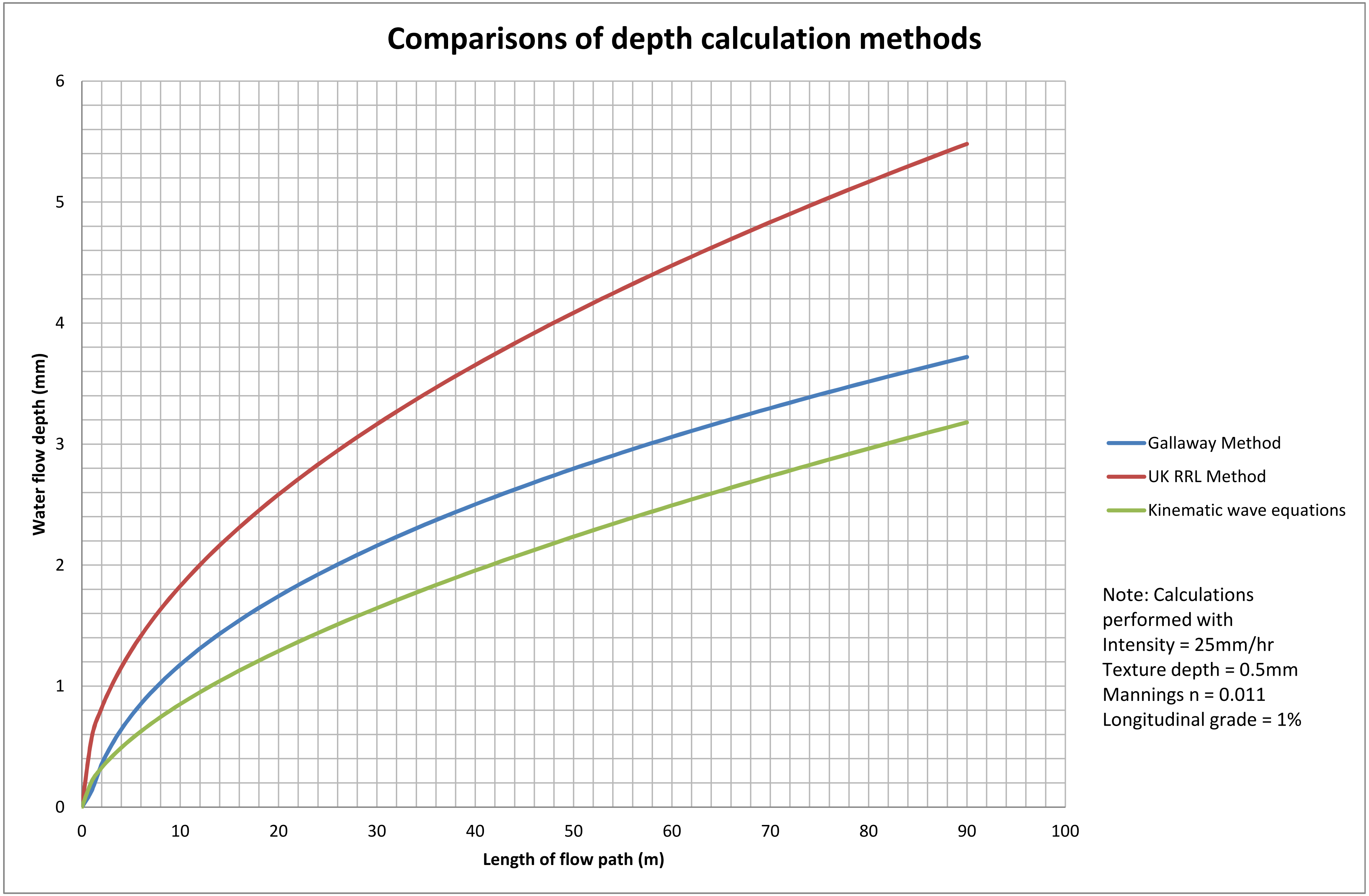


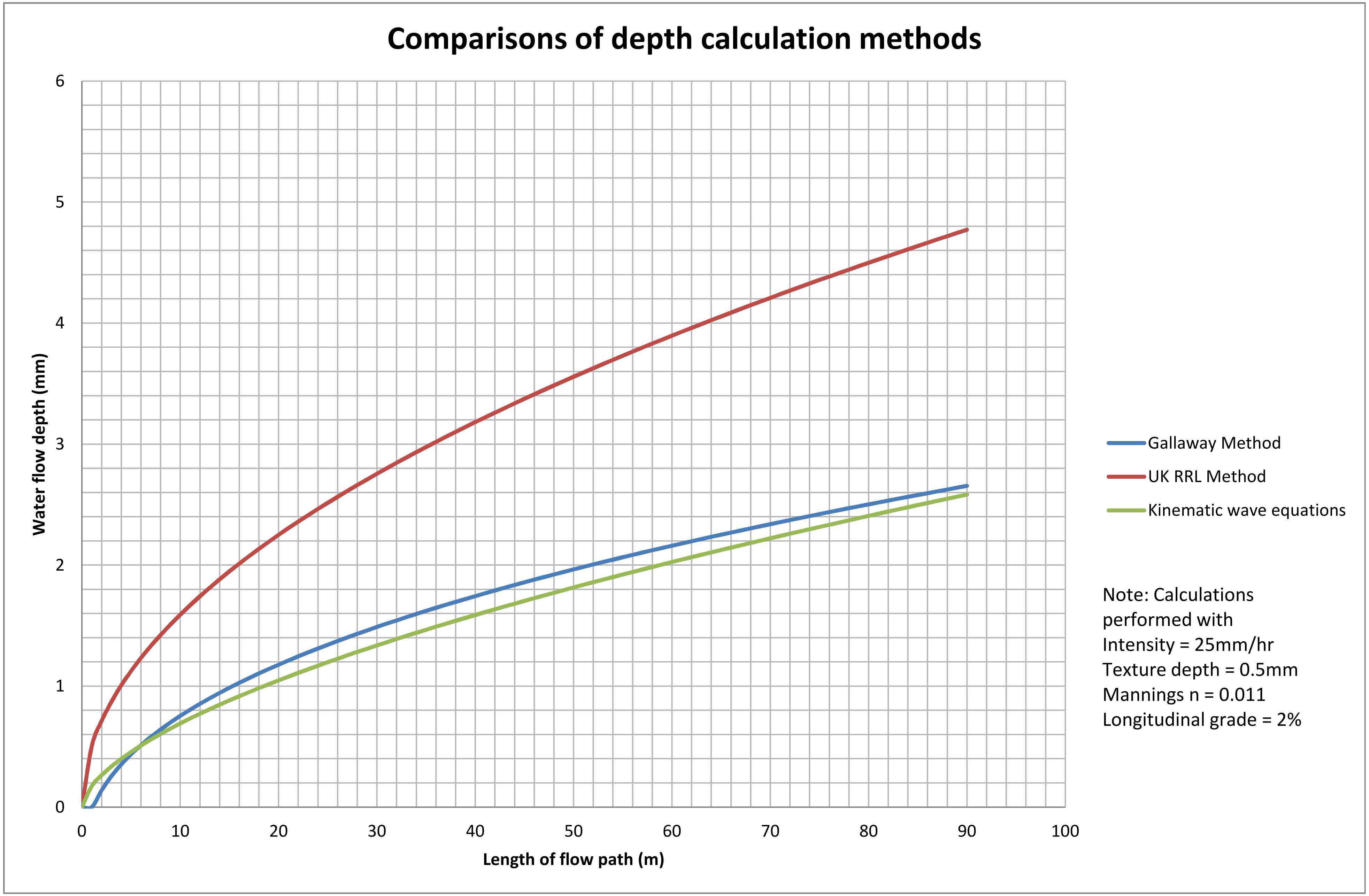
Comparisons of depth calculation methods
Water flow depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
Length of flow path (m)
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 4%

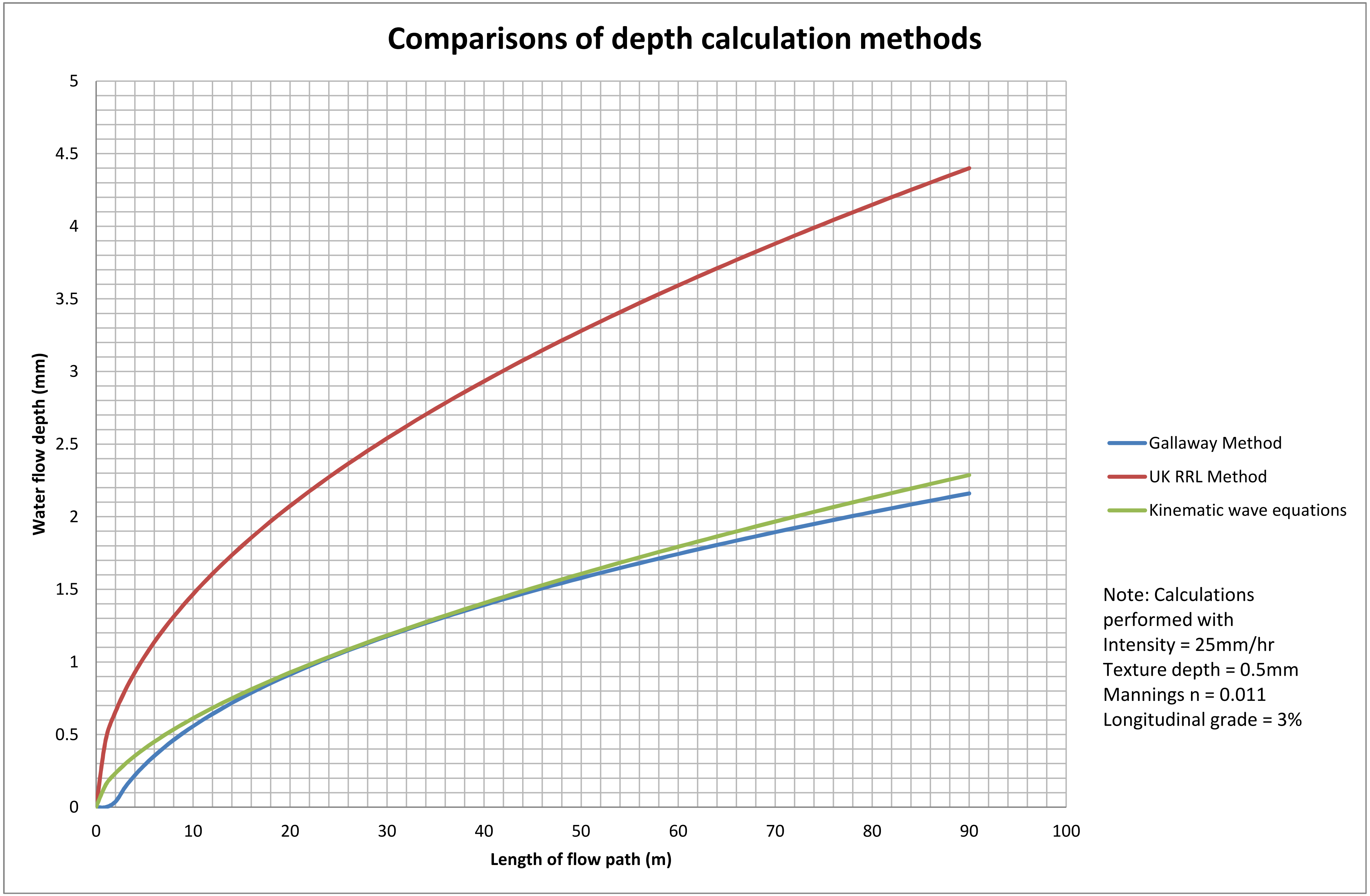

Comparisons of depth calculation methods
Water flow depth (mm)
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 5%


Comparisons of depth calculation methods
3.5
3
2.5
2
1.5
1
0.5
0
Water flow depth (mm)
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 6%

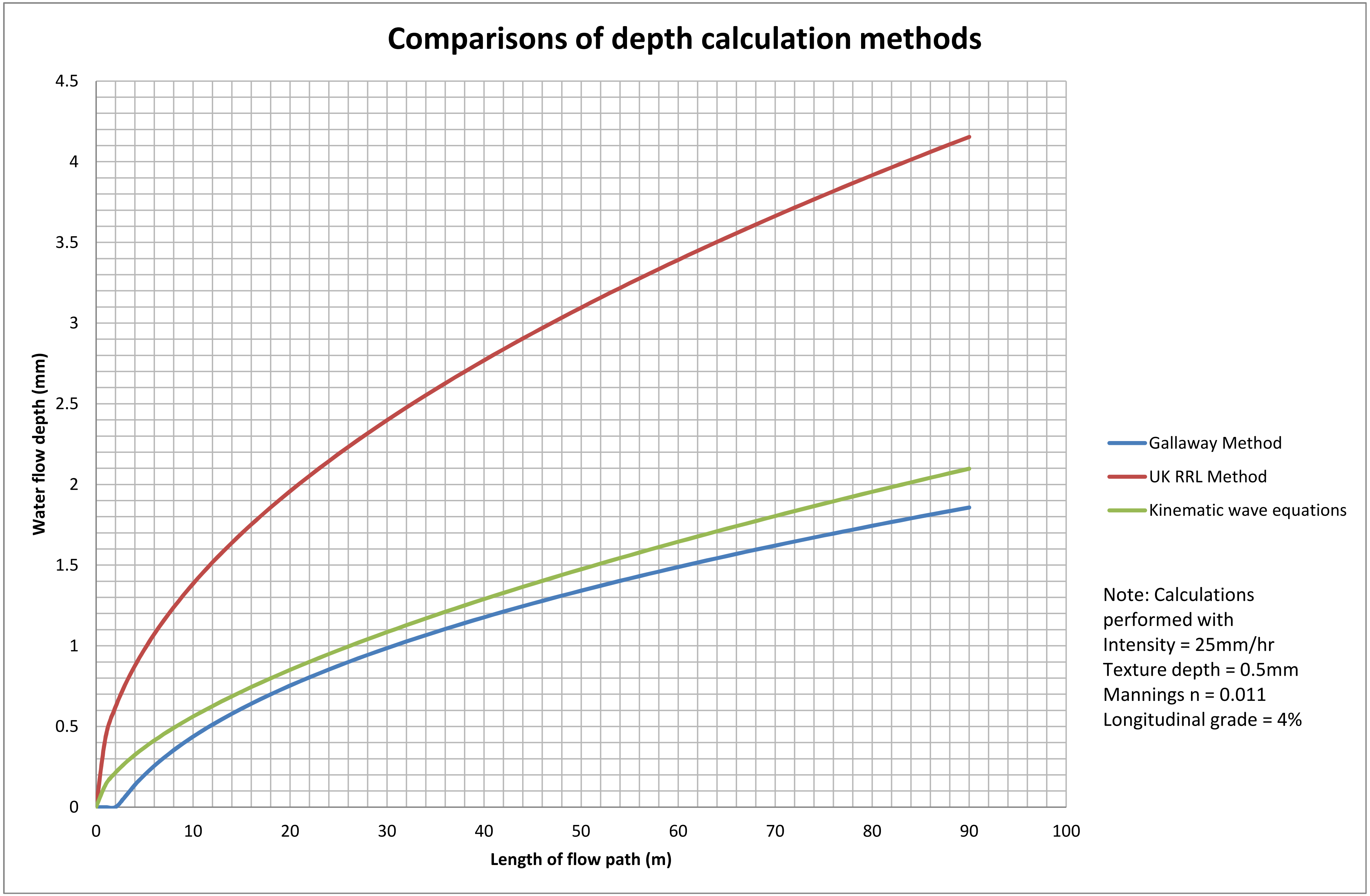

Comparisons of depth calculation methods
Water flow depth (mm)
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 15mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 7%

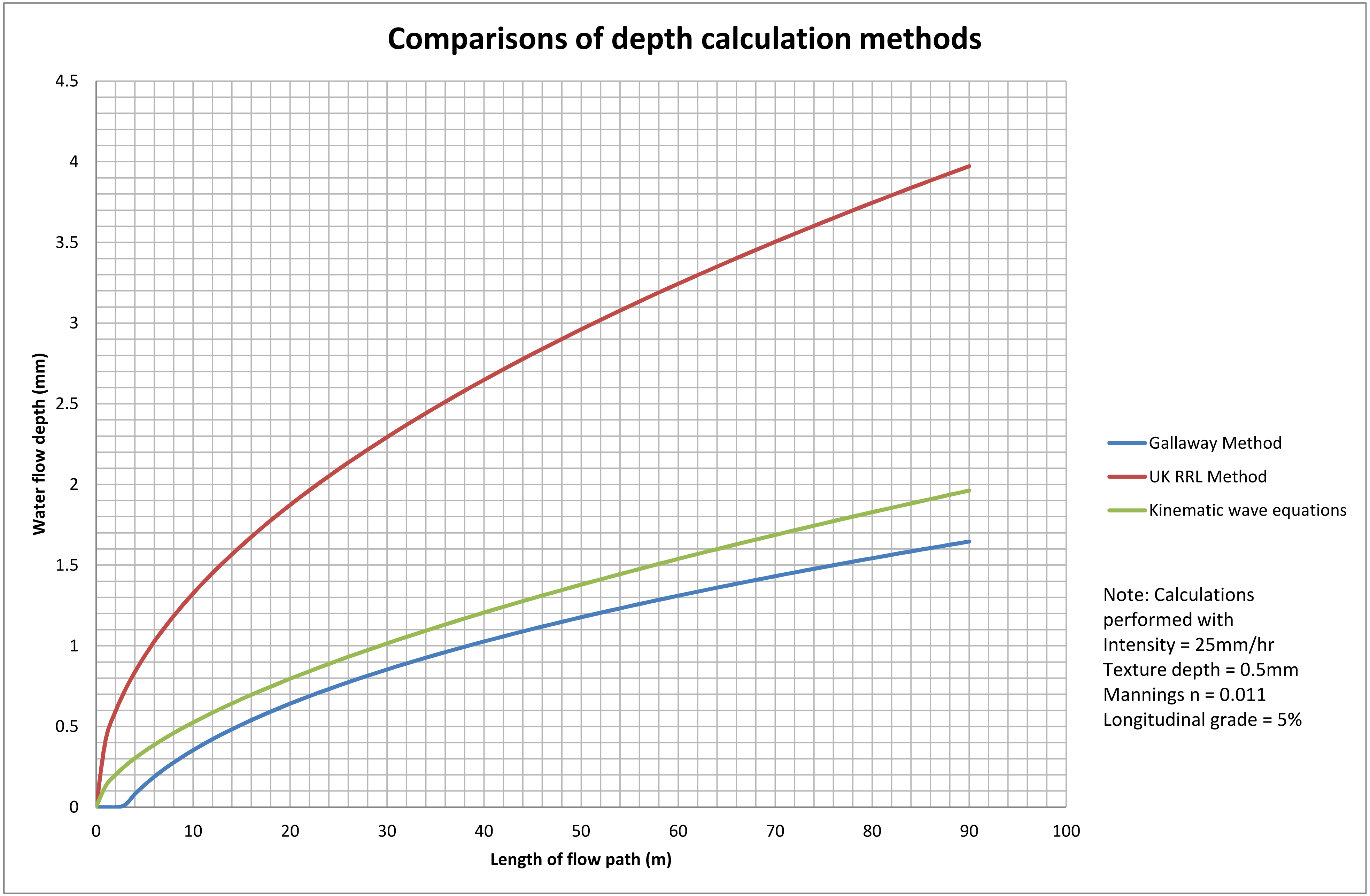

Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 1%


Comparisons of depth calculation methods
Water flow depth (mm)
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 2%

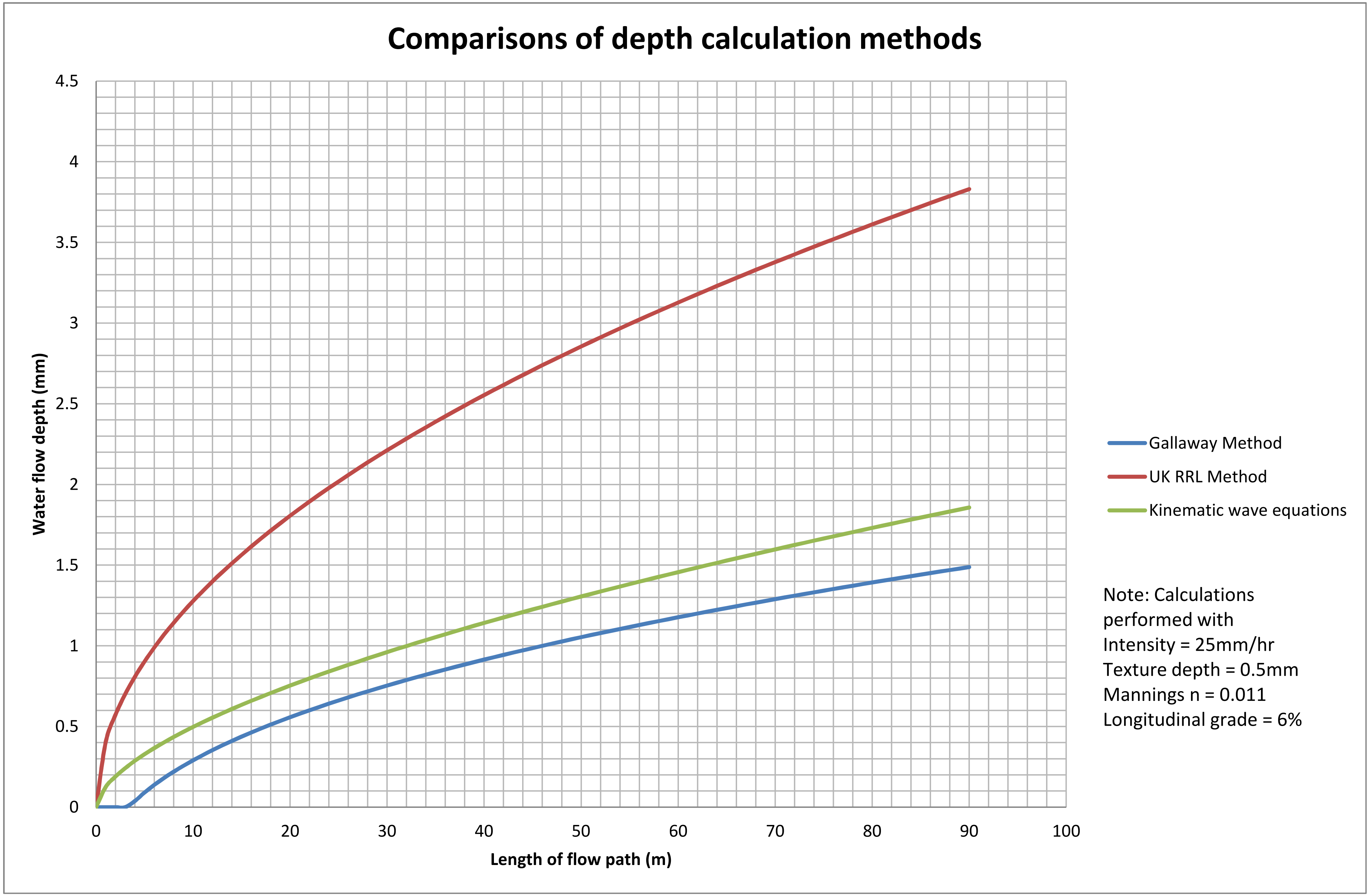


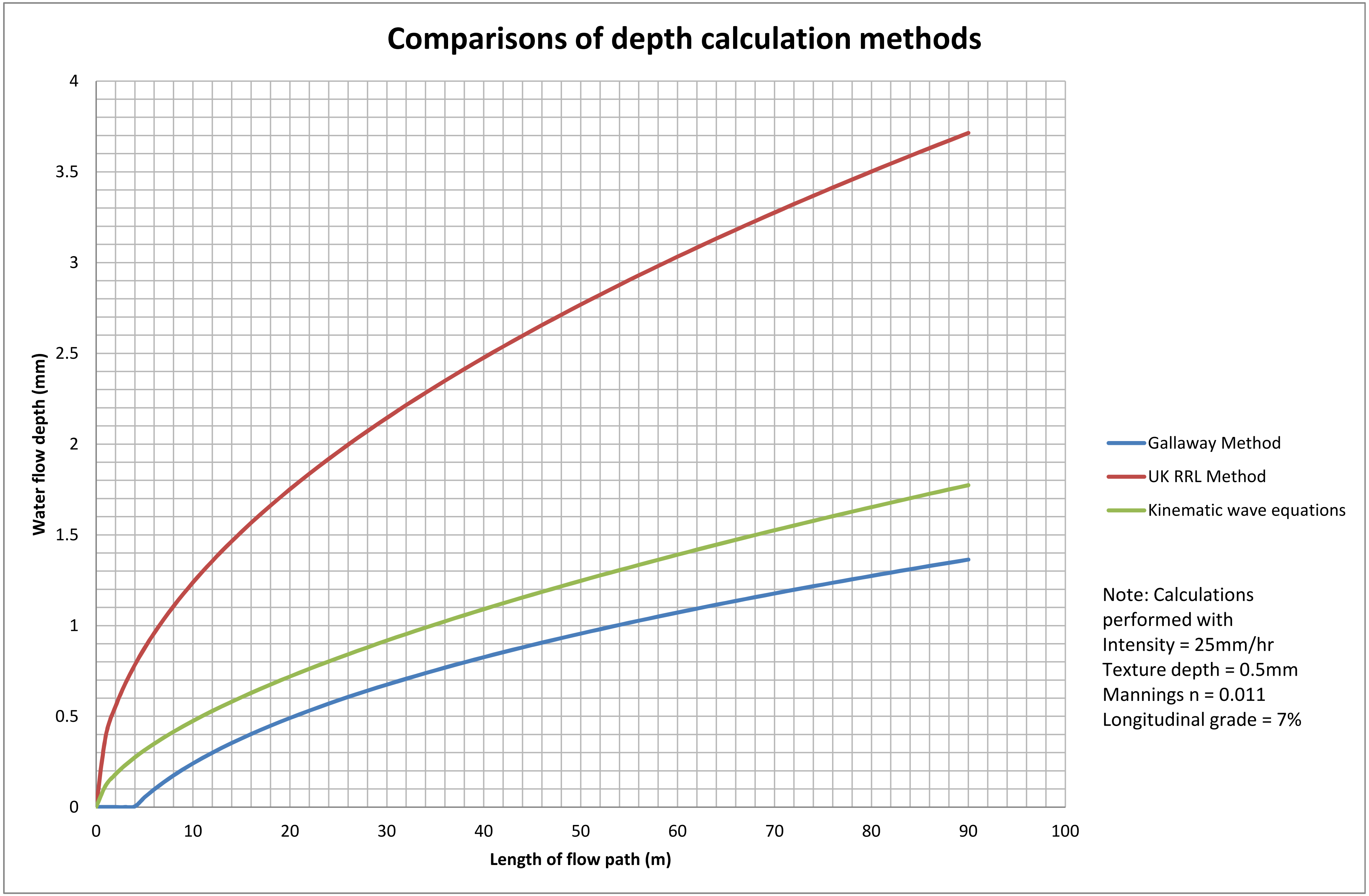
Comparisons of depth calculation methods
Water flow depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 3%

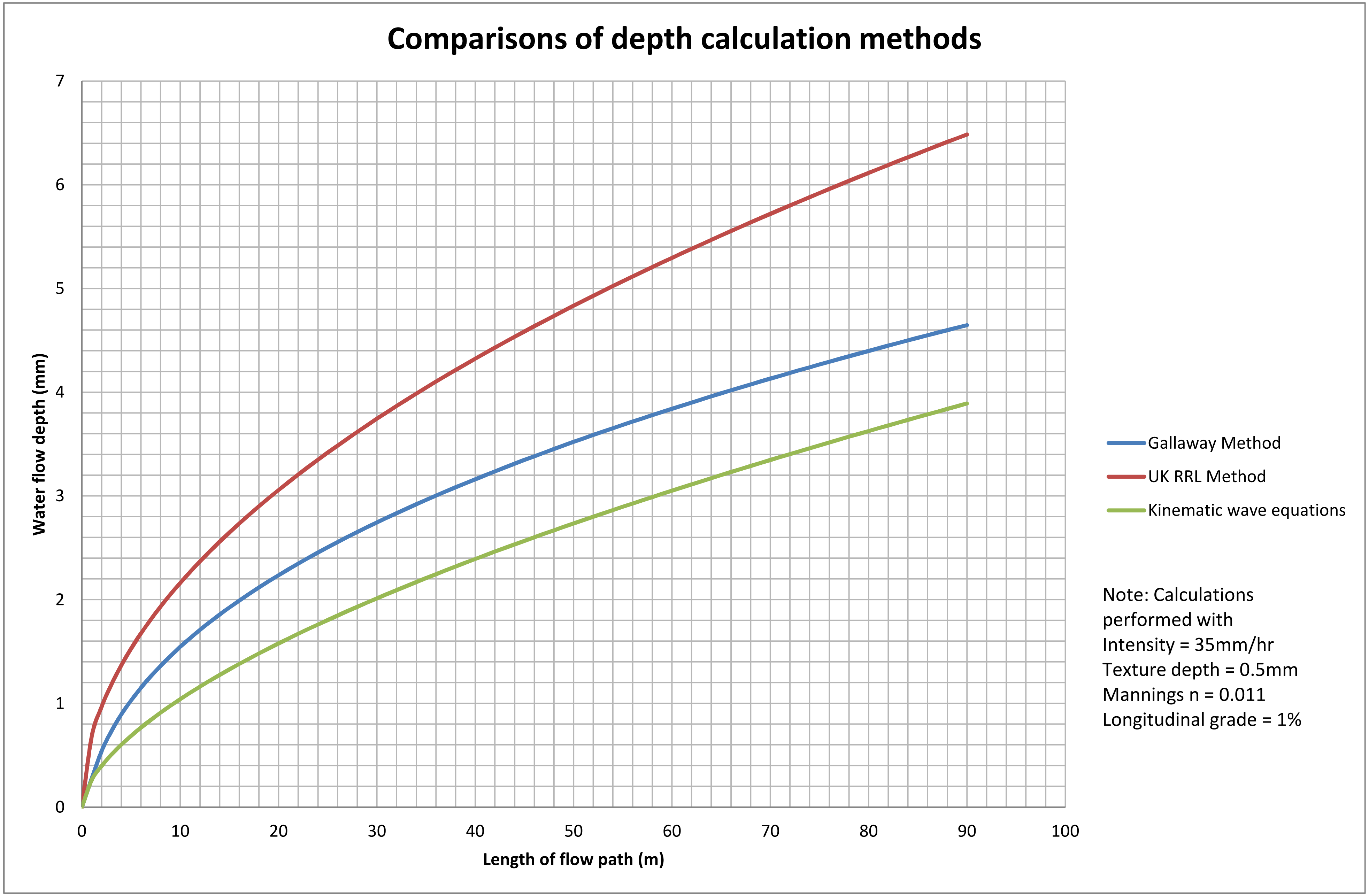

Comparisons of depth calculation methods
Water flow depth (mm)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 4%



Comparisons of depth calculation methods
Water flow depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Length of flow path (m)
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 5%


Comparisons of depth calculation methods
Water flow depth (mm)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 6%


Comparisons of depth calculation methods
Water flow depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 25mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 7%


Comparisons of depth calculation methods
Water flow depth (mm)
0
1
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3
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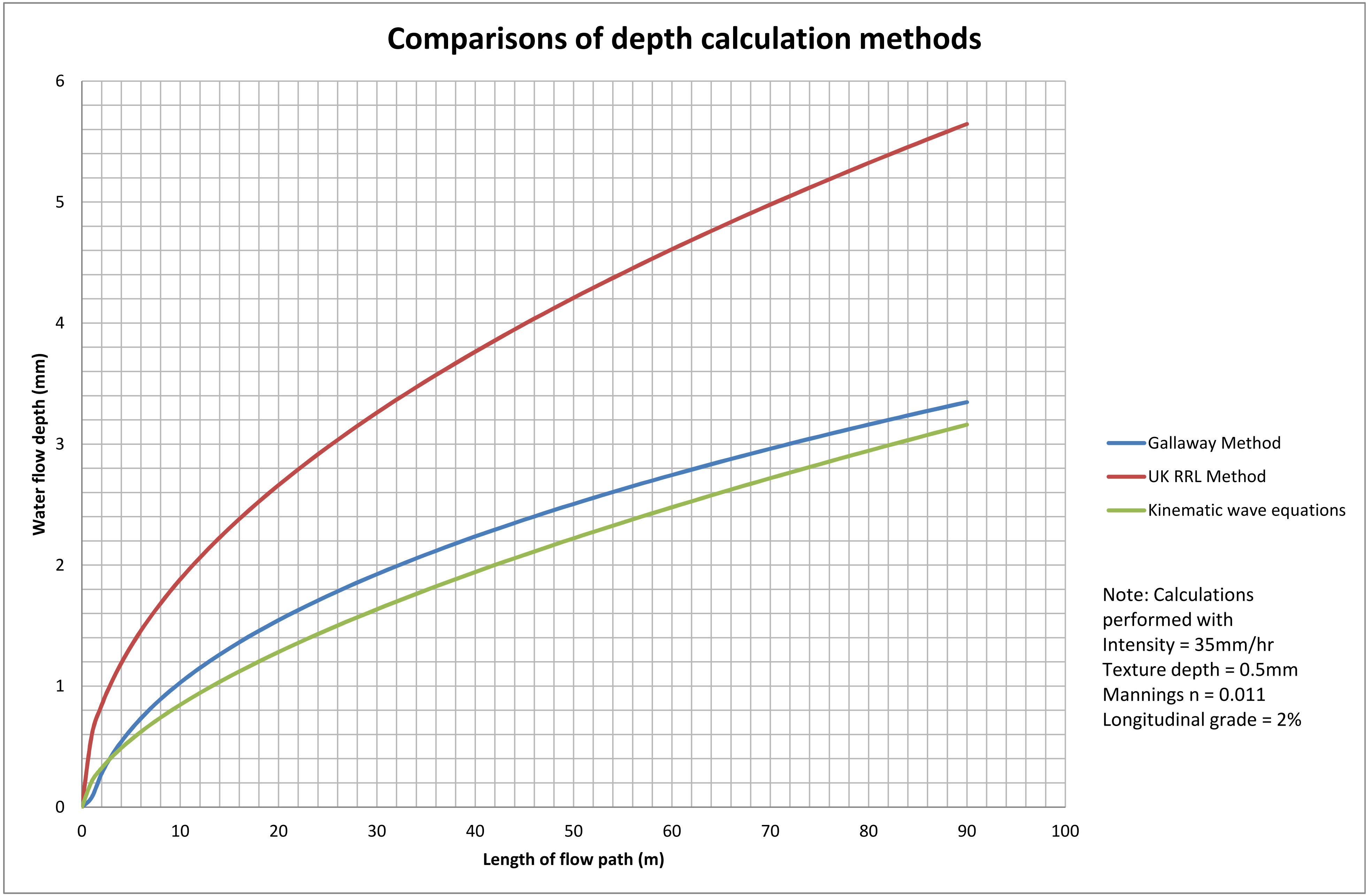
5
6
7
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 1%



Comparisons of depth calculation methods
Water flow depth (mm)
0
1
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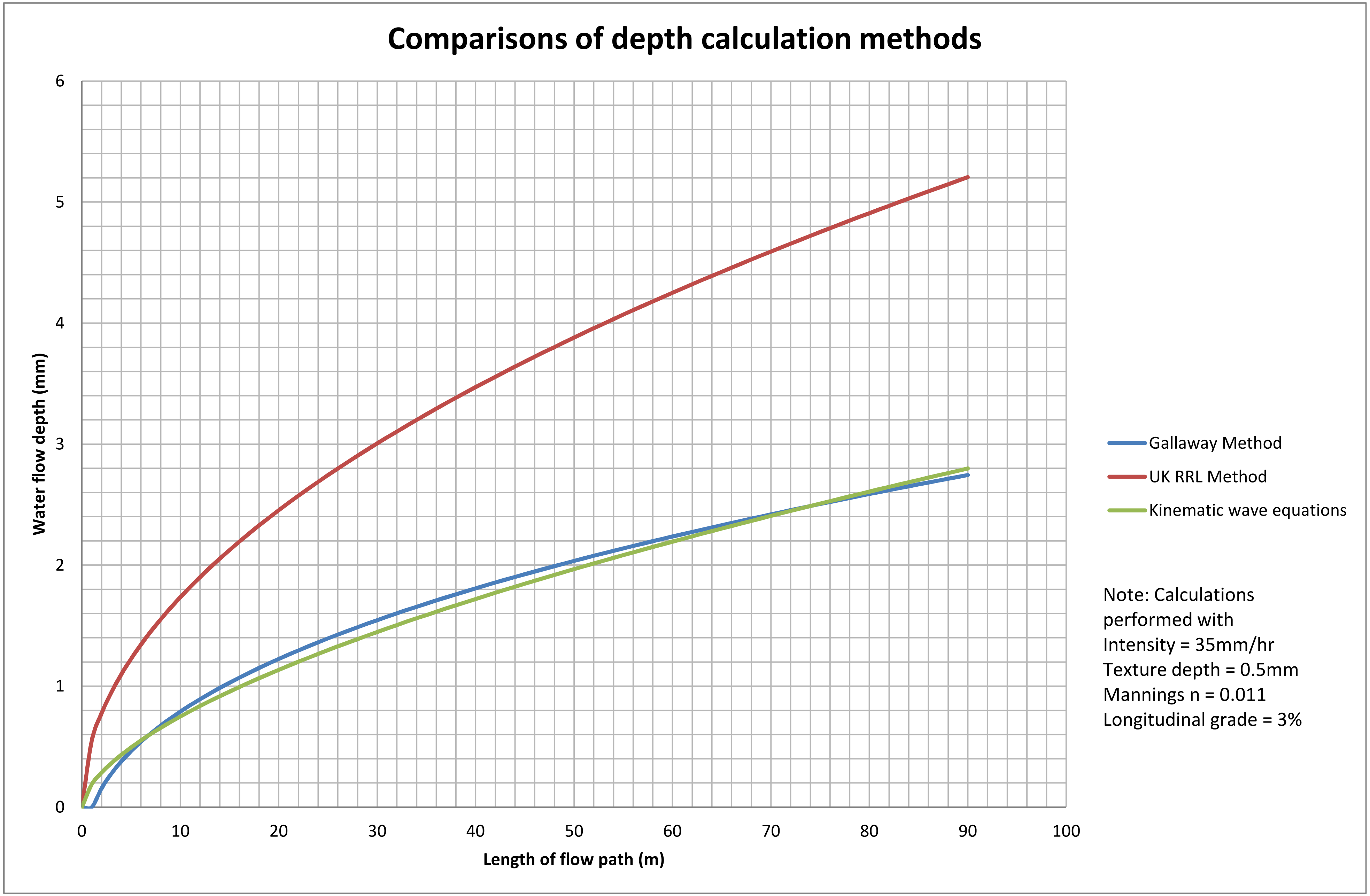
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 2%


Comparisons of depth calculation methods
Water flow depth (mm)
0
1
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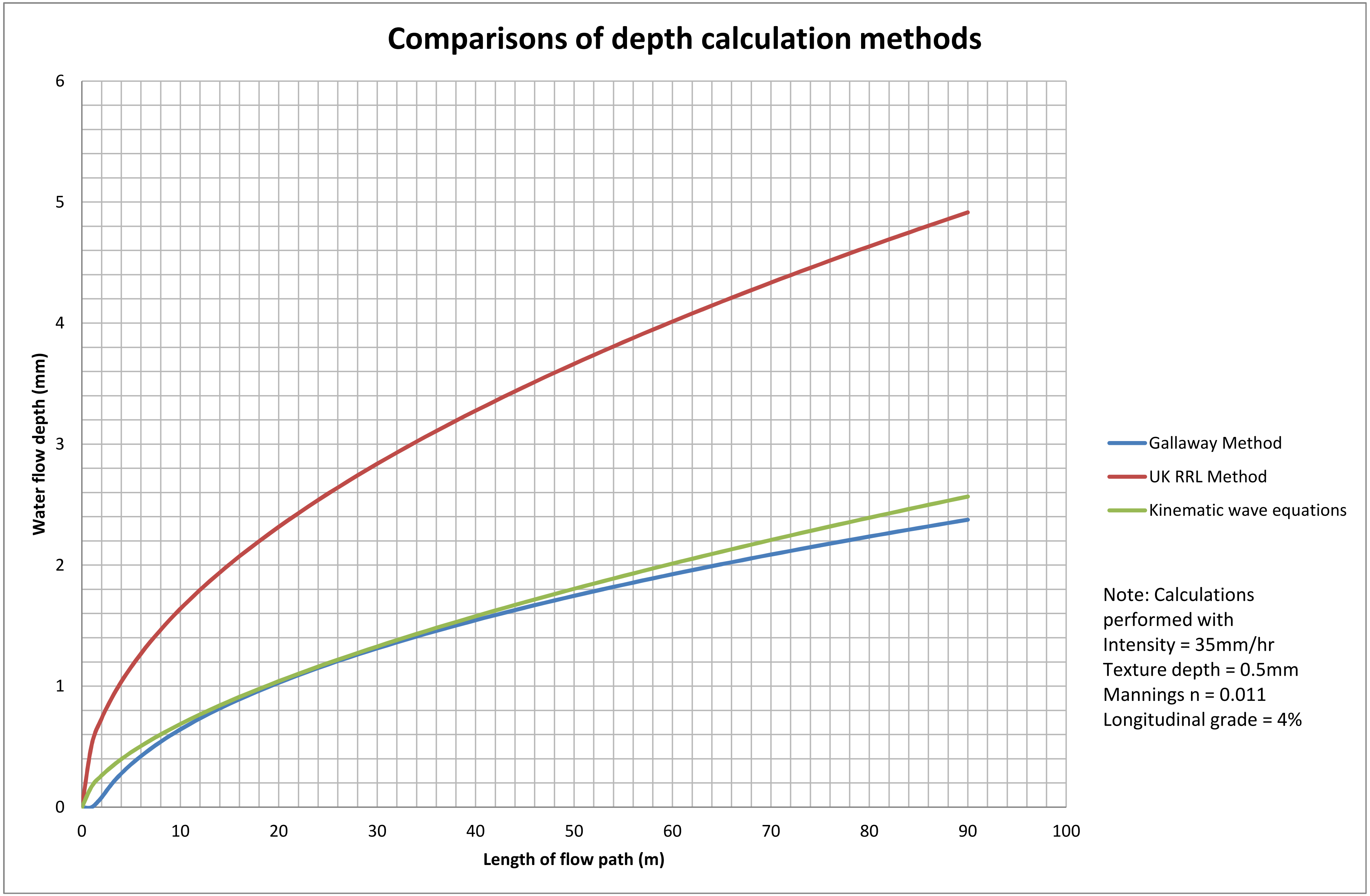
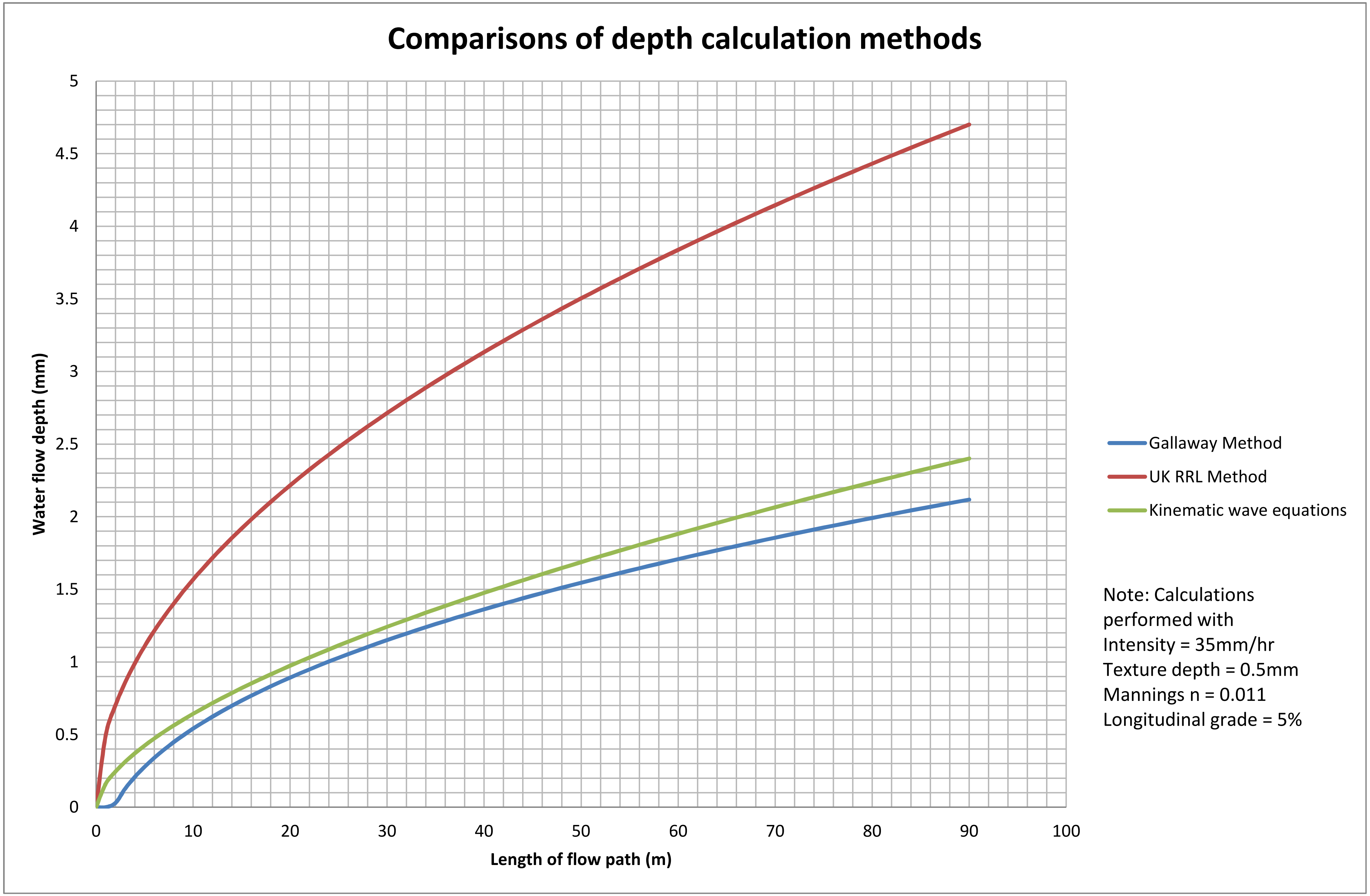
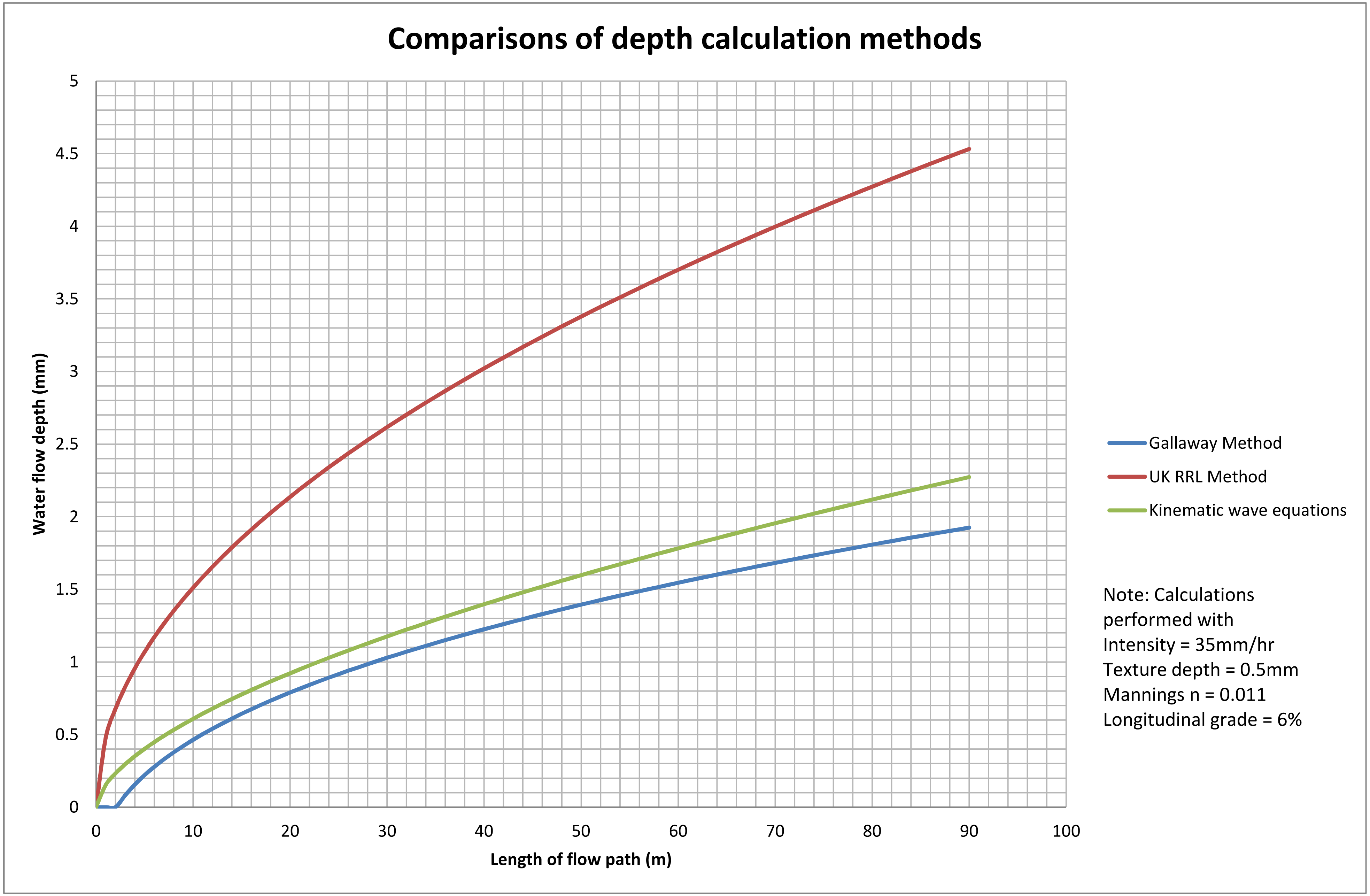
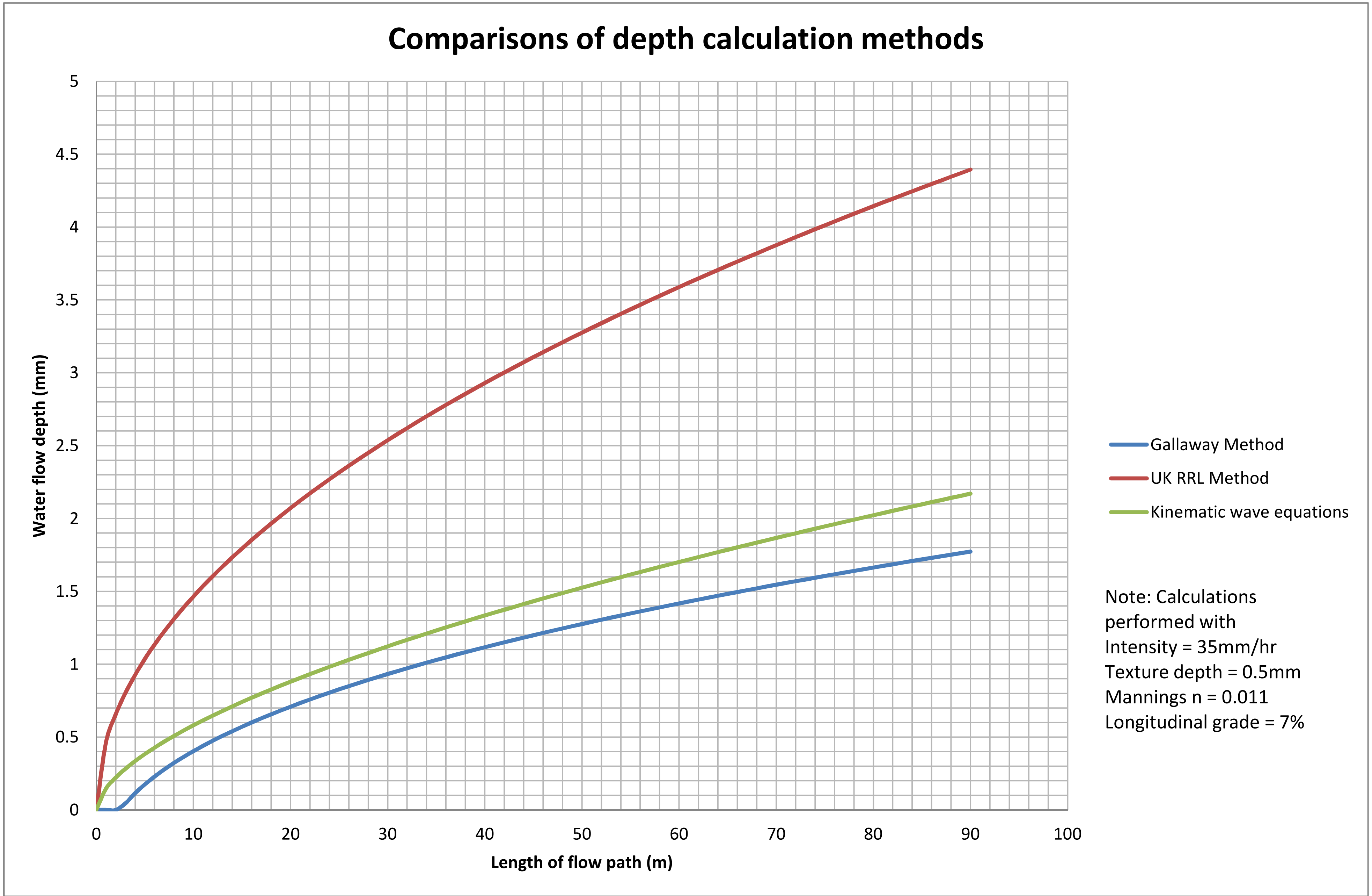
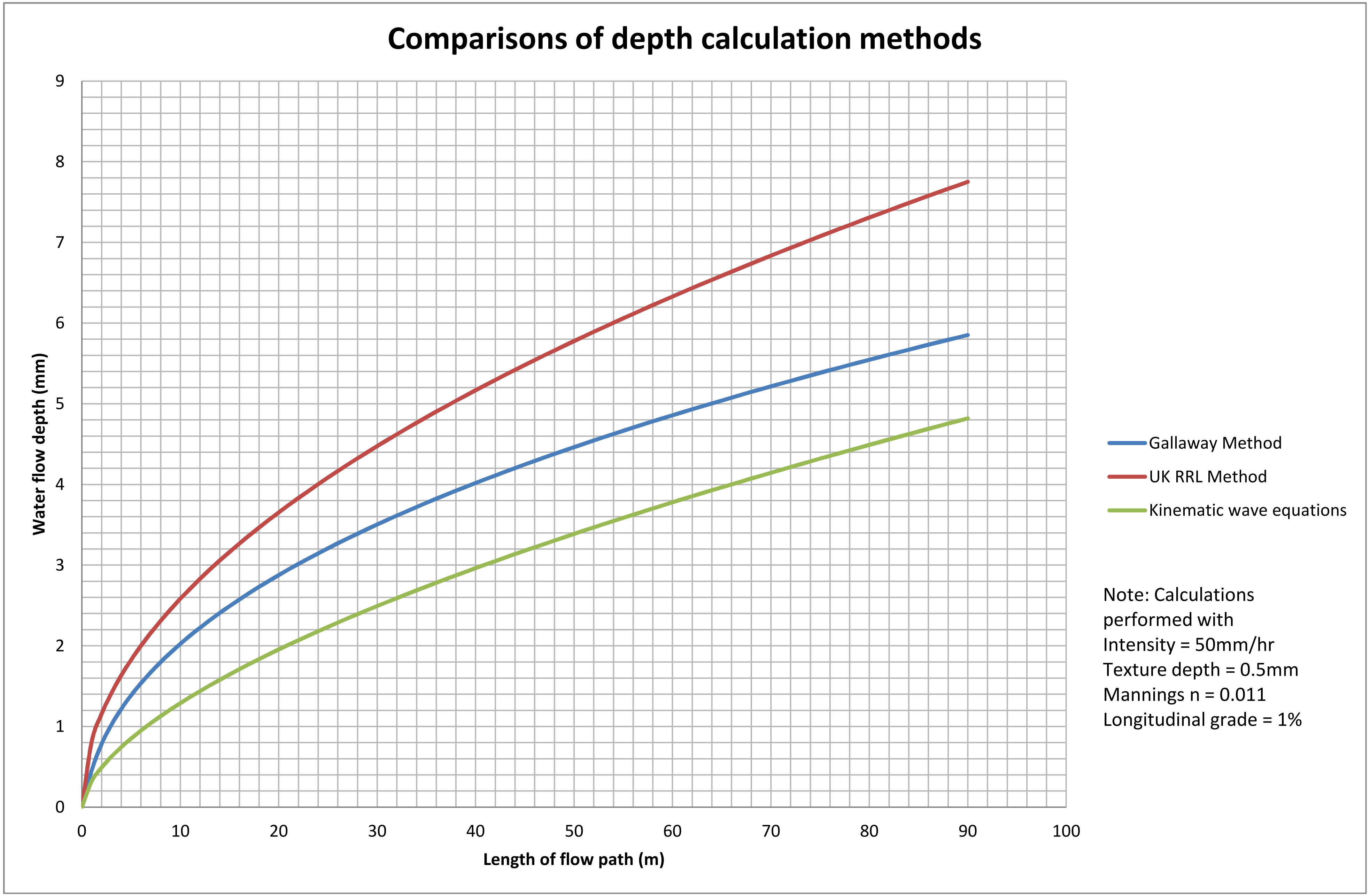
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 3%


Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 4%

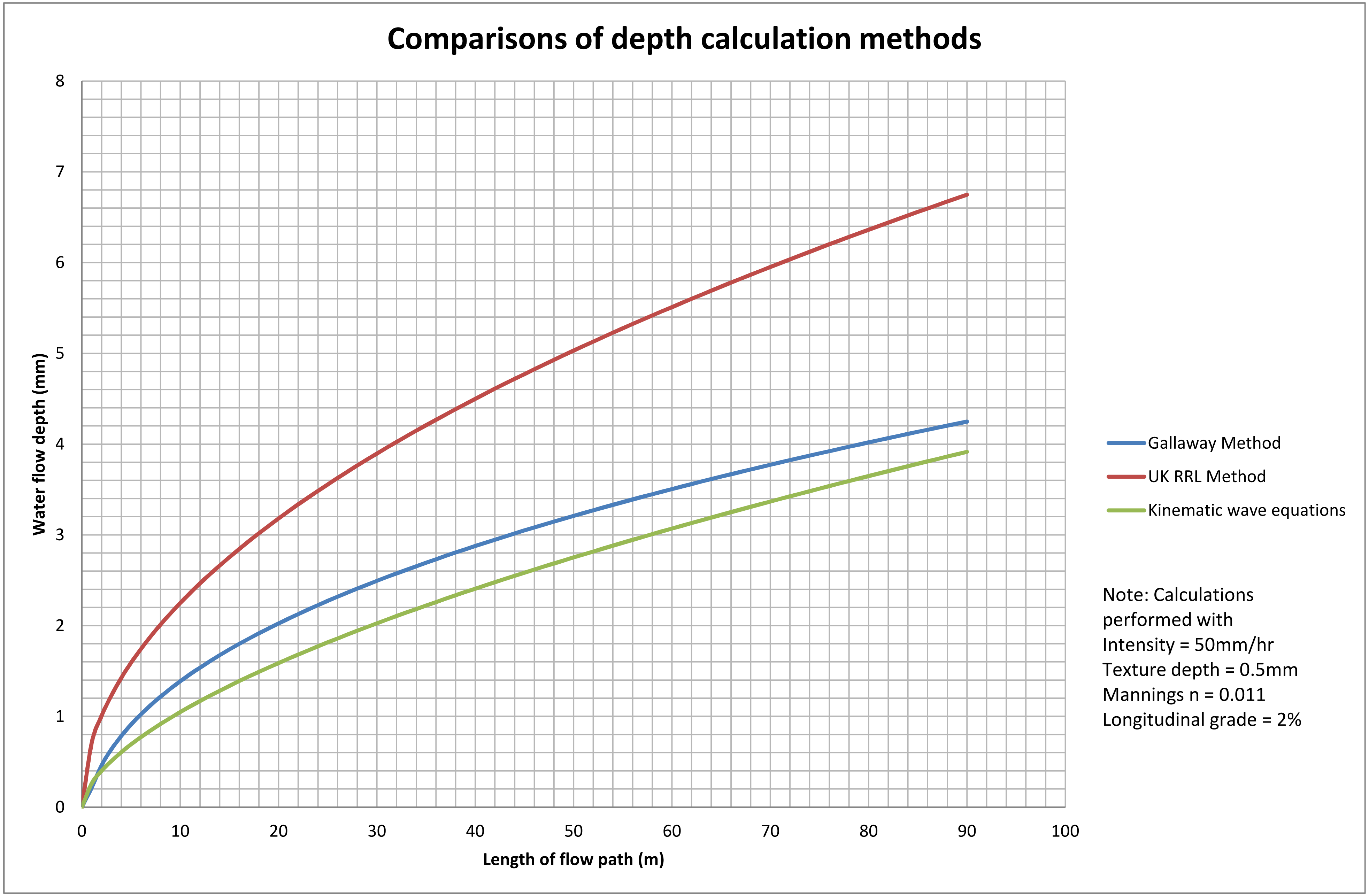

Comparisons of depth calculation methods
Water flow depth (mm)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 5%

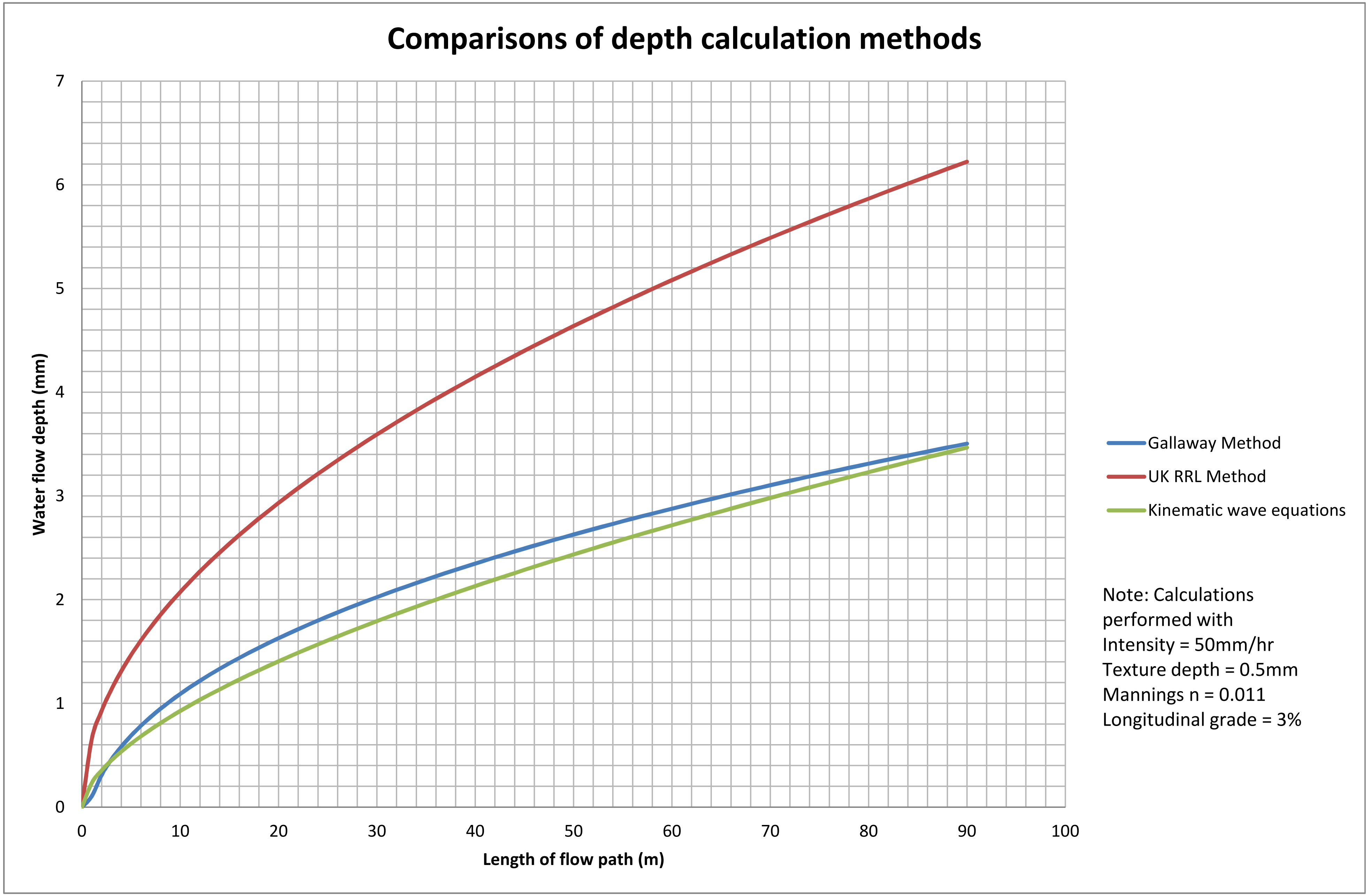

Comparisons of depth calculation methods
Water flow depth (mm)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 6%

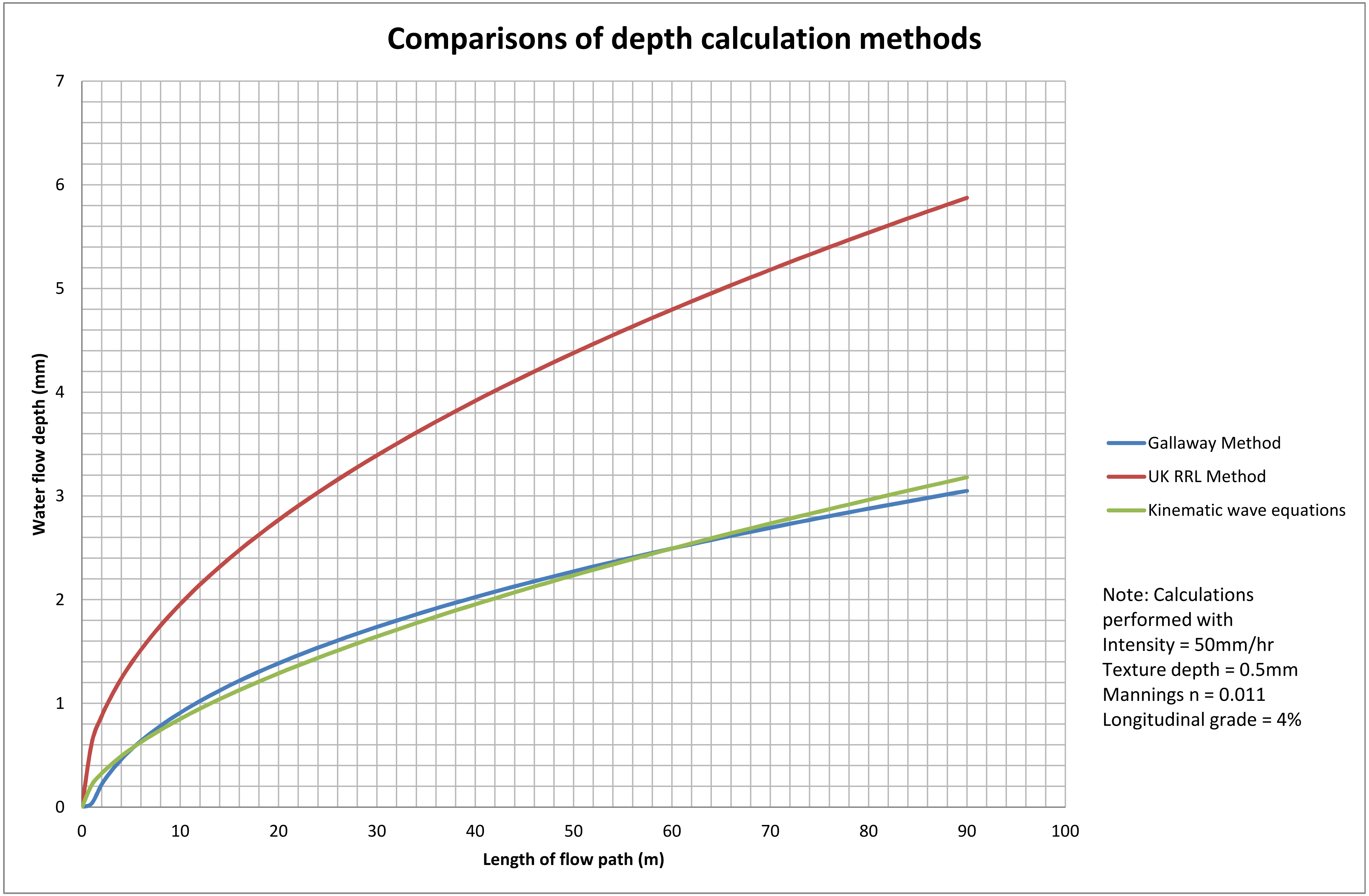

Comparisons of depth calculation methods
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Water flow depth (mm)
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 35mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 7%



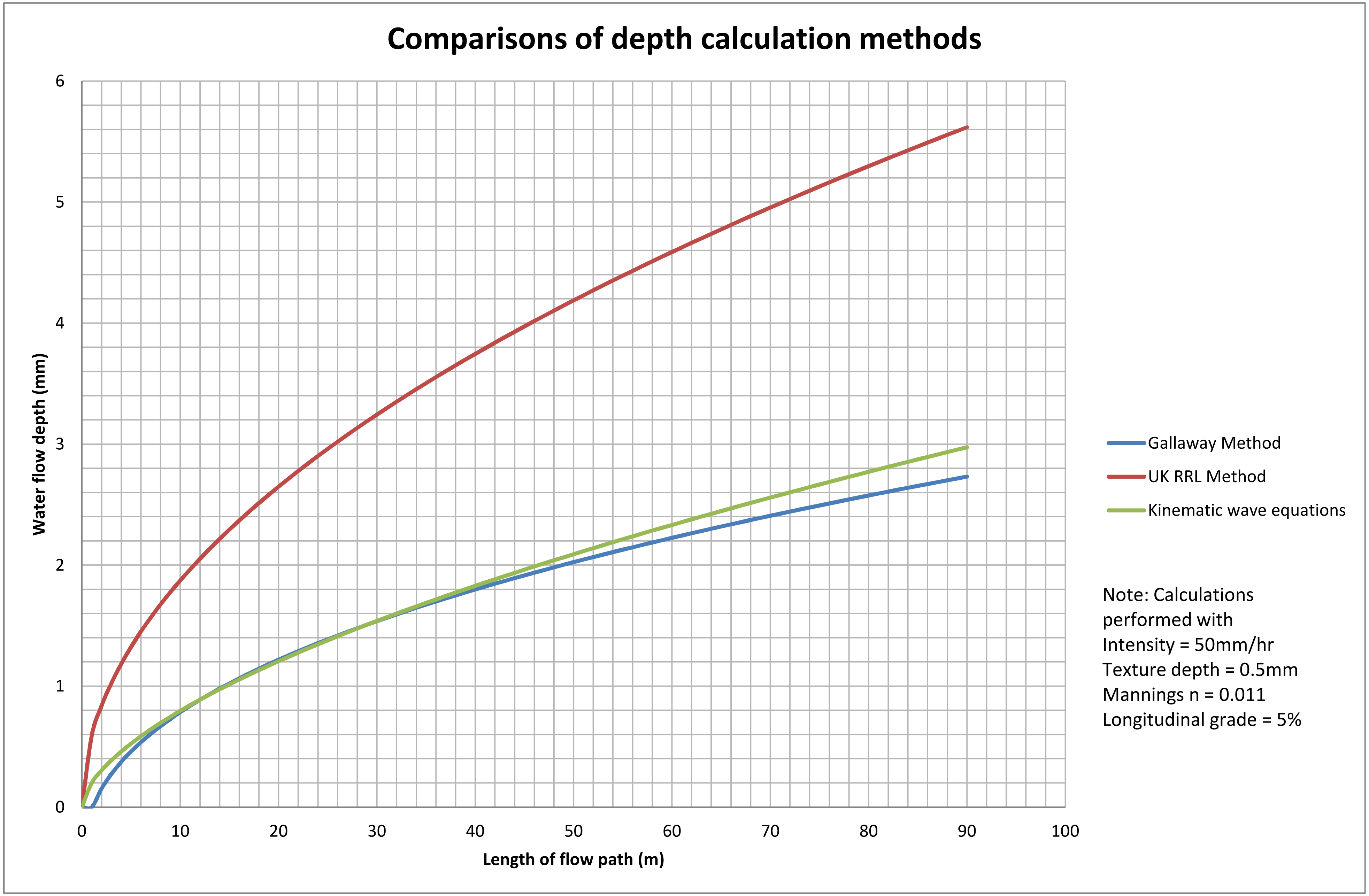
Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 1%

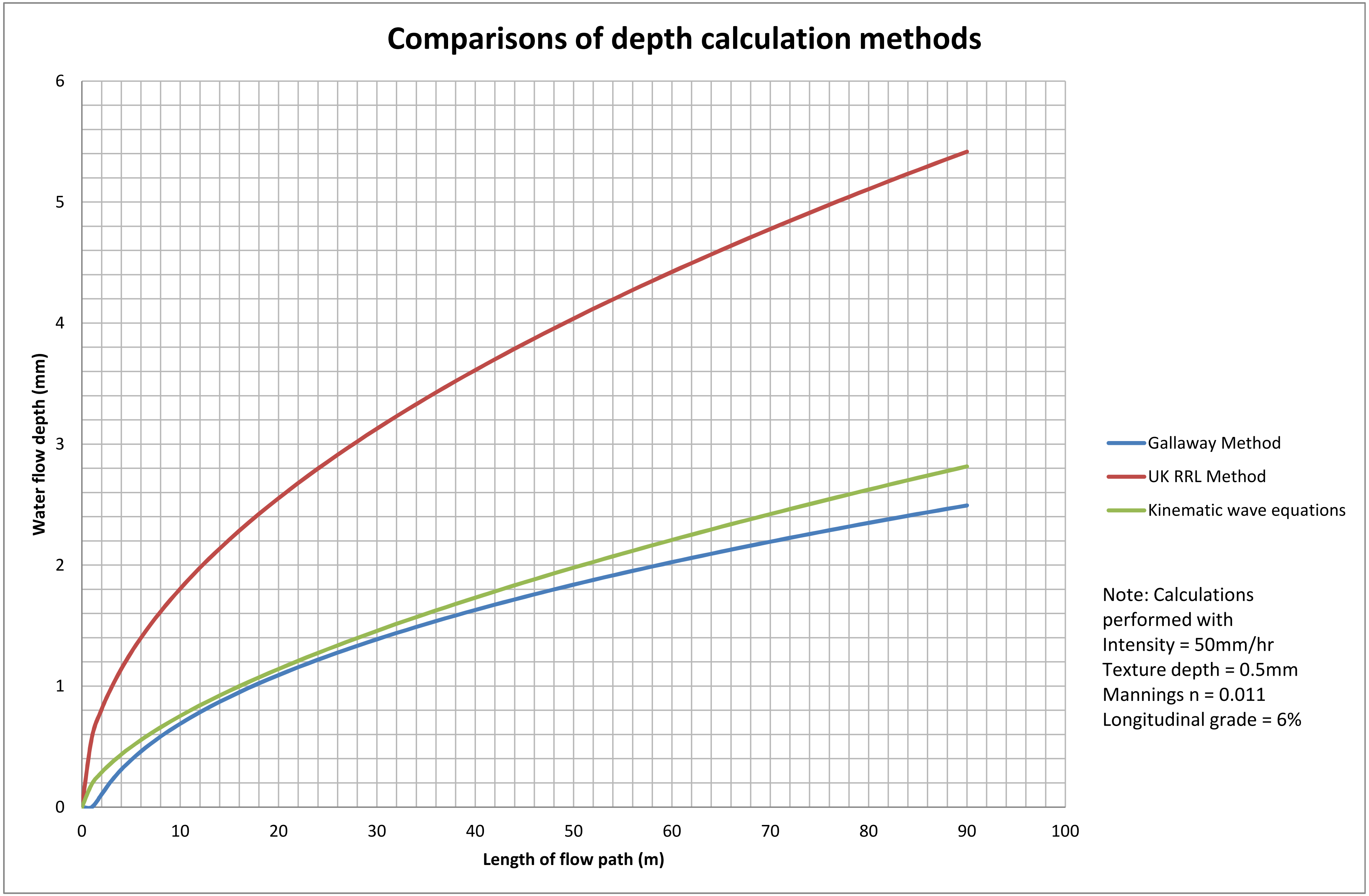

Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 2%


Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 3%

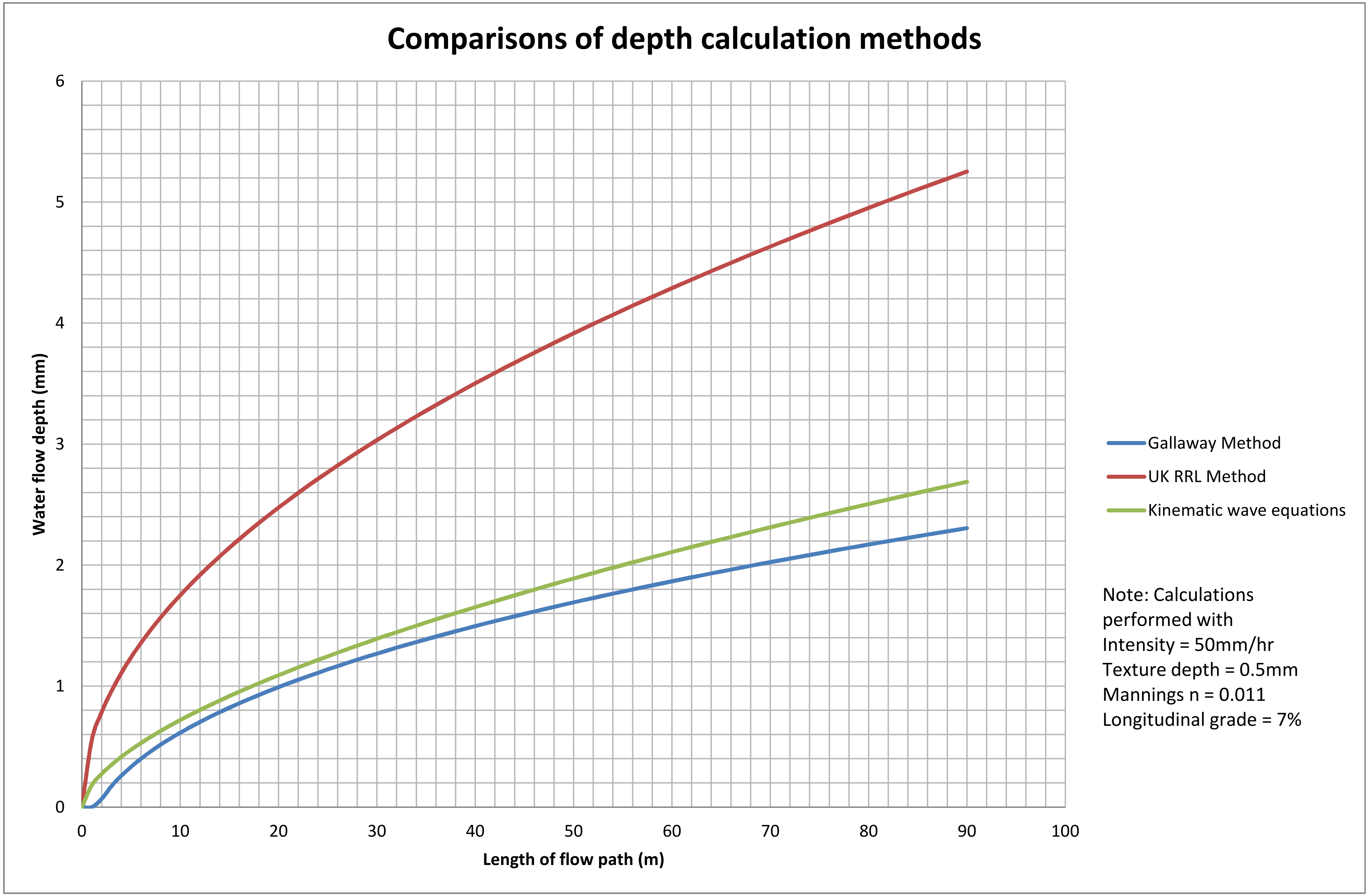


Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 4%

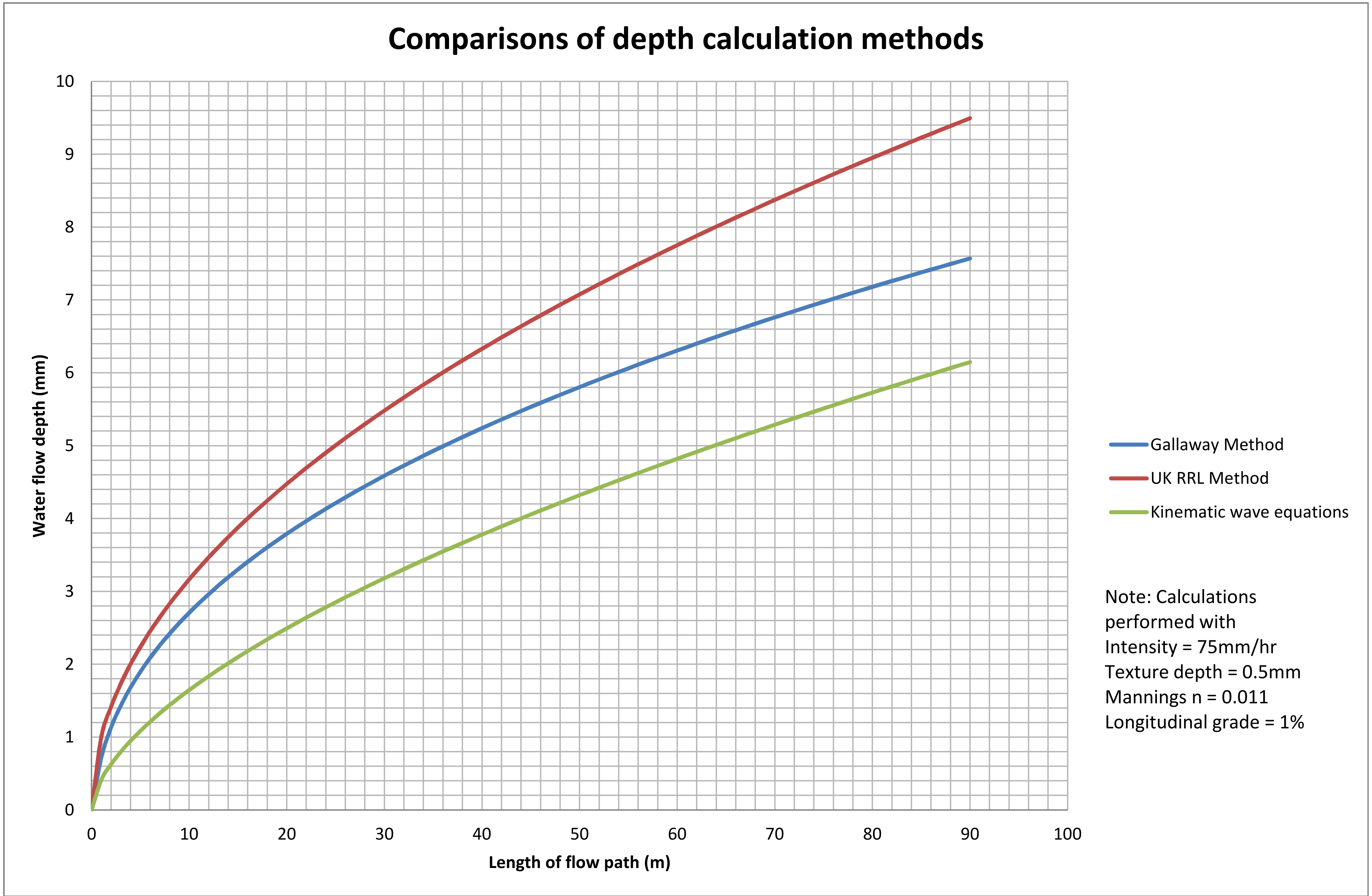

Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 5%



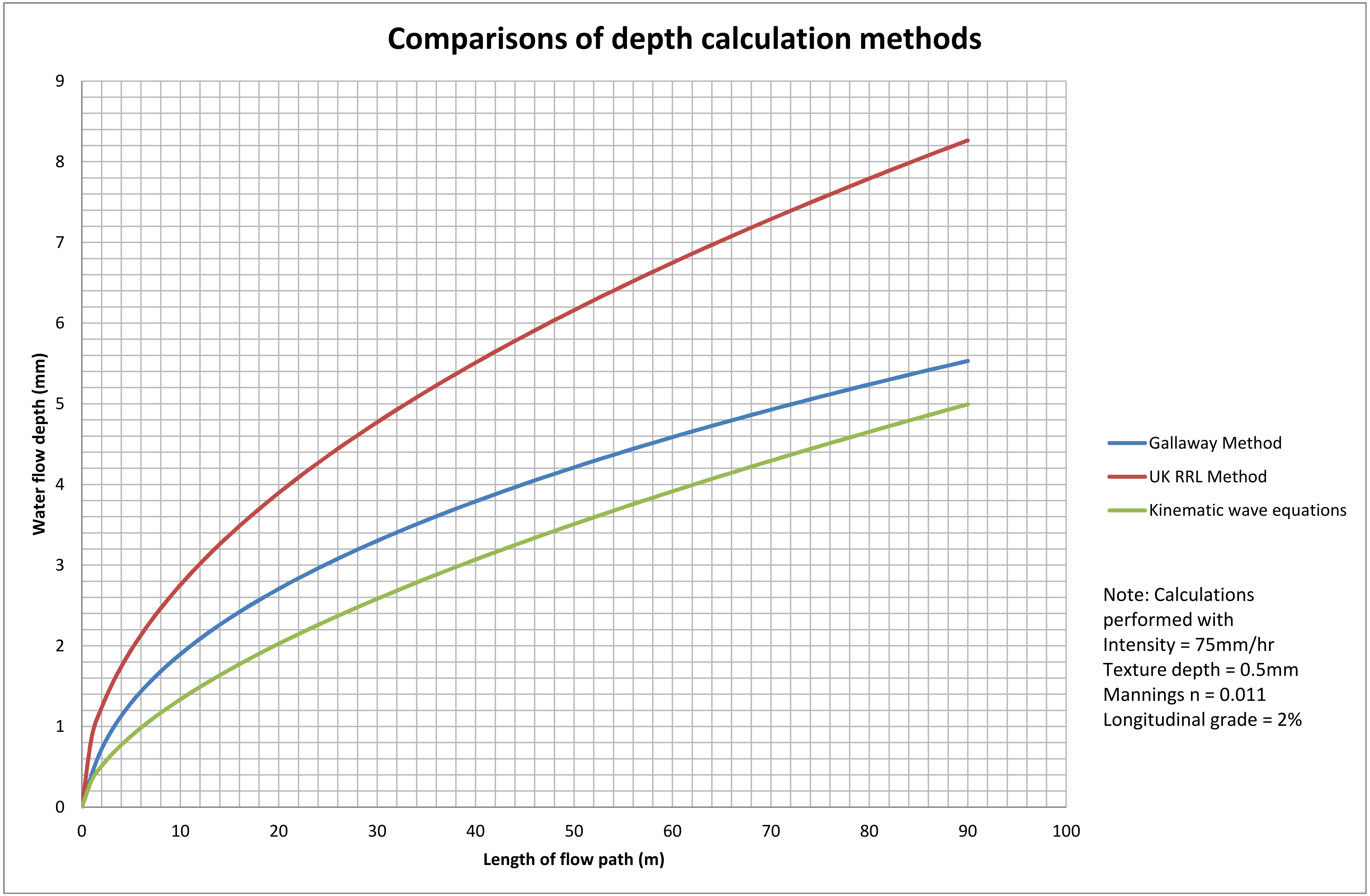
Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 6%



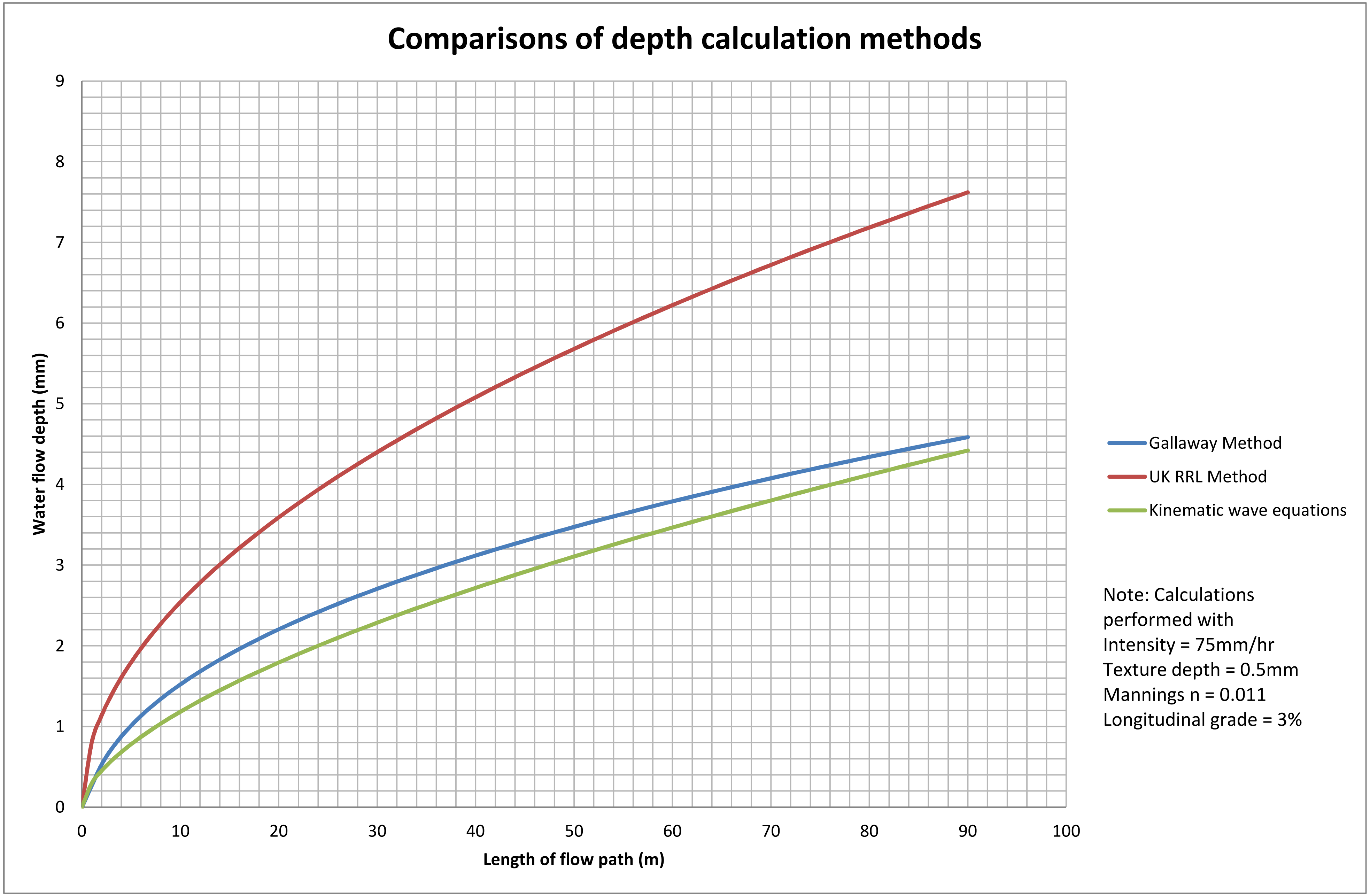
Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 50mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 7%

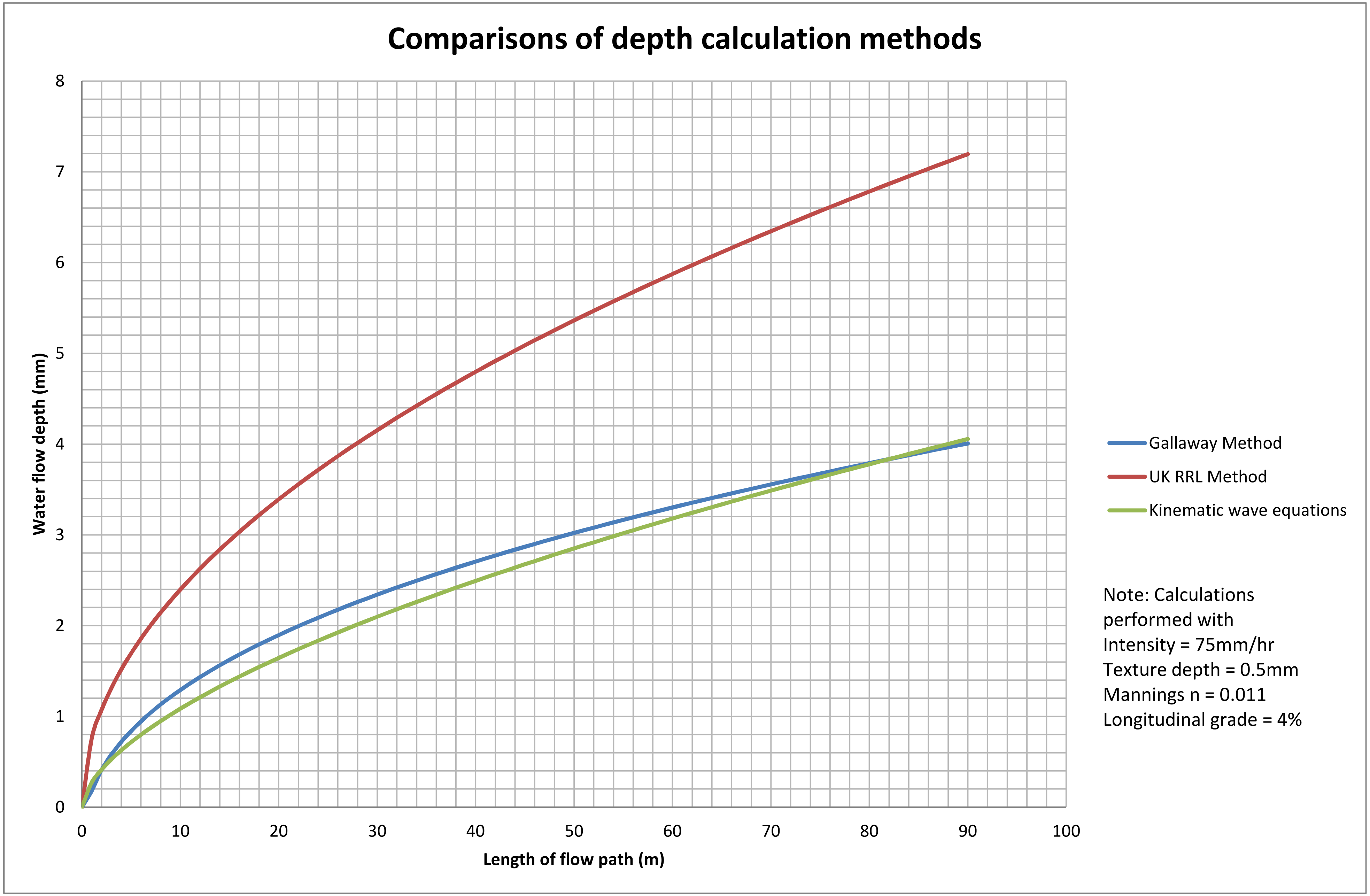


Comparisons of depth calculation methods
10
9
8
7
6
5
4
3
2
1
0
Water flow depth (mm)
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 1%

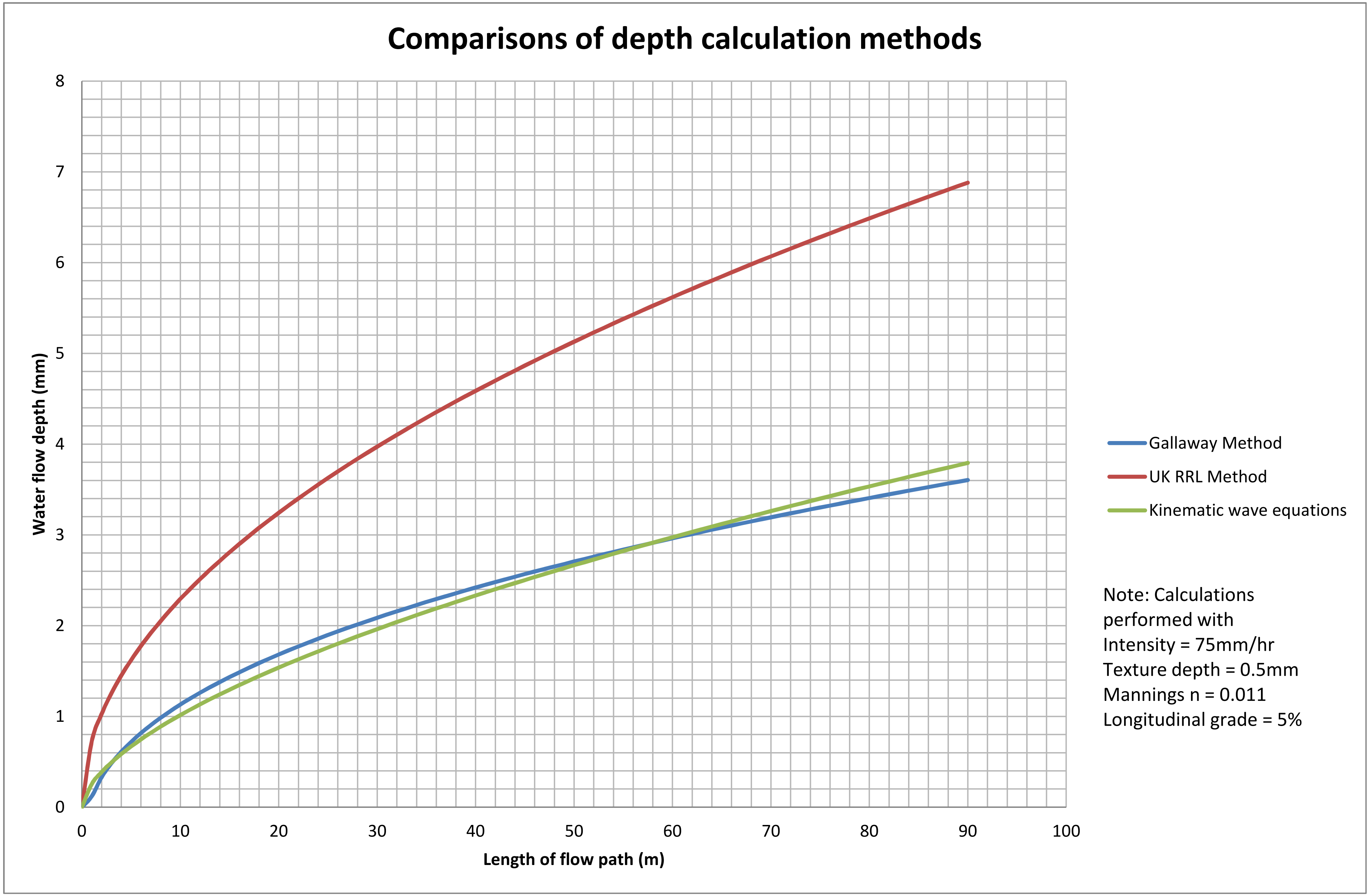


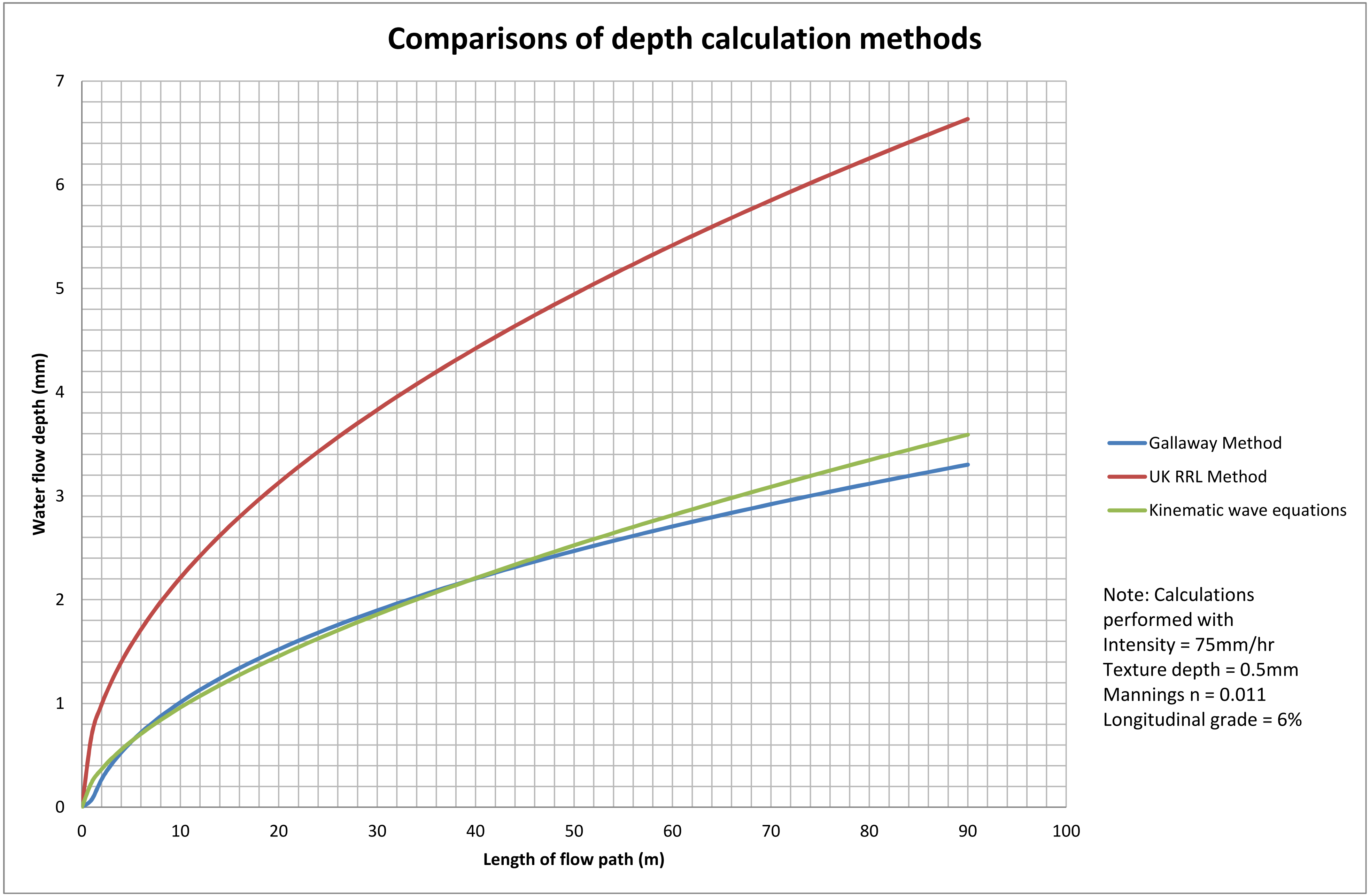
Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 2%

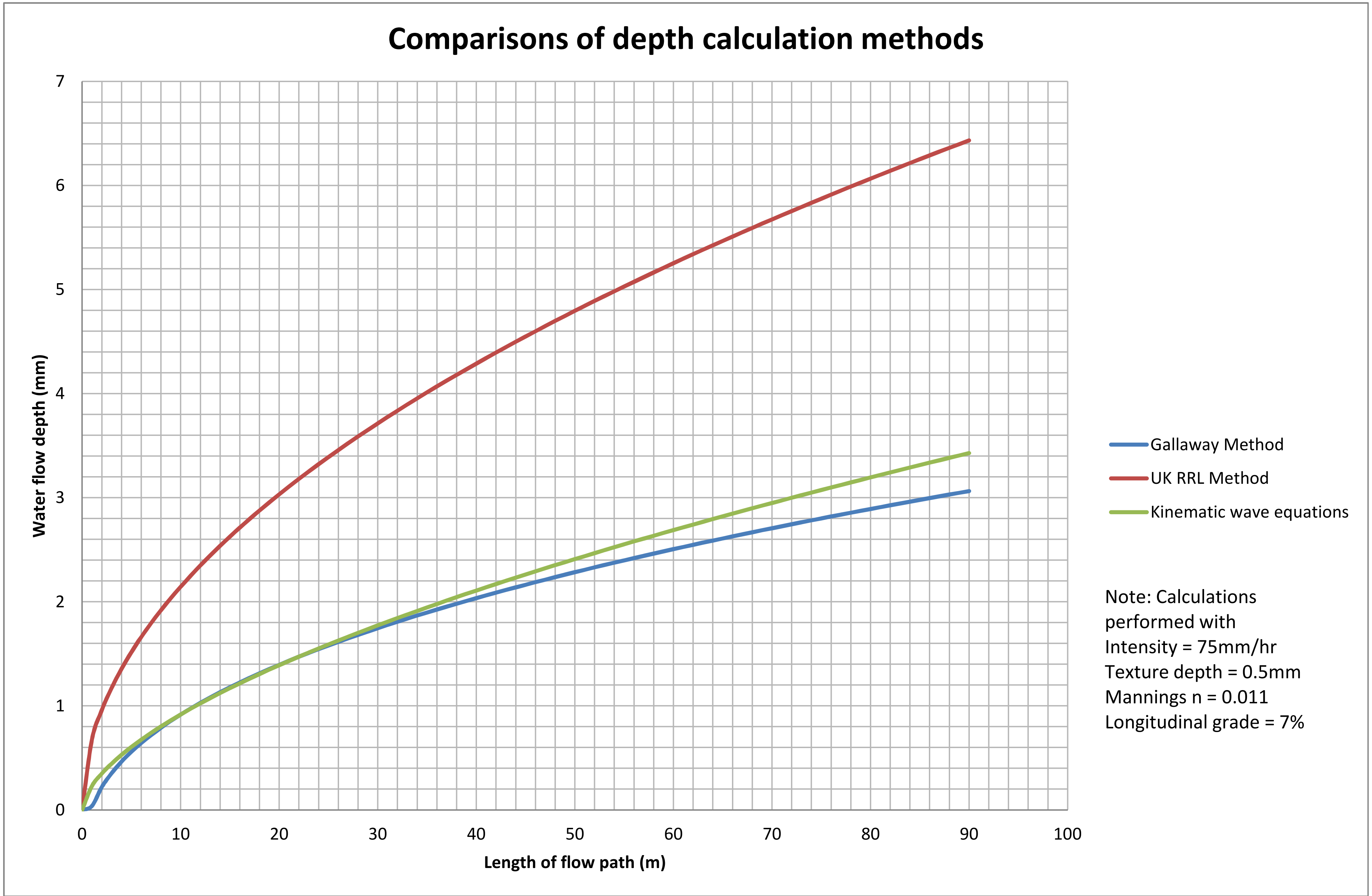

Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 3%



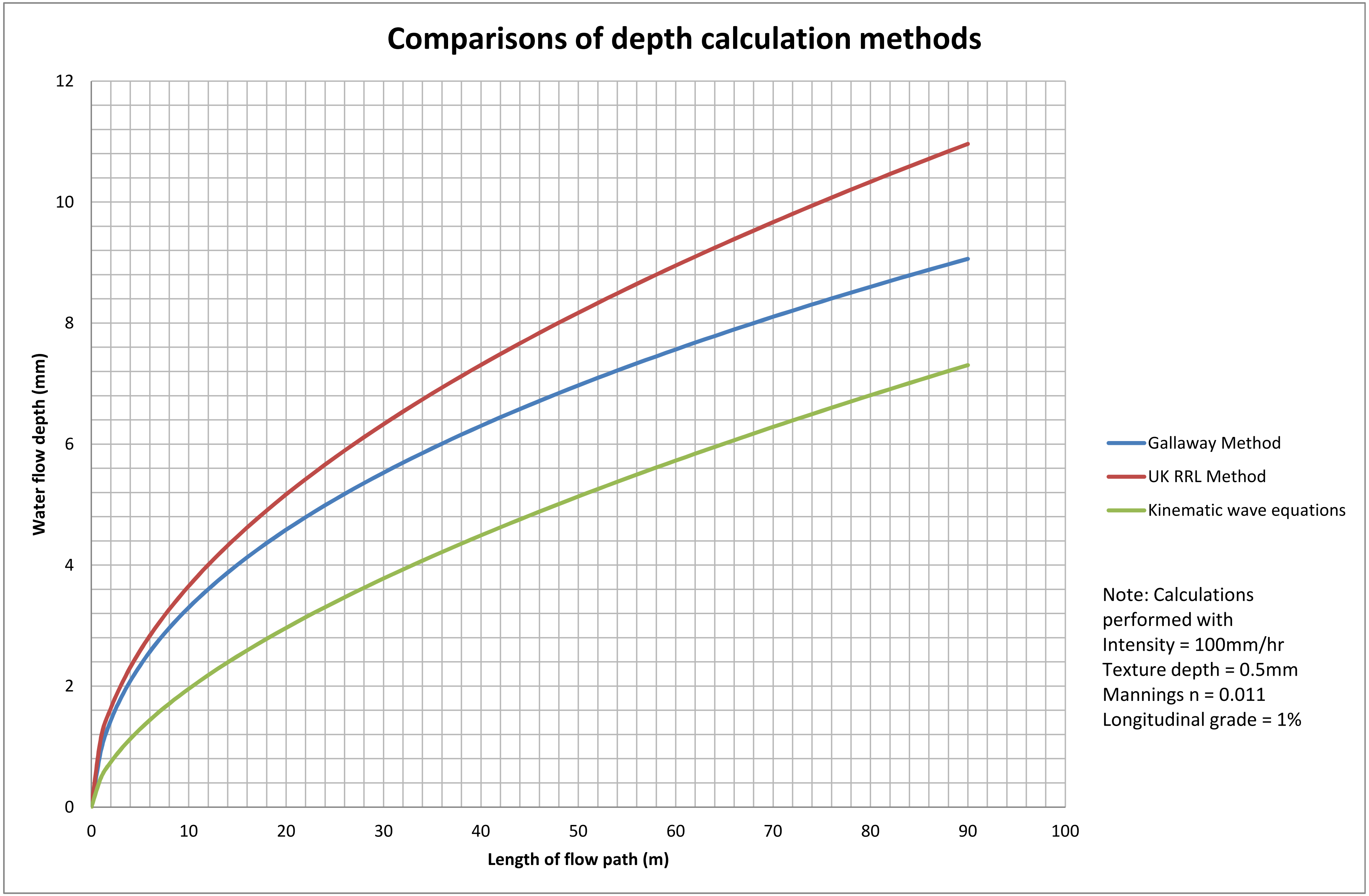
Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 4%


Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 5%

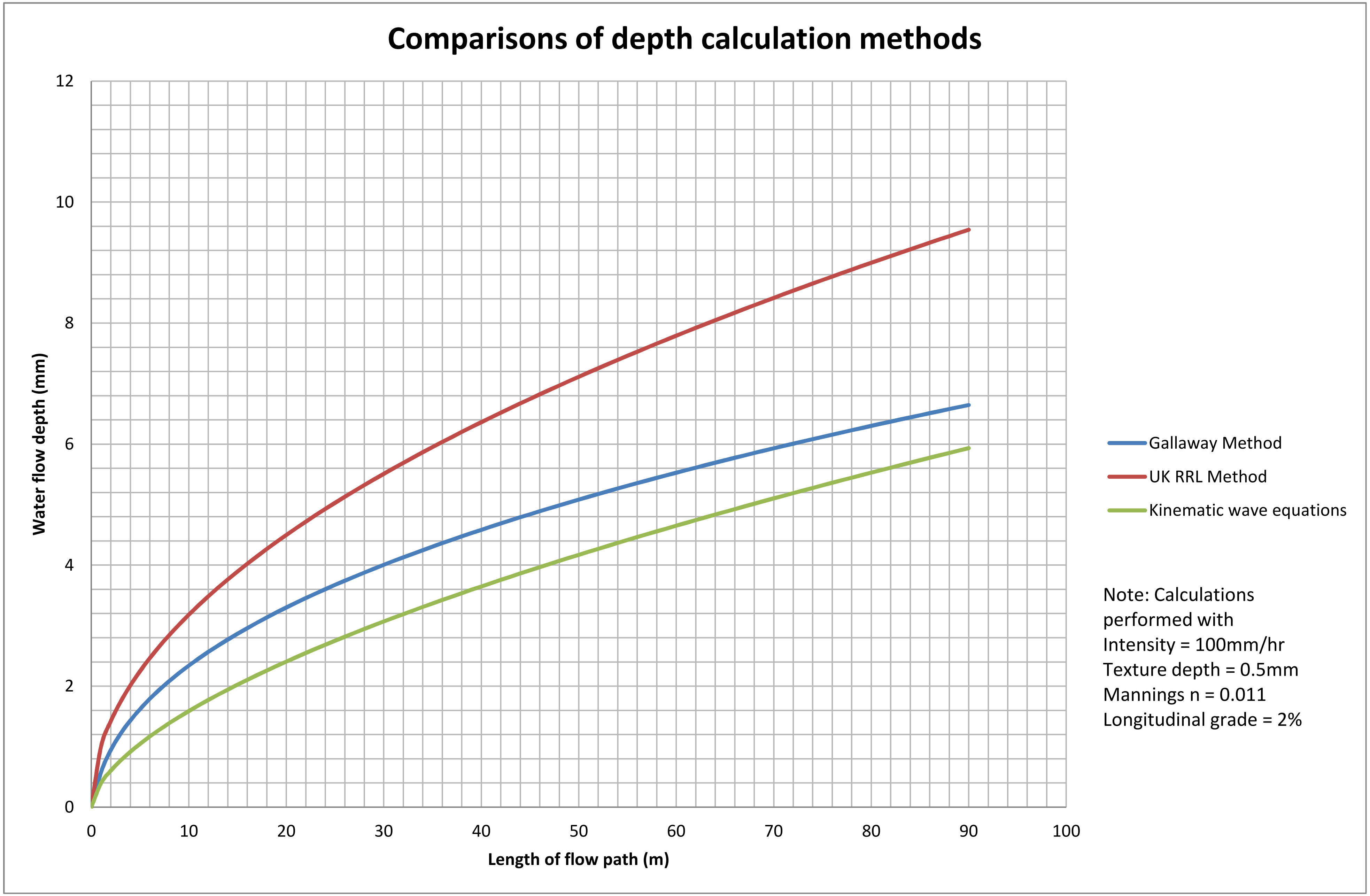

Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 6%



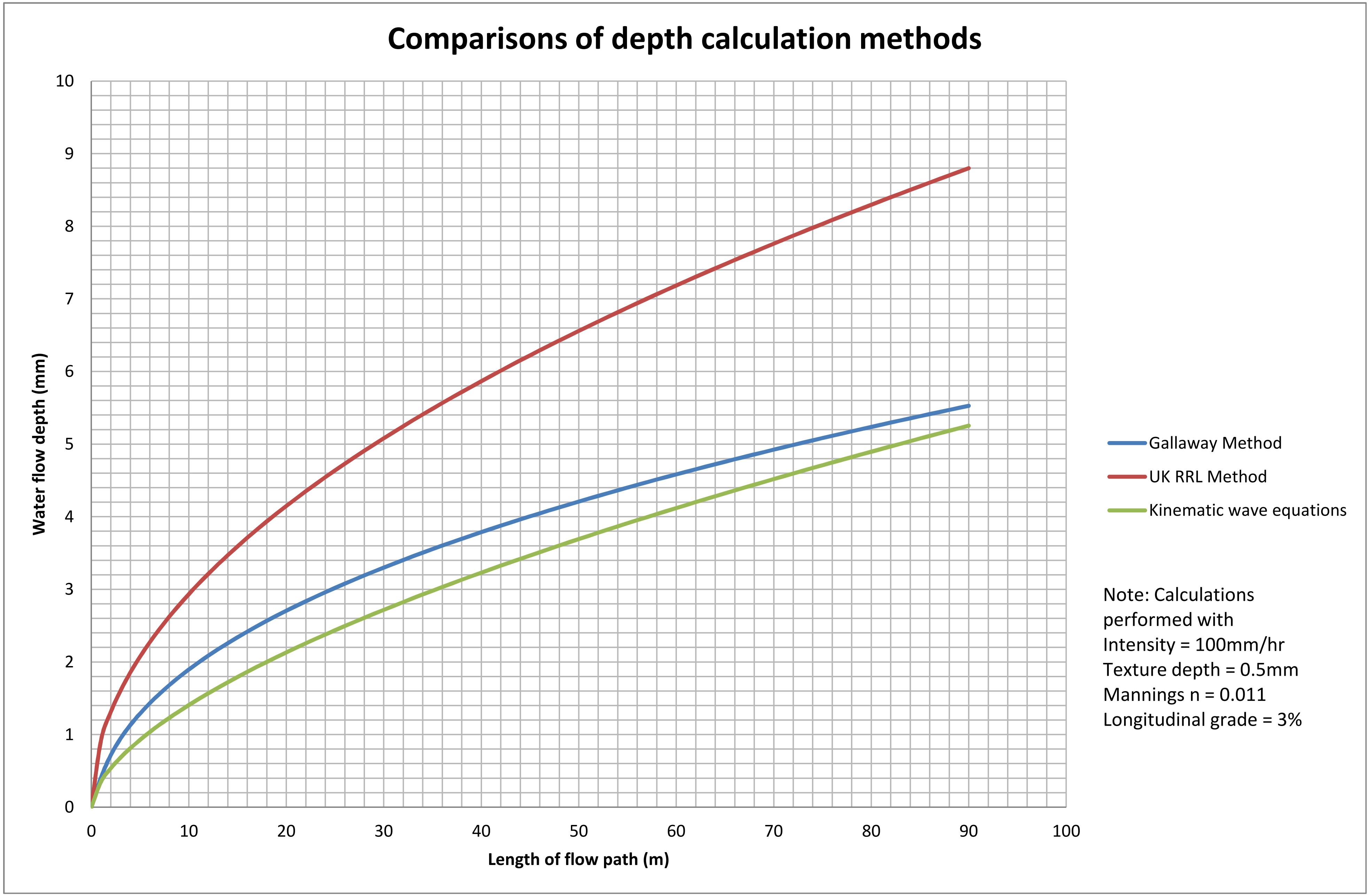
Comparisons of depth calculation methods
7
6
5
4
3
2
1
0
Water flow depth (mm)
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations
performed with
Intensity = 75mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 7%



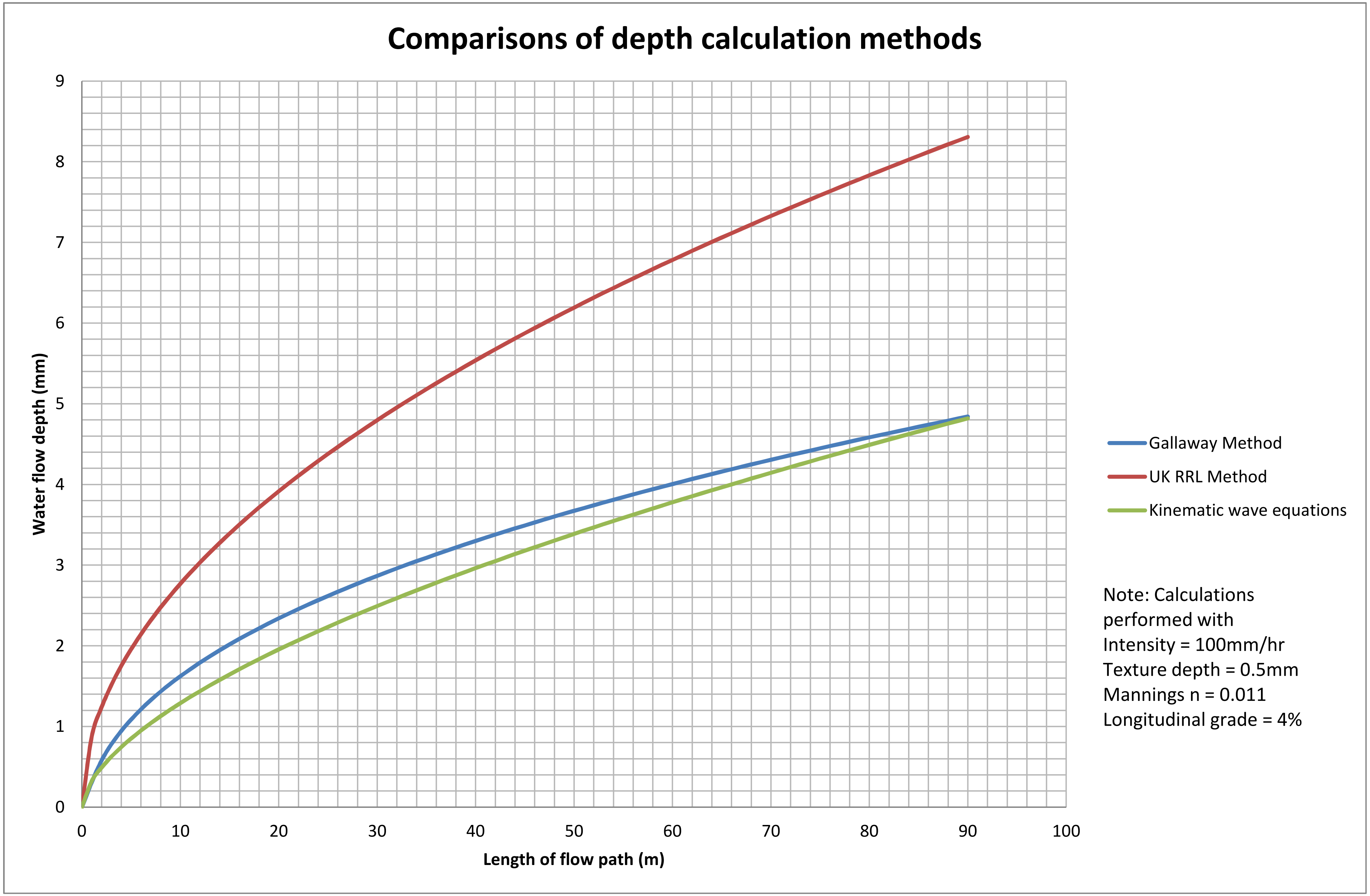
Comparisons of depth calculation methods
Water flow depth (mm)
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 1%

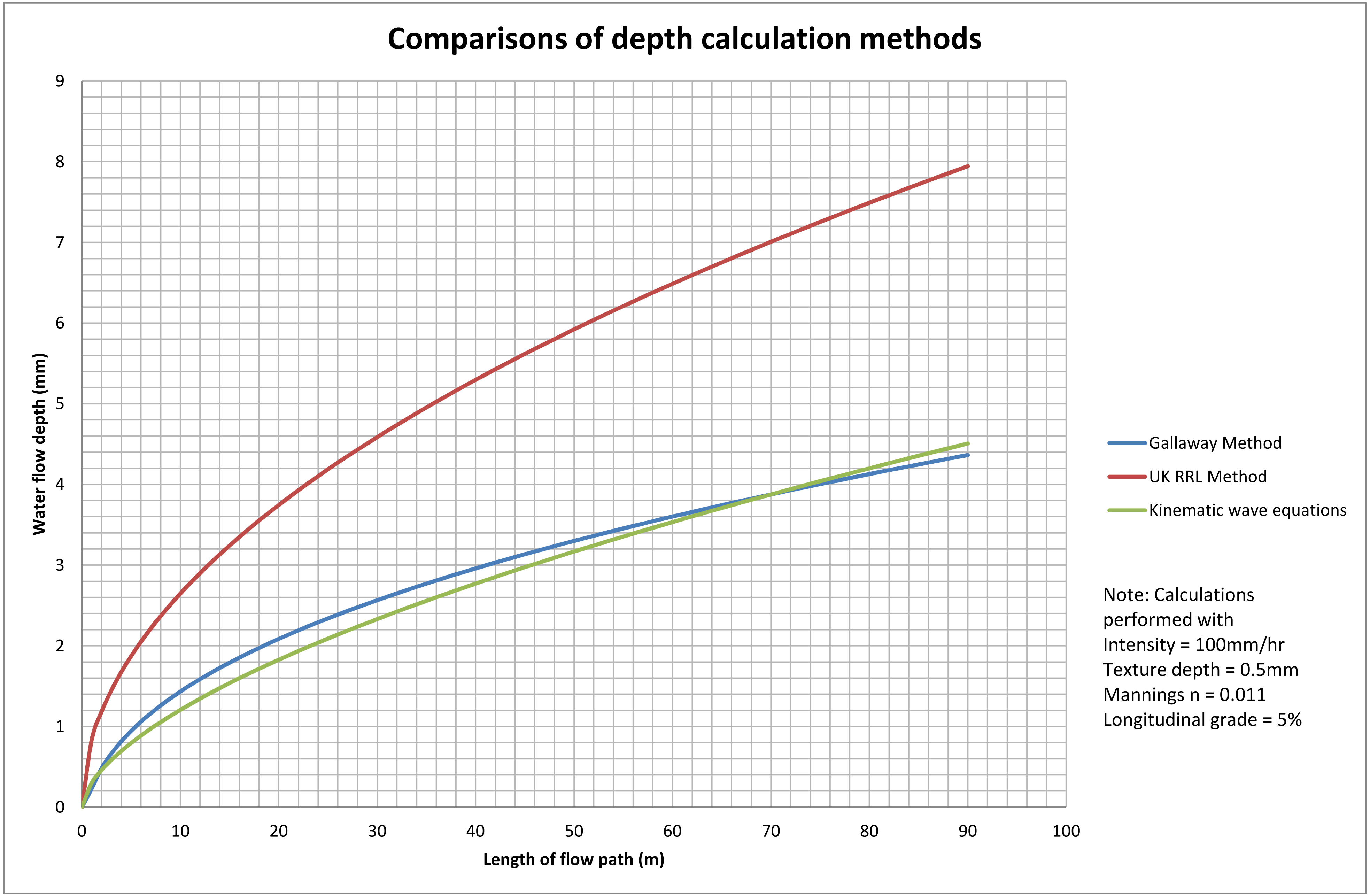


Comparisons of depth calculation methods
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
Water flow depth (mm)
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations
performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 2%

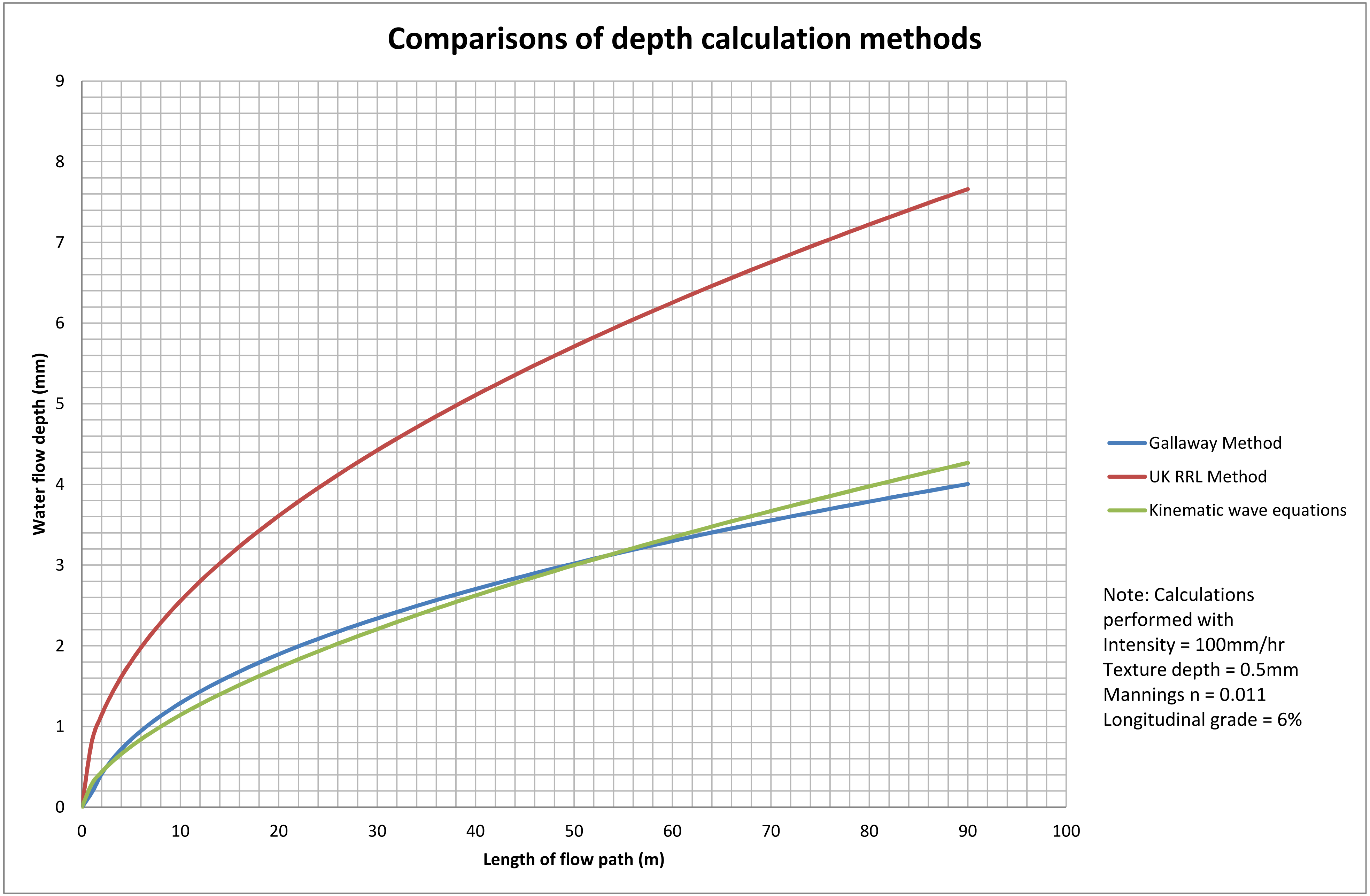


Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations
performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 3%

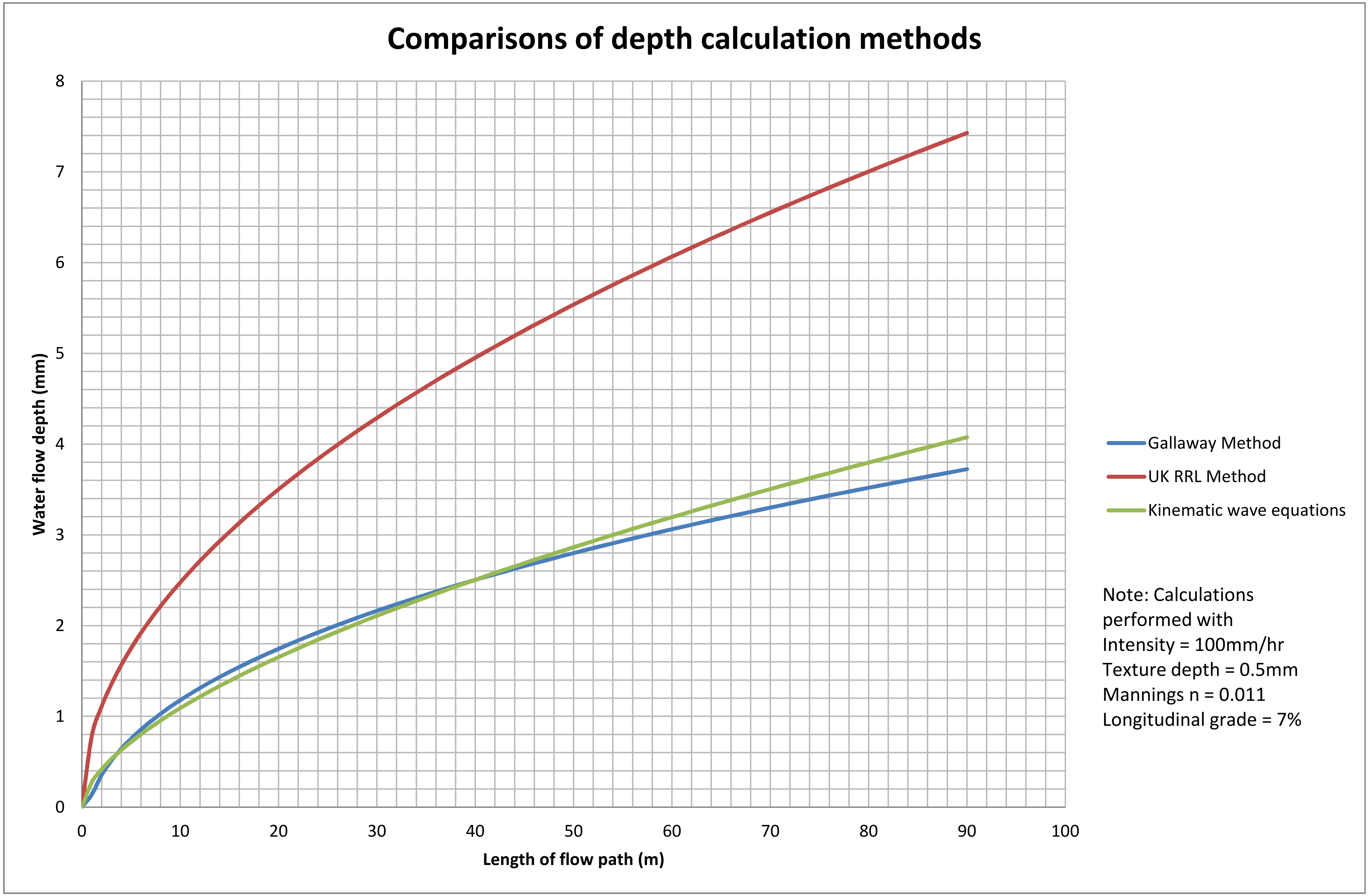

Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
8
9
Length of flow path (m)
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 4%



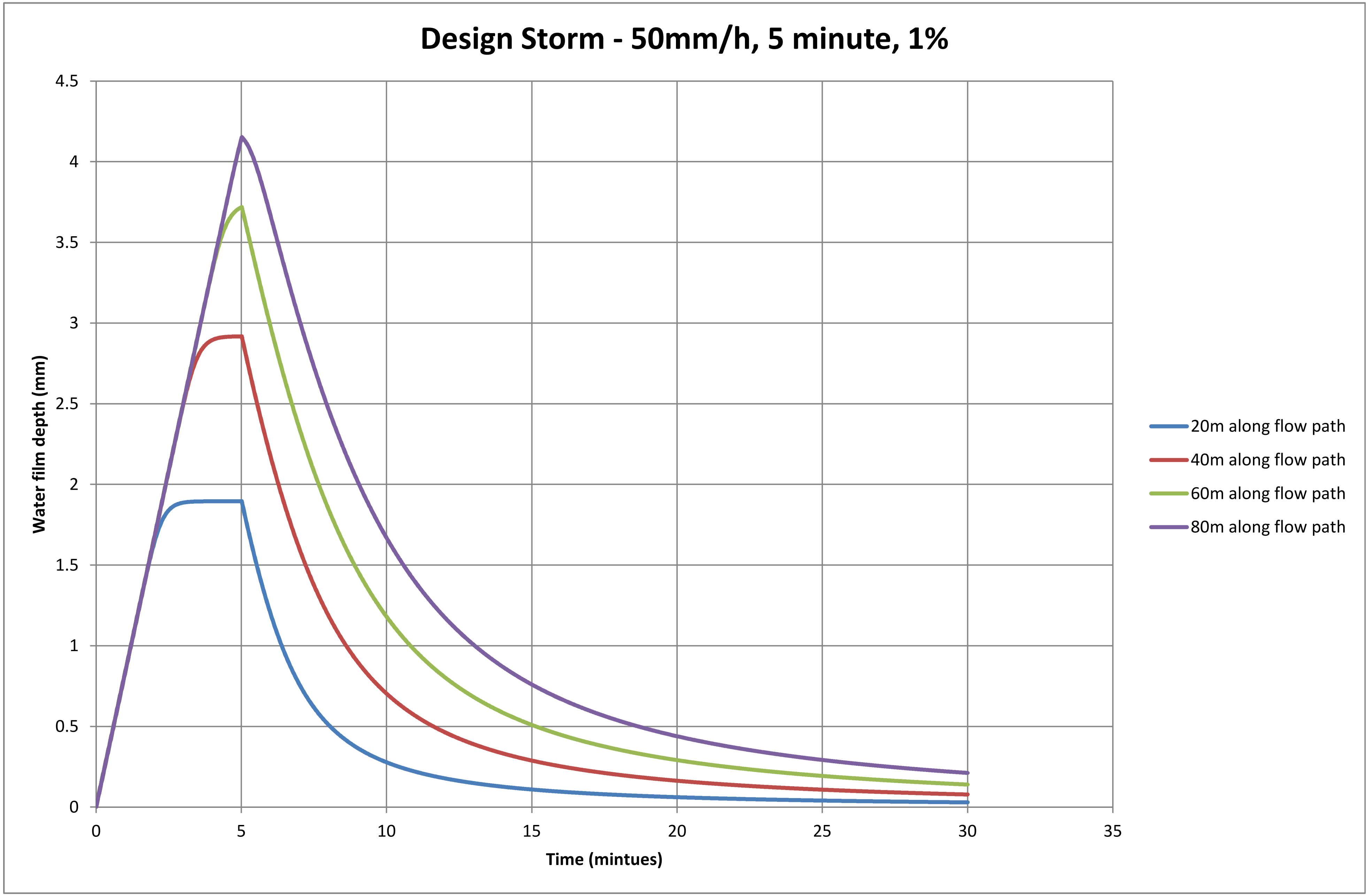
Comparisons of depth calculation methods
Water flow depth (mm)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 5%



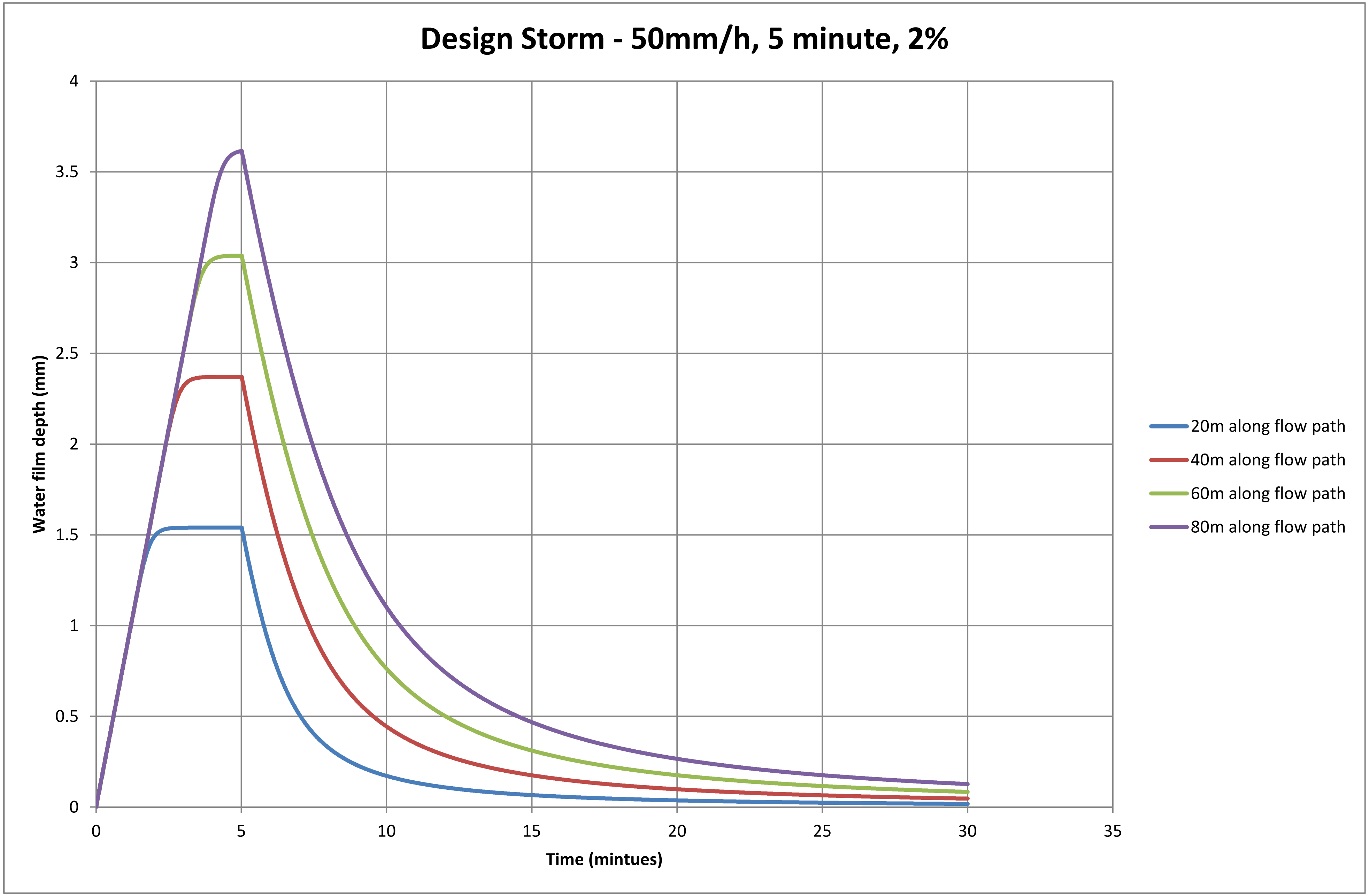
Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
8
9
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 6%


Comparisons of depth calculation methods
Water flow depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
90
100
Gallaway Method
UK RRL Method
Kinematic wave equations
Note: Calculations performed with
Intensity = 100mm/hr
Texture depth = 0.5mm
Mannings n = 0.011
Longitudinal grade = 7%

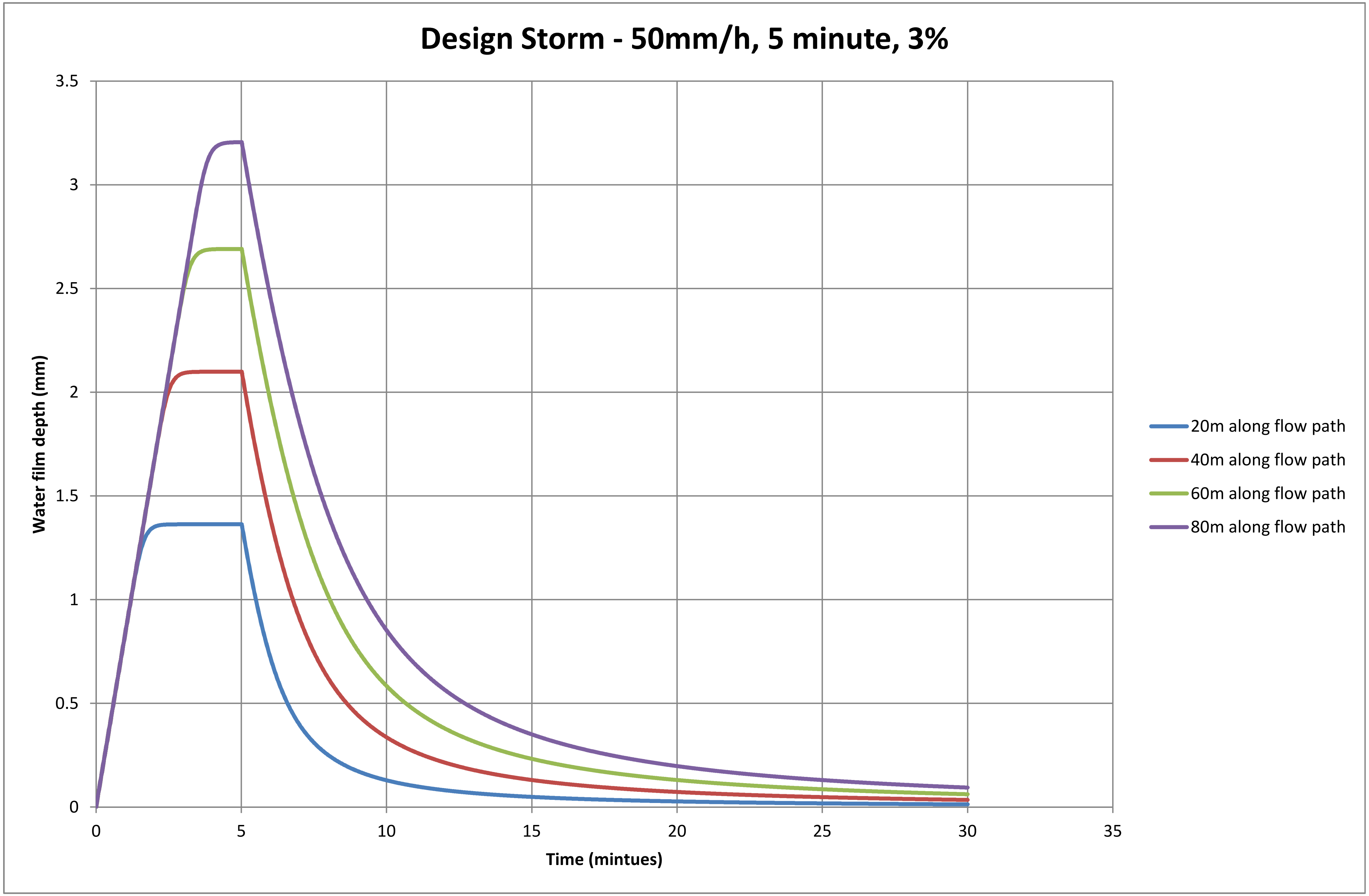
Appendix E - Design Storm graphs



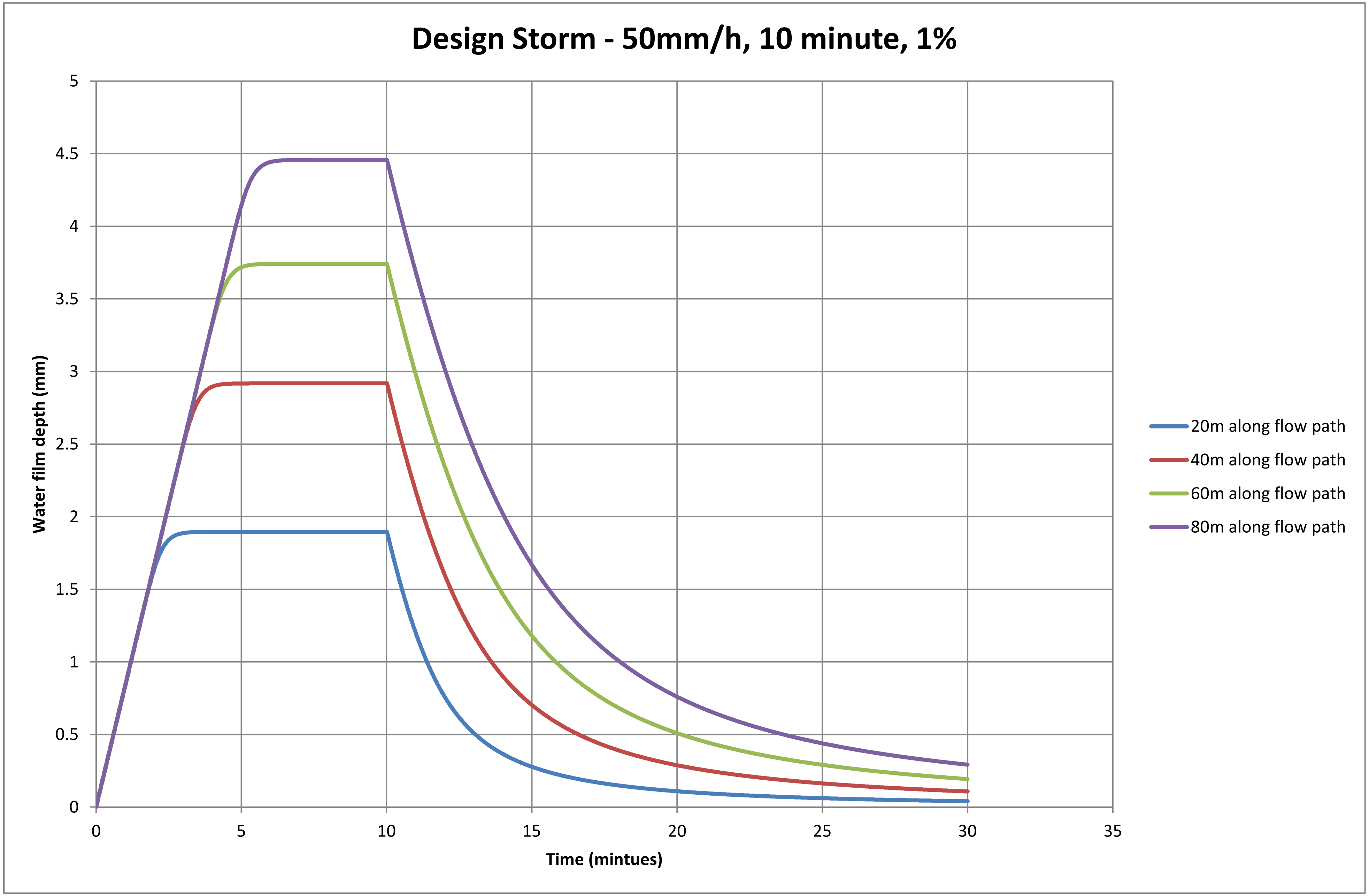
Design Storm - 50mm/h, 5 minute, 1%
Water film depth (mm)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
Time (mintues)
20m along flow path
40m along flow path
60m along flow path
80m along flow path

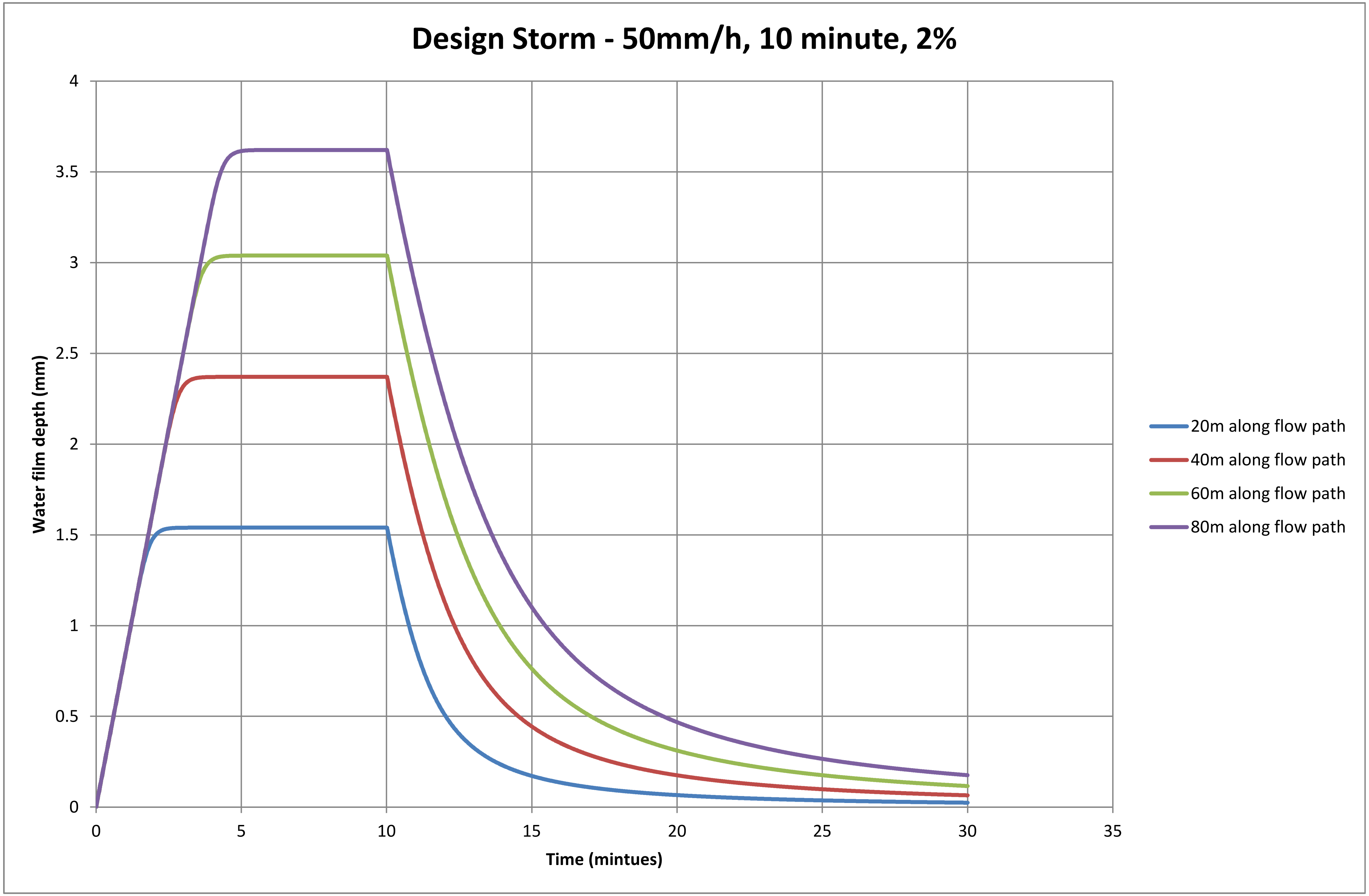


Design Storm - 50mm/h, 5 minute, 2%
Water film depth (mm)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
5
10
15
20
25
30
35
Time (mintues)
20m along flow path
40m along flow path
60m along flow path
80m along flow path

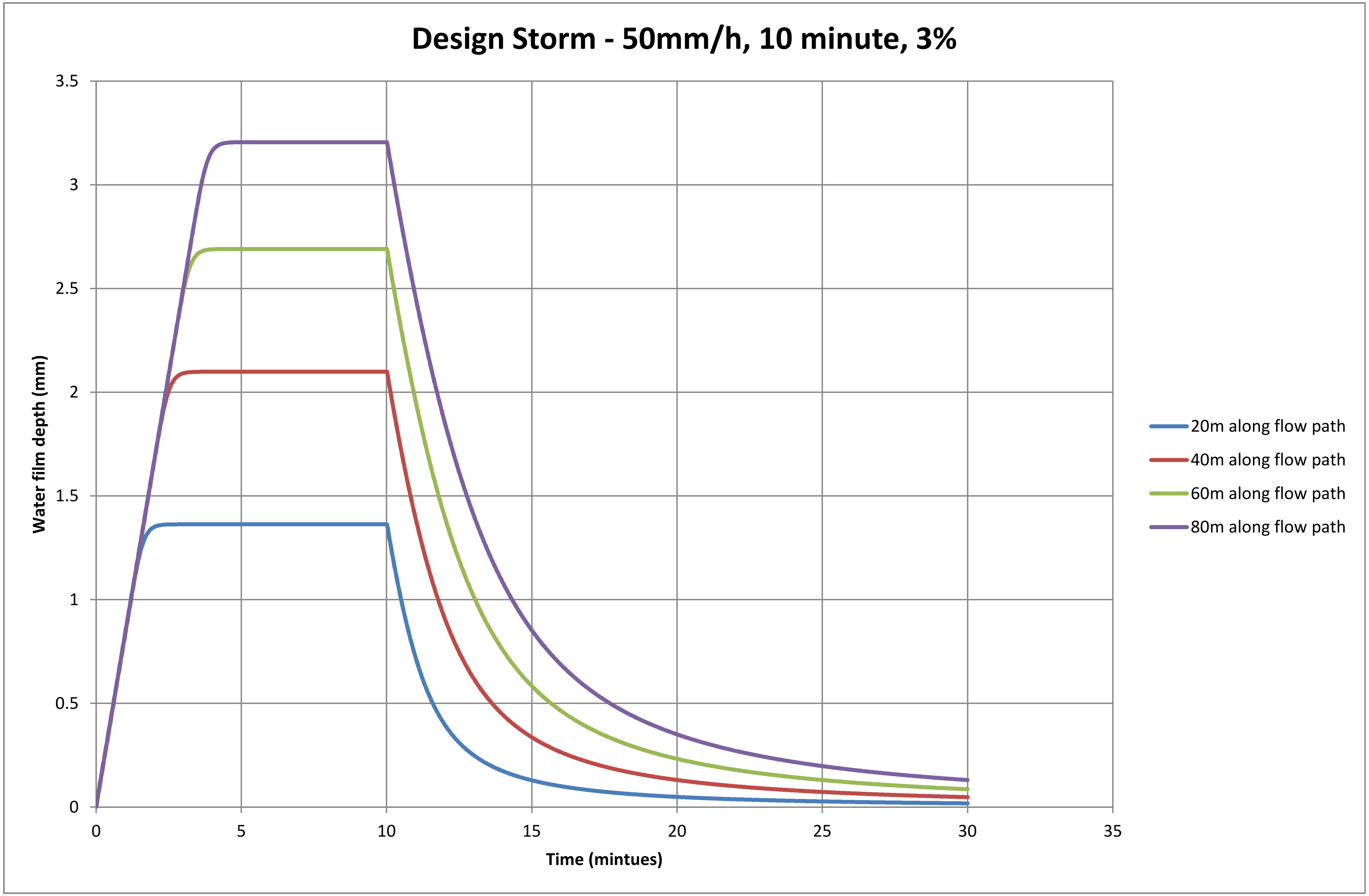


Design Storm - 50mm/h, 5 minute, 3%
Water film depth (mm)
Time (mintues)
0
0.5
1
1.5
2
2.5
3
3.5
5
10
15
20
25
30
35
20m along flow path
40m along flow path
60m along flow path
80m along flow path

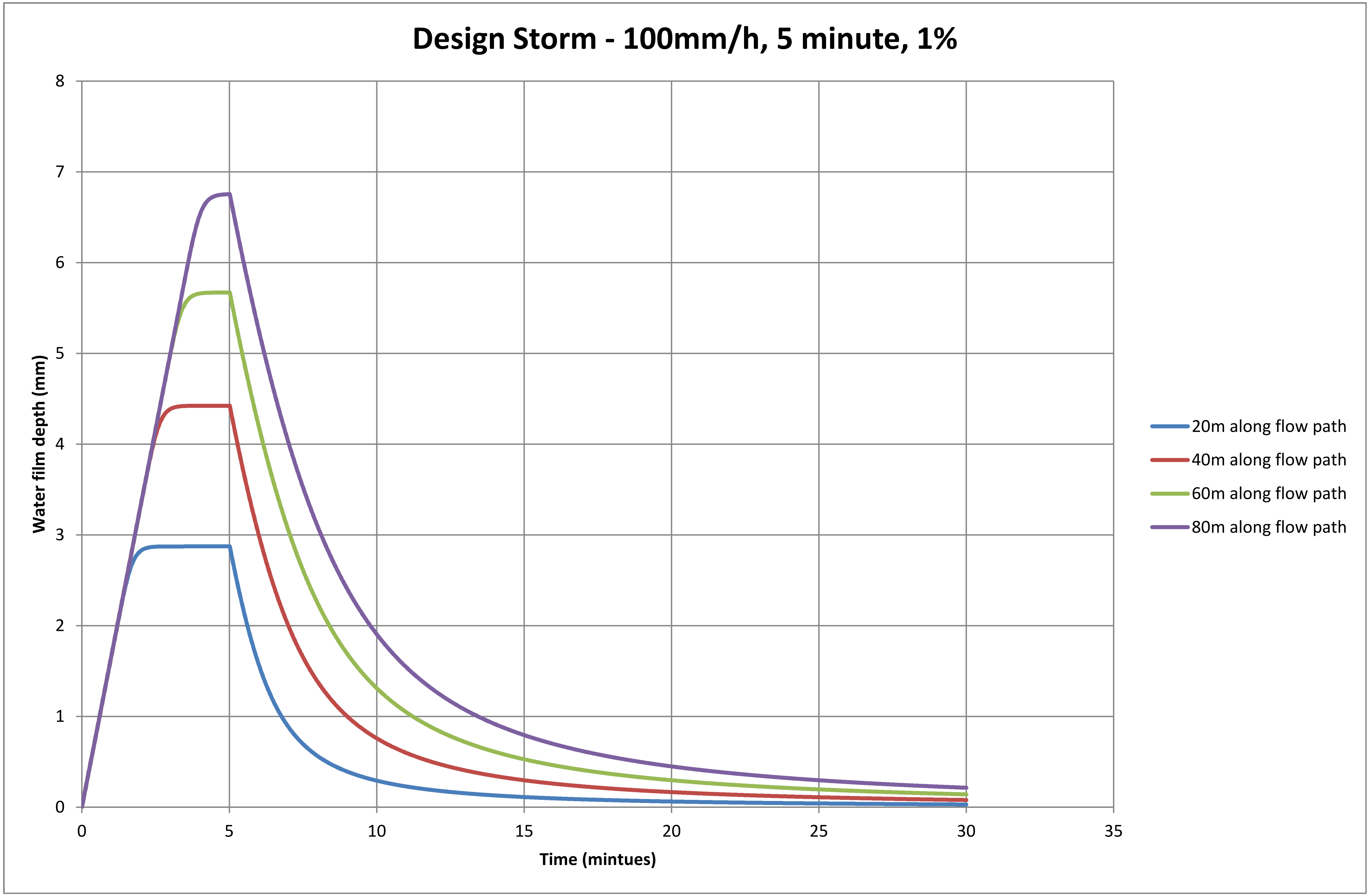

Design Storm - 50mm/h, 10 minute, 1%
Water film depth (mm)
Time (mintues)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
5
10
15
20
25
30
35
20m along flow path
40m along flow path
60m along flow path
80m along flow path



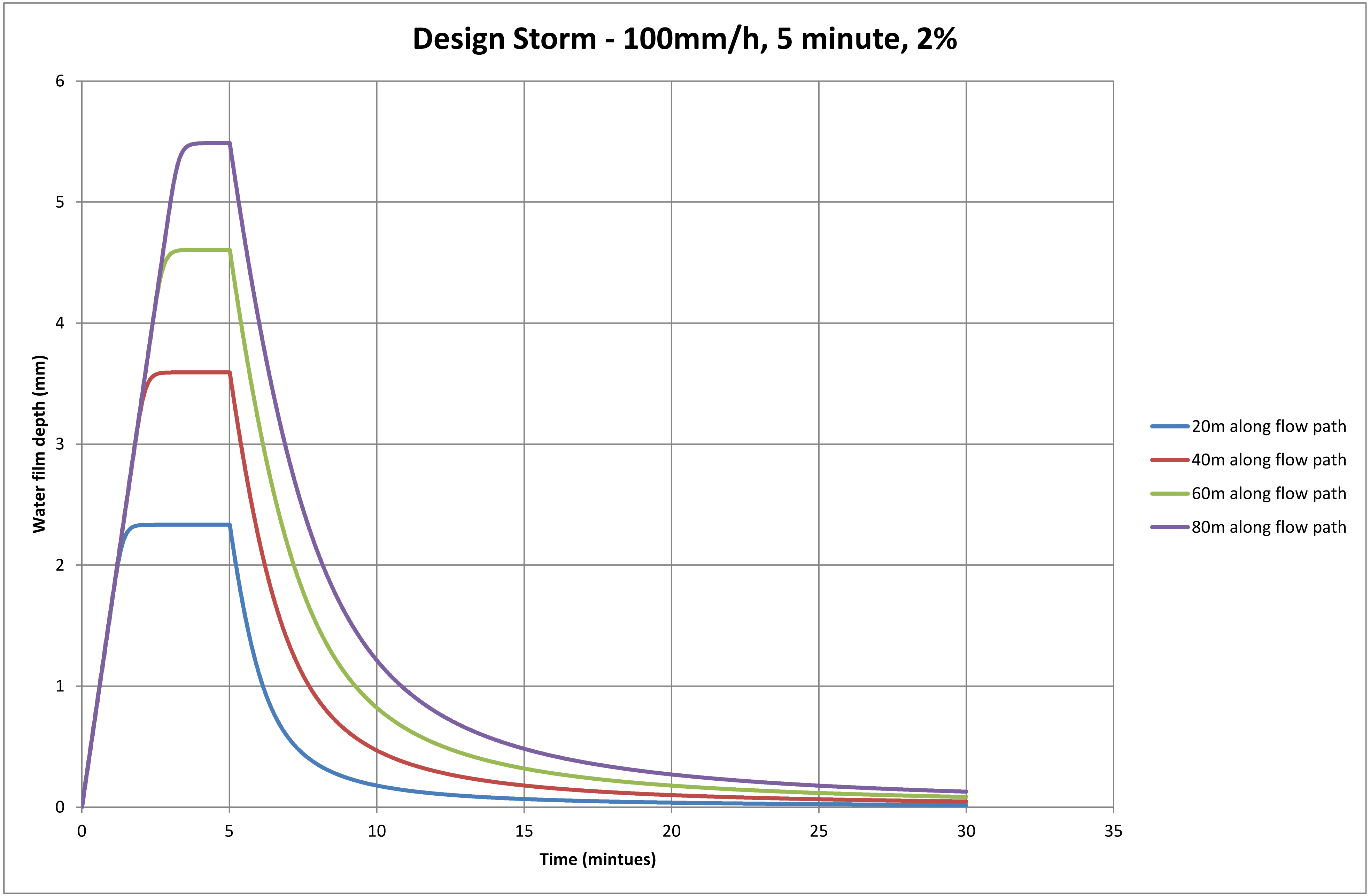
Design Storm - 50mm/h, 10 minute, 2%
Water film depth (mm)
Time (mintues)
0
0.5
1
1.5
2
2.5
3
3.5
4
0
5
10
15
20
25
30
35
20m along flow path
40m along flow path
60m along flow path
80m along flow path

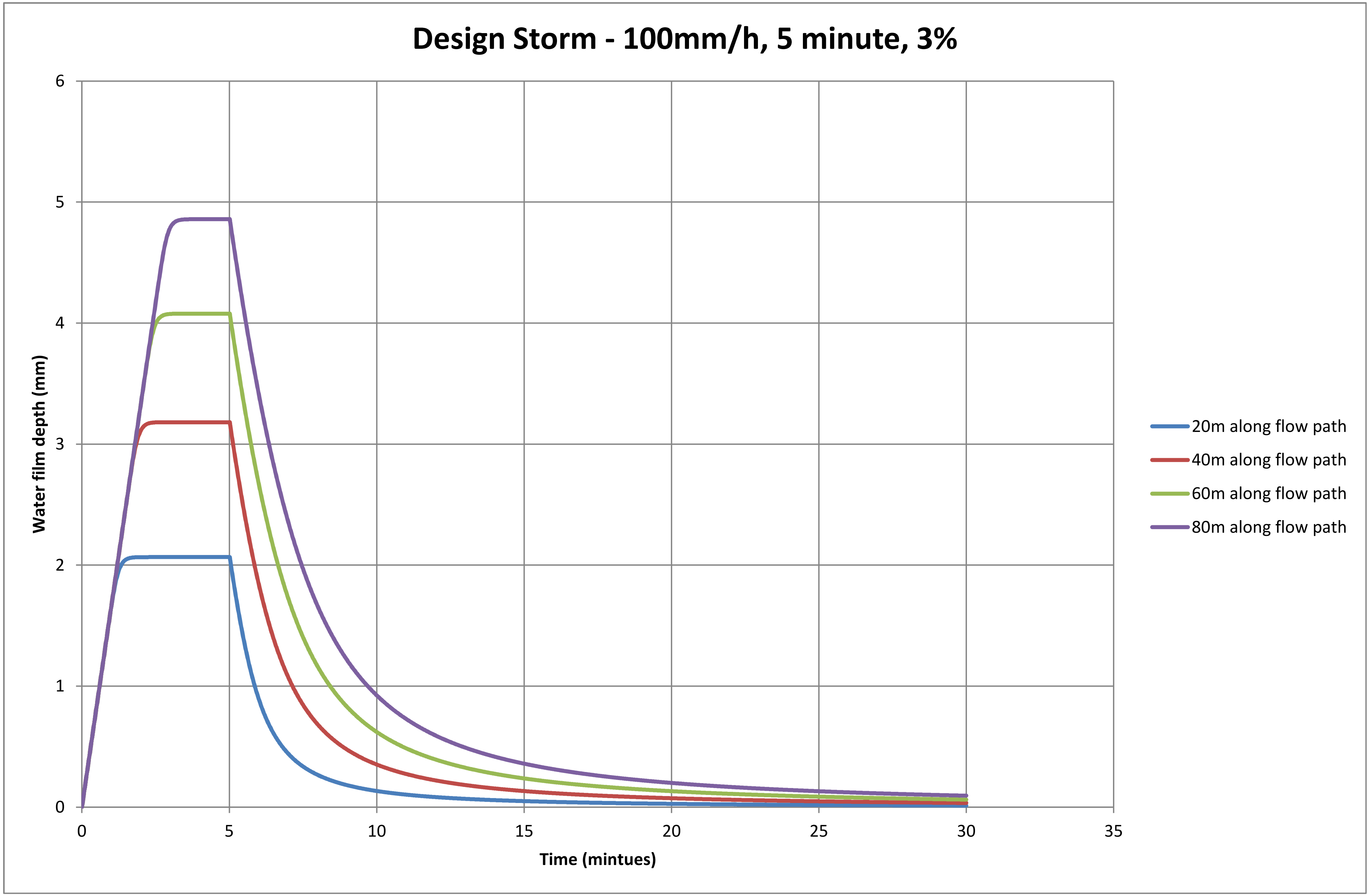


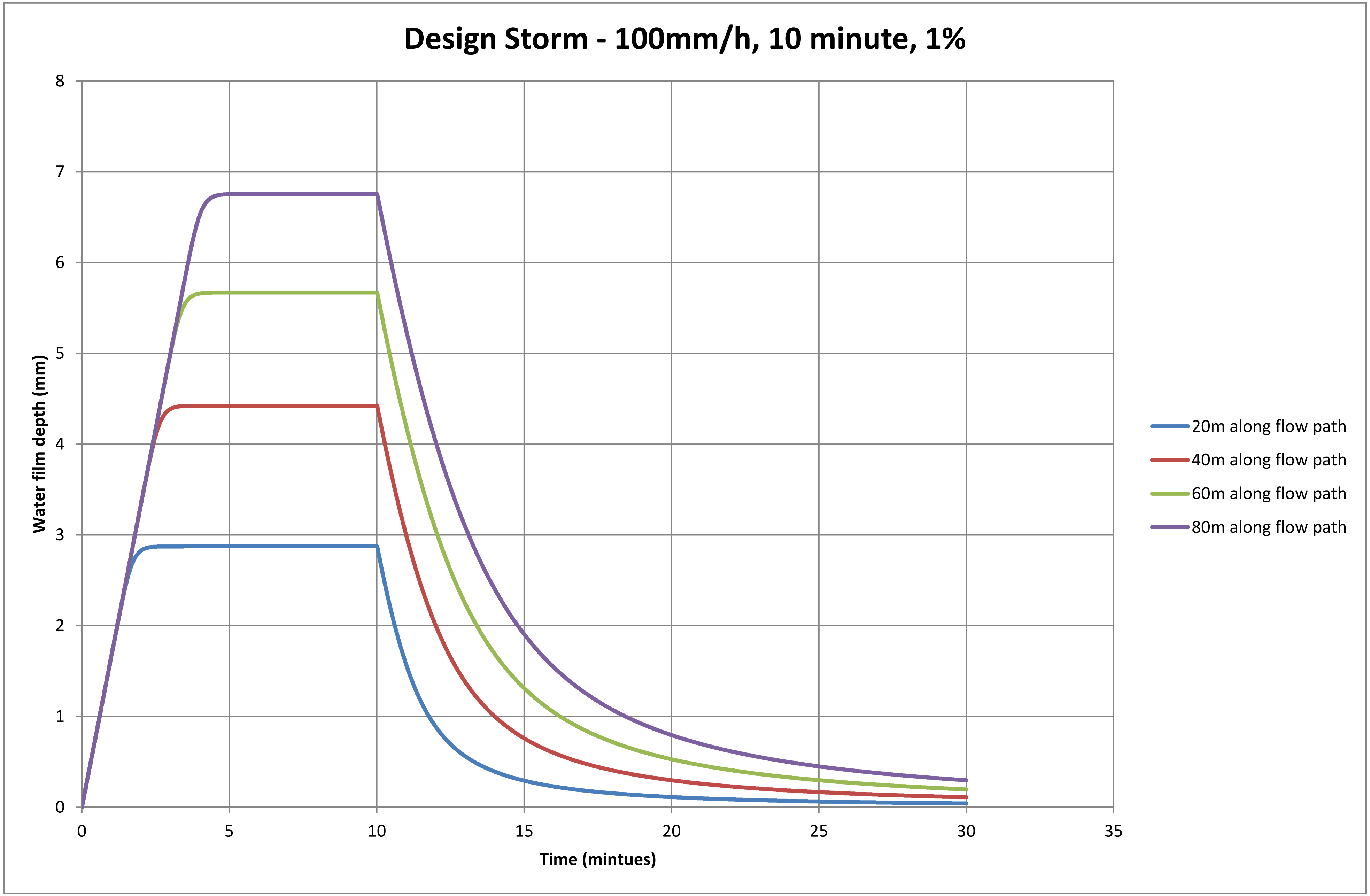
Design Storm - 50mm/h, 10 minute, 3%
Water film depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
0
5
10
15
20
25
30
35
Time (mintues)
20m along flow path
40m along flow path
60m along flow path
80m along flow path



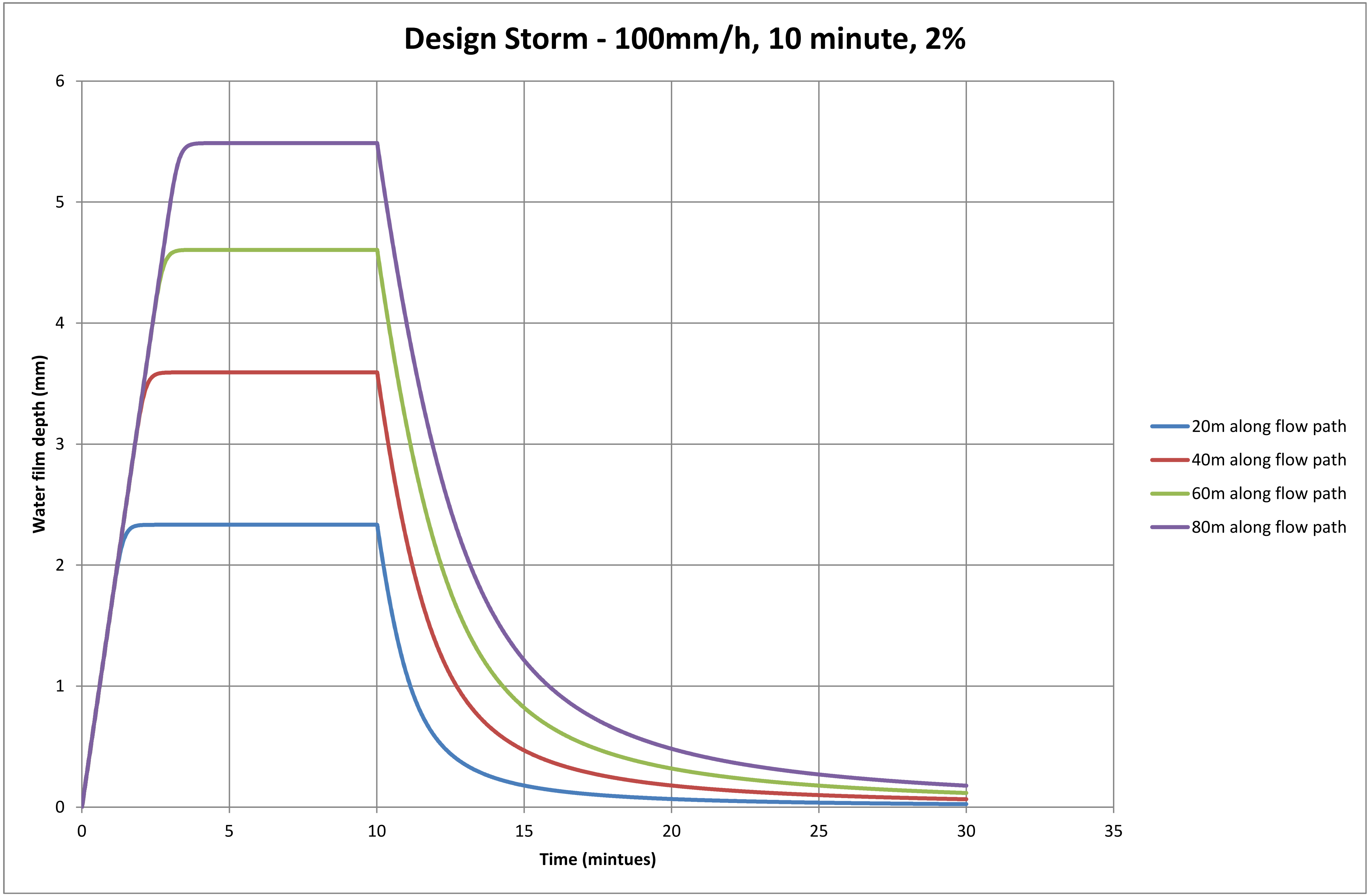
Design Storm - 100mm/h, 5 minute, 1%
Water film depth (mm)
Time (mintues)
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35
20m along flow path
40m along flow path
60m along flow path
80m along flow path


Design Storm - 100mm/h, 5 minute, 2%
Water film depth (mm)
Time (mintues)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
20m along flow path
40m along flow path
60m along flow path
80m along flow path

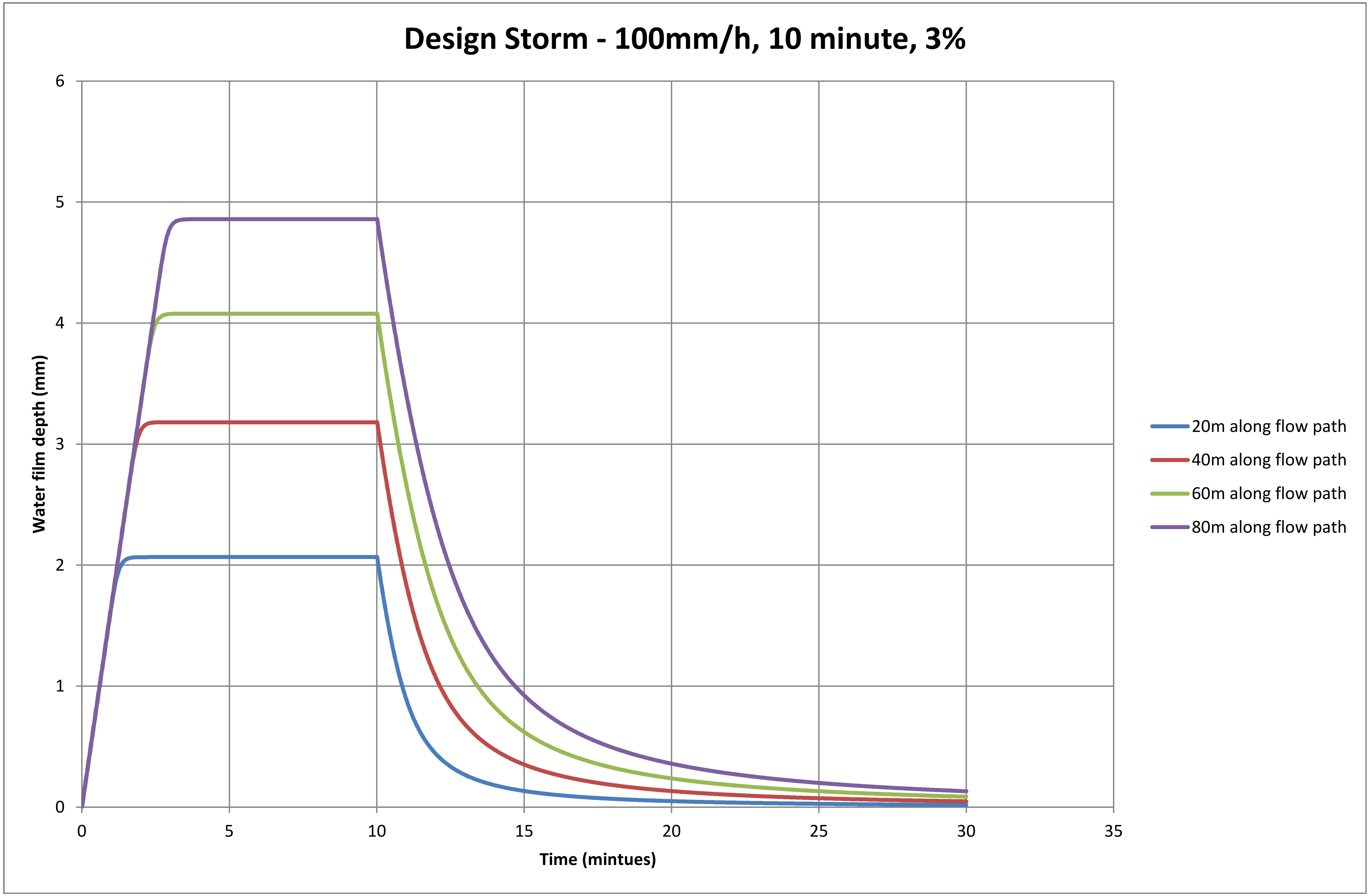

Design Storm - 100mm/h, 5 minute, 3%
Water film depth (mm)
0
1
2
3
4
5
6
Time (mintues)
0
5
10
15
20
25
30
35
20m along flow path
40m along flow path
60m along flow path
80m along flow path



Design Storm - 100mm/h, 10 minute, 1%
Water film depth (mm)
Time (mintues)
20m along flow path
40m along flow path
60m along flow path
80m along flow path
0
1
2
3
4
5
6
7
8
0
5
10
15
20
25
30
35

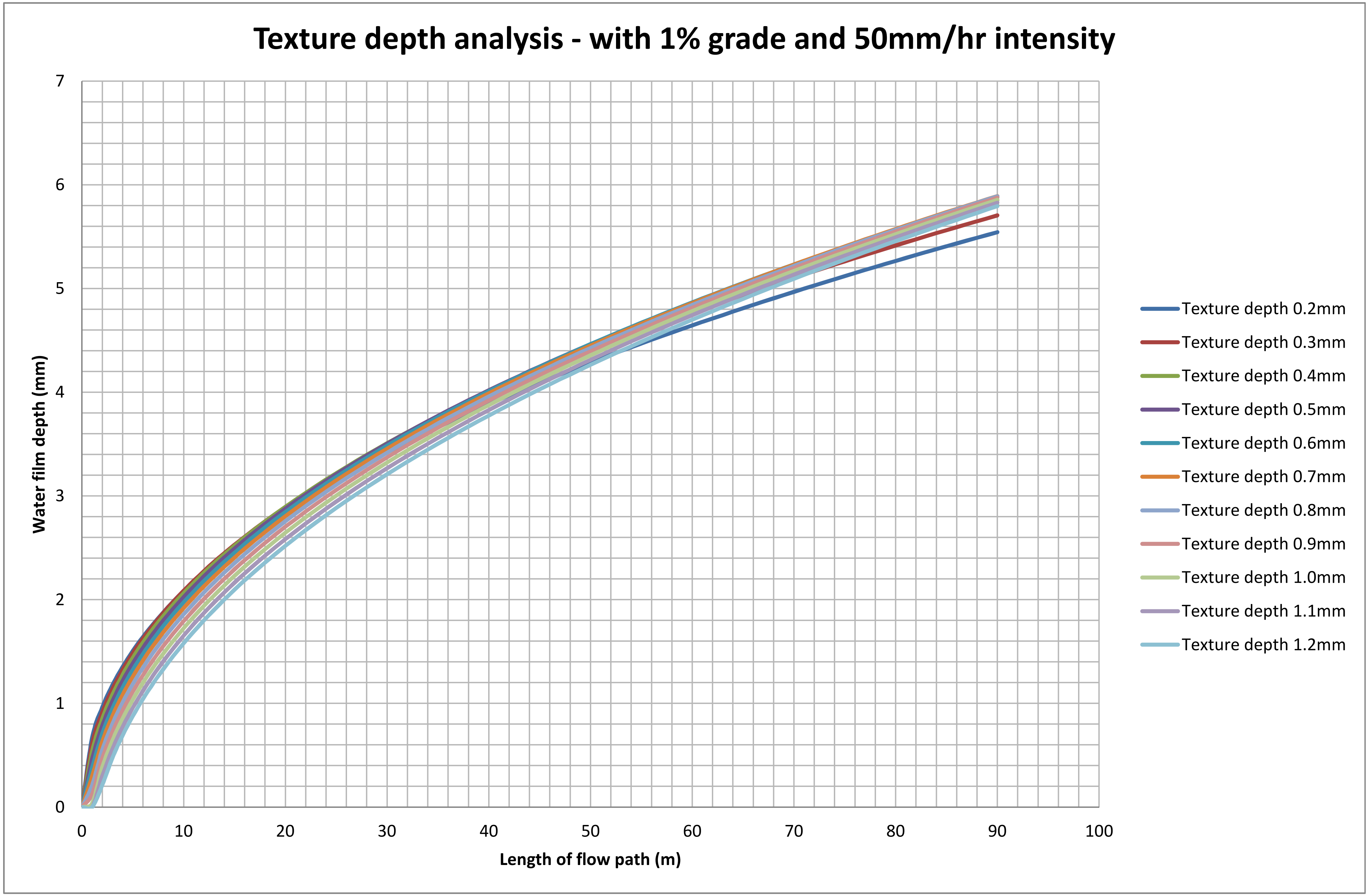


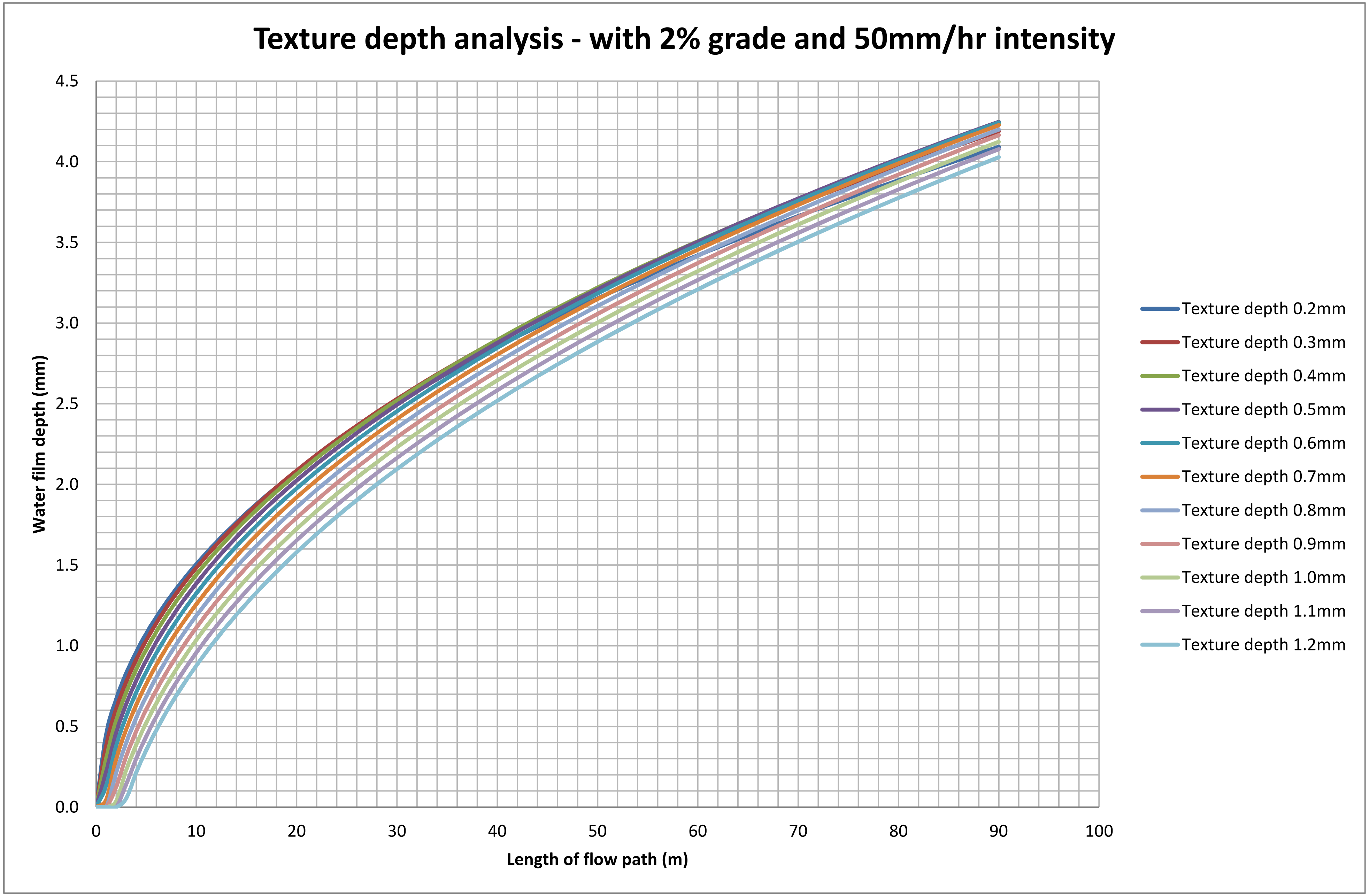
Design Storm - 100mm/h, 10 minute, 2%
Water film depth (mm)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
Time (mintues)
20m along flow path
40m along flow path
60m along flow path
80m along flow path

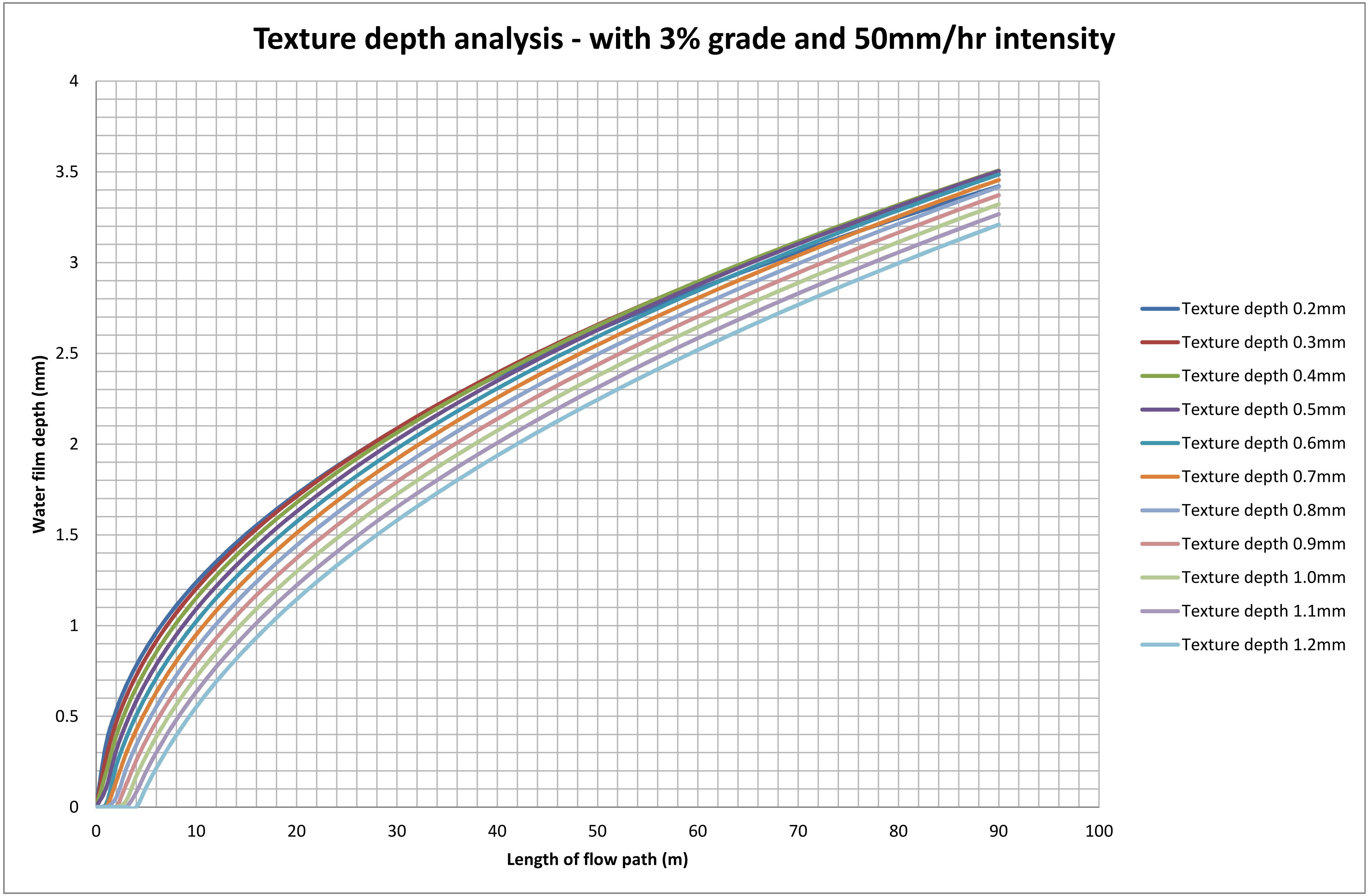


Design Storm - 100mm/h, 10 minute, 3%
Water film depth (mm)
0
1
2
3
4
5
6
0
5
10
15
20
25
30
35
Time (mintues)
20m along flow path
40m along flow path
60m along flow path
80m along flow path

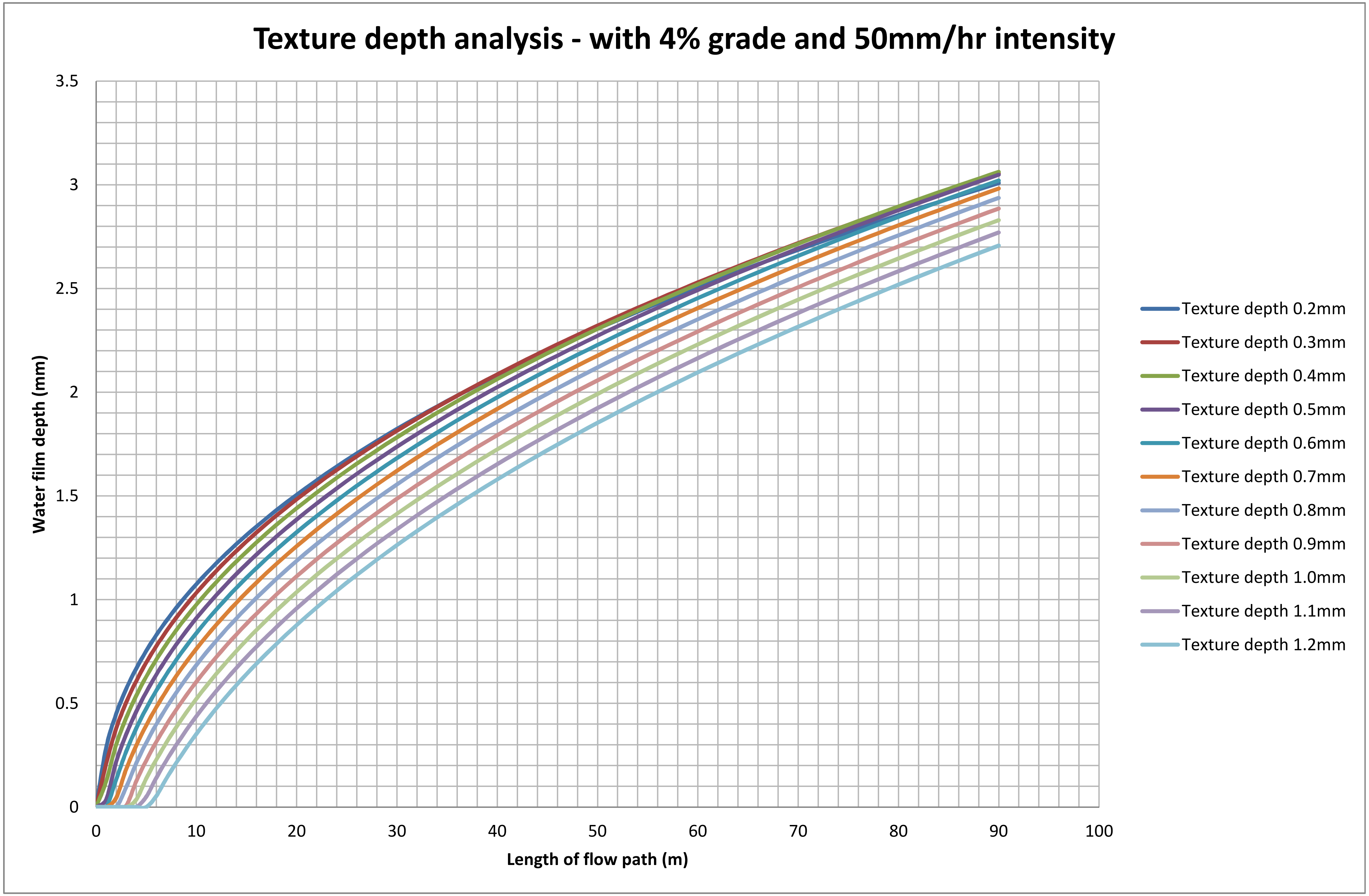
Appendix F - Texture Depth graphs


Texture depth analysis - with 1% grade and 50mm/hr intensity
Water film depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90
100
Texture depth 0.2mm
Texture depth 0.3mm
Texture depth 0.4mm
Texture depth 0.5mm
Texture depth 0.6mm
Texture depth 0.7mm
Texture depth 0.8mm
Texture depth 0.9mm
Texture depth 1.0mm
Texture depth 1.1mm
Texture depth 1.2mm

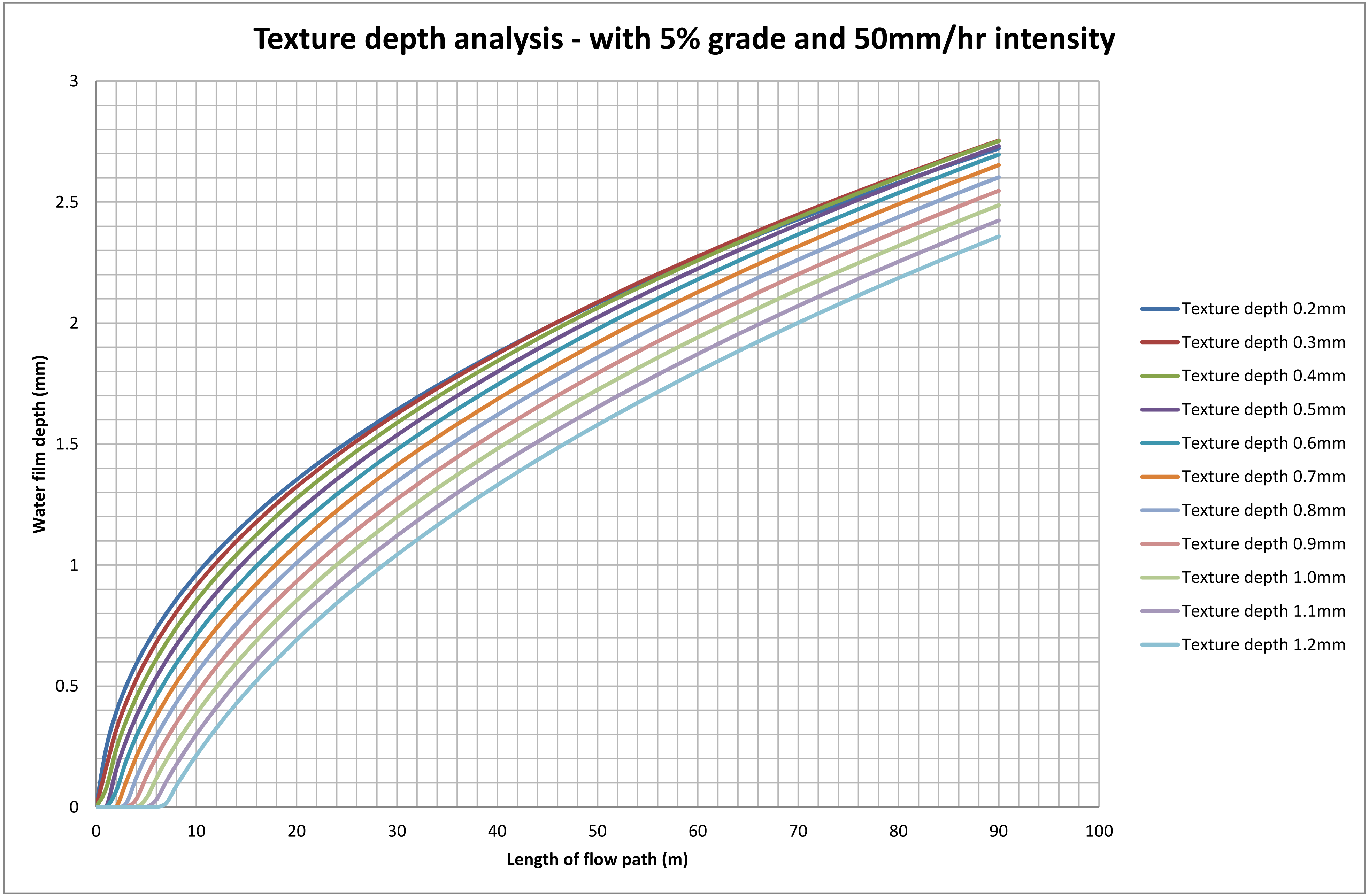

Texture depth analysis - with 2% grade and 50mm/hr intensity
Water film depth (mm)
Length of flow path (m)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
0
10
20
30
40
50
60
70
80
90
100
Texture depth 0.2mm
Texture depth 0.3mm
Texture depth 0.4mm
Texture depth 0.5mm
Texture depth 0.6mm
Texture depth 0.7mm
Texture depth 0.8mm
Texture depth 0.9mm
Texture depth 1.0mm
Texture depth 1.1mm
Texture depth 1.2mm

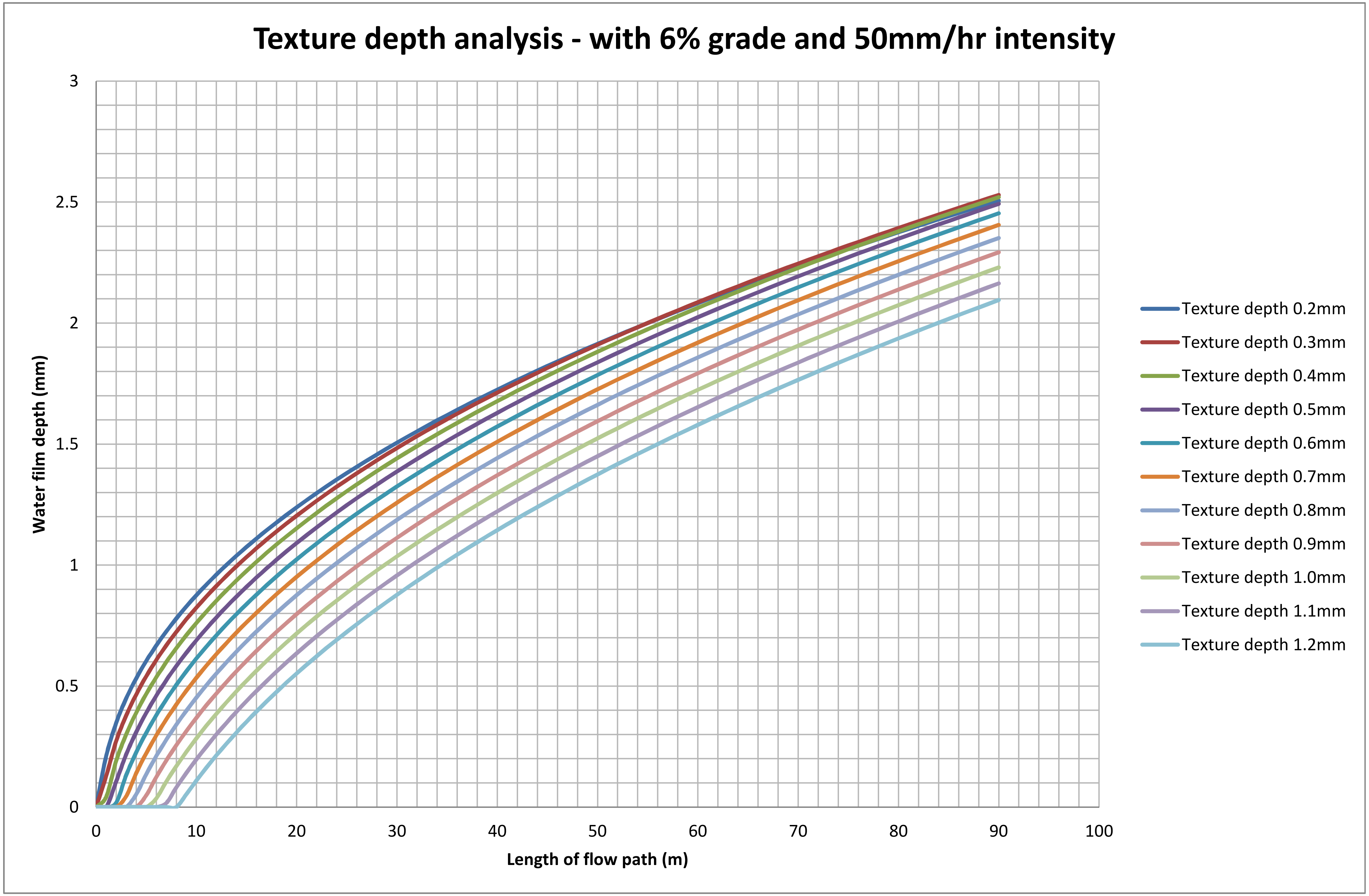


Texture depth analysis - with 3% grade and 50mm/hr intensity
Water film depth (mm)
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Texture depth 0.2mm
Texture depth 0.3mm
Texture depth 0.4mm
Texture depth 0.5mm
Texture depth 0.6mm
Texture depth 0.7mm
Texture depth 0.8mm
Texture depth 0.9mm
Texture depth 1.0mm
Texture depth 1.1mm
Texture depth 1.2mm

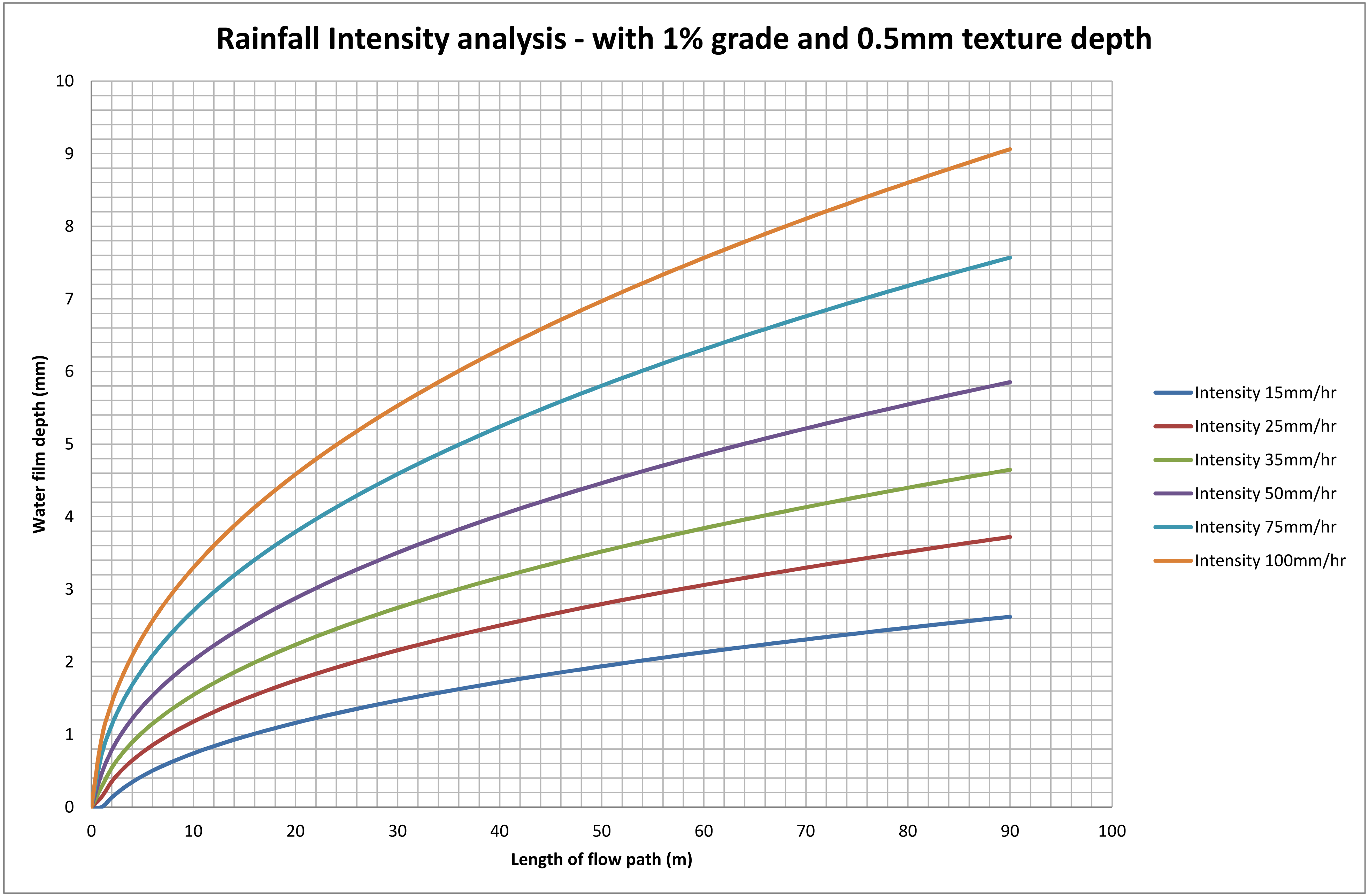


Texture depth analysis - with 4% grade and 50mm/hr intensity
Water film depth (mm)
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Texture depth 0.2mm
Texture depth 0.3mm
Texture depth 0.4mm
Texture depth 0.5mm
Texture depth 0.6mm
Texture depth 0.7mm
Texture depth 0.8mm
Texture depth 0.9mm
Texture depth 1.0mm
Texture depth 1.1mm
Texture depth 1.2mm

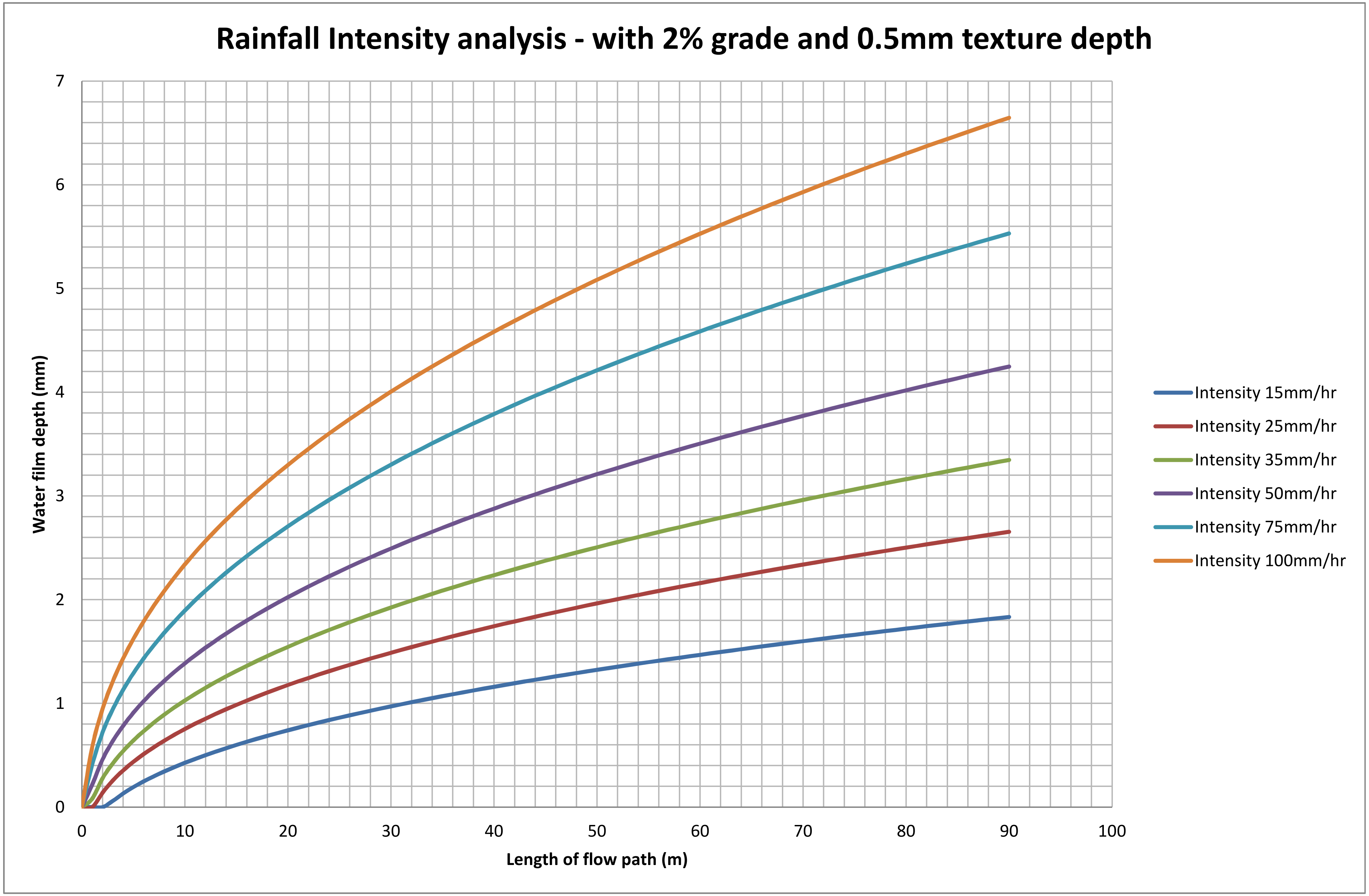

Texture depth analysis - with 5% grade and 50mm/hr intensity
Water film depth (mm)
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Texture depth 0.2mm
Texture depth 0.3mm
Texture depth 0.4mm
Texture depth 0.5mm
Texture depth 0.6mm
Texture depth 0.7mm
Texture depth 0.8mm
Texture depth 0.9mm
Texture depth 1.0mm
Texture depth 1.1mm
Texture depth 1.2mm

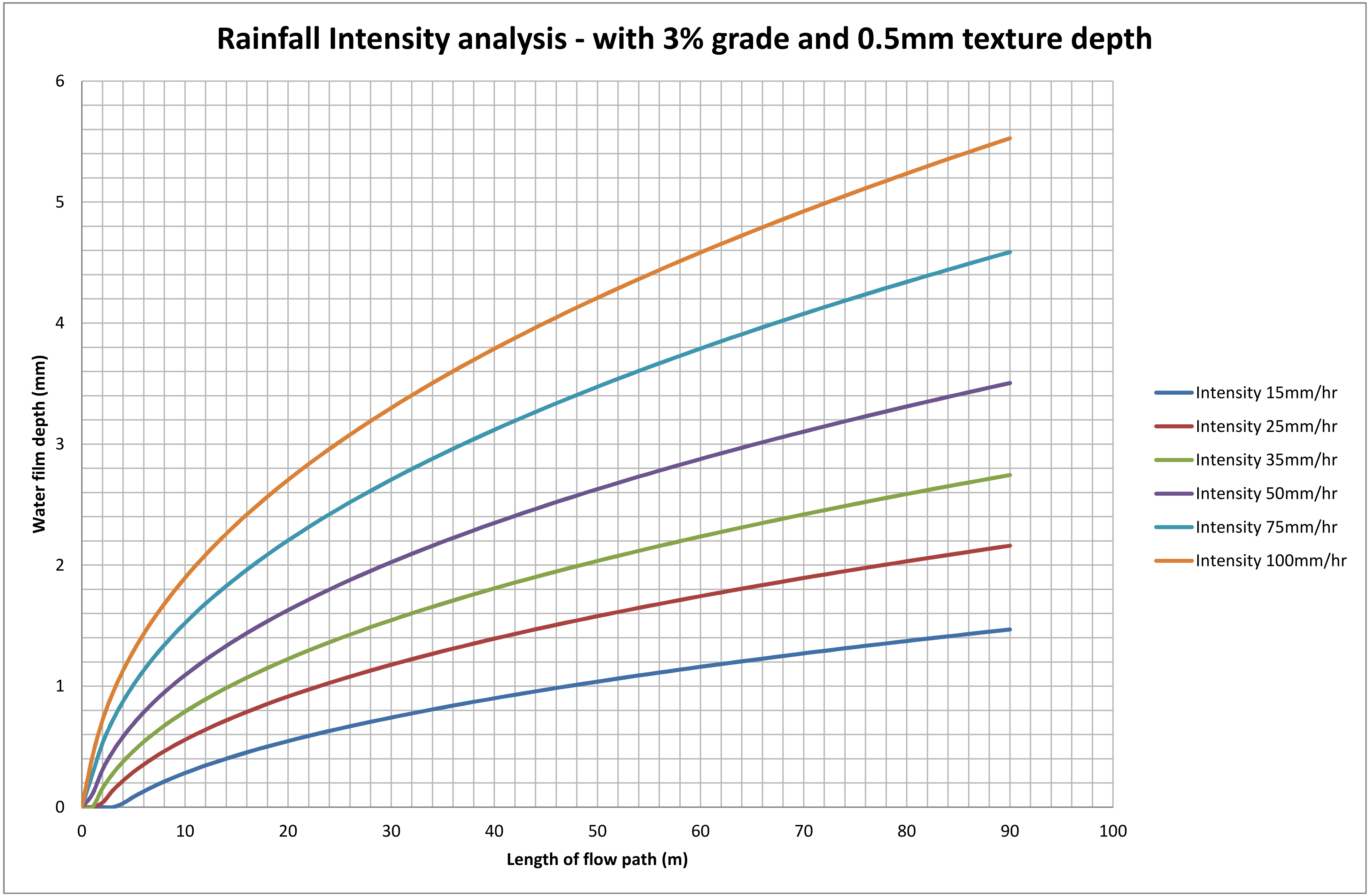

Texture depth analysis - with 6% grade and 50mm/hr intensity
Water film depth (mm)
Length of flow path (m)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
40
50
60
70
80
90
100
Texture depth 0.2mm
Texture depth 0.3mm
Texture depth 0.4mm
Texture depth 0.5mm
Texture depth 0.6mm
Texture depth 0.7mm
Texture depth 0.8mm
Texture depth 0.9mm
Texture depth 1.0mm
Texture depth 1.1mm
Texture depth 1.2mm

Appendix G - Rainfall intensity analysis graphs

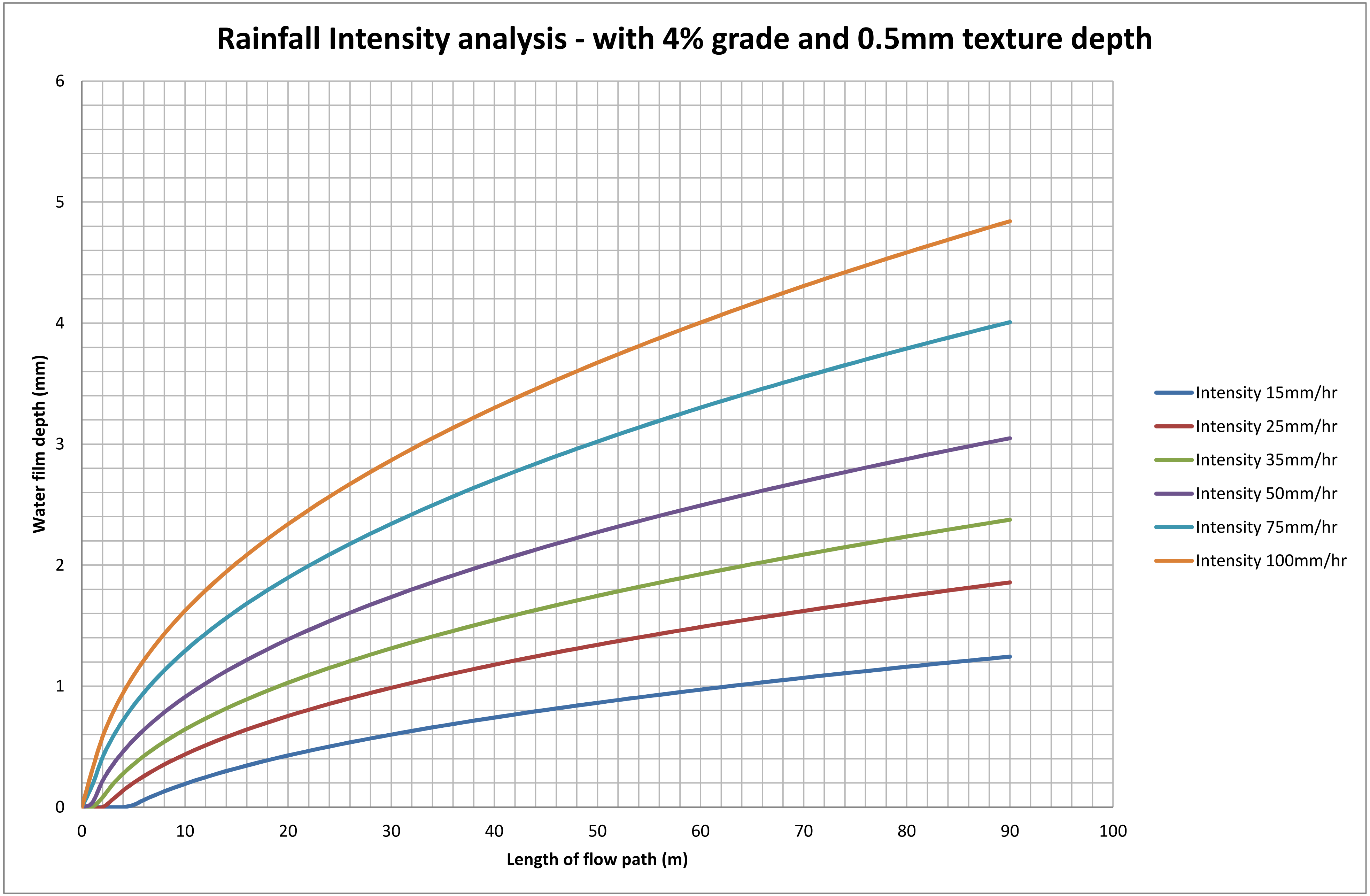


Rainfall Intensity analysis - with 1% grade and 0.5mm texture depth
Water film depth (mm)
0
1
2
3
4
5
6
7
8
9
10
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Intensity 15mm/hr
Intensity 25mm/hr
Intensity 35mm/hr
Intensity 50mm/hr
Intensity 75mm/hr
Intensity 100mm/hr

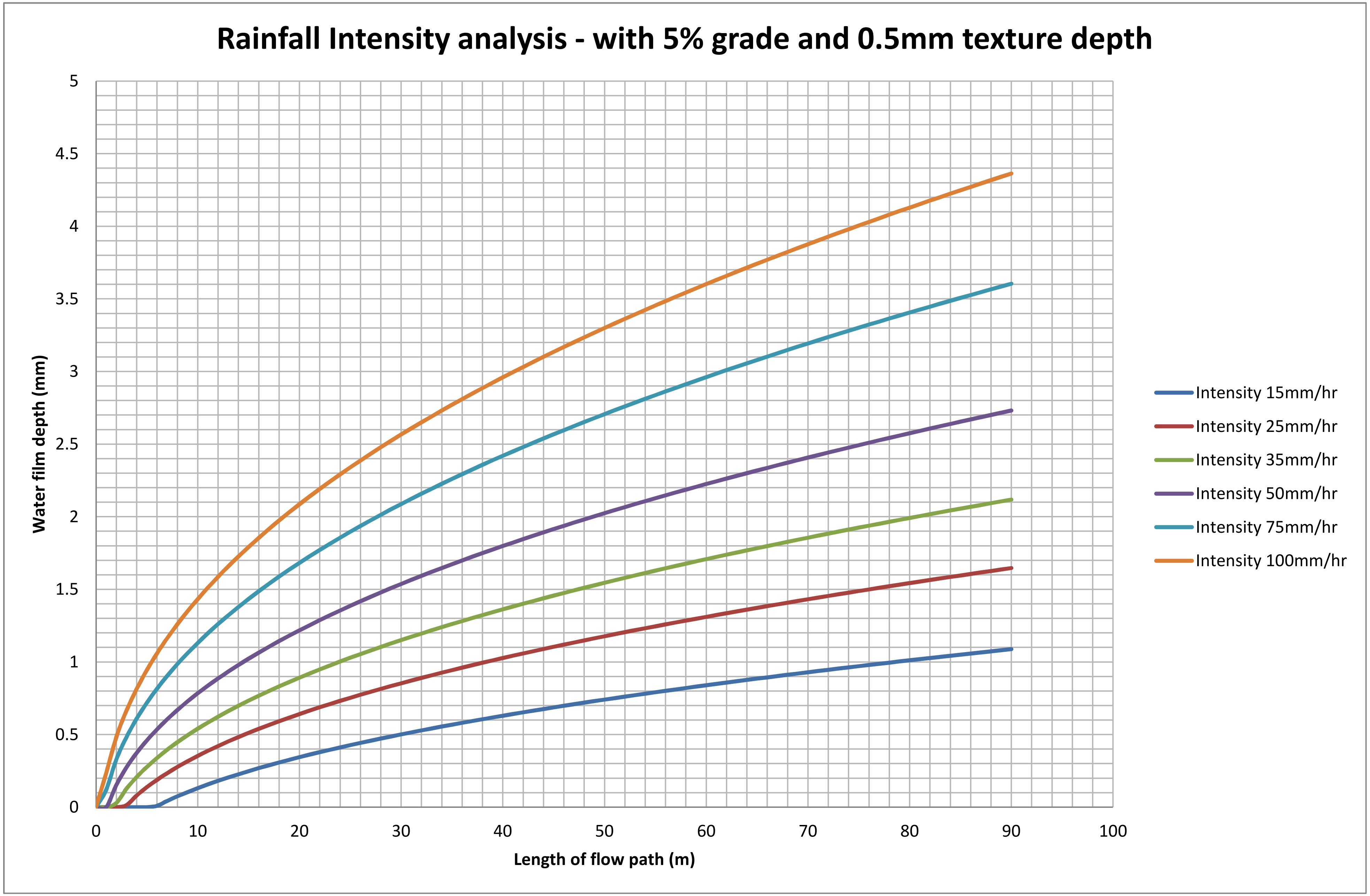

Rainfall Intensity analysis - with 2% grade and 0.5mm texture depth
Water film depth (mm)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Intensity 15mm/hr
Intensity 25mm/hr
Intensity 35mm/hr
Intensity 50mm/hr
Intensity 75mm/hr
Intensity 100mm/hr

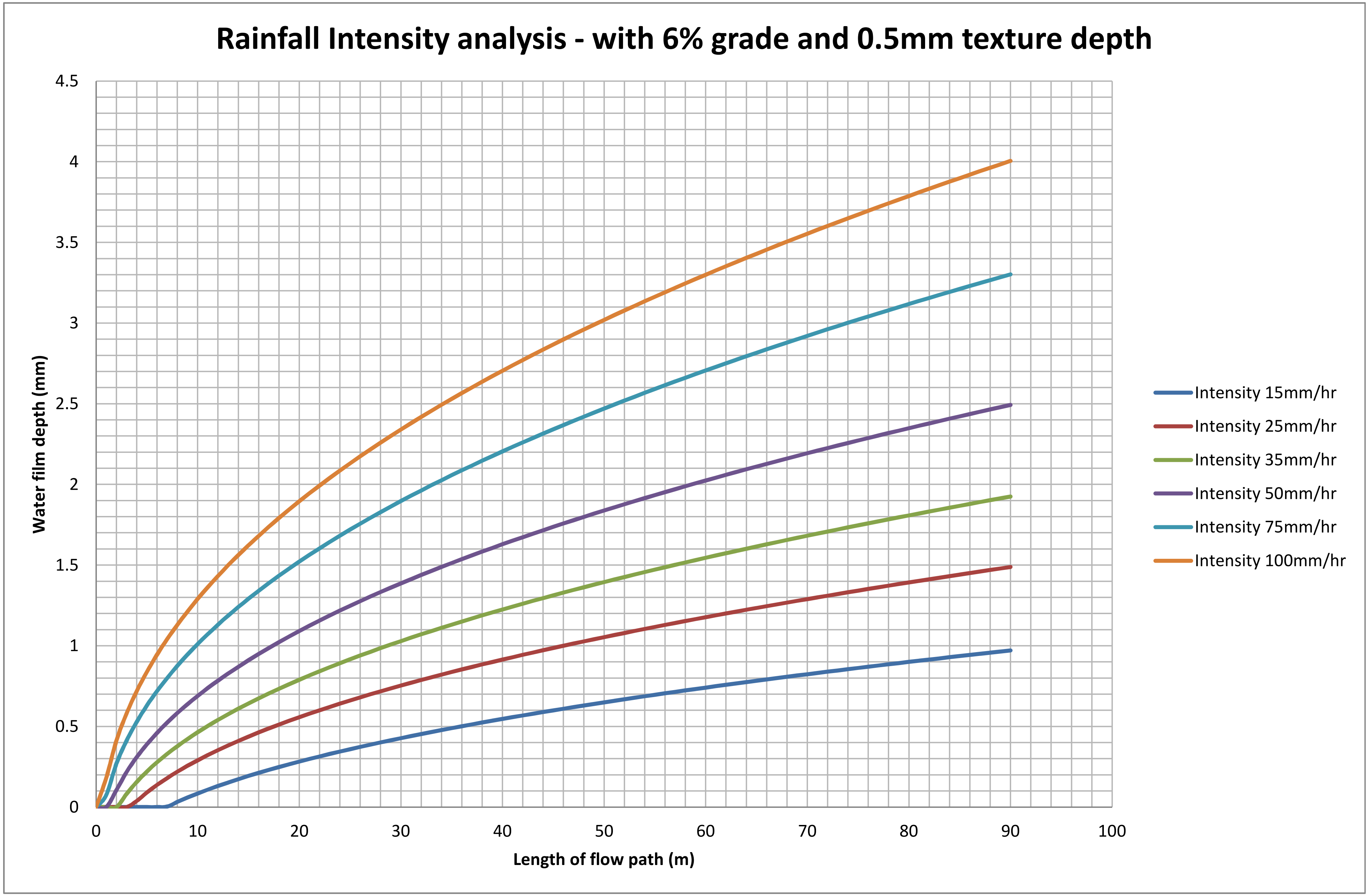


Rainfall Intensity analysis - with 3% grade and 0.5mm texture depth
Water film depth (mm)
Length of flow path (m)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Intensity 15mm/hr
Intensity 25mm/hr
Intensity 35mm/hr
Intensity 50mm/hr
Intensity 75mm/hr
Intensity 100mm/hr



Rainfall Intensity analysis - with 4% grade and 0.5mm texture depth
Water film depth (mm)
0
1
2
3
4
5
6
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Intensity 15mm/hr
Intensity 25mm/hr
Intensity 35mm/hr
Intensity 50mm/hr
Intensity 75mm/hr
Intensity 100mm/hr


Rainfall Intensity analysis - with 5% grade and 0.5mm texture depth
Water film depth (mm)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
10
20
30
40
50
60
70
80
90
100
Length of flow path (m)
Intensity 15mm/hr
Intensity 25mm/hr
Intensity 35mm/hr
Intensity 50mm/hr
Intensity 75mm/hr
Intensity 100mm/hr



Rainfall Intensity analysis - with 6% grade and 0.5mm texture depth
Water film depth (mm)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Length of flow path (m)
0
10
20
30
40
50
60
70
80
90
100
Intensity 15mm/hr
Intensity 25mm/hr
Intensity 35mm/hr
Intensity 50mm/hr
Intensity 75mm/hr
Intensity 100mm/hr