EFFECTS OF SEDIMENT TRANSPORT ON 1-D AND 2-D HYDRODYNAMIC MODELING AND FLOOD INUNDATION

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EFFECTS OF SEDIMENT TRANSPORT ON 1-D AND 2-D HYDRODYNAMIC MODELING AND FLOOD INUNDATION

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ABSTRACT

EFFECTS OF SEDIMENT TRANSPORT ON 1-D AND 2-D HYDRODYNAMIC MODELING AND FLOOD INUNDATION

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In this study, effects of river bed changes on flood inundation are analysed with 1D and 2D coupled hydrodynamic and sediment transport modeling. In order to select the best set of methods depending on qualitative and quantitative indicators, sensitivity of the variables affecting sediment transport processes are presented. Methodology that includes sensitivity analyses of sediment transport processes and real event analyses is implemented for Terme River. Sensitivity analyses are done with 1D modeling by using MIKE 11 HD and MIKE 11 ST software. In these analyses hydrographs having different return periods are used. Effects of sediment transport on flooding are considered with 2D modeling by using MIKE 21 HD and MIKE 21 ST software. Engelund-Fredsoe method with suitable bed level update method is determined as the best method for the study area. Morphological changes and the effect of morphology on hydrodynamics are presented with three real flood events by using 1D modeling. 2D hydrodynamic and sediment transport models are implemented for real flood event occurred in 2014 to examine the effects of morphological changes and grain size diameter on flood inundation. Results of the study show that sediment transport thus morphological changes affect hydrodynamics and flood inundation. In addition, bed level update method and grain size diameter dramatically affect hydrodynamics and flood occurrence. Flood inundation area obtained from coupled modeling decreases compared to pure hydrodynamic modeling for the study area. Analyses show that 2D models give more precise results for bed level changes and sediment transport processes than 1D models but they still demand too much computation time.

Keywords: Sediment Transport Modeling, Hydrodynamic Modeling, MIKE 11, MIKE 21, Terme

ÖZ

SEDİMENT TAŞINIMININ 1-B VE 2-B HİDRODİNAMİK MODELLERE VE TAŞKIN YAYILIMINA ETKİLERİ

Görkem Önder

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Bu çalışmada nehir yatağı değişimlerinin taşkın yayılımına etkisi 1B ve 2B bütünleşik hidrodinamik ve sediment taşınım modelleri kullanılarak analiz edilmiştir. Sediment taşınımına etki eden değişkenlerin hassasiyeti, kalitatif ve kantitatif belirteçlere göre en iyi senaryo setinin belirlenmesi amacıyla sunulmuştur. Sediment taşınım süreçlerinin hassasiyetini ve yaşanmış olayların analizlerini içeren yöntembilim, Terme Nehri için uygulanmıştır. Hassasiyet çalışmaları 1B modellemeyle MIKE 11 HD ve MIKE 11 ST yazılımları kullanılarak gerçekleştirilmiştir. Sediment taşınımın taşkın yayılımına etkileri ise 2B modellemeyle MIKE 21 HD ve MIKE 21 ST yazılımları kullanılarak gerçekleştirilmiştir. Analizlerde farklı taşkın tekerrür debilerine karşılık gelen hidrograflar kullanılmıştır. Çalışma alanı için en uygun senaryo seti, uygun yatak değişim metoduyla kullanılan Engelund-Fredsoe metodu olarak belirlenmiştir. Morfolojik değişimler ve morfolojinin hidrodinamik analizlere etkisi üç yaşanmış taşkın olayı için 1B modellemeyle ortaya konulmuştur. Morfolojik değişimlerin ve tane boyutunun taşkın yayılımına etkisi, 2B hidrodinamik ve sediment taşınımı modelleriyle 2014 yılında yaşanmış olan taşkın olayı verileriyle saptanmıştır. Çalışma sonuçları, sediment taşınımı ve buna bağlı olarak morfolojik değişimlerin

hidrodinamiği ve taşkın yayılımını etkilediğini göstermiştir. Ek olarak, yatak değişim metodu ve tane boyutu hidrodinamiği ve taşkın oluşumunu ciddi şekilde etkilemektedir. Taşkın yayılımları, modellere sediment taşınımı dahil edildiğinde hidrodinamik modele göre azalmıştır. Çalışmalar, 2B modellerin yatak değişimi ve sediment taşınımı süreçleri için 1B modellerden daha hassas sonuç verdiğini göstermiştir fakat hala uzun çalışma sürelerine sahiptirler.

Anahtar Kelimeler: Sediment Taşınım Modeli, Hidrodinamik Modelleme, MIKE 11, MIKE 21, Terme

To My Family…

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CHAPTER 1

INTRODUCTION

Floods can be defined as overflowing of volume of a river or other water body that can affect lives and properties. Thus, if relatively high flow overtops levees of a river, it is stated as flood (Hong et al., 2013).

Flood is one of the most destructive disasters that directly affects lives and properties. More than 80% of population live in places that have flood risk and detrimental effects of floods are going worse due to climate change (Lamond et al., 2011).

Floods occur mostly in populated parts of the world since, human would prefer to live in places that are close to freshwater bodies as rivers and lakes. Due to tendency of people to live near water bodies, inundations affect thousands of people annually. Figure 1-1 presents the annual floods occurred in between 1998-2008 with respect to Global Flood Inventory (Adhikari et al., 2010).

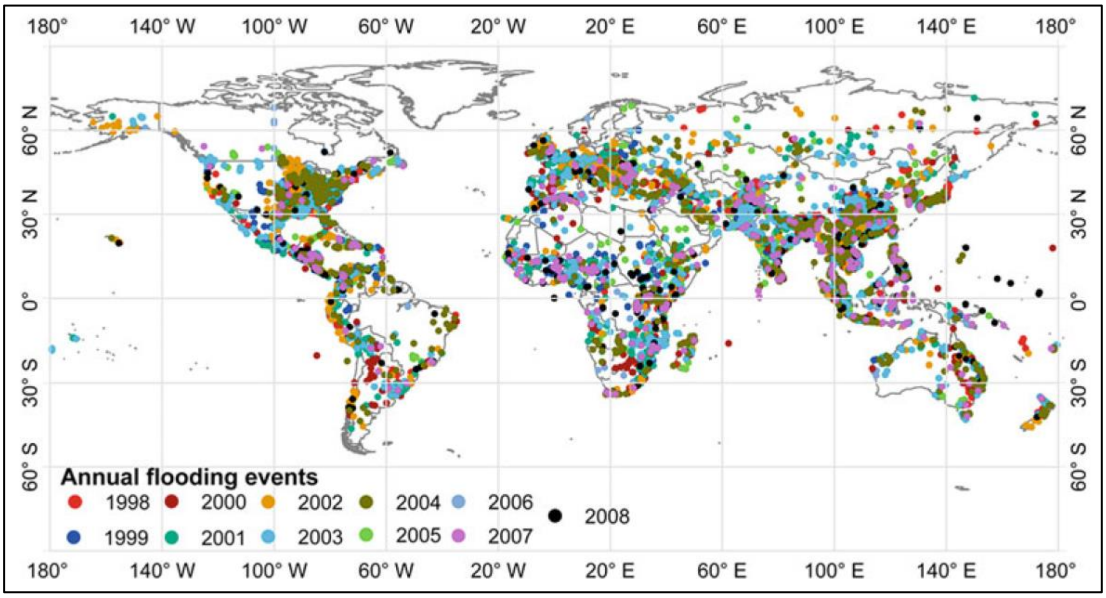


Figure 1-1: Flood Events 1998-2008 (Adhikari et al., 2010)

Generally floods are caused by high amount of precipitation and snowmelt. In addition, natural and man-made structures can also cause floods. These factors can be listed as ice jams, log jams, bridges, weirs, culverts, dam failures etc. (UNESCO, 2011). Factors that can cause flooding occurrence are given in Figure 1-2 (Smith and Petley, 2008).

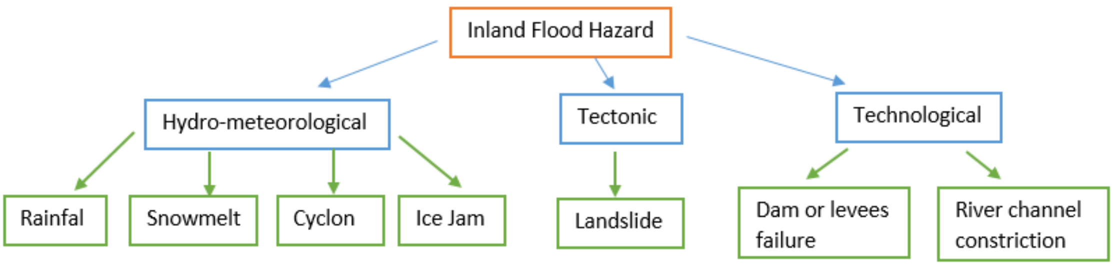


Figure 1-2: Causes of Inland Floods (Smith and Petley, 2008)

Variety of precautions can be taken in order to protect people and properties against floods. Structural measures can be listed as dams, levees and channel improvements. In addition to them, nonstructural measures as flood monitoring and forecasting and floodplain and wetland management applications are considered. Suitable ways to decrease effects of flood occurrence are chosen with respect to flood characteristics and availability. In order to take precautions before flooding, having forecast about possible flood events and their effects are needed. Akyürek et al. (2015) studied upstream structural management measures for Terme River, Samsun. In that study, structural management measures were discussed and different measurement scenarios for subbasins of Terme River were examined. Structural measures and early flood warning systems were proposed for subbasins of the river.

River flow and sediment transport calculations are complex and hard to find analytical solutions for river engineering problems. In addition to that, numerical solutions were not applicable without high speed computers. Thus, physical models, laboratory searches and site investigations were preferred before the 1970s. Recent technological improvements provide the use of computational models. One dimensional, two dimensional and three dimensional models are used with respect to computational needs. Both of the physical and computational modeling have various advantages and disadvantages. Physical models are expensive, time consuming and they are difficult to construct a well scaled physical model due to complicated characteristics of flow and bed change processes. However, physical models give directly visible results in contrast to computational models. Computational models give direct and real-scale assessment and they are cheaper than physical models. Reliability of computational models is strongly related to mathematical governing of physical phenomena, solution method and code trustworthiness of the software (Wu, 2008).

Flood Directive of the European Union Parliament states that all union member states have to prepare flood hazard and risk maps in order to investigate possible flood event outcomes without high expenditures (European Parliament, 2007). Computational flood modeling is cheap and fast way to indicate flood impacts through inundation maps. Computational flood modeling and inundation mapping practices have importance in Turkey in recent years due to Flood Directive of the European Union.

In order to display river flow regime and possible flood impacts, hydraulic modeling is one of the key features. After computations are performed by hydraulic models, inundation maps can be generated that show flood impacts (Gilles and Moore, 2010).

Sediment load is one of the most important phenomena that designates river bed characteristics. Although river morphology is stated that rivers have an equilibrium with fixed cross sections and flow regime, rivers have a dynamic equilibrium with erosion and deposition with bed changes (Thomas and Chang, 2008). Therefore, sediment transport computations should be included to have realistic computational river models.

Hydrodynamic and sediment transport models are evolving from 1D to 2D and 3D but still 1D models can be used successfully for long rivers based on time steps with detailed bathymetric data (Nistoran et al., 2017). Since computation can only be made on cross sections in 1D models, results are determined only for cross sections. Therefore, more detailed studies like 2D modelling should be made in order to have consistent results between cross sections.

Both of the hydraulic models and sediment transport models were included in studies by using several computational software to analyze both sediment transport and hydrodynamic aspects of flow.

A case study is executed by Neary et al., (2001) by using MIKE 11 sediment transport module. This study was performed for Napa River that suffers from flood occurrences, in order to examine sediment effects on Napa River floods and possible maintenance requirements. Van Rijn Method was selected as sediment transport formula based on validation studies and calibrations were made with respect to water depth observations. Small morphological changes were obtained at the river due to tidal sedimentation in short term.

Zavaretto et al., (2016) performed a 2D hydrodynamic and sediment transport study application to Var River, France by using the software MIKE 21. Van Rijn Method (1993) was used to calculate sediment transport and bed level changes without any calibration or validation practice. Different morphology defining types as flexible mesh and grid mesh were used for hydrodynamic modeling and the most suitable mesh size and defining type is stated for study area. As a result, it is stated that topography is crucial parameter to define weir structure properly. In addition, although flexible mesh method is stated as the best way of representation of weir overflow in topography construction, flexible mesh is stated as unsuitable for lower Var valley.

One of the recent 2D sediment transport and hydrodynamic model studies was carried out by Morianou et al., (2016). MIKE 21 software was used for computations and calibration and validation practices were made with respect to water depth and sediment load observations. Engelund and Hansen Method (1967) was selected as sediment transport method. It is stated that modeling practices have given suitable results due to calibration and validation processes and thus water depth, velocity and sediment transport maps were produced.

A 1D and 2D sediment transport and hydrodynamic modeling study was done by Gharbi et al. (2016). This study was carried out by using TELEMAC 2D code coupled with SISYPHE code for 2D analyses and HEC-RAS software for 1D analyses. Sediment amount carried by Medjerda River, Tunisia and morphological changes on river bed were examined. It is concluded that sediment transport problems are strongly related with flooding problems in rivers. In addition, it is stated that 2D models provide more precise results than 1D models of the erosion and deposition rates in the banks and bed of river channels.

Another coupled 2D hydrodynamic and sediment transport modeling practice has been performed by Tu et al. (2017). Studies were performed for Lower Cache Creek system in California by using CCHE2D model. Analyses were performed for 10, 50, 100 and 200 year flood frequencies for two different scenarios; those were the existing condition and potential modifications. It was stated that including sediment transport calculations to hydrodynamic calculations can give better results for flood inundation. In addition, magnitude of flow greatly affects morphological changes and flood inundation.

Demirci (2016) applied XBeach two dimensional sediment transport numerical model for fluvial dominated coastal flooding event at Manavgat river mouth between 4th and 15th December, 1998. Calibration studies were done based on wave, flow and sediment transport. Morphology changes based on sediment transport was examined at Manavgat river mouth and compared with observations. However, sediment transport of river and flooding effect was not examined, but effects of sediment transport on formation of river mouth was studied.

One of the studies that was performed by using XBeach numerical model was done by Söğüt (2014). In this study, long term morphological changes of Yumurtalık region was investigated. Calibration practices were done by using data obtained from field in 2009. Model results that were obtained based on calibration parameters and field measurements were compared. Since model results were in good agreement with field measurements, it was stated that XBeach can be used for long term assessment of sediment transport studies.

A study that includes hydrodynamic modeling was done by Şahin (2016). In this study, performance of FLO-2D software on flood inundation analyses were examined with case studies in Sungurlu and Osmangazi Dams and their effects on Ağva city. It is recommended that early warning system may be established in order to protect from dam breach flooding. In addition, since practices were done by using pure hydrodynamic model, inclusion of sediment transport calculations were recommended by the author.

A study was done by Pulcuoğlu (2009) in order to test sediment transport equations for delta formations in reservoirs. In this study, 32 sediment transport equations were examined by using one dimensional DELTA software that established for determining anticipation of delta formation in reservoirs. 8 of the equations were stated as equations that give closer results to the mean values according to comparison of model results and observed deposition volume percentage. Van Rijn Method (1967) and Engelund-Fredsoe Method (1976) were also examined and they were not selected as suitable formulations. However, deposition in reservoirs was examined and formulations were not investigated for river sediment transport.

Terme River is known as the river that has flooding problems that threaten Terme City. Therefore, many studies have been performed by both Turkish Ministry of Forest and Water Management and academia. One of them is 2-dimensional hydrodynamic modeling study that was performed in Terme River based on several hydrological scenarios (Bozoğlu, 2015). In this study, several structural measures were examined for subbasins of Terme River since channel width cannot be changed due to urbanization problem. Analyses have done by using hydrodynamic model without sediment transport calculations. Some measures were recommended to prevent Terme

City from flooding. State Hydraulic Works, DSI (2013) also studied Terme River in order to investigate flooding problem with a project, “Terme River Flood Hazard Map Designation Project”. This study also demonstrated possible flood inundations and it’s effects. Another study was performed by Özkaya (2017) in order to make hydrological analyses for Terme River by using different rainfall products. Many products were tested in this study and observed flood event hydrographs were stated. In addition to these studies, Nimaev (2015) performed a study to investigate the use of shallow water equations in 2D flood inundation modeling by using software including Lisflood-FP and MIKE21 in Terme River.

In recent studies as stated, sediment transport and hydrodynamic models were constructed and performed based on 1D and 2D computational models. However, effects of sediment transport computations on flood inundation were not focused in Turkey. In this study, effects of sediment transport on flood inundation is investigated in Terme River. In addition, sensitivity of sediment transport models with respect to river channel bed level update method and sediment calculation methods namely; Engelund and Fredsoe and Van Rijn are examined. After deciding to use Engelund and Fredsoe Method as sediment transport model, 1D and 2D hydrodynamic and sediment transport models are constructed to explore the effects of sediment transport on flood inundation. Sensitivity of 2D sediment transport models to grain size diameter is also tested. Differences in flood inundation areas with including sediment transport calculations and with pure hydrodynamic model are studied with respect to observed hydrograph of a real flood event occurred on 22 November 2014. Methodology of the study is described in Chapter 2, all of the analyses are presented in Chapter 3 and discussion of the results are given in Chapter 4.

MIKE 11 and MIKE 21 software of Danish Hydraulic Institute (DHI) were used for modeling practices and ArcGIS software of Environmental Systems Research Institute (ESRI) was used for mapping, DEM and drawing practices.

CHAPTER 2

METHODOLOGY

2.1. Introduction

In flood inundation modelling model calibration and validation are important steps where hydrodynamics, sediment transport, and morphology processes are calibrated sequentially assuming that the morphology changes do not significantly affect the hydrodynamics. However, in some cases, the morphologic processes modify substantially the hydrodynamics due to the quick bed level accession and erosion as a function of the hydrological regime. In this study the effect of morphology in flood inundation modelling is analyzed by coupled 1D hydrodynamic and sediment transportation modelling and 2D hydrodynamic and sediment transportation modelling. The sensitivity of the variables in order to select the best set of scenarios based on quantitative and qualitative indicators are presented. Effects of sedimentation and morphological changes on inundation area are presented by using 2D coupled hydrodynamic and sediment transport models.

2.2. Study Area

In this study, part of Terme River is selected as the study area due to data availability and previous studies those have been done on hydrology and flood modelling of the river.

Terme District is located at the Middle Black Sea Region of Turkey having the coordinates of 41.21° Latitude and 36.98° Longitude. Basin of Terme River has 436.4 km^2 area. Terme River separates Terme District of Samsun into two. Study area starts from 1750 meters upstream of Gökçeli Bridge of Salıpazarı District to 800 meters upstream of Terme Bridge. River passes through Salıpazarı District along this route. The studied river network can be seen in Figure 2-1.

Study area has typical characteristics of Black Sea climate. Basin is wet in all seasons, summers are temperate and winters are warm and rainy. Most of the precipitation occurs in winter and fall. Rains are generally cyclonic. Since upstream part of the basin is elevated, transition of precipitation systems falls more rainfall due to orographic effects (DSİ, 2013).

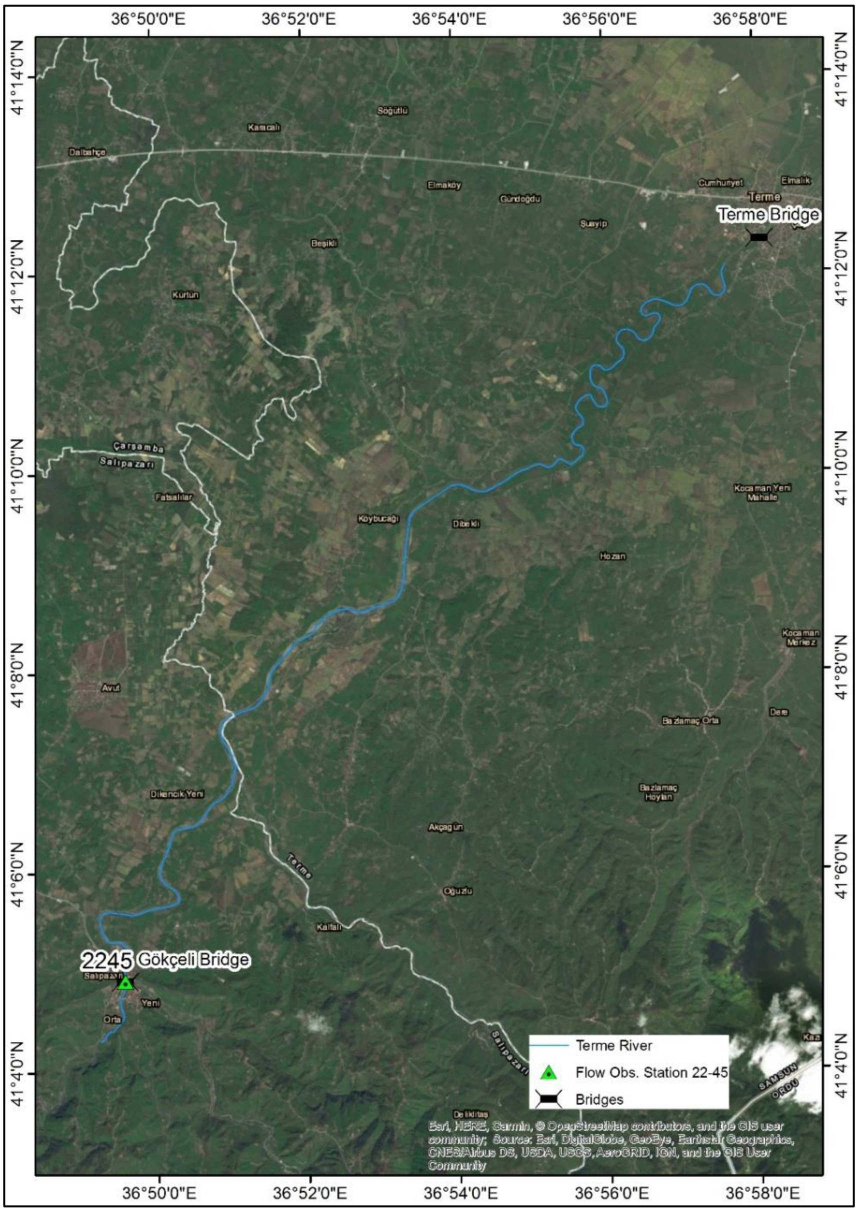


Figure 2-1: Study Area along Terme River

2.3. Sediment Transport Calculation Methods

Several sediment transport calculation methods are investigated throughout many studies. Choosing a method to calculate sediment transport is strongly related with study area characteristics and data availability (van Rijn, 1993). Some of the methods those are commonly used are listed below.

- Engelund – Hansen (Total load)
- Ackers – White (Total load)
- Smart - Jaeggi (Total load)
- Engelund – Fredsoe (Bed load and Suspended load)
- Van Rijn (Bed load and Suspended load)
- Meyer, Peter and Muller (Bed load)
- Sato, Kikkawa and Ashida (Bed load)
- Ashida and Michiue Model (Bed load and Suspended load)
- Lane – Kalinske (Suspended load)
- Ashida, Takahashi and Mizuyama (ATM) (Bed load)

Since available observed sediment data only consist of suspended sediment, Engelund and Fredsoe Method and Van Rijn Method are used in this study for sensitivity analyses. Thus, Engelund and Fredsoe Method as the sediment transport metod is used for 1D and 2D analyses in this study.

2.3.1. Engelund and Fredsoe Method

A mathematical model is conceived by Engelund and Fredsoe (1976) based on physical phenomena introduced by Bagnold (1954). This model is used for calculating both bed load and suspended load. Calculating both suspended load and bed load is a challenge in sediment transport calculations and many of the researchers do not calculate both of them (Engelund and Fredsoe, 1976).

Bed Load

Bed load calculations of Engelund and Fredsoe Methods are made by following equations (DHI, 2015).

$$u_{bs} = 10u'_f(1 - 0.7\sqrt{\frac{\theta_c}{\theta}}) \qquad (2\text{-}1)$$

u'$_f$: Friction velocity

u_{bs} : Velocity of bed load particles

θ : Dimensionless bed shear stress

θ_c : Critical dimensionless bed shear stress

$$p = \left[1 + \left(\frac{\frac{\pi}{6}\beta}{\theta' - \theta_c}\right)^4\right]^{-1/4} \quad (2\text{-}2)$$

where,

p : Probability for bed load particles to move

β : Dynamic friction coefficient

θ' : Dimensionless skin friction

$$\Phi_b = 5\left[1 + \left(\frac{\frac{\pi}{6}\beta}{\theta' - \theta_c}\right)^4\right]\left(\sqrt{\theta'} - 0.7\sqrt{\theta_c}\right) \; and \; \Phi_b = \frac{q_b}{\sqrt{(s-1)gd^3}} \quad (2\text{-}3)$$

Φ_b : Dimensionless sediment transport rate

q_b : Bed load transport rate

s : Specific gravity of sediment

g : Acceleration due to gravity

d : Median grain size

$$\theta = \frac{\tau/\rho}{(s-1)gd} \quad (2\text{-}4)$$

$$\theta' = \frac{\tau\prime/\rho}{(s-1)gd} \quad (2\text{-}5)$$

where ρ is the density of water, s is the specific gravity of bed material, d is the mean grain size of the bed material and g is acceleration of gravity.

Suspended Load

Suspended load (q_s) calculation of Engelund and Fredsoe depends on current velocity (u) and concentration of suspended sediment (c). Formula is given below (DHI, 2015).

$$q_s = \int_a^D cudy \quad (2\text{-}6)$$

q_s : Suspended load

u : Mean flow velocity at the distance y from bed level

c : Concentration of suspended sediment

a : Thickness of bed layer. Can be approximated as 2d where d is grain diameter as stated by Einstein (1950).

D: Depth of water

Velocity of current with respect to a distance y above bed level is defined by the equation given below.

According to research by Rouse (as cited in DHI, 2015) concentration of sediment load calculation is derived by formulation below.

$$c = c_a \left(\frac{D-y}{y}\frac{a}{D-a}\right)^z \quad (2\text{-}7)$$

where,

c : Concentration of suspended sediment at y above the bed

c_a : Concentration at reference level (y = a)

y : Distance from bed level

z : $w/(0.4U_f)$ (Rouse number) where w is the settling velocity and U_f is friction velocity.

D : Depth of water

2.3.2. Van Rijn Method

Van Rijn Method is dividing sediment transport into two as suspended sediment and bed load. When bed shear velocity exceeds the fall velocity, sediment is transported as suspended load (Yanmaz, 2002).

Bed Load

Bed load transport that is used in Van Rijn Method is given by following equation (DHI, 2015).

$$q_b = u_{bs}\delta_b c_b \tag{2-8}$$

where,

q_b : Volumetric bed load transport rate

u_{bs} : Velocity of particle level

δ_b : Saltation height

c_b : Bed load concentration,

Saltation height and velocity at particle level are defined by using two dimensionless parameters that are D_* (particle diameter) and T (bed shear stress parameter).

$$D_* = d_{50}\left[\frac{s-1}{v^2}g\right]^{1/3} \tag{2-9}$$

$$T = \frac{(\tau_{b,c}-\tau_{b,cr})}{\tau_{b,cr}} \tag{2-10}$$

where,

d_{50} : Median grain size

$\tau_{b,c}$: Effective current related bed shear stress

$\tau_{b,cr}$: Critical bed shear stress according to Shields

v : Kinematic viscosity coefficient

s : Relative density ρ_s/ρ

By using the equations given above, these relationships are defined and these are valid for particles having grain size diameters between 0.2 and 2 mm.

$$\Phi_b = \frac{0.053T^{2.1}}{D_*^{0.3}} \tag{2-11}$$

Suspended Load

Suspended load transport is calculated by the equation below (DHI, 2015).

$$q_s = FuDc_a \tag{2-12}$$

where,

F : Dimensionless shape factor

u : Mean flow velocity

D : Total flow depth

c_a : Reference sediment concentration

Calculation of F is stated as below.

$$F = \frac{\left[\frac{a}{D}\right]^{Z'} - \left[\frac{a}{D}\right]^{1.2}}{\left[1-\frac{a}{D}\right]^{Z'}[1.2-Z']} \tag{2-13}$$

where,

a : Reference level

D : Total flow depth

Z' : Modified suspension number

Suspension parameter Z and modified suspension number Z' are calculated by equations below.

$$Z' = Z + \Psi \tag{2-14}$$

$$Z = \frac{w}{\beta \kappa u'_f} \tag{2-15}$$

$$\Psi = 2.5\left[\frac{\mathrm{w}}{u'_f}\right]^{0.8}\left[\frac{c_a}{c_o}\right]^{0.4} \tag{2-16}$$

Z : Suspension parameter

Z' : Modified suspension number

Ψ : Stratification correction factor

w : Fall velocity

β : Coefficient related to diffusion of sediment particles

κ : von Karman's constant

u'_f : Bed shear velocity

c_a : Reference sediment concentration

c_o : Maximum bed concentration

Equation of calculating diffusion of sediment particle coefficient is given equation below.

$$\beta = 1 + 2\left[\frac{w}{u'_f}\right]^2 \; for\; 0.1 < \frac{w}{u'_f} < 1 \qquad (2\text{-}17)$$

2.3.3. Bed Level Update Methods

Two different bed level update methods those are available in the 1D sediment transport model were used in sensitivity analyses.

Method-1

Deposition and erosion calculated proportional with depth below water surface. Above water surface, deposition or erosion do not occur (Figure 2-2).

Figure 2-2: Bed Level Update Method-1

Method-2

In this model, deposition and erosion uniformly distributed over the whole cross section. Therefore, deposition and erosion are independent from water level (Figure 2-3).

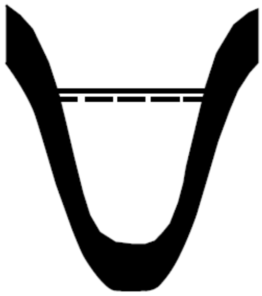


Figure 2-3: Bed Level Update Method-2

2.4. Dataset

In order to perform 1D hydrodynamic modeling, three main data must be used. These are morphological data/cross sections of river, hydrological data either hydrograph or steady flow data and bed resistance data. In this study, 1D sediment transport model is constructed besides hydrodynamic model. Therefore, bed characteristics with grain size and sediment observations with respect to flow measurements must be taken into account.

Moreover the data that are used in 1D modeling, digital elevation model is needed to constitute 2D hydrodynamic and sediment transport modeling. Bed resistance and grain size distributions over modeling area must be considered.

2.4.1. Morphological Data

Cross section data must be used to construct a 1D hydrodynamic model. Digital elevation model that has detailed information is used to obtain cross sections instead of measuring cross section at the field. This approach provides flexibility to obtain cross sections from every preferred point with desired broadness.

Digital elevation model is also used for 2D modeling. Motion of water and sediment particles are calculated over the modeling area. Accuracy of the digital elevation model could greatly affect models.

Digital elevation model was constructed by using data that contains 296538 elevation points. These points are arranged by tachometric survey and digital elevation model was constructed as having 1 meter of resolution (Akyürek and Demir, 2016).

Although, tachometric survey has a margin of error due to human error and some local deposits as big rock, etc., this DEM is decided to be sufficient to conduct 1D model cross sections and 2D modeling. This DEM is given in Figure 2-4 below.

In this study, cross sections were obtained from Digital Elevation Model. MIKE HYDRO software was used to get perpendicular cross sections along the river from DEM.

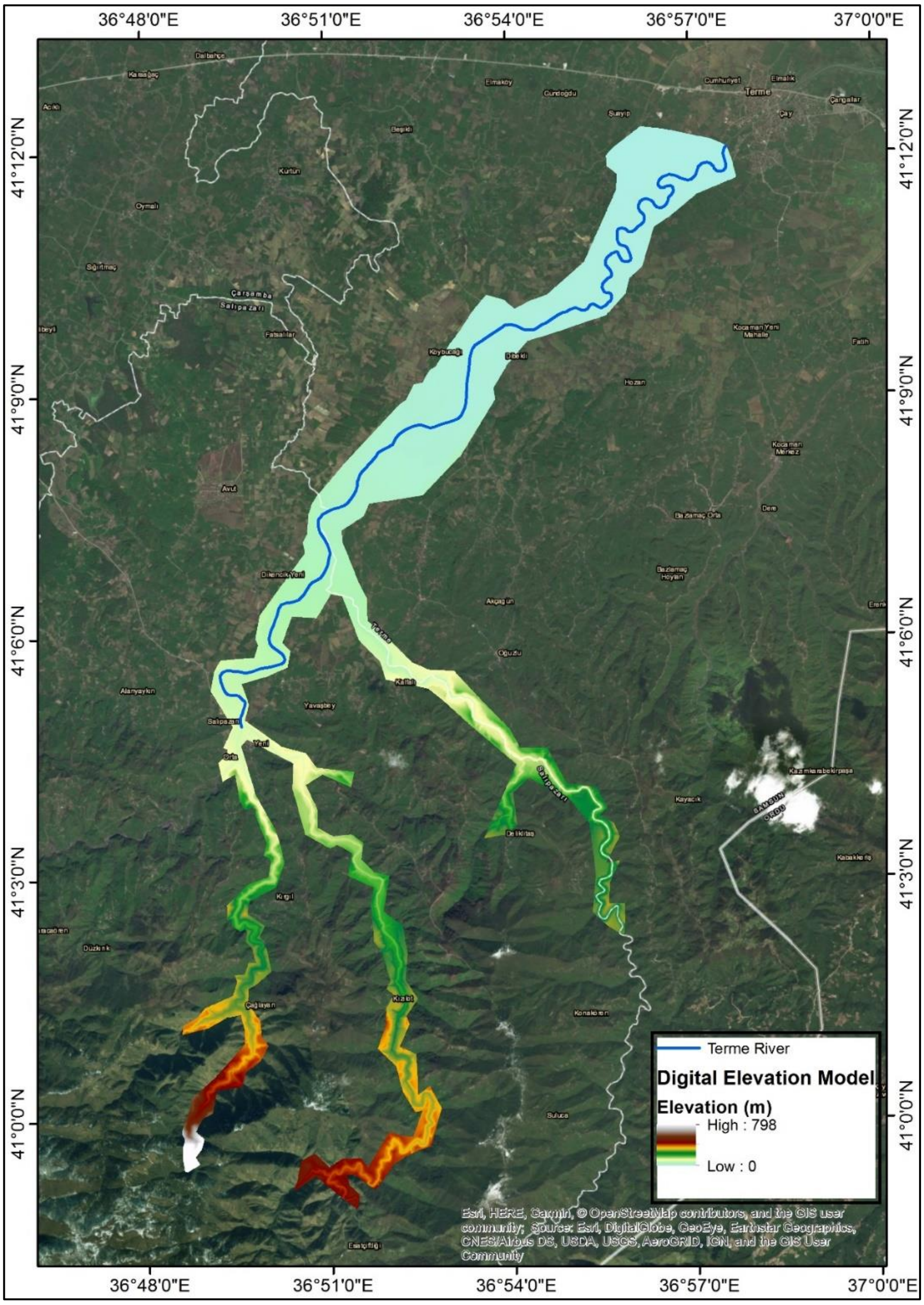


Figure 2-4: Digital Elevation Model

2.4.2. Sediment Measurement

Sediment measurement must be taken into account with respect to related observed flow. Measurements at flow gauging station E22A045 was used for the model calibration.

Station is located at Gökçeli Bridge in the Salıpazarı District having the coordinates of 36° 49' 35" E - 41° 05' 00" N. Its basin area is 232.8 km^2 and altitude of the station is 66 meters (Figure 2-1).

Sediment observations at the station between 4.4.1988 and 9.19.2012 have 305 samples. Observations include concentration of sedimentation and discharge when sediment sample was taken. State Water Works (DSI) has calculated the suspended sediment amount by the formulation given below.

$$Q_s = Q*C*0.0864 \tag{2-18}$$

where

Q_s – daily suspended sediment amount (ton/day);

Q – discharge at the moment of sample observation (m^3/s);

C – concentration of suspended sediment (ppm).

Calculated suspended sediment amount versus discharge graph was constituted by DSI. Linear trendline gives the correlation between discharge and suspended load amount. The graph and the equation can be seen in Figure 2-5.

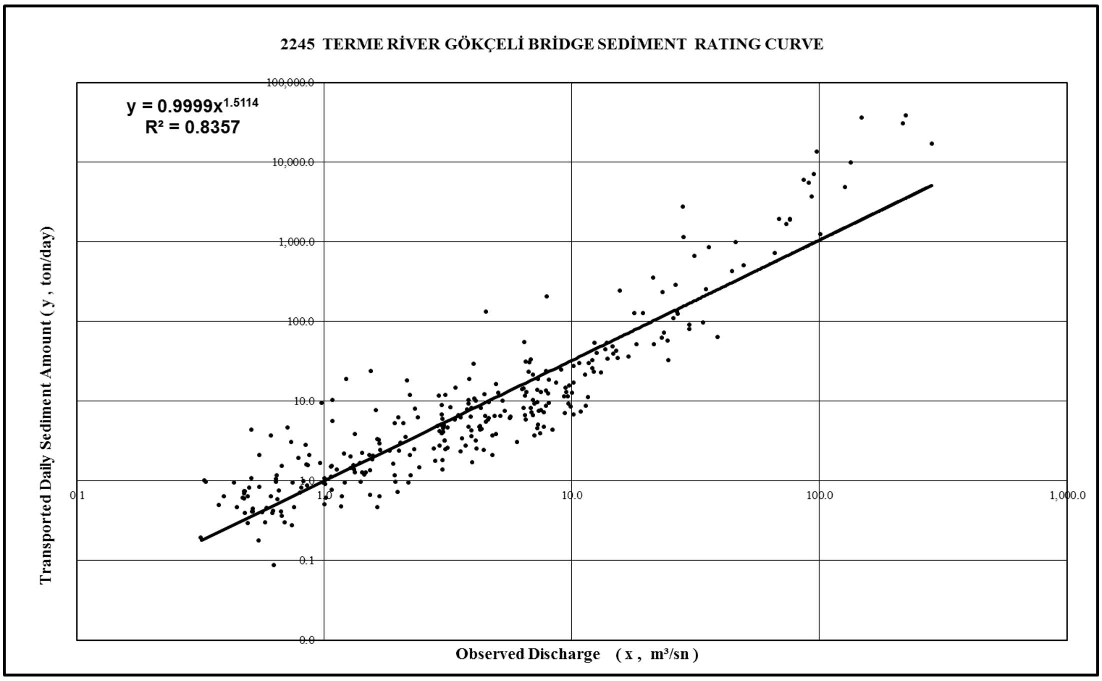


Figure 2-5: E22A045 Sediment Rating Curve

2.4.3. Hydrological Data

Two types of hydrological data were used in this study. First one is calculated hydrographs for Terme River in the previous studies. The other one is real event observations that caused flood events in Terme River and Terme District.

Calculated Hydrographs

Calculated hydrographs were used for sensitivity analyses. These hydrographs were calculated by using data of E22A045 stream gauging station. This station has maximum discharge data between 1969 and 2011 and these data appraised as sufficient dataset to calculate flood peak discharges. Point flood frequency analysis was used to calculate flood hydrographs of the station (Bozoğlu, 2015). Hydrographs of the station for all peak discharges can be seen in Figure 2-6 and peak discharges for several flood frequencies are presented in Table 2-1.

Table 2-1: Peak Discharges of Several Flood Frequencies at E22A045 (Bozoğlu, 2015)

Flood Frequency	**Q_2**	**Q_5**	**Q_{10}**	**Q_{25}**	**Q_{50}**	**Q_{100}**	**Q_{500}**
Discharge (m^3/s)	219.71	350.43	446.74	578.27	682.83	792.41	1041.34

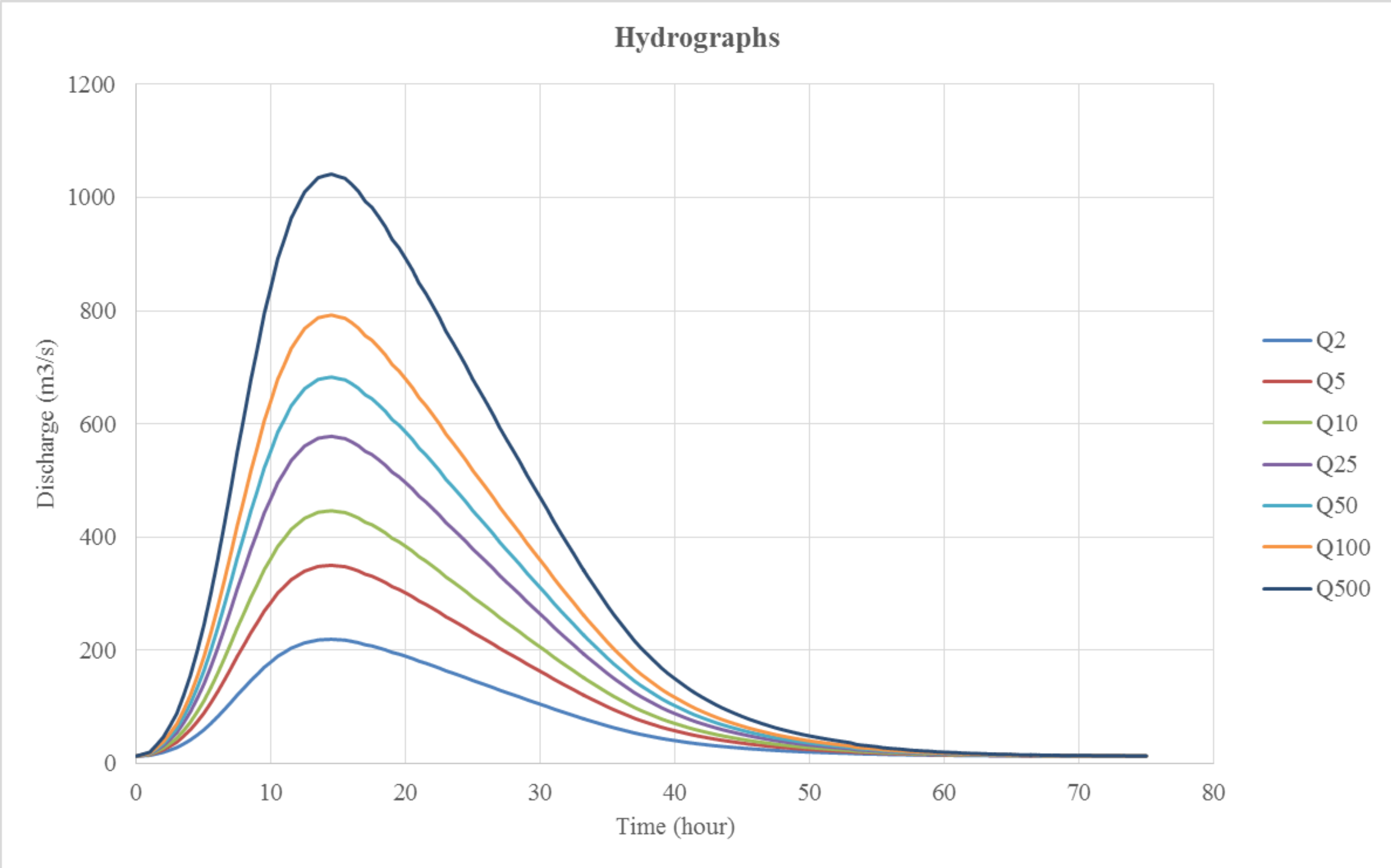


Figure 2-6: Hydrographs of Several Flood Frequencies at E22A045 (Bozoğlu, 2015)

Real Flood Events

Three real flood events were observed at the Terme River on 22 November 2014, 02 August 2015 and 28 May 2016. Flow data of these flood events were observed at stream gauging E22A045 (Özkaya, 2017). All of the observations have hourly basis and suitable to monitor flood event. Hydrographs observed at the station were shown in Figure 2-7, Figure 2-8 and Figure 2-9 and peak discharges of the events are presented in Table 2-2.

Table 2-2: Peak Discharges of Real Flood Events (Özkaya, 2017)

Years	**22 Nov. 2014**	**02 Aug. 2015**	**28 May 2016**
Discharge (m^3/s)	541	88.1	355

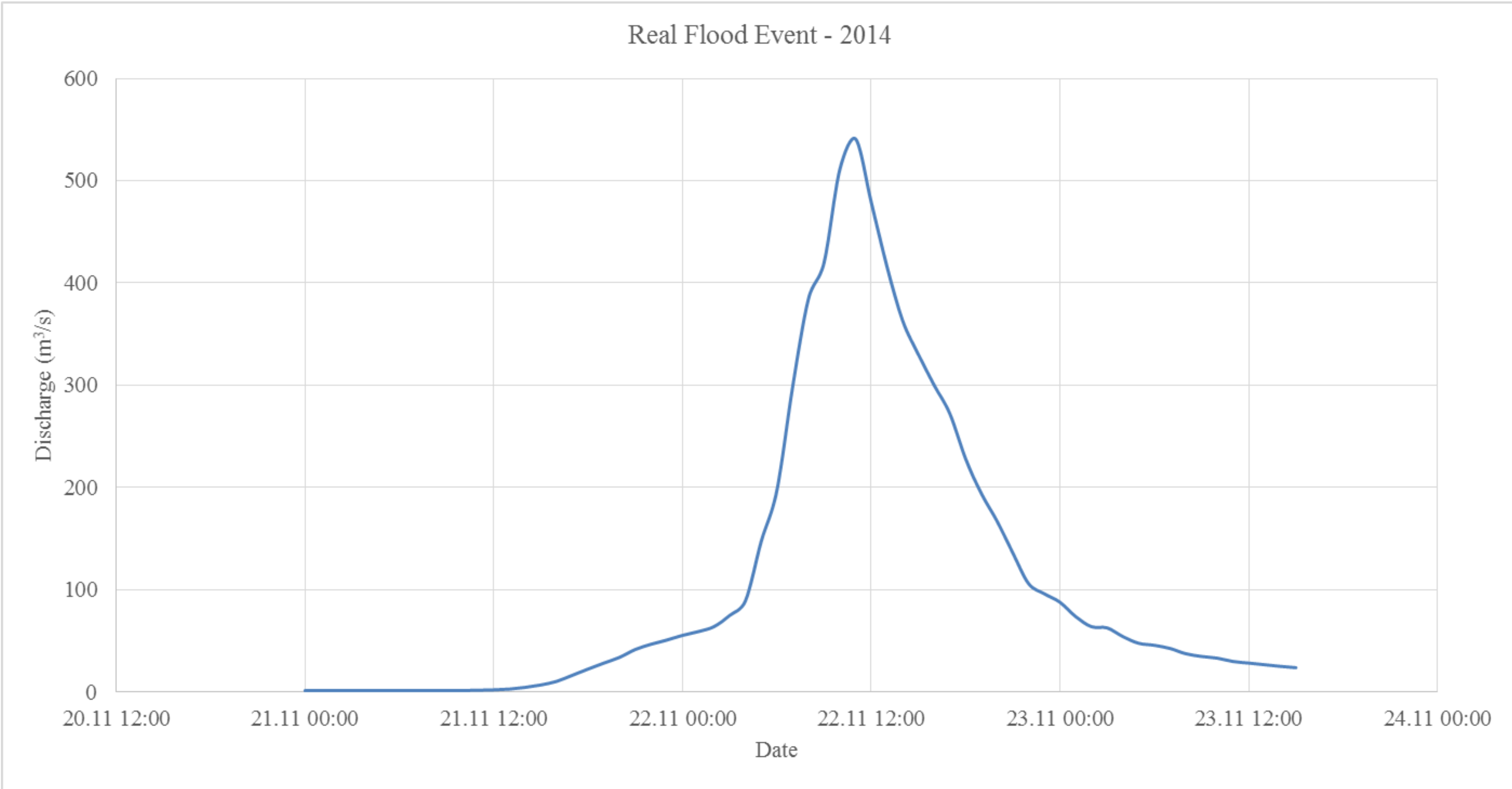


Figure 2-7: Hydrograph of Flood Event on 22 November 2014 (Özkaya, 2017)

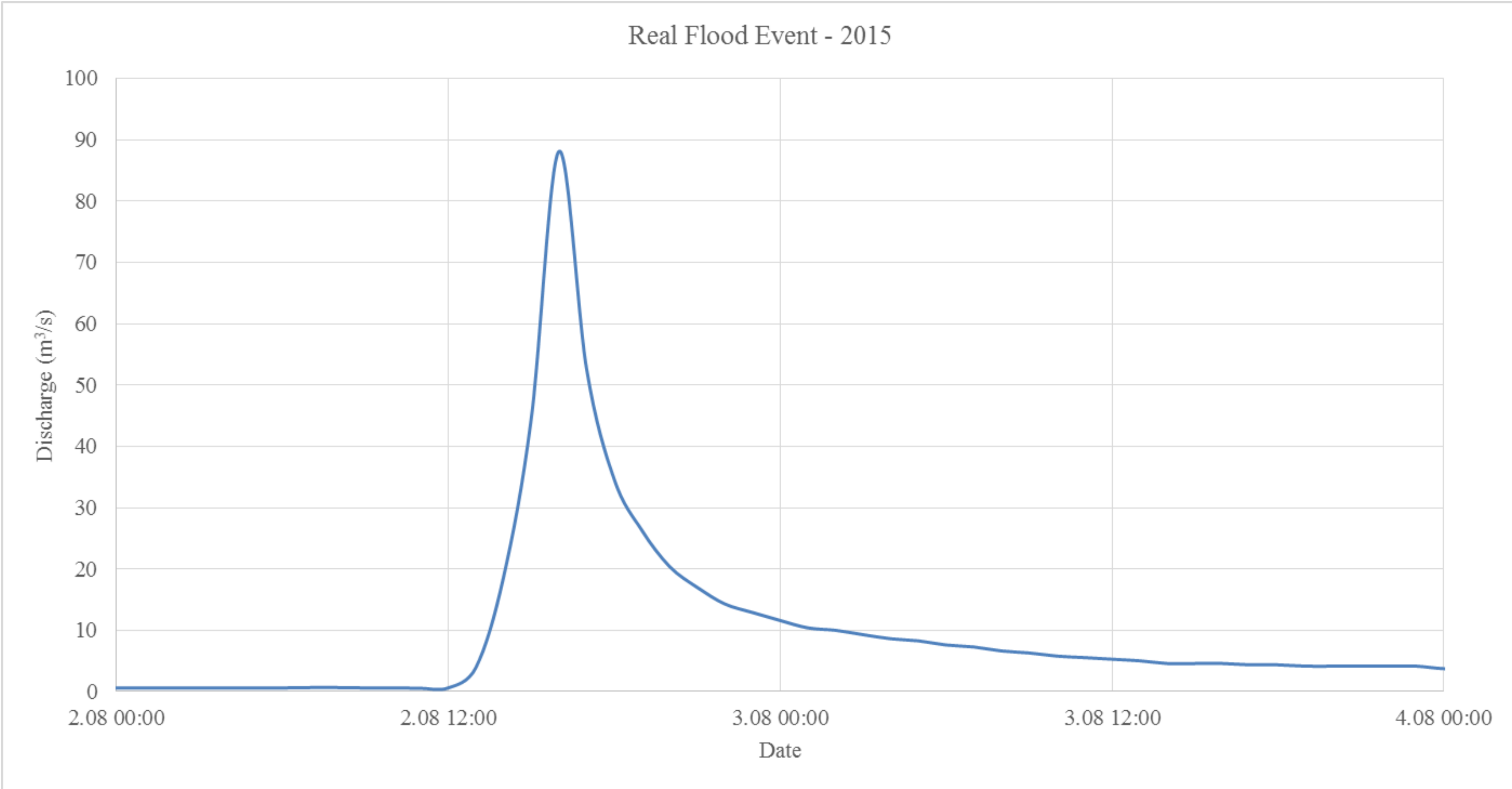


Figure 2-8: Hydrograph of Flood Event on 02 August 2015 (Özkaya, 2017)

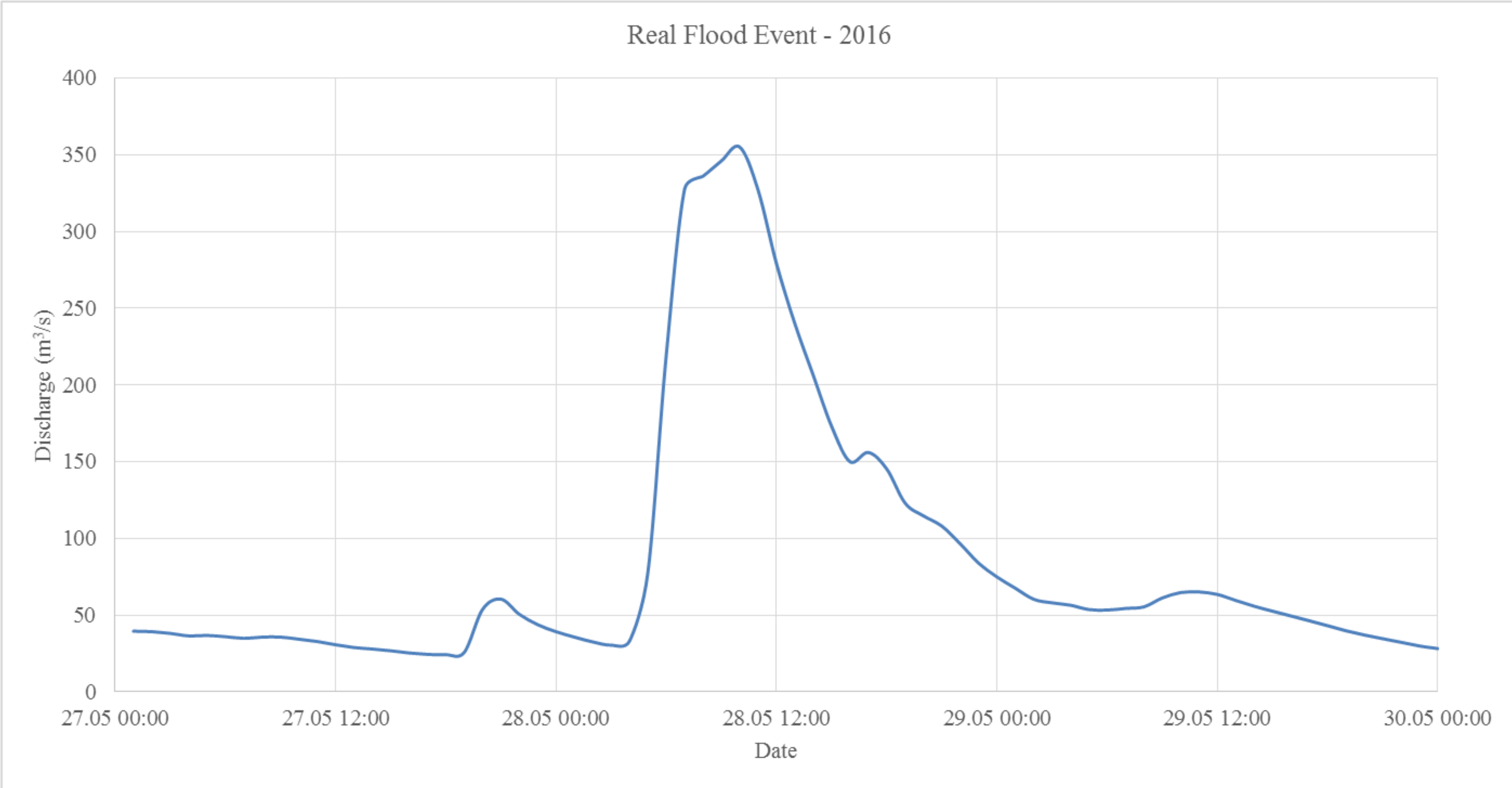


Figure 2-9: Hydrograph of Flood Event on 28 May 2016 (Özkaya, 2017)

2.4.4. Bed Characteristics

River bed characteristics play significant roles in 1D hydrodynamic and sediment models. Bed resistance coefficients are used in 1D and 2D hydrodynamic models as input to Saint Venant Equations. Moreover to bed resistance coefficients, grain size of bed material is one of the most important variables of sediment transport models.

Bed Resistance

Manning's n coefficient was used for 1D and 2D hydrodynamic models. With respect to recent studies of Terme River performed by DSI, various Manning's roughness coefficients were calculated. Calculations of DSI depend on field trips, sample tests and expertizes of local engineers. Basically, Cowan Method (1956) had been implemented to calculate Manning's n coefficient with respect to sample tests and other characteristics of the river that affects roughness calculations. Four samples had been taken from the river material to represent Manning's n coefficient along the river.

Determination of bed resistance is considered for a part of the river, especially for downstream part of the river that is close to Black Sea and Terme District. Determination contains the river part from Akbucak Neighborhood to Black Sea. Due to lack of data, bed resistance is assumed to be the same for the upstream part of Akbucak. Calculated Manning's n values can be seen in Figure 2-10.

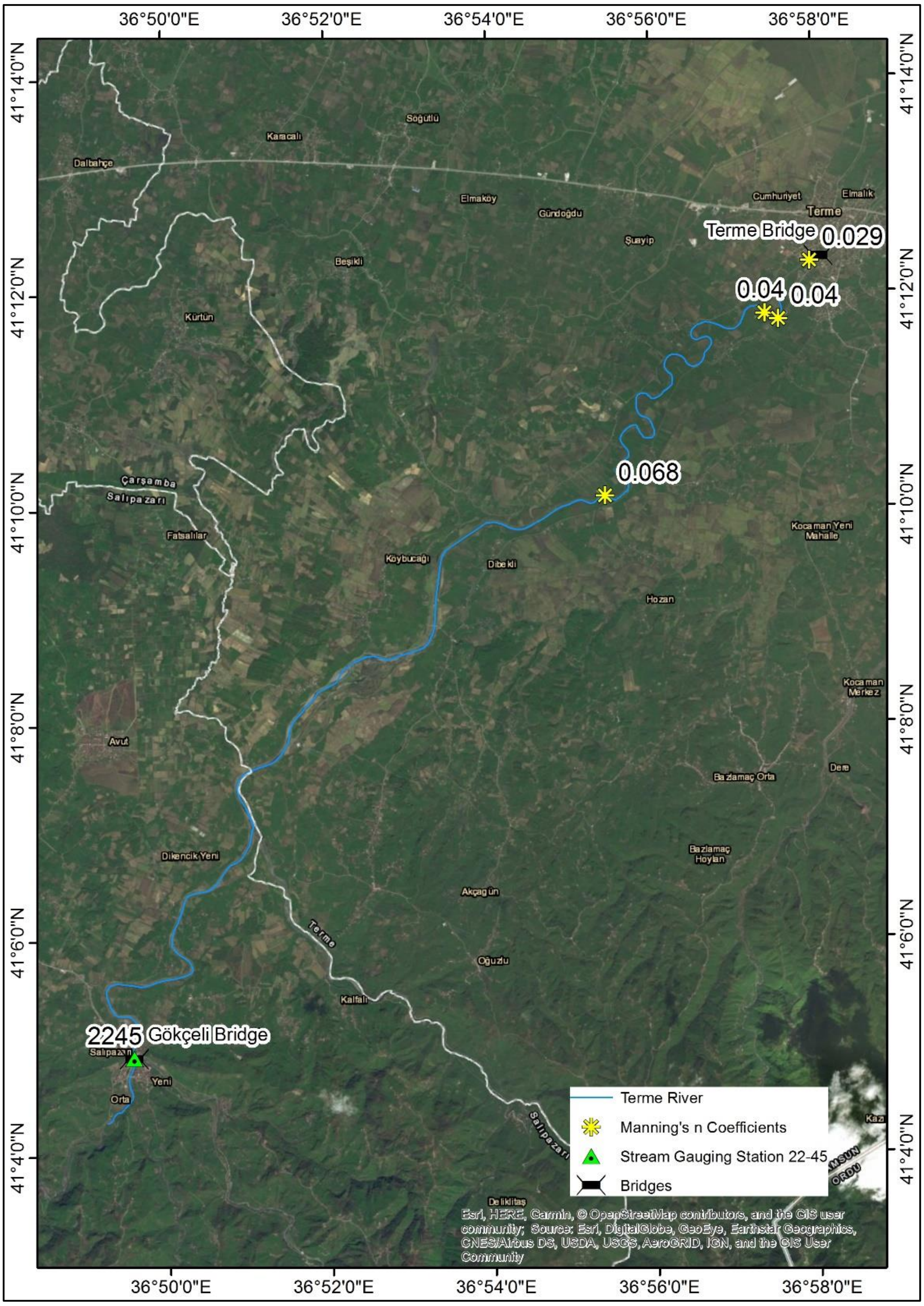


Figure 2-10: Manning's n Coefficients in Terme River

Grain Size

Grain diameter is one of the major inputs of sediment transport calculations that can directly affect transported sediment amount and hydrodynamic conditions with various types of deposition and erosion.

Grain sizes over Terme River are obtained from "Samsun Terme District, Terme River Flood Hazard Map Designation" report (DSI, 2013). Data contain the same part of the river with Manning's n calculation. Grain size values change between 5.5 mm to 0.2 mm along the studied area. Due to lack of data, 5.5 mm grain size is used for the upstream part of the river. Observed grain size diameter locations along the studied part of the river is shown in Figure 2-11.

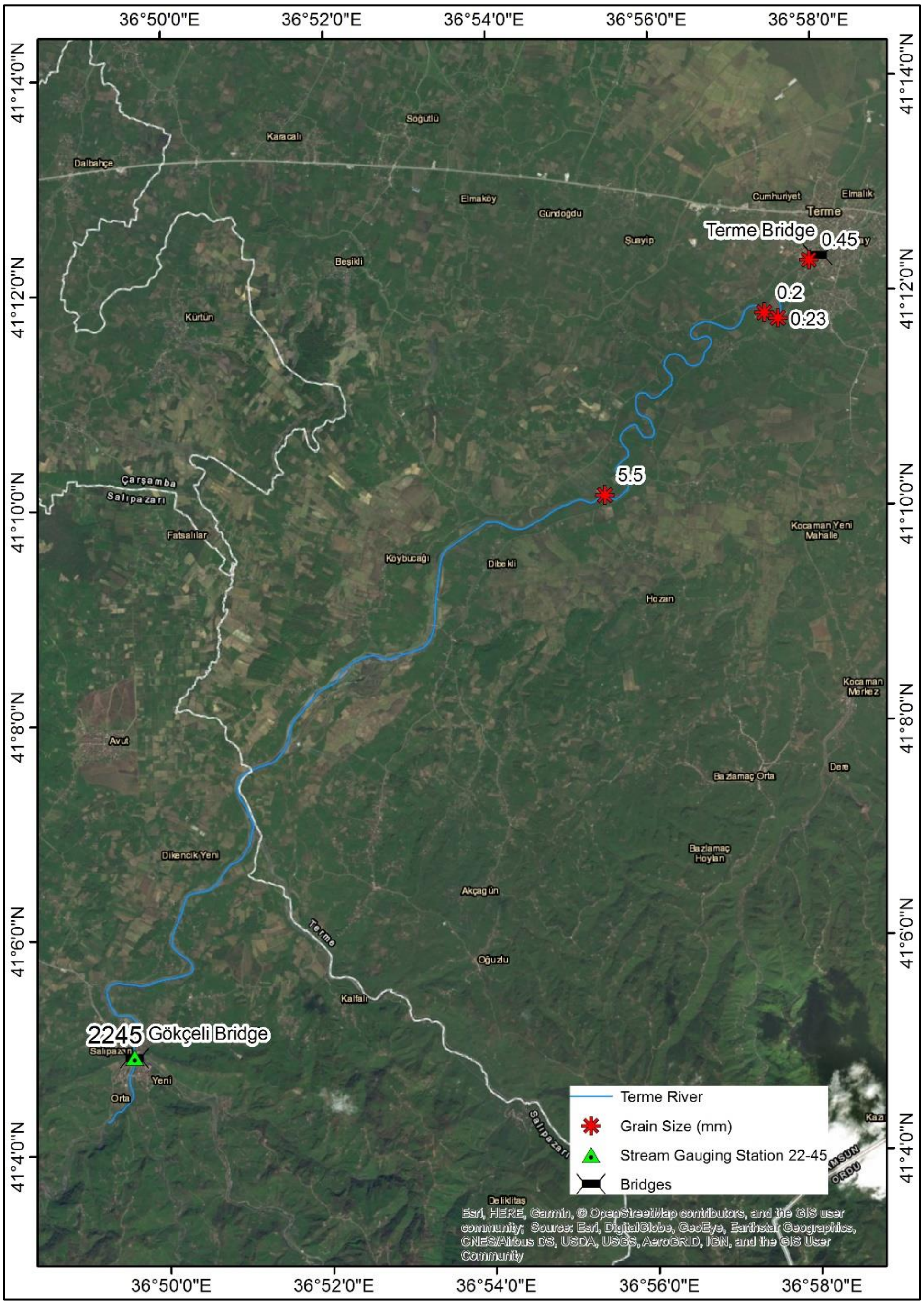


Figure 2-11: Grain Size in Terme River

2.5. Software

MIKE 11 software was used for 1D hydrodynamic, 1D sediment transport (ST) modeling and coupled modeling studies of these two modules. Coupling gives interacting chance between two modules.

MIKE 21 FM software was also used for 2D hydrodynamic and 2D hydrodynamic and sediment transport coupled models.

2.5.1. 1-Dimensional Modeling Software

1D Sediment Transport Model

Software has an option to calculate morphological changes that is updating bed level or calculating sediment transport without bed level update. In the morphological mode, HD module works with ST module as coupled. Calculations of sediment transport affect HD module through bed resistance and sediment continuity equation.

Continuity equation for sediment transport is used to calculate bed level update due to erosion and deposition. Bed level changes can be applied for entire cross section or a part of it. This determination can be made by user by using bed level update methods.

Calculation of sediment transportation is performed based on flow velocity, depth and transporting width. The equations are given below (DHI, 2013).

$$u = \frac{Q_c}{A_c} \tag{2-19}$$

$$D = R_c \tag{2-20}$$

$$W_t = \frac{A_c}{R_c} \tag{2-21}$$

u :	flow velocity (m/s)
D :	water depth (m)
W_t :	transporting Width (m)
Q :	discharge (m^3/s)
A :	cross sectional area (m^2)
R :	resistance radius (m)

Subscript c in the equations describes river channel values. If different flood plain coefficients are not defined in the model, constant values are used for the entire cross sections.

River channel discharge is defined by using formula below if constant friction slope for the whole free water surface width is assumed (DHI, 2013).

$$Q_c = Q_t \begin{cases} \frac{M_c R_c^{2/3} A_c}{M_t R_t^{2/3} A_t} & \text{Manning No.} \\ \frac{C_c R_c^{1/2} A_c}{C_t R_t^{1/2} A_t} & \text{Chezy No.} \end{cases} \quad (2\text{-}22)$$

$$R_t = \left(\frac{\sqrt{R_c} A_c + \sqrt{R_f} A_f}{A_t}\right)^2 \quad (2\text{-}23)$$

$$M_t = \left(\frac{M_c \sqrt{R_c} A_c + M_f \sqrt{R_f} A_f}{\sqrt{R_t} A_t}\right)^2 \quad (2\text{-}24)$$

$$C_t = \left(\frac{C_c \sqrt{R_c} A_c + C_f \sqrt{R_f} A_f}{\sqrt{R_t} A_t}\right)^2 \quad (2\text{-}25)$$

Q : discharge (m^3/s)

M : Manning's roughness coefficient

C : Chezy's roughness coefficient

R_t : composite resistance radius

M_t : composite Manning roughness coefficient

C_t : composite Chezy roughness coefficient

Subscripts t, c and f describes entire cross section, river channel part and flood plain part respectively.

Preissmann scheme is better than Aboott-Ionescu and Vasiliev scheme for stability and accuracy in modeling open channel flow since Preissmann scheme is preferable if supercritical flow occurs (Skeels and Samuels, 1989). Preismann Scheme is used by the software to solve sediment continuity equation is given below.

$$(1-\varepsilon)\left[(1-\Psi)\frac{W\Delta z_j^{n+1}}{\Delta t}+\Psi\frac{W\Delta z_{j+1}^{n+1}}{\Delta t}\right]+\theta\frac{Qt_{j+1}^{n+1}-Qt_j^{n+1}}{\Delta x}+(1-$$

$$\theta)\frac{Qt_{j+1}^{n}-Qt_j^{n}}{\Delta x}=0 \qquad (2\text{-}26)$$

W : width of river channel

Δz^{n+1} : change of bottom level

$$Qt_j^n = W_t qt_j^n \qquad (2\text{-}27)$$

qt_j^n : sediment transport rate per unit width

ε : porosity of sediment

Ψ: space centring coefficient ($0.5 \leq \psi \leq 1$)

θ : time centring coefficient ($0.5 \leq \theta \leq 1$)

Sediment transport at t = (n+1)Δt is approximated by following equation.

$$Qt_j^{n+1} = Qt_j^n + \left(\frac{\partial Qt}{\partial u}\frac{\partial u}{\partial z}+\frac{\partial Qt}{\partial D}\frac{\partial D}{\partial z}\right)_j \Delta z_j^{n+1} \qquad (2\text{-}28)$$

u : flow velocity

D : flow depth

$\partial u/\partial z$ and $\partial D/\partial z$ are calculated assuming back water curve (under a given time step).

$\partial Qt/\partial zu$ and $\partial Qt/\partial D$ are obtained by numerical differentiation.

$$\frac{\partial Qt}{\partial u} \approx \frac{Qt(u+\Delta u,D)-(Qt(u,D)}{\Delta u} \; or \; \frac{\partial Qt}{\partial u} \approx \frac{Qt(ufacD)-Qt(u,D)}{ufac-u} \qquad (2\text{-}29)$$

where,

$$fac = \frac{u+\Delta u}{u} \qquad (2\text{-}30)$$

In order to validate and make sensitivity analyses of sediment model, bed load and suspended load would be calculated separately, since data of sediment load obtained from DSI indicates suspended load only. If total load calculation methods are used, it is not possible to calculate suspended sediment load seperately and thus it cannot be compared with observed data. Two sediment calculation methods are considered to make sensitivity analyses and suitable methods those are Engelund and Fredsoe Method and Van Rijn Method were selected for the analyses.

Modeling Technique of 1D Sediment Transport Model

Sediment transportation module of MIKE 11 defines with editor file Sediment Transport Editor (.st11). This editor file controls all of the sediment transport coefficients, calculation method definitions and inputs.

Minimum required input to construct a sediment model is basically grain size. Possible other input data are described below.

- Active and passive layers can be defined to specify if required data are obtained.
- Passive river branches can be defined to exclude from sediment transport calculations.
- Initial dunes with dimensions and initial sediment amounts in the river at certain points can be defined.

Determination of method to calculate sediment transport must be made. There are several options to perform sediment calculations. All of the methods are listed below.

- Engelund – Hansen (Total load)
- Ackers – White (Total load)
- Smart - Jaeggi (Total load)
- Engelund – Fredsoe (Bed load and Suspended load)
- Van Rijn (Bed load and Suspended load)
- Meyer, Peter and Muller (Bed load)
- Sato, Kikkawa and Ashida (Bed load)
- Ashida and Michiue Model (Bed load and Suspended load)
- Lane – Kalinske (Suspended load)
- Ashida, Takahashi and Mizuyama (ATM) (Bed load)

These methods can be used separately e.g. Van Rijn Method for suspended load and Meyer, Peter and Muller Method for bed load calculations. However, when a method is chosen, it is recommended that the same author's method should be used in order to have the same assumptions, if it is possible (DHI, 2012). Therefore in this study, Engelund and Fredsoe Method was used for both bed load and suspended load calculations and Van Rijn Method was used for both of bed load and suspended load calculations separately.

Model parameters that will be used in calculations can be modified. Each method has some parameters used in equations. These parameters are listed below.

- Relative density or specific gravity of the sediment. Relative density was taken as 2.65 in this study.
- Kinematic viscosity of water.
- Beta: dynamic friction coefficient of Engelund-Fredsoe model.
- Theta Critical: Incipent motion of sediment's Critical Shields' parameter. It was taken as 0.056 in this study which corresponds to turbulent flow conditions at the bed level.
- Gamma: Engelund-Fredsoe Method's suspended load calculation calibration parameter that defines height of sand dunes.
- Ackers-White: Represented grain size can be d_{35} or d_{65}.

When applying morphological computations that updates bed level, some parameters and thresholds can be changed.

- dH/dZ: Calculation parameter of morphological model that can be chosen as backwater or -1.
- PSI: Centring of morphological computation in space. It is one of the parameters in Preissmann Scheme. It was taken as 0.9 in this study as recommended by the software.
- FI: Centring of morphological computation in time. It is one of the parameters in Preissmann Scheme. It was taken as 0.9 in this study as recommended by the software.
- FAC: $\frac{u+\Delta u}{u}$ Morphological model's calibration parameter for derivative computations. It was taken as 1.5 in this study as recommended by the software.

- Porosity: Porosity value of the sediment that will be transported. It was taken as 0.35 in this study.

If bed shear stress calculation is included in the sediment transport model, some parameters can be determined by the user.

- Manning's n coefficient, Manning's M coefficient (1/n) or Chezy' coefficient can be used.
- Minimum and maximum values of roughness coefficient that will be calculated can be determined.
- A calibration parameter named as omega can be defined. ($Resistance_{ST}$ = Omega * $Resistance_{HD}$).

The list of bed shear stress methods available in the software is given in Table 2-3.

Table 2-3: Methods applied for updating bed shear stress in sediment transport formulas (DHI, 2012)

Transport Formula	Bed Shear Stress Method
Ackers-White	Ackers White formulation
Engelund - Hansen	Engelund - Hansen method
Smart & Jaeggi	Engelund - Hansen method
Engelund - Fredsoe	Engelund - Fredsoe method
Van Rijn	No method implemented
Meyer, Peter & Mueller	Engelund - Hansen method
Sato, Kikkawa & Ashida	Engelund - Hansen method
Ashida & Michiue	Engelund - Hansen method
Lane - Kalinski	Engelund - Hansen method

It is recommended that if a method that does not have a specified bed shear stress method to be used, updating of bed shear stress should not be activated (DHI, 2012).

1D Hydrodynamic Model

Hydrodynamic model was used for monitoring effects of sedimentation. These effects have been realized at cross sections for the whole modeling area. In this study, MIKE 11 1D hydrodynamic model was used.

1D hydrodynamic model was needed at the four phases of the study which are preliminary analysis, cross section defining approach determination, sensitivity analyses and real event analyses. In order to compare and realize the effect of sedimentation, coupled ST-HD models were prepared and also HD models were computed without sediment transport module.

Unsteady calculations were performed for all of the phases. Hydrographs calculated by DSI was used to determine cross section defining approach and sensitivity analyses. After realizing the most consistent approaches, real event analyses were performed with flood hydrographs observed on given dates.

MIKE 11 hydrodynamic module (HD) computes unsteady flows in rivers and estuaries by using implicit finite difference scheme (DHI, 2013). This module can calculate sub-critical and super critical flow conditions in steady or unsteady manner.

Basis of MIKE 11 computation is simplified hydraulic calculations that are Saint Venant Equations. Continuity and momentum equations are solved for all cross sections defined in the model to calculate water level and flow velocity.

Momentum and continuity equations were given in the following equations.

$$q = \frac{\partial q}{\partial x} + \frac{\partial A_{fl}}{\partial t} \quad (2\text{-}31)$$

$$\frac{\partial q}{\partial t} + \frac{\partial\left(\alpha \frac{q^2}{A_{fl}}\right)}{\partial x} + \frac{g A_{fl} \partial h}{\partial x} + \frac{g q|q|}{C^2 A_{fl} R} = 0 \quad (2\text{-}32)$$

A : flow area, m^2

q : lateral flow, m^2s^{-1}

h : depth above datum, m

C : Chezy resistance coefficient, $m^{1/2}s^{-1}$

R :	hydraulic radius, m

α :	momentum distribution coefficient

x :	Cartesian coordinates

g :	acceleration due to gravity (m/s^2)

Modeling Technique of 1D Hydrodynamic Model

Interface of MIKE 11 includes components to define a 1D hydrodynamic model. All of them must be defined to run a model. The components are running together and they consist a proper model. A standard hydrodynamic model consists of 6 different parameter editors. In order to include another module to the model as rainfall runoff, sediment transport, etc. extra parameters must be included to model setup. These parameters were shown in Figure 2-12.

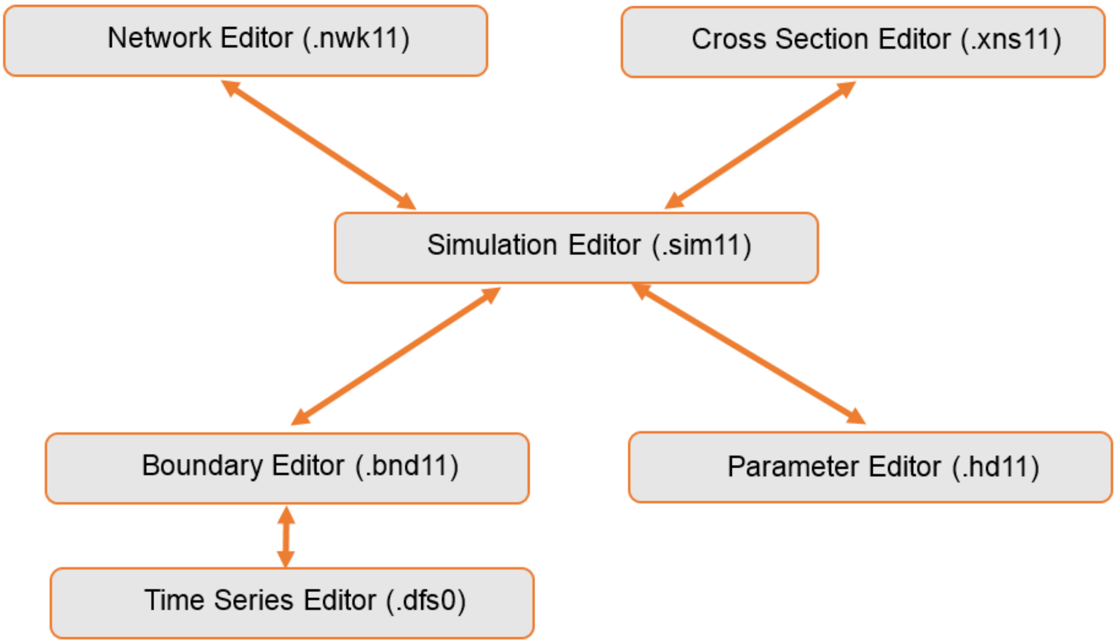


Figure 2-12: MIKE 11 HD Model Scheme (DHI, 2012)

Simulation editor of MIKE 11 HD model is the base editor that controls and makes interaction between other components. If any other module i.e component is added to these editors, it will be controlled by simulation editor also.

- Network Editor (.nwk11): includes river network and any other structures as dams, weirs and culverts etc.
- Cross Section Editor (.xns11): contains all of the cross sections defined in the model.
- Boundary Editor (.bnd1): involves boundary conditions as inflows, dam break definitions, outflows etc.
- Time Series Editor (.dfs0): contains all of the time series as hydrographs, downstream conditions etc.
- Parameter Editor (.hd11): includes hydrodynamic parameters that are using in hydrodynamic analyses as initial conditions, roughness coefficients etc.

2.5.2. 2-Dimensional Modeling Software

2D Sediment Transport Model

MIKE 21 FM ST (Flexible Mesh Sand Transport) software is used to calculate sediment transport in the study area. Software has an option to run coupled with hydrodynamic model. By using that approach, it is possible to investigate sediment transport effects on hydrodynamic model and the inundation result.

Sediment transport module calculates bed level, bed level changes, sediment loads, etc. for all of the meshes that are defined in the model structure. Therefore, it is possible to observe morphological changes and sediment transport for all of the study area rather than cross sections defined in 1D model.

Software includes transport of non-cohesive materials with respect to hydrodynamic flow conditions and flood wave conditions, if included (DHI, 2016). In this study, waves are not included and only sediment transport is taken into account.

Bed load and suspended sediment load can be calculated separately. Wash load is not included. Layers of bed can be defined and non-erodible layers can be defined in the model. However, layers are not defined in this study due to lack of data.

Four of the sediment transport methods are included in the software. These methods are listed below.

- Engelund and Hansen (Total Load)

- Van Rijn (Bed Load + Suspended Load)
- Engelund and Fredsoe (Bed Load + Suspended Load)
- Meyer-Peter-Müller (Bed Load)

One of the methods must be chosen by the user to calculate sediment transport with respect to the specifications and equations of the method. In this study, Engelund and Fredsoe Method is applied for 2D sediment modeling due to the results obtained from 1D sensitivity analyses.

Modeling Technique of 2D Sediment Transport Model

MIKE 21 FM ST software defines study area morphology with a flexible mesh structure. Sediment transport calculations are related with hydrodynamic calculations that are performed in that mesh structure.

Basic inputs of the sediment transport model stated below.

- Morphological data: Constructed by using Digital Elevation Model.
- Bed resistance data: Can be defined as varying in domain and time. In this study, defined with respect to calculations made by DSI as constant in time and varying in domain.
- Grain size: Can be defined as varying in domain and time. In this study it is defined as constant in time and domain for 2D modeling. Calculations made by DSI at the downstream part of the river shows 5.5 mm grain size diameter (DSI, 2013). In order to observe differentiations with respect to grain size and make sensitivity analyses 0.55 mm and 3 mm grain size diameters are also considered and modelled.
- Boundary conditions: Boundary conditions can be defined as sediment inflow or outflow if it is known that additional sediment load input or output is occurred. In this study, boundary conditions defined as in equilibrium.
- Porosity: Porosity of sediment must be defined. In this study, porosity is taken as 0.35.
- Relative Density: Relative density of sediment must be defined. In this study, relative density is taken as 2.65.

Moreover to basic inputs stated, more inputs and transport specifications can be defined, those are not considered in this study.

- Wave and current
- Helical flow
- Dispersion
- Slope failure

Detailed information about sediment transport calculations can be taken as a result of the model. Result file can contain many items based on selected modules. In this study, 8 result files were selected and obtained as listed below. All of these results were obtained as maximum result of simulation period and dynamic through simulation period.

- Rate of bed level change: Bed level change based on time
- Bed level change: Morphological difference
- Bed level: Updated bed level
- Bed load magnitude
- Suspended load magnitude
- Total load magnitude
- Surface elevation: Elevation of water
- Total water depth

2D Hydrodynamic Model

MIKE 21 FM HD (Flexible Mesh Hydrodynamic Module) software is used in this study. MIKE 21 is constituted in order to calculate free surface flows. Model can be used to calculate free surface flow in lakes, estuaries, bays, coastal areas and seas.

Hydrodynamic module basically solve two dimensional shallow water equations that are depth integrated Reynolds averaged Navier Stokes equations. Therefore, model includes continuity, momentum, salinity, density and temperature equations. Explicit scheme is used for time integration (DHI, 2014).

Modeling Technique of 2D Hydrodynamic Model

Using flexible meshes in order to represent bathymetry of the study area is a very detailed and precise way of defining of morphology. Since using flexible meshes give an advantage of changing mesh sizes, it is possible to use smaller meshes for area where user needs detailed information and larger meshes for other parts of the study area. This flexibility brings faster computation and detailed results for the interested parts.

Inputs needed in 2D hydrodynamic model are listed below.

- Domain: Morphological data constructed by using Digital Elevation Model.
- Mesh: Can be constructed as triangular and quadrangular. In this study, only triangular meshes are used for defining bathymetry (Figure 2-13). Meshes having maximum 10 m^2 area are used for river bed and possible inundation area. Other parts of the study area defined with meshes having maximum 100 m^2 area.
- Bed Resistance: Can be defined as varying in domain and time. In this study, it is defined as constant in time and varying in domain according to the observations made by DSI.
- Boundary Conditions: Can be defined for inflow and outflow as boundary of computation meshes. In this study, outflow boundaries are defined and one inflow boundary is defined as real flood event hydrograph of 22 November 2014.

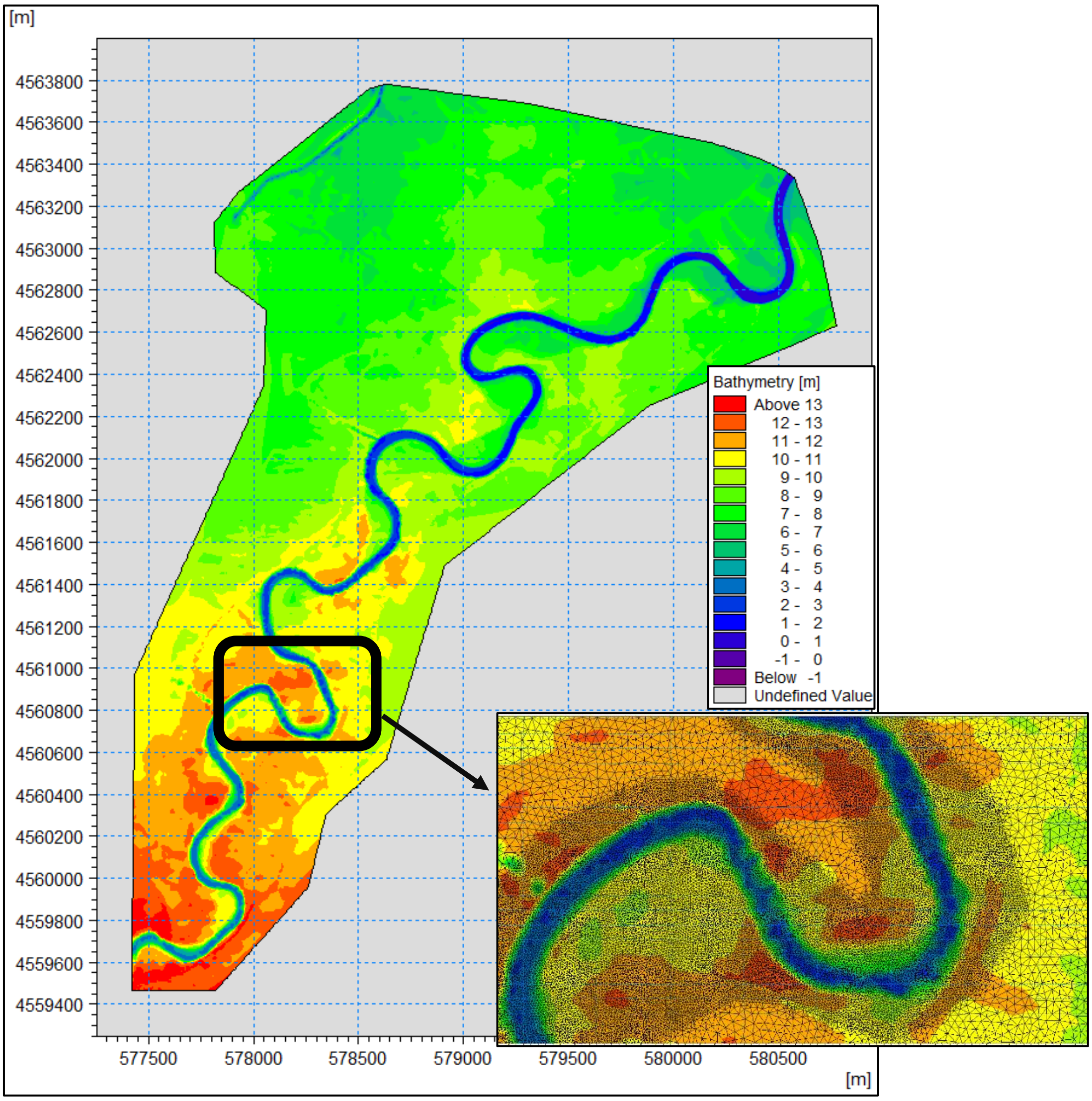


Figure 2-13: Terme River Mesh Setup

Moreover to inputs stated above, some specifications can be defined for hydrodynamic model. The list is given below.

- Salinity and temperature
- Eddy viscosity formulation
- Coriolis force
- Wind forcing
- Ice coverage
- Tidal potential
- Precipitation and evaporation
- Infiltration

- Wave radiation
- Structures
- Initial conditions

These inputs and additional specifications are not considered in this study. After computing hydrodynamic model, listed results were obtained. These results were obtained in terms of maximum values and dynamically changed values over simulation period and modeling area.

- Water depth
- Surface elevation
- Mean flow velocity

CHAPTER 3

ANALYSES

Analyses are performed by modelling software 1D hydrodynamic and 1D sediment transport modules of MIKE 11 and 2D hydrodynamic and sediment transport modules of MIKE 21 FM. These sediment transport and hydrodynamic model setups were used as coupled also.

Analyses are considered as four steps. Firstly, preliminary analyses were made by using 1D modeling. Secondly, cross section defining analyses are made by using two different approaches. After that, sensitivity analyses are implemented in order to determine the most suitable sediment transport calculation equation for study area by using 1D modeling. After considering suitable variables and methods, real flood events those are modelled with sediment transport contribution as 1D and 2D are performed.

When 1D and 2D models were practiced, some assumptions were made due to lack of data, modeling approaches and software restrictions. Assumptions for 1D modeling practices are listed below.

- Cross sections are obtained as frequent as possible. However, cross section intervals were enlarged for some parts of the river to prevent cross sections intersections and unrealistic water level increases for high flow regimes.
- Manning'n coefficients and grain size diameters were assumed constant for upstream part of the river due to lack of data. Particle size decreases negative exponentially with respect to distance in the flow direction (Yanmaz, 2002).

However, only D_{50} values are available for grain size and particle gradation curves are missing.

- Sediment transport boundaries were assumed as in equilibrium since sediment input or outflow data are not available.

Assumptions made for 2D modeling practices are listed below.

- Constant grain size diameter values were used due to lack of data and software restrictions. Obtained data are available for only upstream and downstream parts of the study area. Software does not allow to use a formulated grain size distribution instead of defining grain size for every computation mesh.
- Sediment transport boundaries were assumed as in equilibrium since sediment input or outflow data are not available.

3.1. Preliminary Analysis

In order to investigate capabilities of the 1D coupled sediment transport and hydrodynamic modeling approach, a preliminary analysis has been performed for the meandering 300 meters part of the river. Study area and obtained cross sections are shown in Figure 3-1. Cross sections are obtained with 10 meters of interval in general and 40 m^3/s discharge has been used as flow input.

Figure 3-1: Preliminary Analysis Study Area

Longitudinal profile of the preliminary analysis result is shown in Figure 3-2. At the first half of the river portion, water levels are almost same for both pure hydrodynamic and coupled sediment transport and hydraulic model since bed level changes are minimal. Second half of the portion shows that river bed changes occurred and water levels are smaller for coupled model than pure hydraulic model.

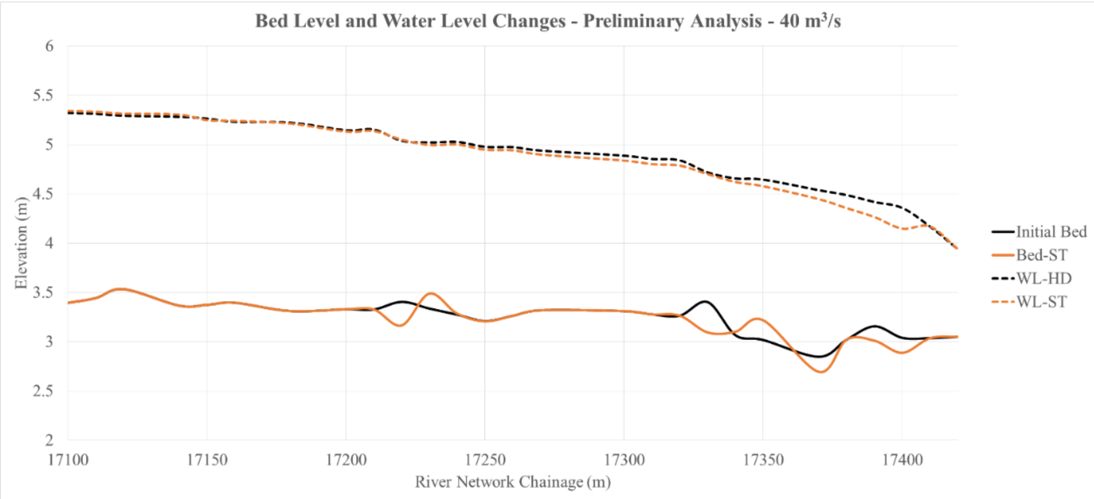


Figure 3-2: Longitudinal Profile Changes – Preliminary Analysis

3.2.Cross Section Defining Analyses

Two approaches are considered to obtain cross sections.

Firstly, cross sections were obtained from river with constant 50 meters of intervals. These cross sections were limited with river bank extent. Cross sections of the first approach can be seen in Figure 3-3.

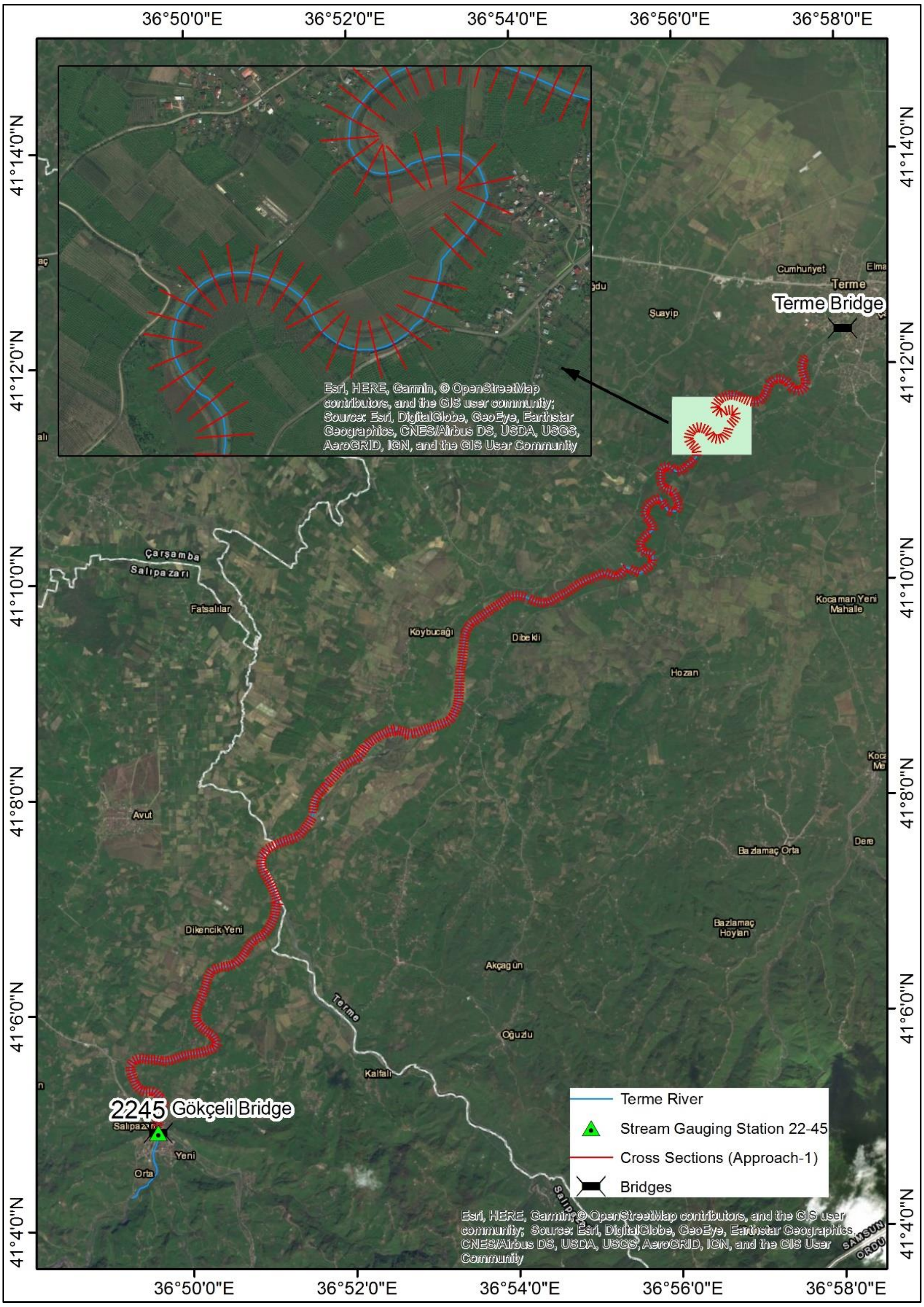


Figure 3-3: Cross Sections of Approach-1

This approach of cross section construction defines river bed and the river extend limited with banks. However, when a flood event occurs water level exceeds bank level and inundation starts.

1D hydrodynamic models show that hydrographs having return periods greater than 25 years cause flooding in Terme River (Figure 2-6). This flooding and exceeding of bank level gives unrealistic velocity and water level values in river bed. Since, water level increases with the extent of banks. Examples from cross section with two different hydrographs are shown in Figure 3-4 and Figure 3-5.

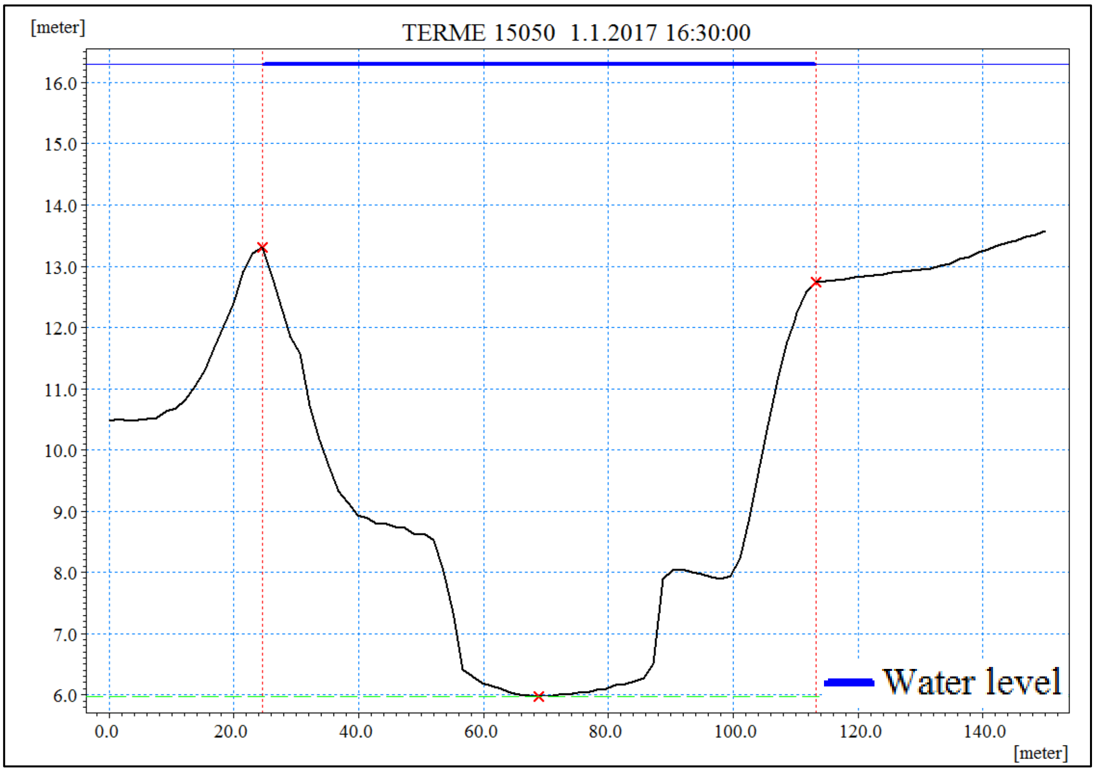


Figure 3-4: Water Level with Cross Section Defining Approach-1 (Q_{500})

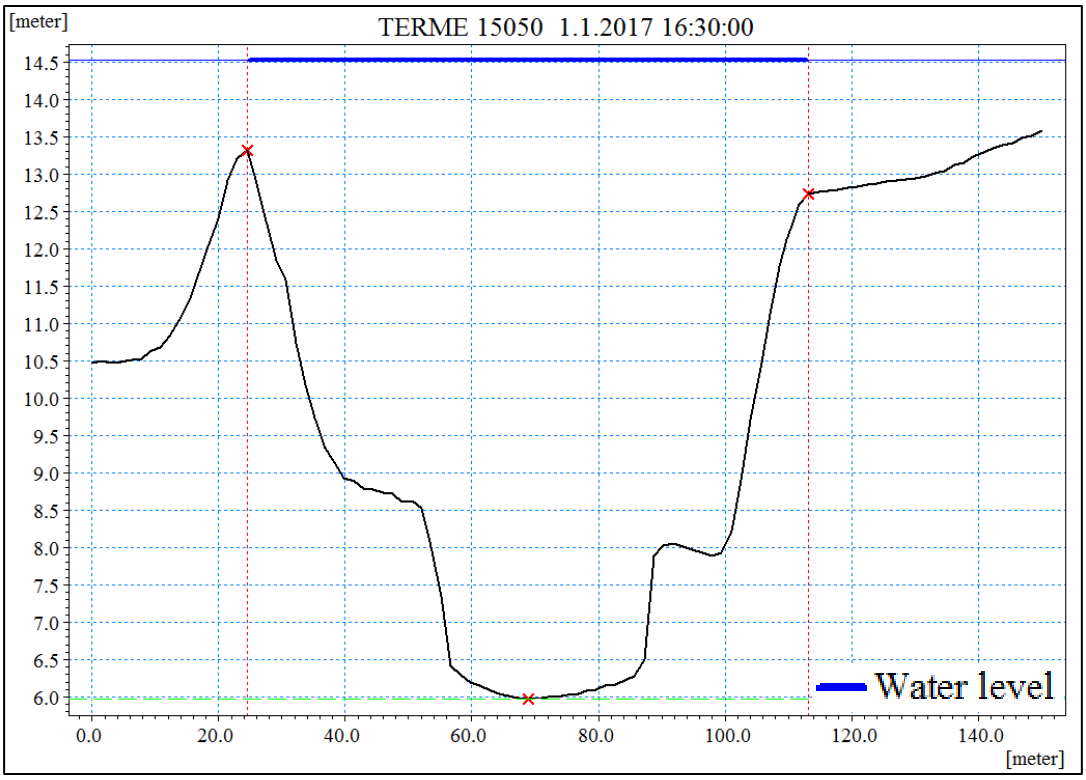


Figure 3-5: Water Level with Cross Section Defining Approach-1 (Q_{50})

This approach can give reasonable results for the parts of the river that water level does not exceed bank levels. However, unrealistic calculation from a cross section can affect calculations at previous or subsequent cross sections. In order to analyze the river properly, this exceeding must be limited. Longitudinal profiles obtained by using Q_{500} and Q_{50} are given in Figure 3-6 and Figure 3-7 respectively.

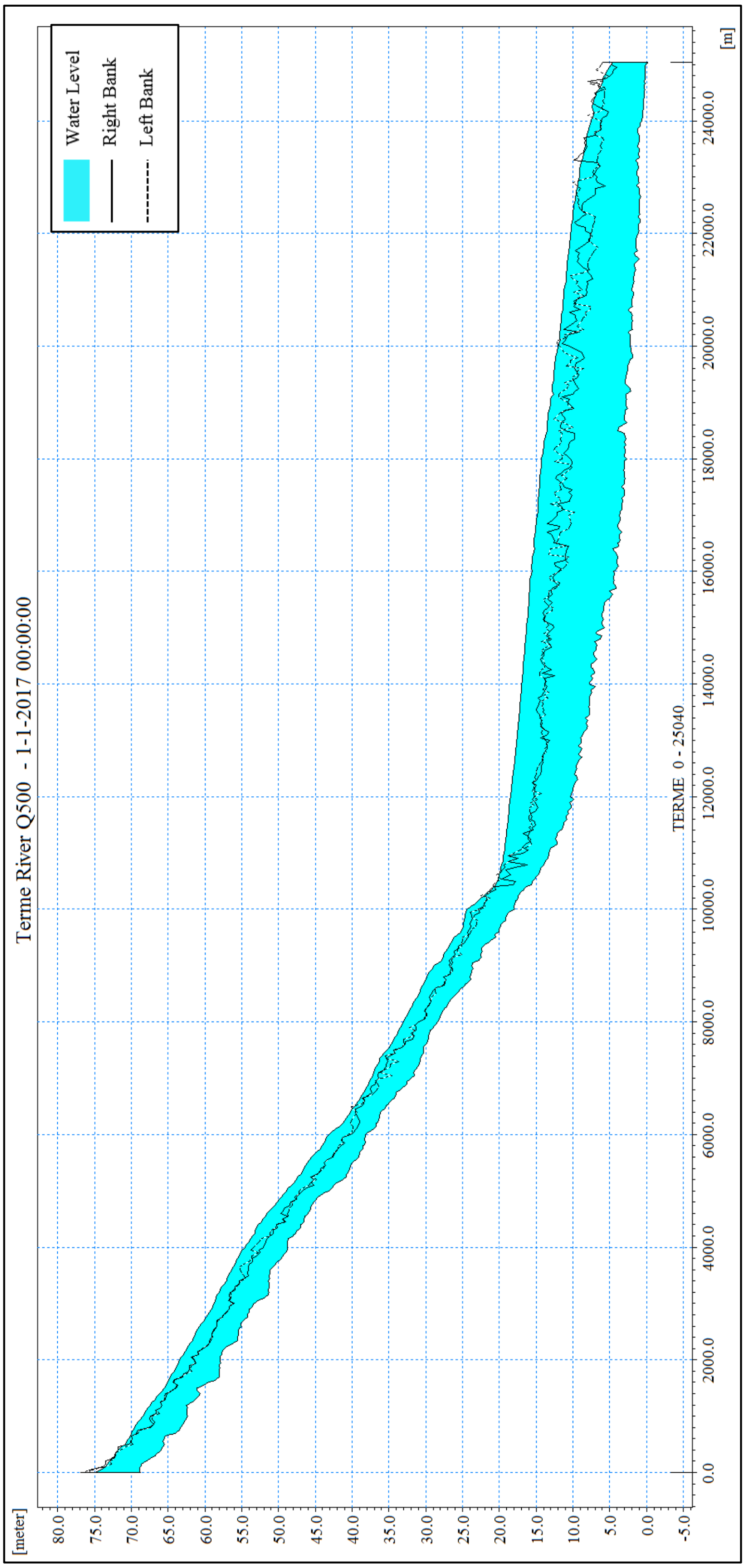


Figure 3-6: Longitudinal Profile of Terme River Cross Section Defining Approach-1 (Q_{500})

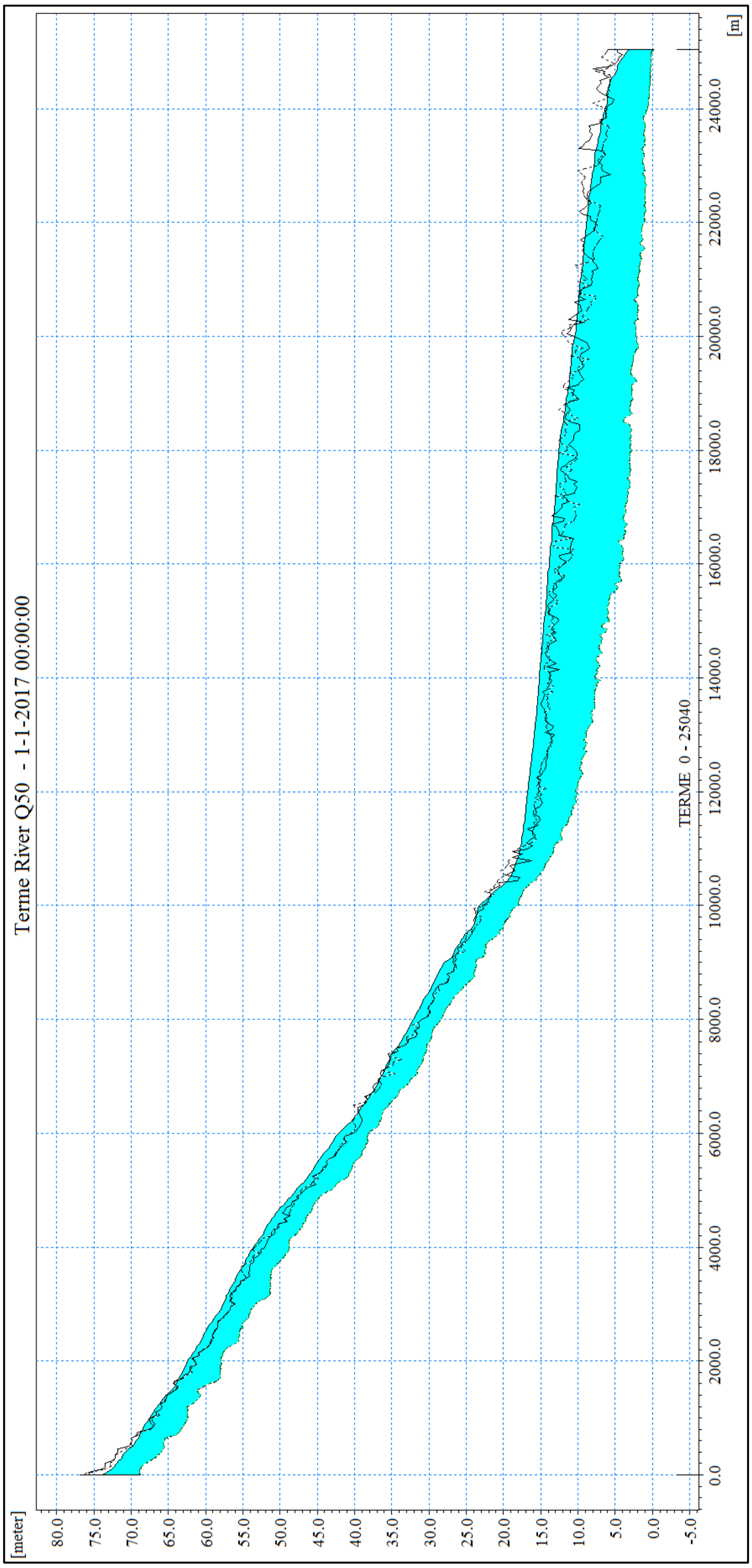


Figure 3-7: Longitudinal Profile of Terme River Cross Section Defining Approach-1 (Q_{50})

In order to prevent calculation of abnormal water level and velocities, cross section intervals should not be limited with a constant value to have extensive cross sections along the river and flood area. Since a cross section must intersect with river only once and must not intersect with another cross section, intervals between cross sections were increased especially at the meandering parts of the river. Although this approach gives more realistic water level values, river morphology could not represented due to big intervals between cross sections.

Cross sections of second approach can be seen in Figure 3-8.

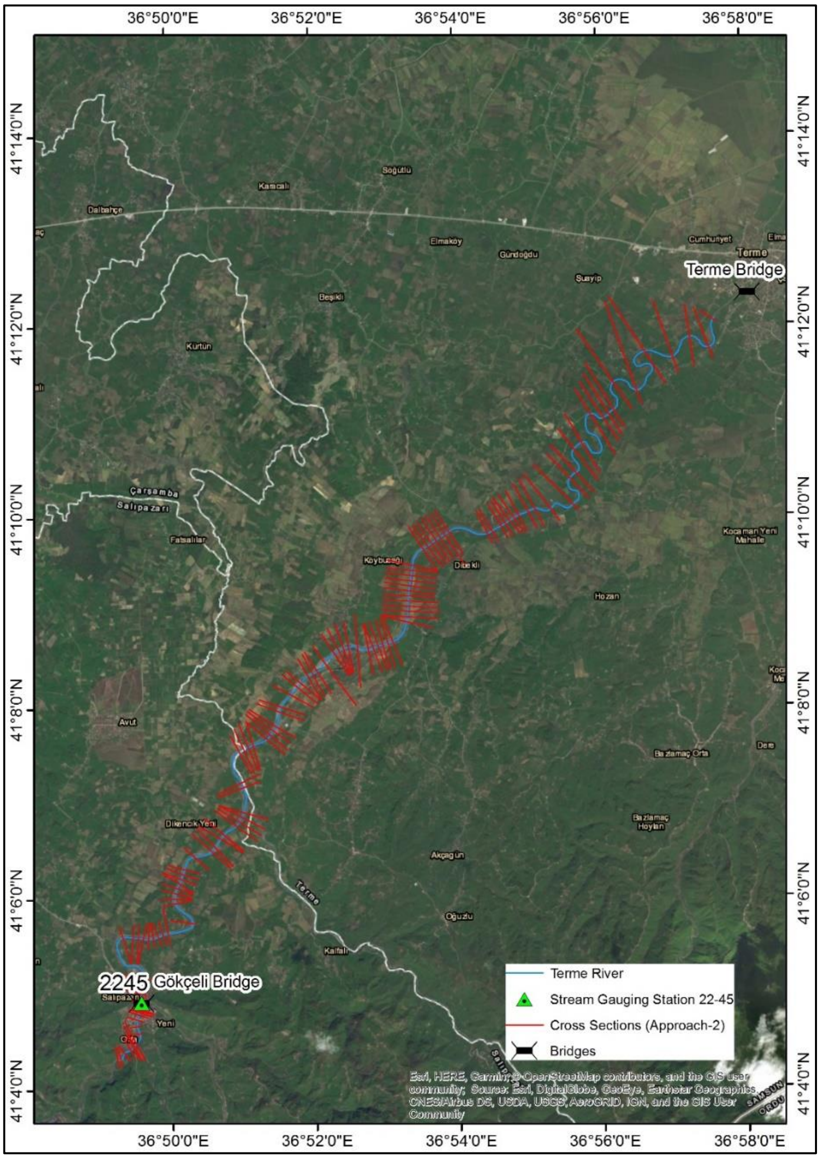


Figure 3-8: Cross Sections of Approach-2

This approach gives flexibility to extend cross section along the area that will be flooded. Only limitation to have extended cross section is morphological data availability. Therefore, cross sections are stretched out as much as possible. This cross section distribution and definition type of morphological data conceive a hydraulic model that is interpreted as Quasi-2D.

This approach affects velocity and water depth calculations of all cross sections. Although there is not any 2D modeling area for the outside of river banks, all of the water volume is carrying to downstream. Examples from cross section for modelling with two different hydrographs are shown in Figure 3-9 and Figure 3-10.

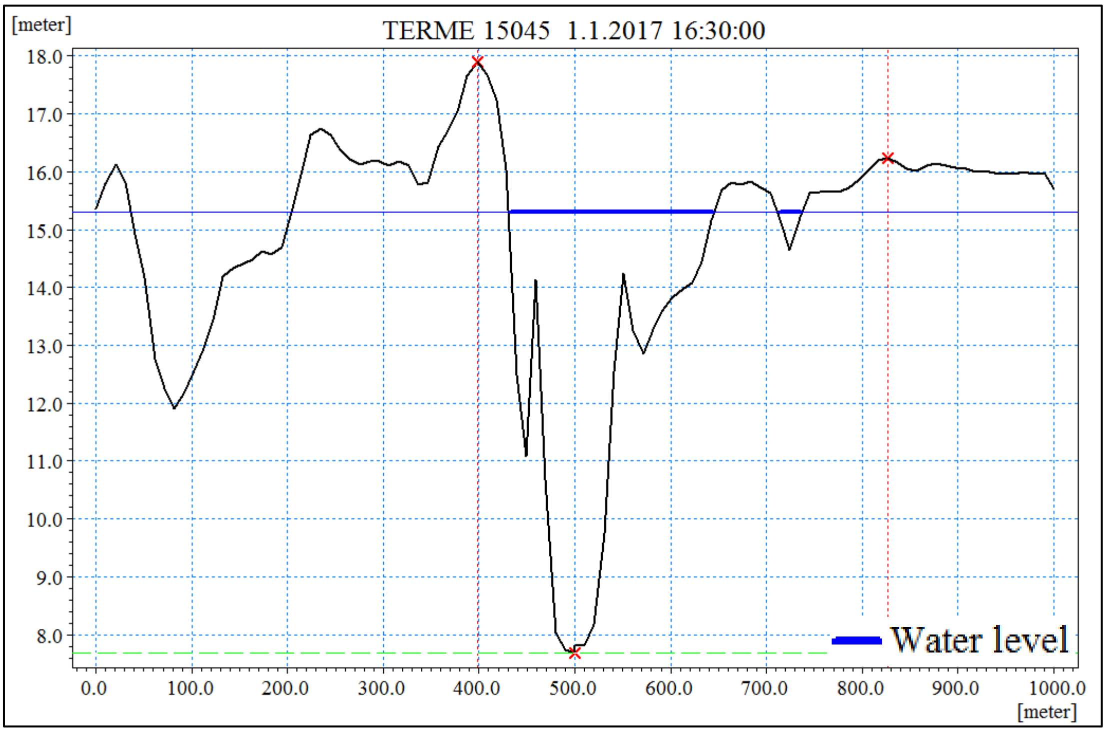


Figure 3-9: Water Level with Cross Section Defining Approach-2 (Q_{500})

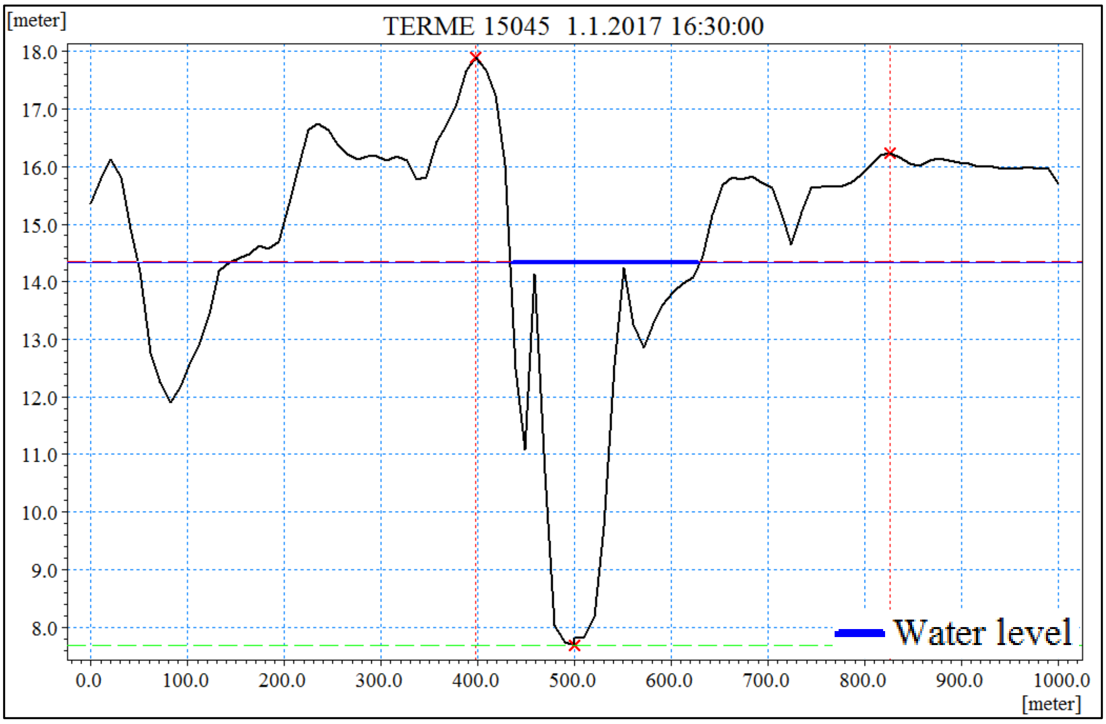


Figure 3-10: Water Level with Cross Section Defining Approach-2 (Q_{50})

As shown in Figure 3-4 and Figure 3-9, water level at the 16.5th hour of hydrograph, decreased from 16.3 meters to 15.3 meters. Changing of the approach for the cross section construction used for Q_{500} hydrograph gives 1 meter of water level decrease.

Comparison of Figure 3-5 and Figure 3-10 presents the water level change between the cross section definition approach does not affect as much as Q_{500} hydrograph. Water level differences at the 6.5th hour of hydrograph at this cross section is 0.17 meters.

Longitudinal profiles of second approach of cross section definition shows that water level at almost all cross sections are less than bank level. Profiles are presented in Figure 3-11 and Figure 3-12 for Q_{500} and Q_{50} hydrographs respectively.

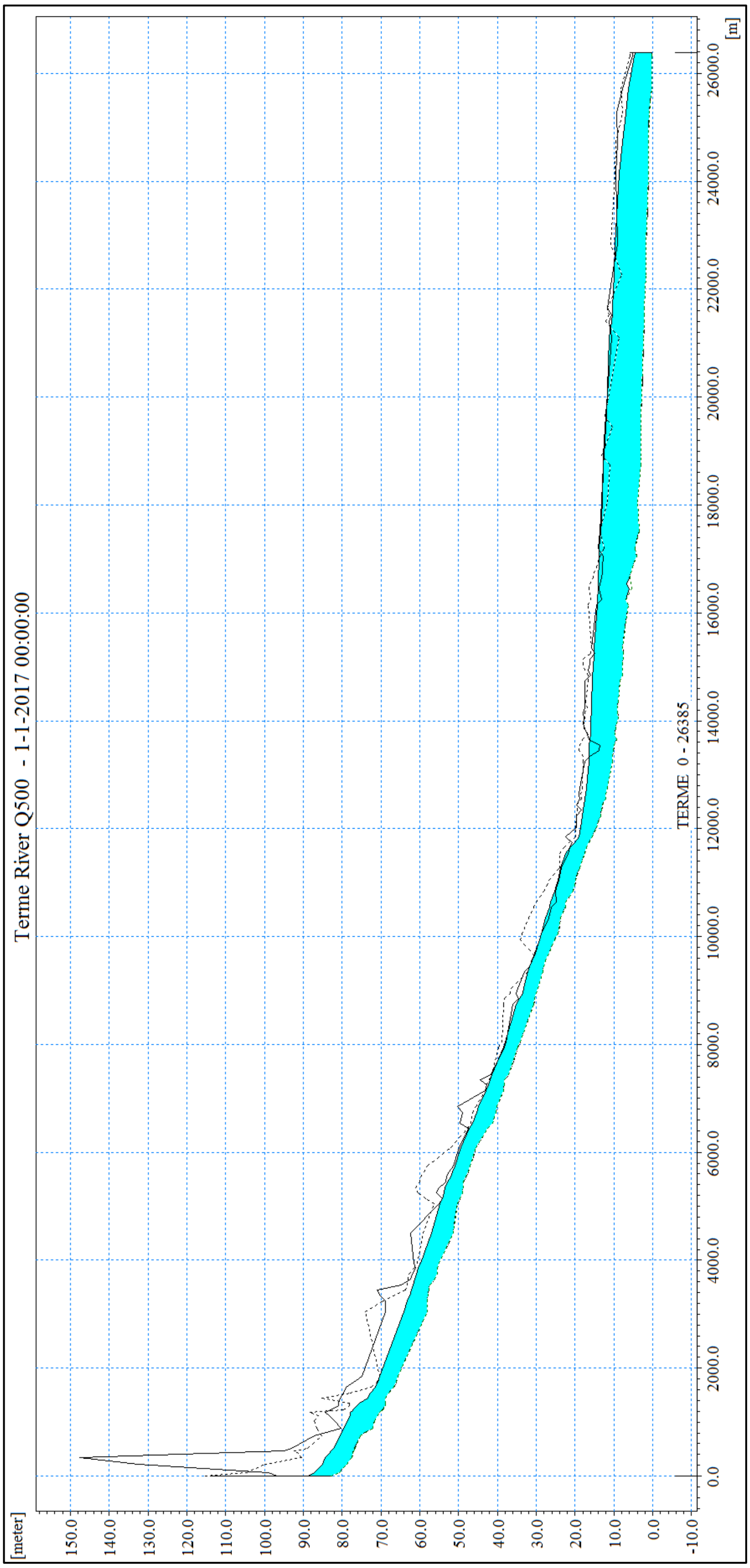


Figure 3-11: Longitudinal Profile of Terme River Cross Section Approach-2 (Q_{500})

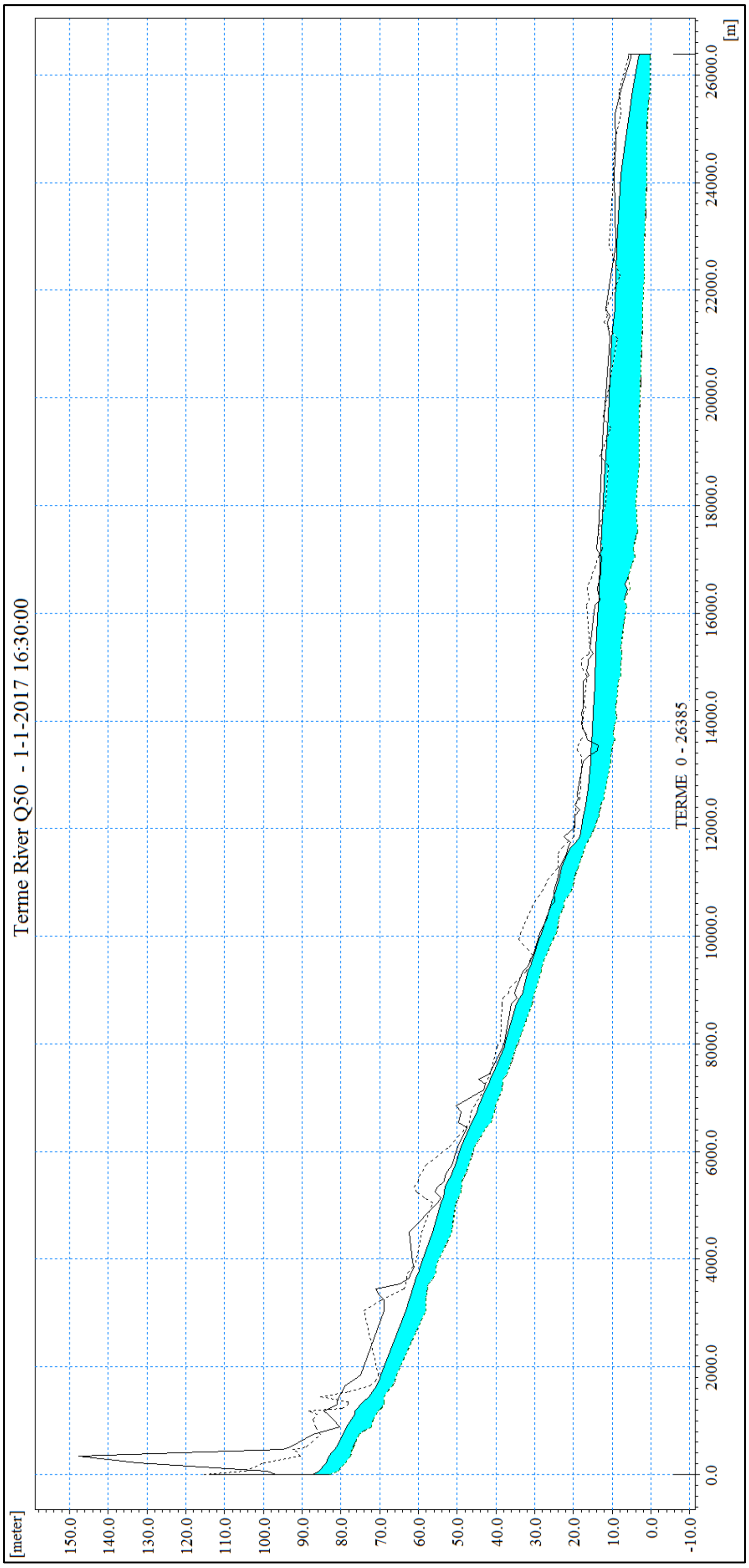


Figure 3-12: Longitudinal Profile of Terme River Cross Section Approach-2 (Q_{50})

3.3. Sensitivity Analyses

Sensitivity analyses of sediment transport methods were performed by using 1D coupled sediment transport and hydrodynamic models.

Observed sediment data from gauge station of DSI, E22A045 with respect to Q_{500}, Q_{50} and Q_5 hydrographs were used. Data obtained between 4.4.1988 and 19.9.2011 were used to construct the sediment rating curve by DSI.

Two sediment calculation formulations were used; Van Rijn Method and Engelund and Fredsoe Method. Both of the methods were applied for bed load and suspended load calculations. Sensitivity analyses were based on suspended sediment calculations since observed data present only suspended sediment load.

Deposition and erosion of bed directly affect hydrodynamic model and the results. Therefore, two different bed level update methods were considered and tested with respect to data obtained at gauging station 22-45.

3.3.1. Results of Sensitivity Analyses

Sensitivity analyses contain two variables as sediment transport formulas (Engelund and Fredsoe and Van Rijn) and bed level update methods (Method-1 and Method-2).

Differences between observed and modelled suspended load are investigated to decide methods that are suitable for study area. These differences are studied for three flood frequencies those are Q_{500}, Q_{50} and Q_5. Three phases of these three flood frequencies which are increasing phase of hydrograph, peak discharge and decreasing phase of hydrograph, are tested. However, phases of measurements are not known. Model results give different sediment load values for increasing and decreasing phase of the hydrograph but measurements have only one value for a measured discharge.

Since measurements are made for sediment load as ton/day and model results are in m^3/s, W_{50} that is measured by using samples from flow gauging station is used to compare measurements and model results. W_{50} for flow gauging station 22-45 is measured as 1.29 ton/m^3.

Van Rijn and Bed Level Update Method-2

Results obtained by Van Rijn Method and Bed Level Update Method-2 are shown in Table 3-1. These results show that decreasing phase of the hydrograph gives underestimated values and increasing phase of hydrograph and peak discharge gives overestimated values. Although model results are generally close to measurements, overestimated values increase up to two times of observed suspended sediment load.

Table 3-1: Van Rijn and Bed Level Update Method-2 Results

Flood Frequency	Discharge (m^3/s)	Suspended Load - Model (m^3/s)	Total Load - Model (m^3/s)	Bed Load	Bed Load / Total Load	Suspended Load - Model (ton/day)	Suspended Load - Observed (ton/day)	Bias (Modelled/ Observed)
Q_{500}	505	0.218	0.301	0.083	0.28	24297.41	12181.79	1.99
	1041	0.556	0.752	0.196	0.26	61969.54	36352.28	1.7
	500	0.041	0.058	0.017	0.29	4569.7	11999.96	0.38
Q_{50}	304	0.07	0.097	0.027	0.28	7801.92	5656.81	1.38
	682	0.273	0.386	0.113	0.29	30427.49	19183.96	1.59
	300	0.018	0.024	0.006	0.25	2006.21	5544.69	0.36
Q_5	149	0.014	0.017	0.003	0.18	1560.38	1925.35	0.81
	350.4	0.079	0.116	0.037	0.32	8805.02	7011.5	1.26
	150	0.007	0.009	0.002	0.22	780.19	1944.92	0.4

Engelund-Fredsoe and Bed Level Update Method-2

Results obtained by Engelund and Fredsoe Method and Bed Level Update Method-2 are shown in Table 3-2. Results of the scenario indicate that differences are generally underestimated for decreasing phase of hydrograph. Results for peak discharge are underestimated for Q_{500} and reasonable for Q_{50} and Q_5. Increasing phase of hydrograph gives overestimated result for Q_{50}, underestimated result for Q_5 and almost matched for Q_{500}.

Table 3-2: Engelund-Fredsoe and Bed Level Update Method-2 Results

Flood Frequency	Discharge (m^3/s)	Suspended Load - Model (m^3/s)	Total Load - Model (m^3/s)	Bed Load	Bed Load / Total Load	Suspended Load - Model (ton/day)	Suspended Load - Observed (ton/day)	Bias (Modelled/ Observed)
Q_{500}	561.86	0.139	0.311	0.172	0.55	15492.38	14313.53	1.08
	1041	0.187	0.421	0.234	0.56	20842.27	36352.28	0.57
	500	0.111	0.232	0.121	0.52	12371.62	11999.96	1.03
Q_{50}	304	0.073	0.178	0.105	0.59	8136.29	5656.81	1.44
	682	0.153	0.337	0.184	0.55	17052.77	19183.96	0.89
	300	0.024	0.076	0.052	0.68	2674.94	5544.69	0.48
Q_5	150	0.005	0.045	0.04	0.89	557.28	1944.92	0.29
	350.2	0.073	0.189	0.116	0.61	8136.29	7005.45	1.16
	210	0.004	0.045	0.041	0.91	445.82	3234.14	0.14

Calculations of suspended load by using Engelund-Fredsoe Method and Van Rijn Method with Bed Level Update Method-2 show that Engelund-Fredsoe Method is the most consistent method for study area since differences between observed and modelled load amounts are closer to the results obtained from Van Rijn Method.

Other decision is made for bed level update method. Therefore, Bed Level Update Method-1 is tested with Engelund-Fredsoe Method.

Engelund-Fredsoe and Bed Level Update Method-1

Results obtained by Engelund and Fredsoe Method and Bed Level Update Method-1 are shown in Table 3-3. Sediment load test for Bed Level Update Method-1 gives underestimated results.

Table 3-3: Engelund-Fredsoe and Bed Level Update Method-1 Results

Flood Frequency	Discharge (m^3/s)	Suspended Load - Model (m^3/s)	Total Load - Model (m^3/s)	Bed Load	Bed Load / Total Load	Suspended Load - Model (ton/day)	Suspended Load - Observed (ton/day)	Bias (Modelled/ Observed)
Q_{500}	561.86	0.106	0.242	0.136	0.56	11814.34	14313.53	0.83
	1041	0.151	0.346	0.195	0.56	16829.86	36352.28	0.46
	500	0.086	0.207	0.121	0.58	9585.22	11999.96	0.8
Q_{50}	304	0.051	0.178	0.127	0.71	5684.26	5656.81	1
	682	0.115	0.337	0.222	0.66	12817.44	19183.96	0.67
	300	0.018	0.076	0.058	0.76	2006.21	5544.69	0.36
Q_5	150	0.004	0.036	0.032	0.89	445.82	1944.92	0.23
	350.2	0.048	0.134	0.086	0.64	5349.89	7005.45	0.76
	210	0.005	0.044	0.039	0.89	557.28	3234.14	0.17

Moreover to sediment load testing and validation with observed sediment load data of two bed level update methods, bed level changes are investigated.

Bed level update methods are examined for three areas that have different characteristics as steep having slope of 2.3%, braided having slope of 0.5% and meandering having slope of 0.04%. River part between chainages 745 and 890 is decided as steep slope, area between chainages 9645 and 12345 is defined as braided and area between chainages 18055 and 24700 is defined as meandering. These areas and river chainages are shown in Figure 3-13, Figure 3-15, Figure 3-17 and Figure 3-20.

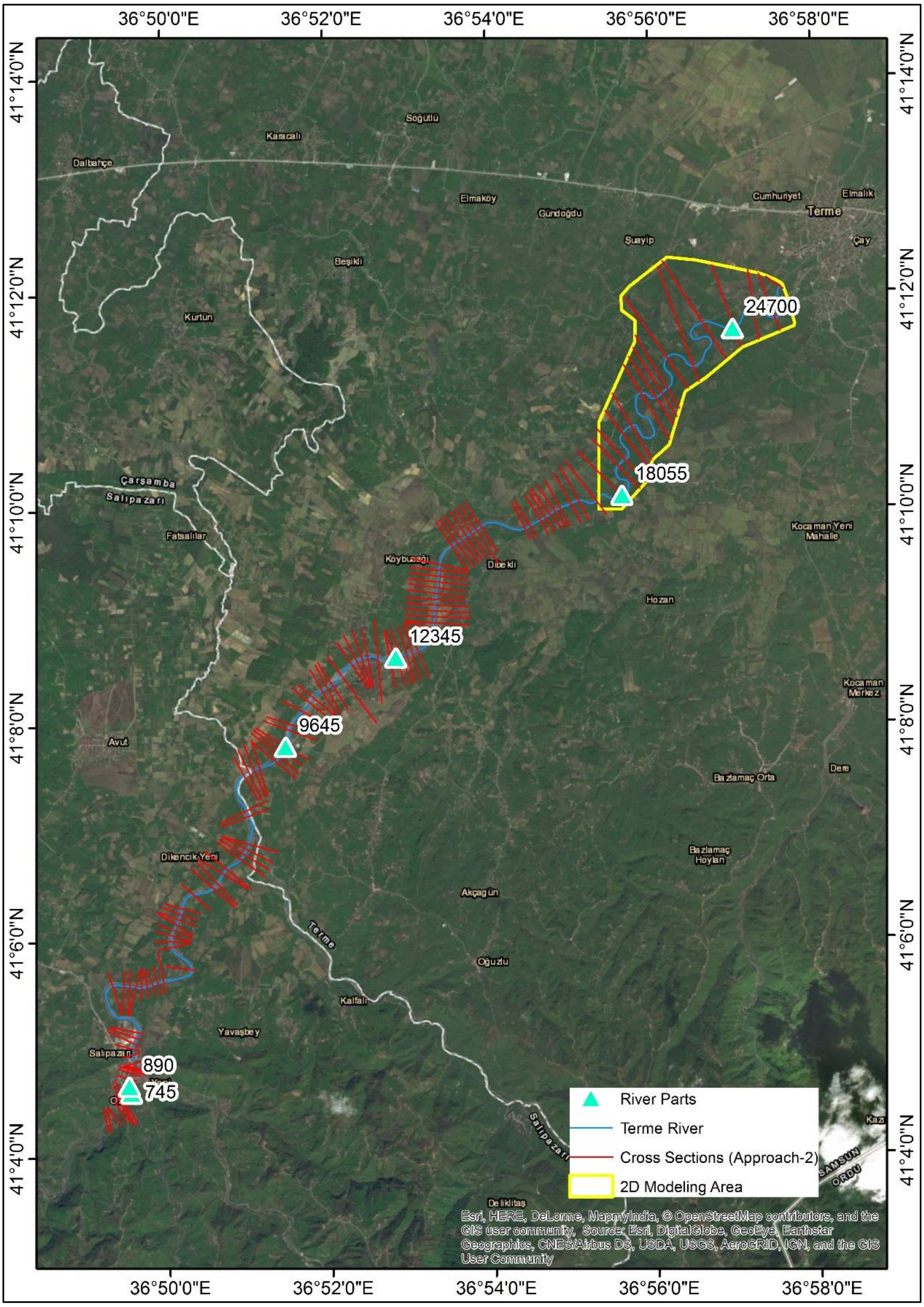


Figure 3-13: River Parts of Study Area and Cross Sections

Two bed level methods are examined for three different river parts and bed levels are shown in the following figures and graphs.

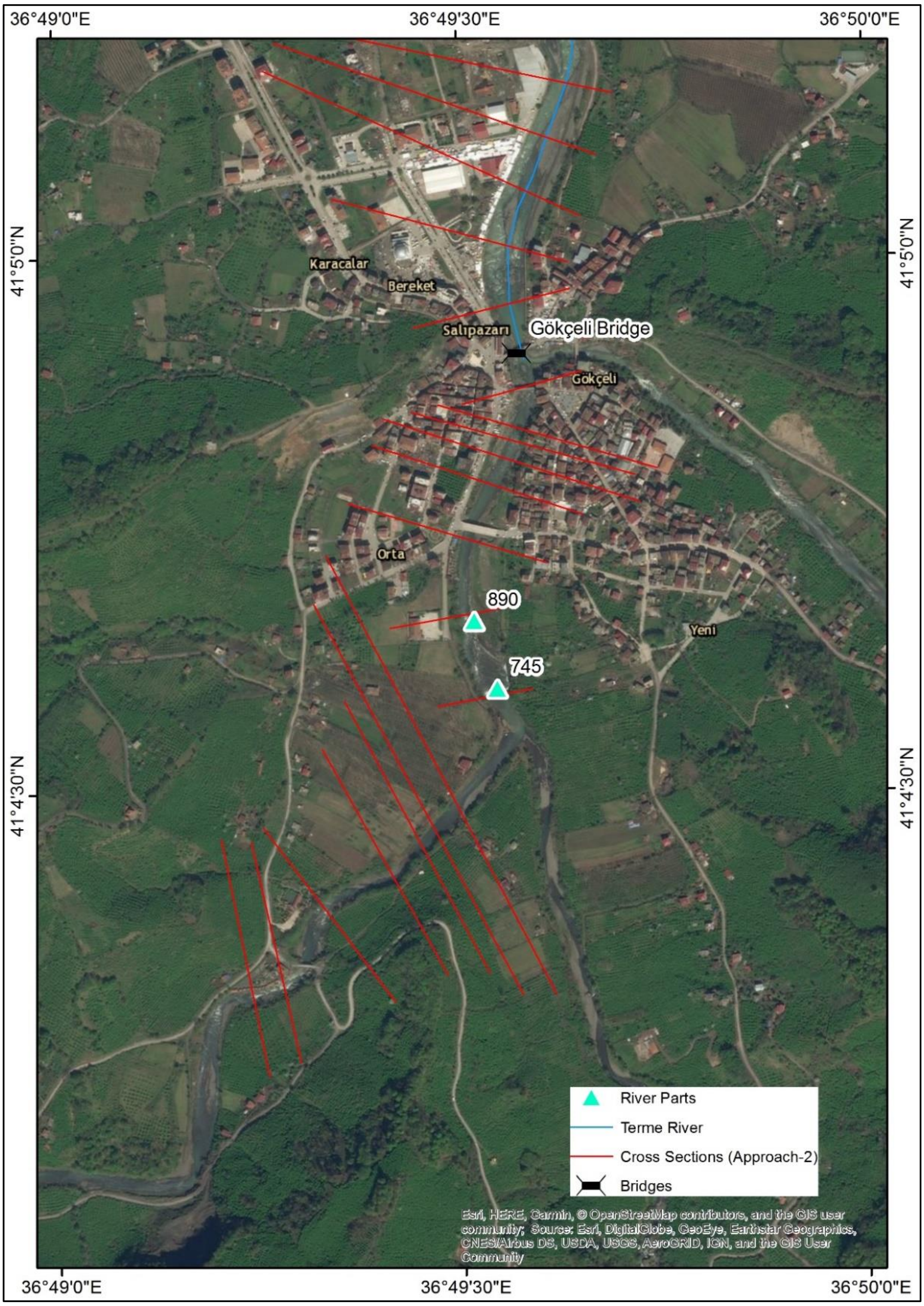


Figure 3-14: Steep Part of Terme River

Study area includes Gökçeli Bridge that is at the chainage 1345. Bridge is ignored for all computations and it is not defined in 1D and 2D modeling studies since sensitivity of modeling approaches is explored in this study. Bed level change at upstream cross section of the bridge can be seen in Figure 3-15 with respect to Engelund-Fredsoe Method and Bed Level Update Method-1. Extra care must be taken in order to investigate effects of bridge on sediment transport and hydrodynamics.

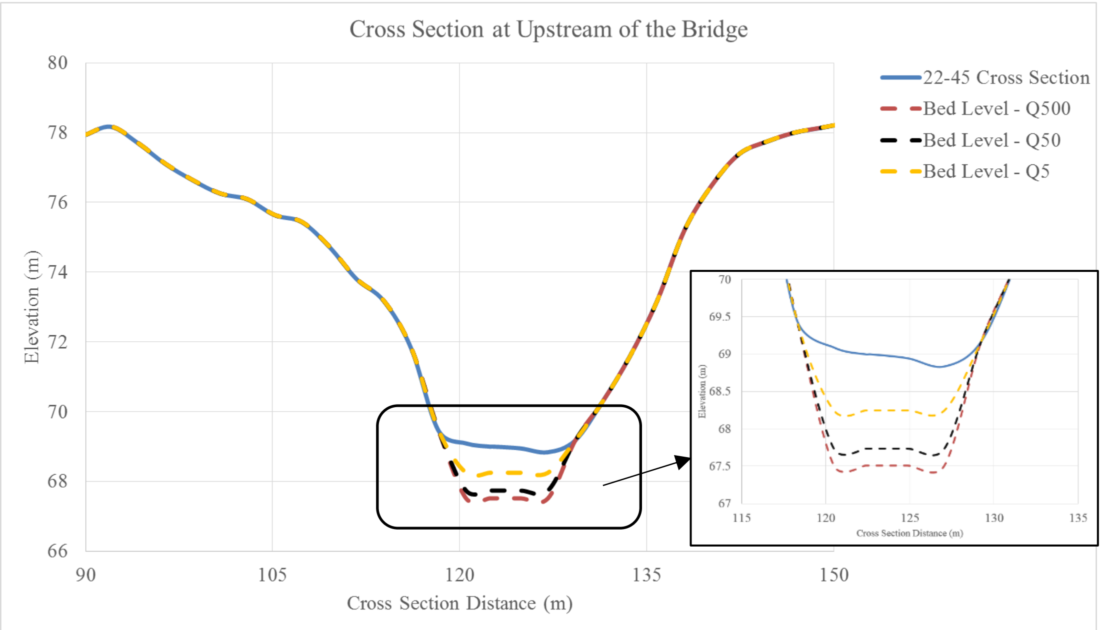


Figure 3-15: Cross Section at Upstream of the Bridge (Chainage 1310)

With respect to model results obtained at steep part of the river, Bed Level Update Method-1 gives changes on river bed level as deposition for Q_{500} and both deposition and erosion for Q_{50} and Q_5. Slope of the initial bed level becomes smoother for all flood frequency hydrographs (Figure 3-16).

Results of Bed Level Update Method-2 indicates deposition for Q_{500}. Q_{50} and Q_5 results are almost the same with initial bed level. Only deposition is obtained for Q_{500} due to erosions from upstream part of the river. Since Bed Level Update Method-2 distribute sediment load to whole cross section, effects on bed level update are minimal (Figure 3-17).

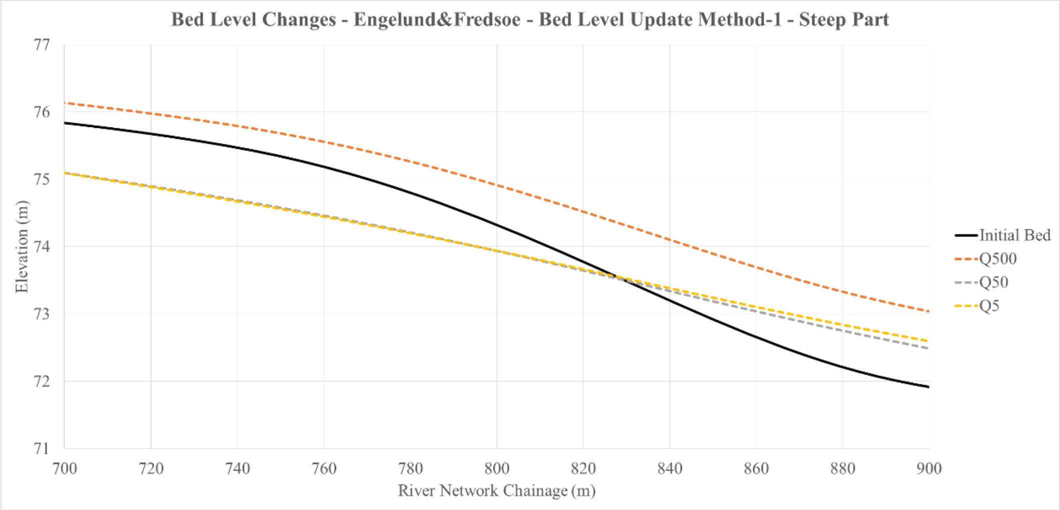


Figure 3-16: Bed Level Changes – Steep Part (Bed Level Update Method-1 and Engelund&Fredsoe)

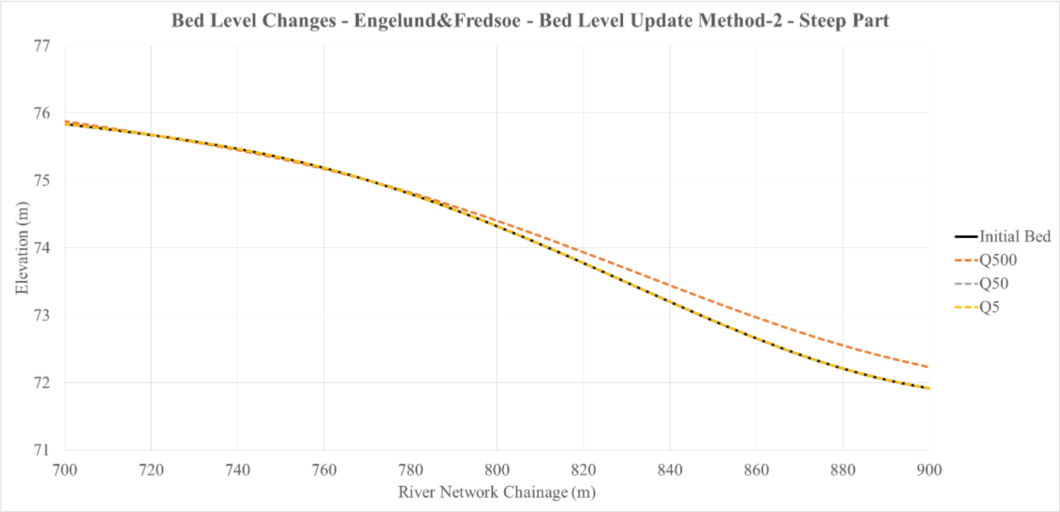


Figure 3-17: Bed Level Changes – Steep Part (Bed Level Update Method-2 and Engelund&Fredsoe)

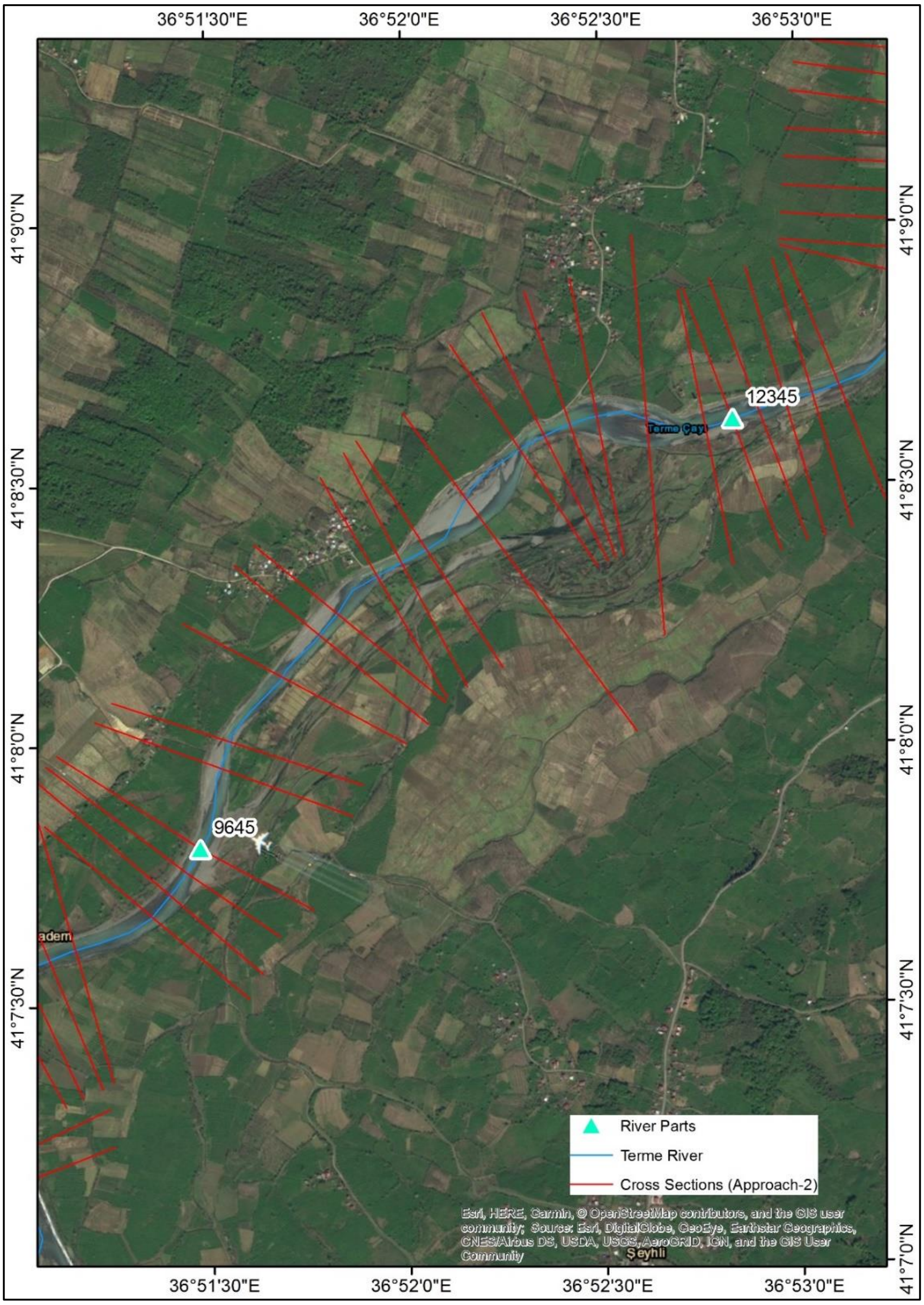


Figure 3-18: Braided Part of Terme River

Results that are observed by using Bed Level Update Method-1 at braided part of Terme River reveals that deposition is occurred for Q_{500}. Deposition and erosion are obtained for local parts of the braided part. Q_{50} and Q_5 results show the same tendency but differences are larger for Q_{50} (Figure 3-19).

Results of scenario that is constructed by using Bed Level Update Method-2 shows minimal bed level changes. Q_{500} results are more visible than Q_{50} and Q_5. Deposition and erosion trends are the same with Method-1 but differences are lower than Method-1 (Figure 3-20).

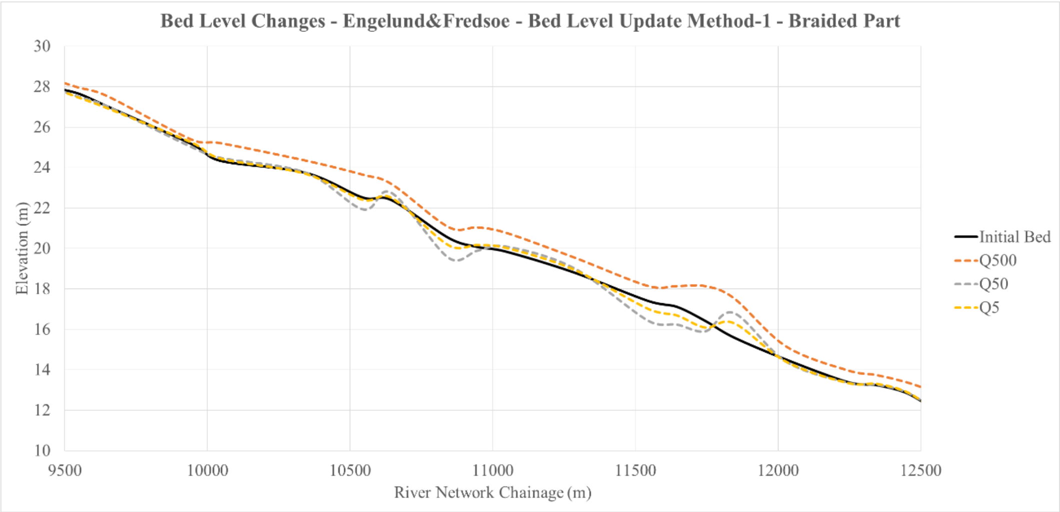


Figure 3-19: Bed Level Changes – Braided Part (Bed Level Update Method-1 and Engelund Fredsoe)

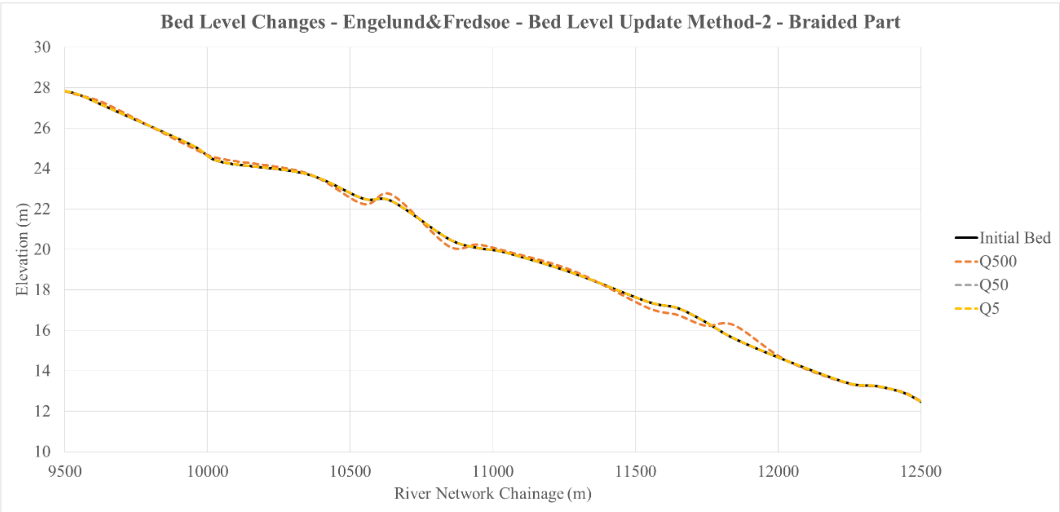


Figure 3-20: Bed Level Changes – Braided Part (Bed Level Update Method-2 and Engelund Fredsoe)

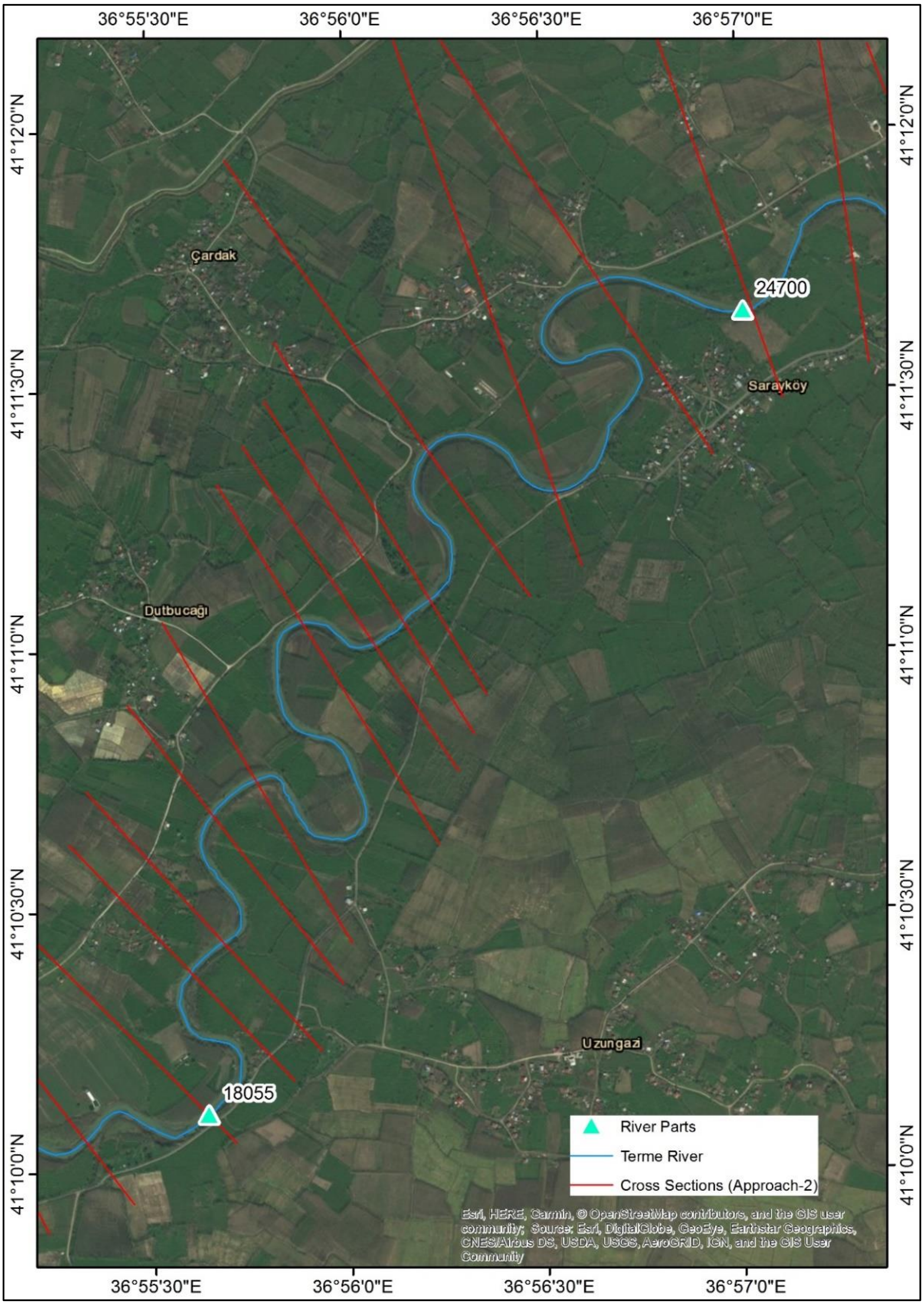


Figure 3-21: Meandering Part of Terme River

Results obtained by Bed Level Update Method-1 at meandering part of the river reveal that deposition occurs for hydrograph of Q_{500} (Figure 3-22). Local deposition and erosion areas are obtained for Q_{50} and Q_5. Trend of these two peak flood discharges are the same.

Erosion is attained for a local part of meandering part of the river for Bed Level Update Method-2 for Q_{500}. Bed level difference is almost not detected for Q_{50} and Q_5 (Figure 3-23).

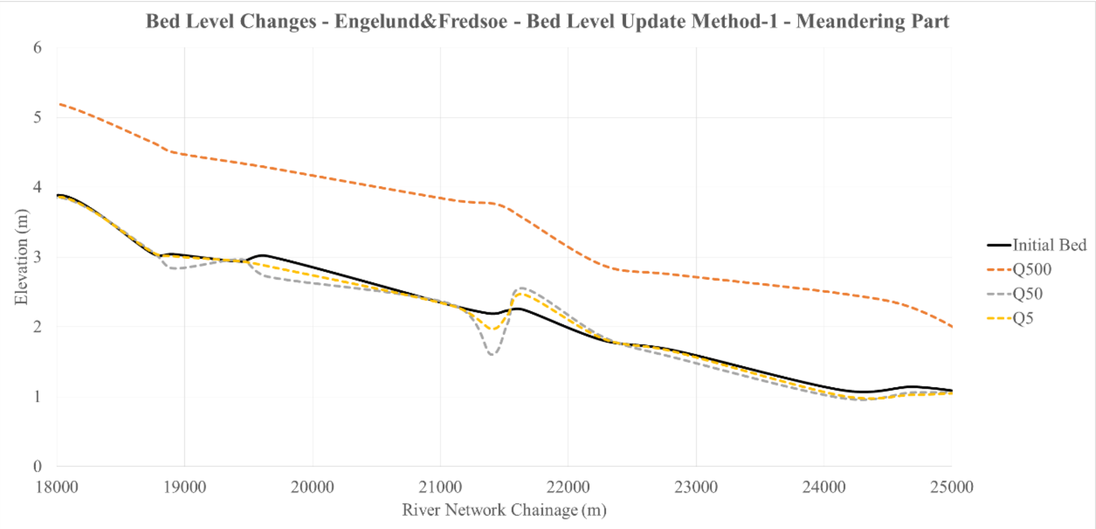


Figure 3-22: Bed Level Changes – Meandering Part (Bed Level Update Method-1 and Engelund&Fredsoe)

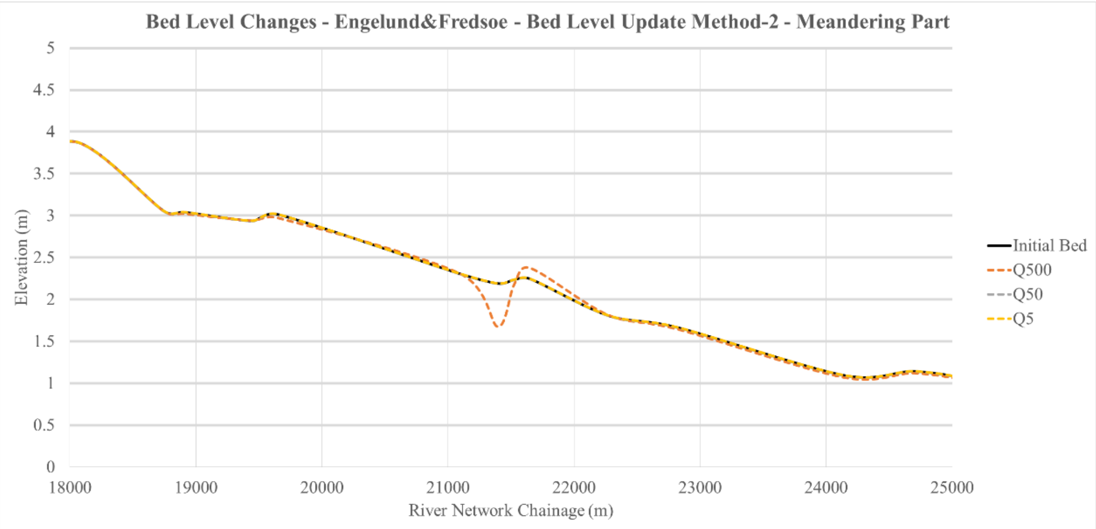


Figure 3-23: Bed Level Changes – Meandering Part (Bed Level Update Method-2 and Engelund&Fredsoe)

Results of bed level update methods show that Bed Level Update Method-2 do not affect morphology as much as Method-1. Since first method affects all parts of the cross section instead of cross section part that contacts with water, erosion and deposition in cross sections are underestimated. Therefore, bed level changes are very low for Method-2.

Results of Bed Level Update Method-1 are more consistent than the results obtained by Method-2. Since 1D model only works at cross sections, bed level changes presented at the location of the cross sections. From the sensitivity analyses, Engelund and Fredsoe Method with Bed Level Update Method-1 are decided as suitable scenario for the study area.

3.4. Real Event Analyses

Real event analyses are performed by using 1D and 2D models. Real flood events were observed in the study area on 22 November 2014, 02 August 2015 and 28 May 2016.

Sediment observations are not available for these periods. Selection of modelling methods are decided by sensitivity analyses and applied for real flood events.

3.4.1. 1D Real Event Analyses

1D sediment transport models of real flood events were analyzed by using Engelund and Fredsoe Method with Bed Level Update Method-1.

Results are presented with longitudinal profiles of hydrodynamic model and sediment transport and hydrodynamic coupled model. All related results of real events are given in the following figures and graphs. Black line (Initial Bed) indicates initial bed, orange line (Bed-ST) shows bed of coupled sediment transport and hydrodynamic model, black dashed line (WL-HD) is water level result of hydrodynamic model and orange dashed line (WL-ST) is water level result of coupled hydrodynamic and sediment transport model.

With respect to modeling analyses of real flood events, water level is decreased due to erosion for all three scenario. Result of 28 May 2016 event shows that, slope of river bed is being linear due to erosion and deposition. Water level result of coupled model is lower than hydrodynamic model due to flow capacity increasing of river (Figure 3-24).

Minimal river bed change is observed for flood event on 02 August 2015. Therefore, water level is almost the same for hydrodynamic and coupled models (Figure 3-25).

Result of flood event occurred in 2014 reveals that bed level and water level changes are greater than event in 2015 and lower than event in 2016 (Figure 3-26).

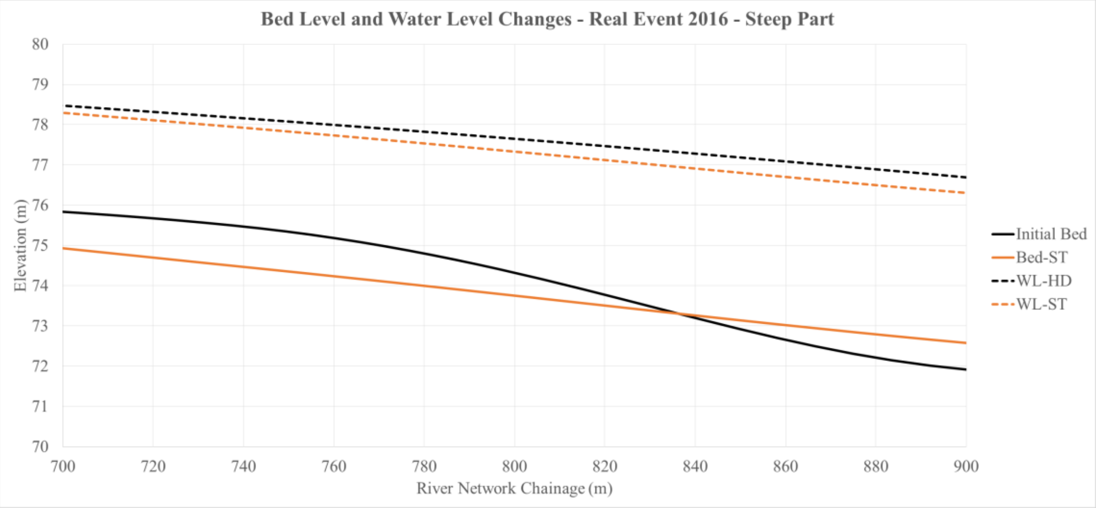


Figure 3-24: Longitudinal Profile Changes – Steep Part, Real Event 28 May 2016

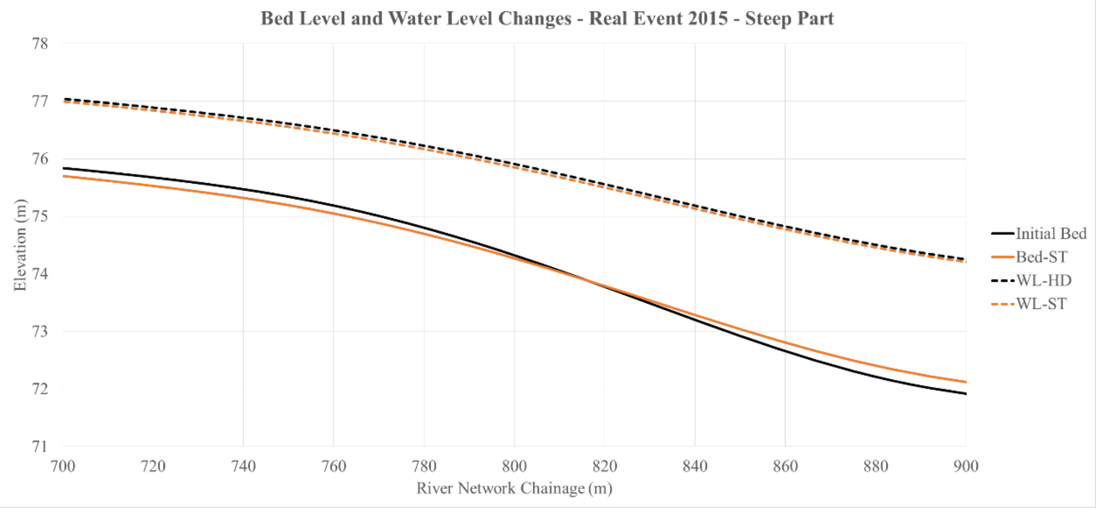


Figure 3-25: Longitudinal Profile Changes – Steep Part, Real Event 02 August 2015

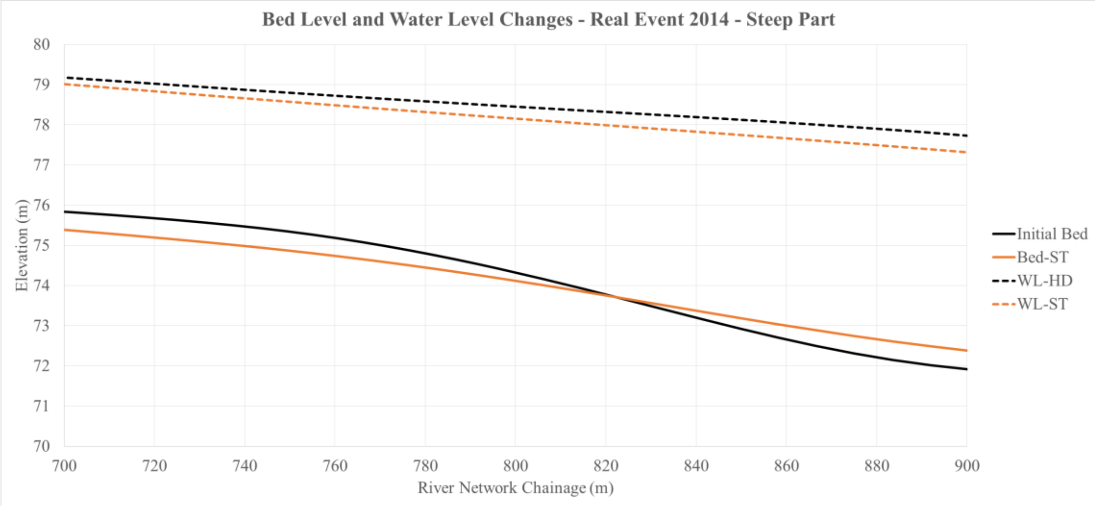


Figure 3-26: Longitudinal Profile Changes – Steep Part, Real Event 22 November 2014

Results for braided part of river show that river bed and water level changes are very limited. Generally water levels are minimally decreased for all scenarios. Result of 28 May 2016 scenario indicates that bed level changes occur for some parts and water level decreases for these parts (Figure 3-27).

Result of 02 August 2015 scenario shows that bed level change is almost not occurred. Water level is also almost the same for coupled model and hydrodynamic model (Figure 3-28).

Bed level change is more apparent for the event on 22 November 2014. Water level presents similar trend with bed level change. At the parts of erosion, water level is decreased and increased for the parts having deposition (Figure 3-29).

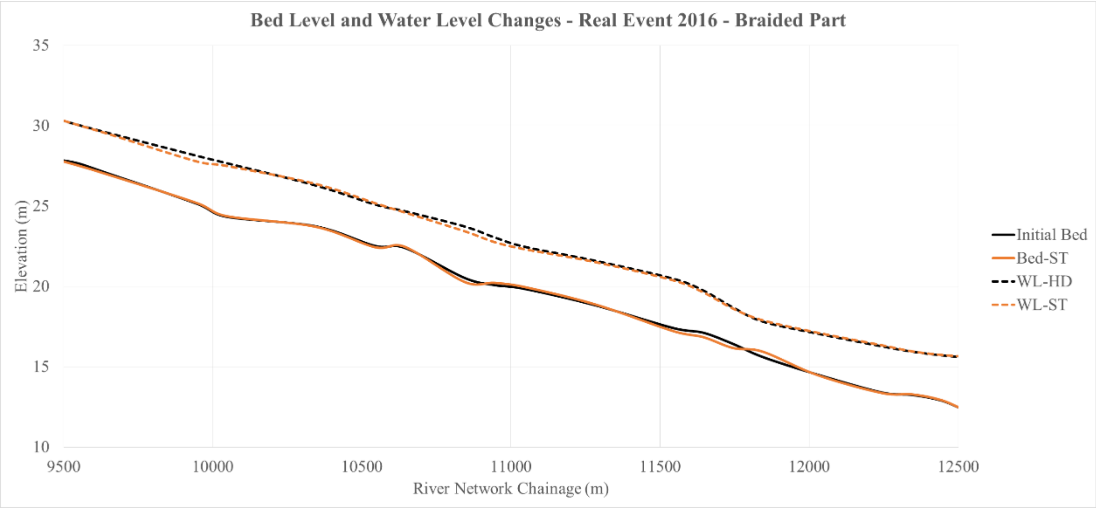


Figure 3-27: Longitudinal Profile Changes – Braided Part, Real Event 28 May 2016

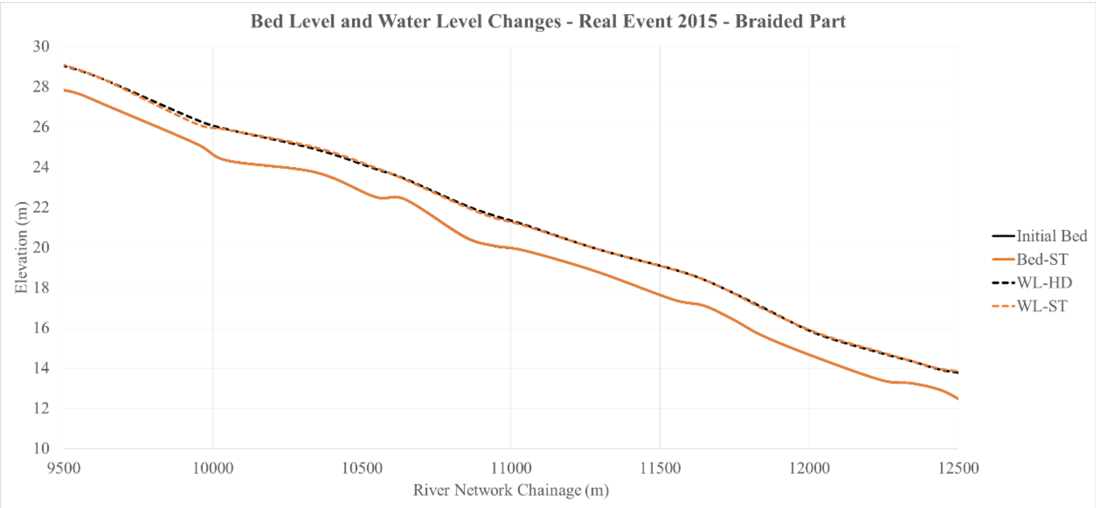


Figure 3-28: Longitudinal Profile Changes – Braided Part, Real Event 02 August 2015

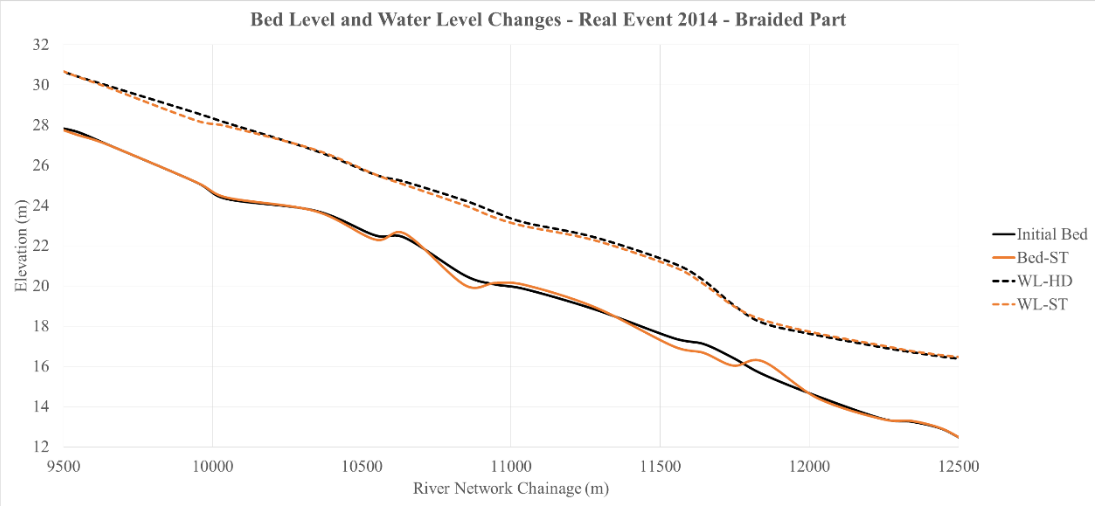


Figure 3-29: Longitudinal Profile Changes – Braided Part, Real Event 22 November 2014

Results of meandering part of Terme River state that bed level and water level changes are minimal. Real event occurred on 28 May 2016 scenario result indicates that bed level changes are limited and water level is also not changed much (Figure 3-30).

Result of real event on 02 August 2015 shows that almost nothing changed for water level and bed level (Figure 3-31).

Changes of water level and bed level are very limited for real event occurred on 22 November 2014. Erosion and deposition parts are investigated for some part of the river. Water level also changes for these parts similar with bed level change (Figure 3-32).

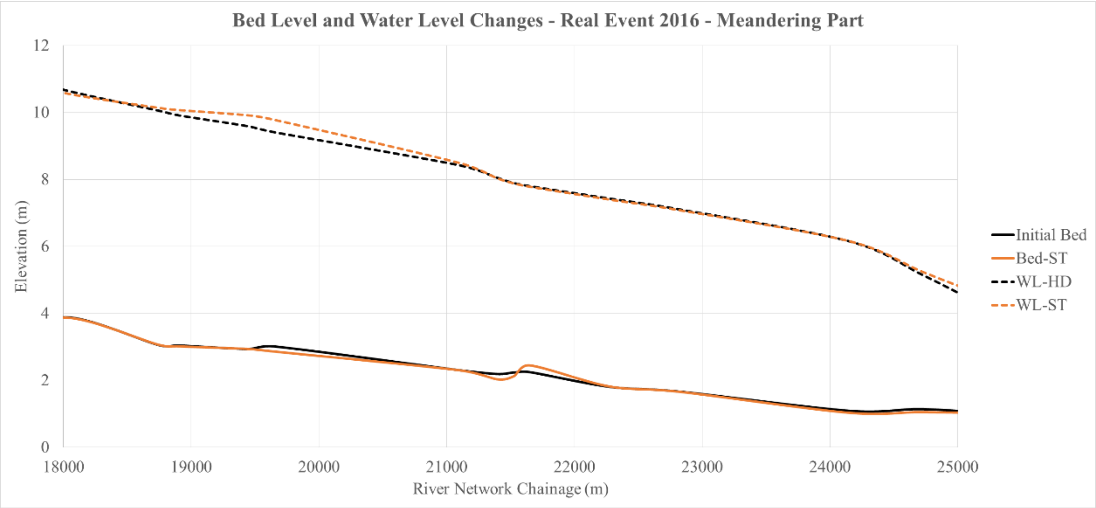


Figure 3-30: Longitudinal Profile Changes – Meandering Part, Real Event 28 May 2016

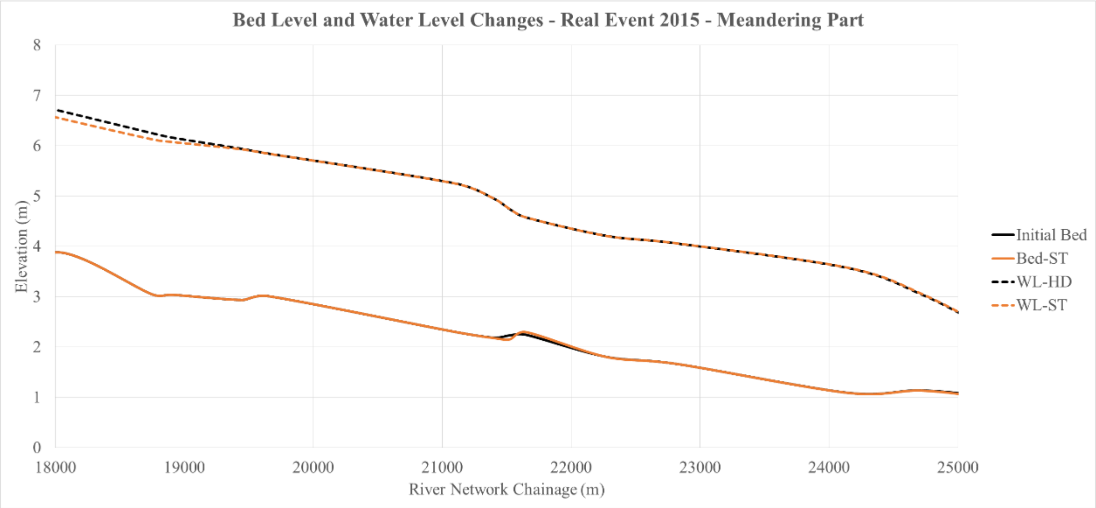


Figure 3-31: Longitudinal Profile Changes – Meandering Part, Real Event 02 August 2015

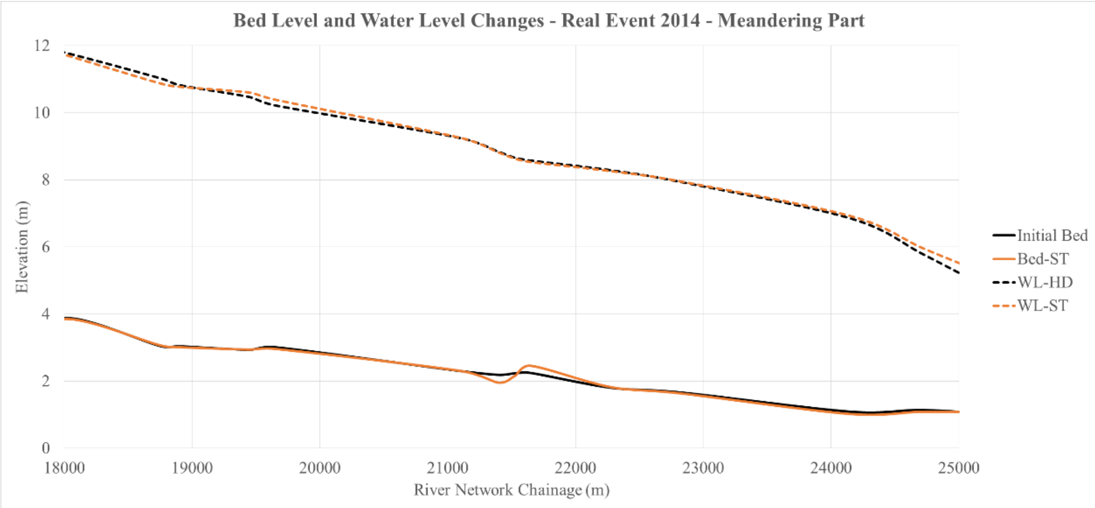


Figure 3-32: Longitudinal Profile Changes – Meandering Part, Real Event 22 November 2014

3.4.2. 2D Real Event Analyses

2D modelling studies are made by using data obtained at real flood event for 22 November 2014. Therefore, upstream boundary condition is defined as hydrograph of flood event. Although this hydrograph is observed by gauging station 22-45 and the station is far from 2D modeling area, hydrograph is used and subbasin between 22-45 and upstream of 2D modeling area are ignored. 2D modeling is performed for 4 different scenarios that are pure hydrodynamic and coupled hydrodynamic and sediment transport computations for 5.5 mm grain size, 3 mm grain size and 0.55 mm grain size.

Pure 2D hydrodynamic model is constructed to obtain inundation map and water level values without any bed update.

Sediment transport model coupled with hydrodynamic model is also computed to include bed level update to model. Inundation map, water level and bed level change data are obtained. Engleund and Fredsoe Method is used for both of suspended load and bed load computations.

2D model is performed at the downstream part of the river. Study area is between chainages 17550 and 26330. This part of the river is selected due to its meandering characteristics and expectation of being affected by sediment transport. Pure 2D hydrodynamic model without sedimentation module gives the result that flood occurs in that area. Applying hydrodynamic analyze coupled with sediment module represents the effect of sedimentation on inundation and flood occurrence.

2D modeling study area is in between cross sections having chainage 17525 and 26330 2D modeling study area and digital elevation model that is used for 2D modeling can be seen in Figure 3-33.

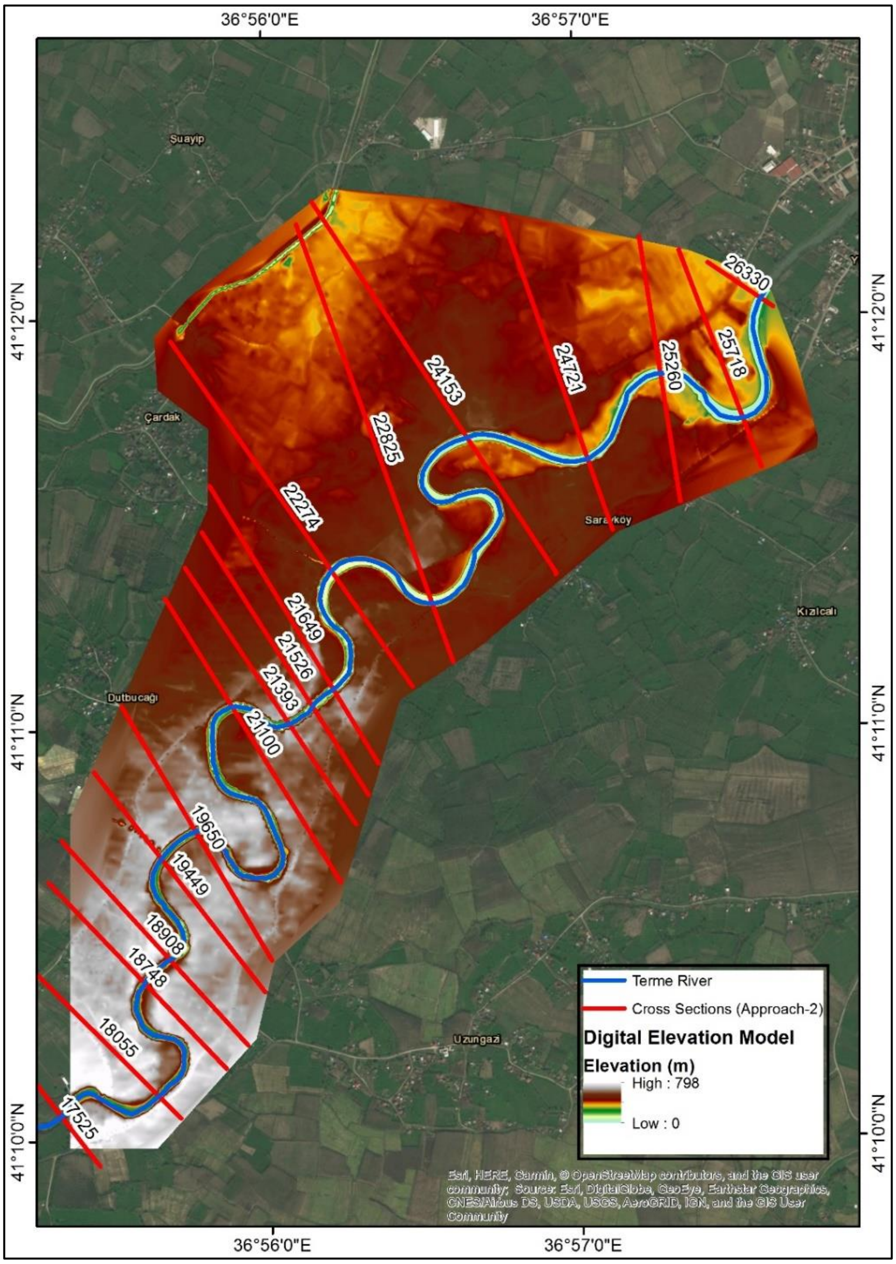


Figure 3-33: 2D Modeling Study Area and DEM

Different scenarios of 2D models are constructed to test inundation change with respect to sediment transport and grain size diameter.

Flood extent obtained from pure hydrodynamic model due to the event occurred on 22 November 2014 is depicted in Figure 3-34. Especially at the downstream part of the river inundation area is extensive. Outflow is defined at the downstream part of the river and free flow is identified as the boundary of modeling. Therefore, water accumulation and backwatering do not occur at that part but, since study area is ended, inundation between downstream of study area and Black Sea cannot be mapped.

Coupled hydrodynamic and sediment transport model having 5.5 mm diameter grain size gives the inundation result narrower than pure hydrodynamic model (Figure 3-35). This is caused by erosion of bed. Since bed capacity is increased, flooding is limited with meandering part of the river.

If 0.55 mm diameter grain size is used in coupled hydrodynamic and sediment transport model, flooding is less than other scenarios (Figure 3-36). Since grain size diameter affects erosion and deposition rate, river characteristics differ for different grain size diameters. It is obtained that 0.55 mm diameter grain size scenario resulted river embankments as higher and bed level as lower than scenario having 5.5 mm diameter grain size due to erosion at bed and deposition at the embankments. This is obvious that including sediment transport to hydrodynamic model gives results of smaller inundation area due to bed level erosion.

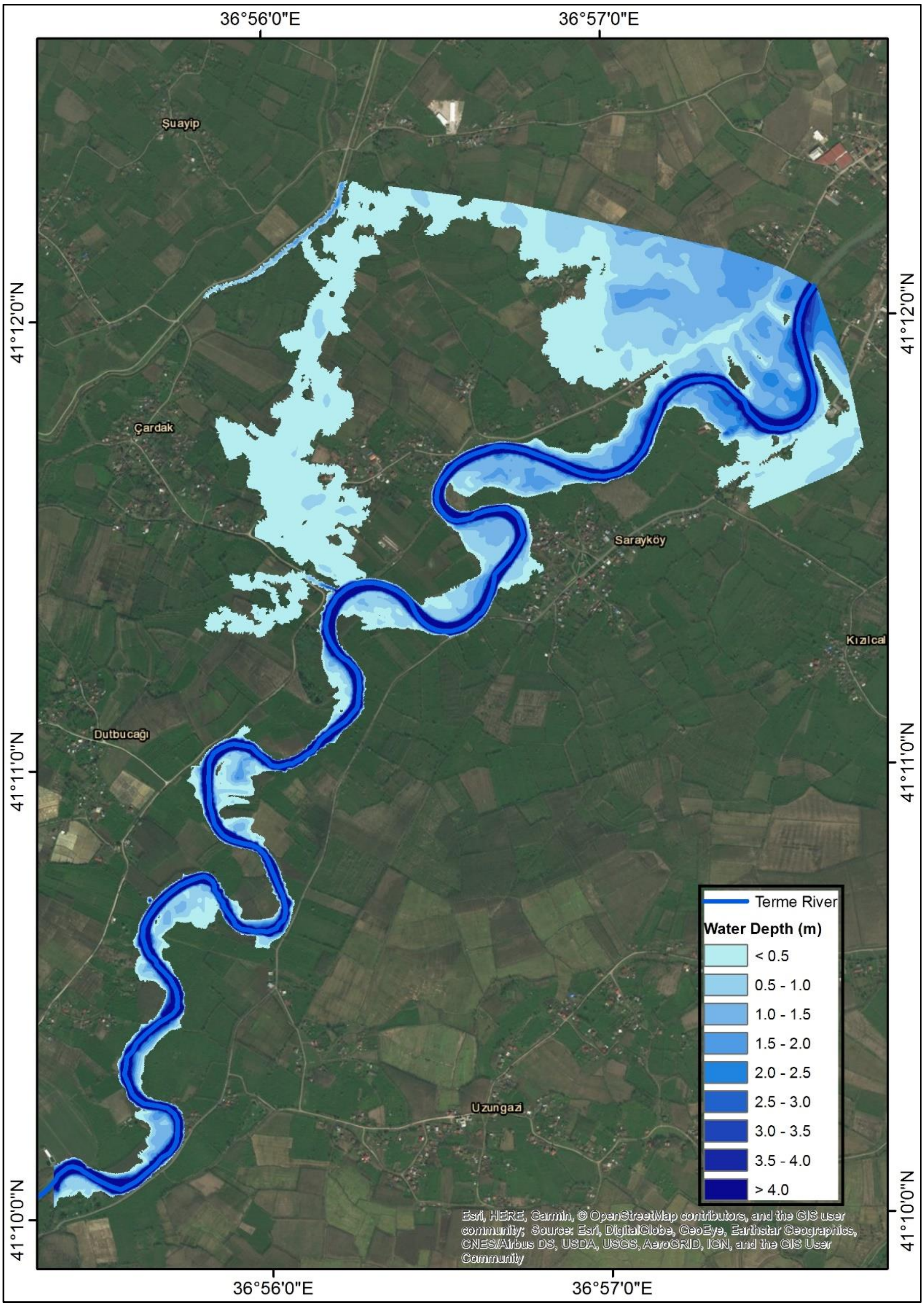


Figure 3-34: Inundation Map of 2D Pure Hydrodynamic Model for Hydrograph of 22 November 2014

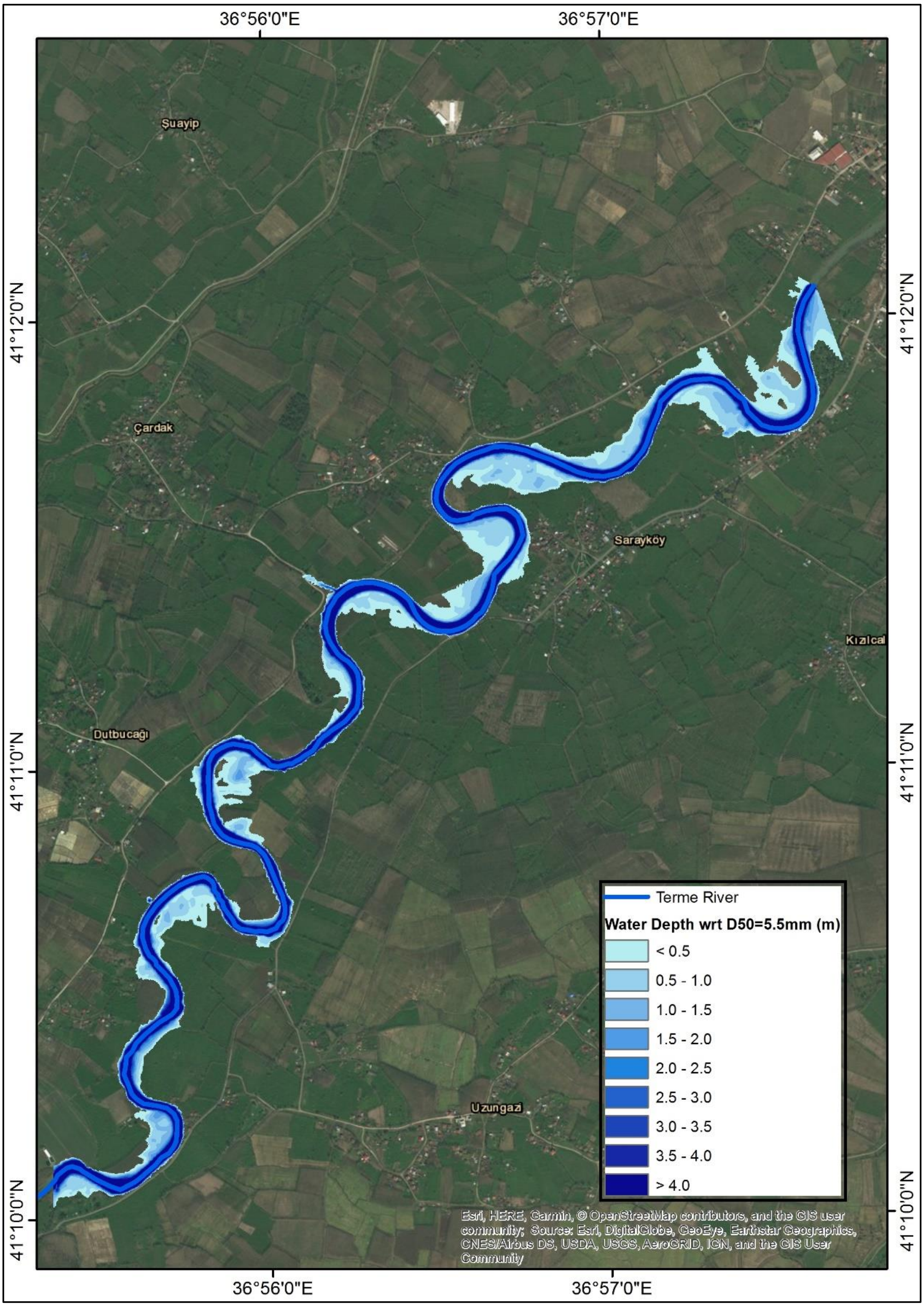


Figure 3-35: Inundation Map of 2D Coupled Hydrodynamic and Sediment Transport Model Having 5.5 mm Grain Size for Hydrograph of 22 November 2014

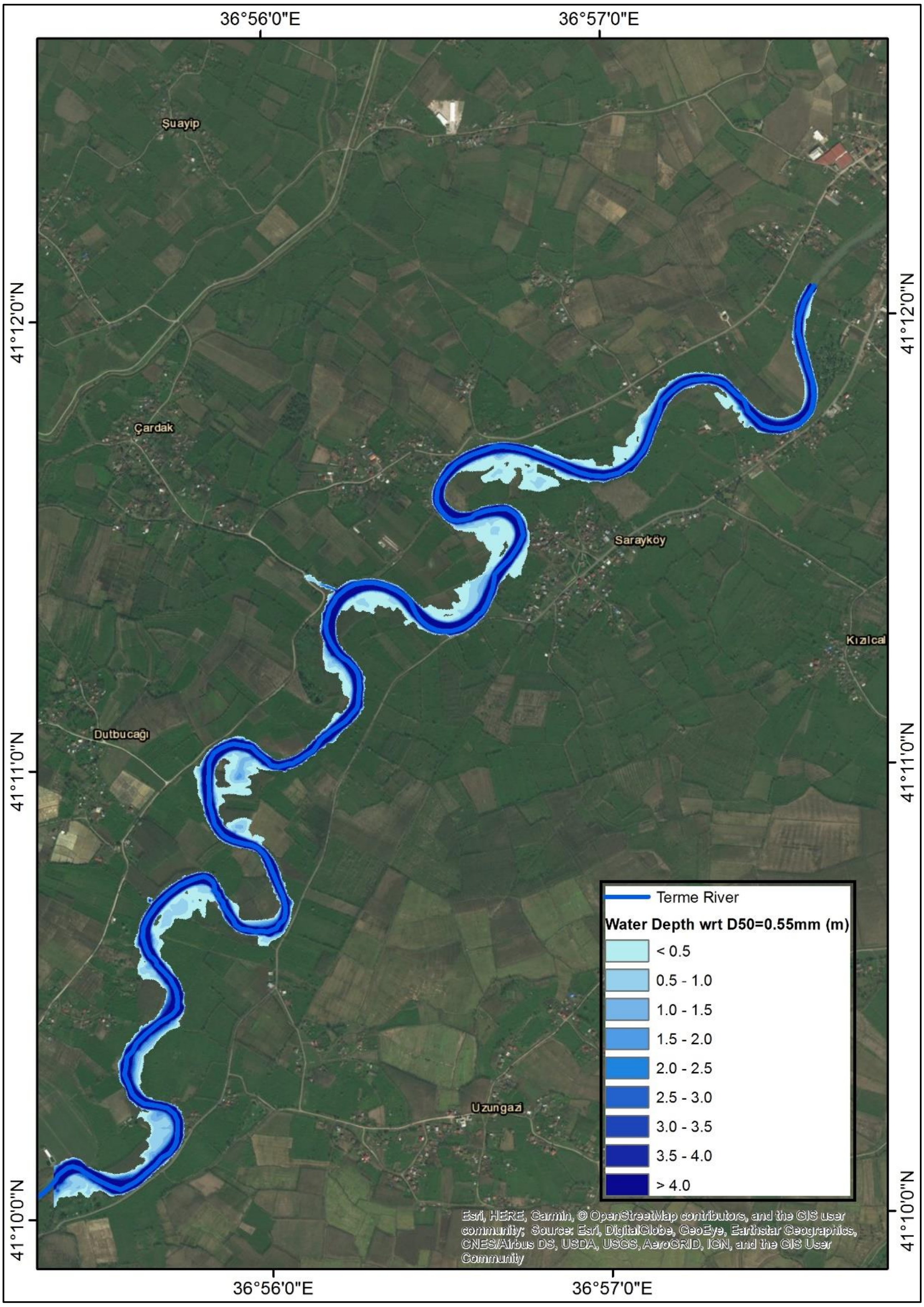


Figure 3-36: Inundation Map of 2D Coupled Hydrodynamic and Sediment Transport Model Having 0.55 mm Grain Size for Hydrograph of 22 November 2014

Velocity maps are prepared and given in figures below. Since velocity greatly affect sediment transport amount and therefore river bed, velocities must be examined.

Velocity map of pure hydrodynamic model shows that velocities at river bed are generally in between 1.5 and 2 m/sec. Speed of flow at the inundation part is substantially lower than 1 m/sec and generally lower than 0.5 m/sec (Figure 3-37).

Flow velocity at river bed for coupled hydrodynamic and sediment transport model having 5.5 mm grain size diameter is greater than pure hydrodynamic model (Figure 3-38). Since erosion occurred at river bed and capacity of river is increased, flow carrying capacity is greater in river bed.

Since smaller grain size causes more sediment transport and erosion, flow velocity of 0.55 mm grain size scenario is greater than the velocities for 5.5 mm grain size scenario (Figure 3-39). Changes on velocity results are more visible at the downstream part of study area. Since inundation area is smaller for small grain size, more water volume is carried by river and it causes greater velocities.

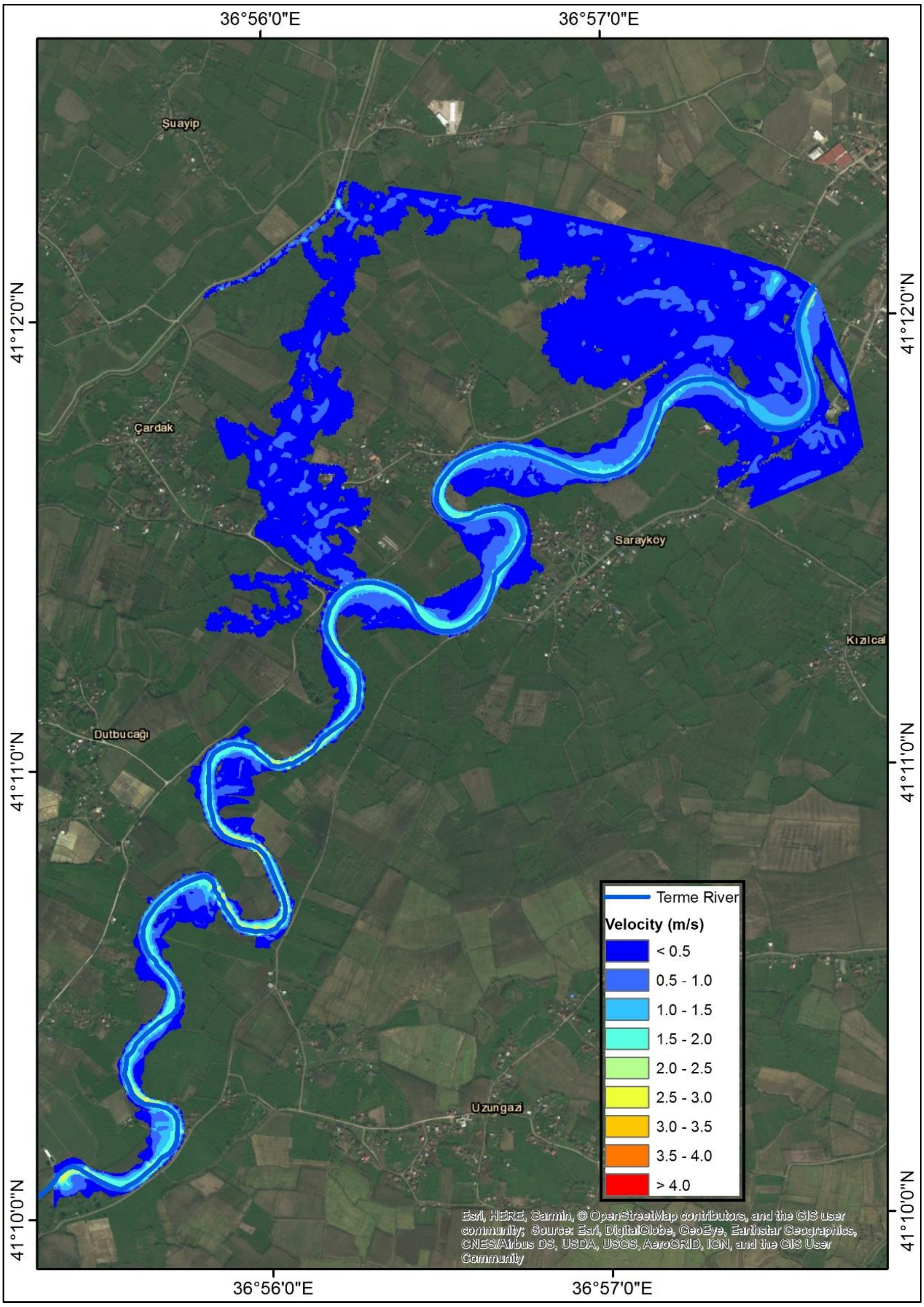


Figure 3-37: Velocity Map of 2D Pure Hydrodynamic Model for Hydrograph of 22 November 2014

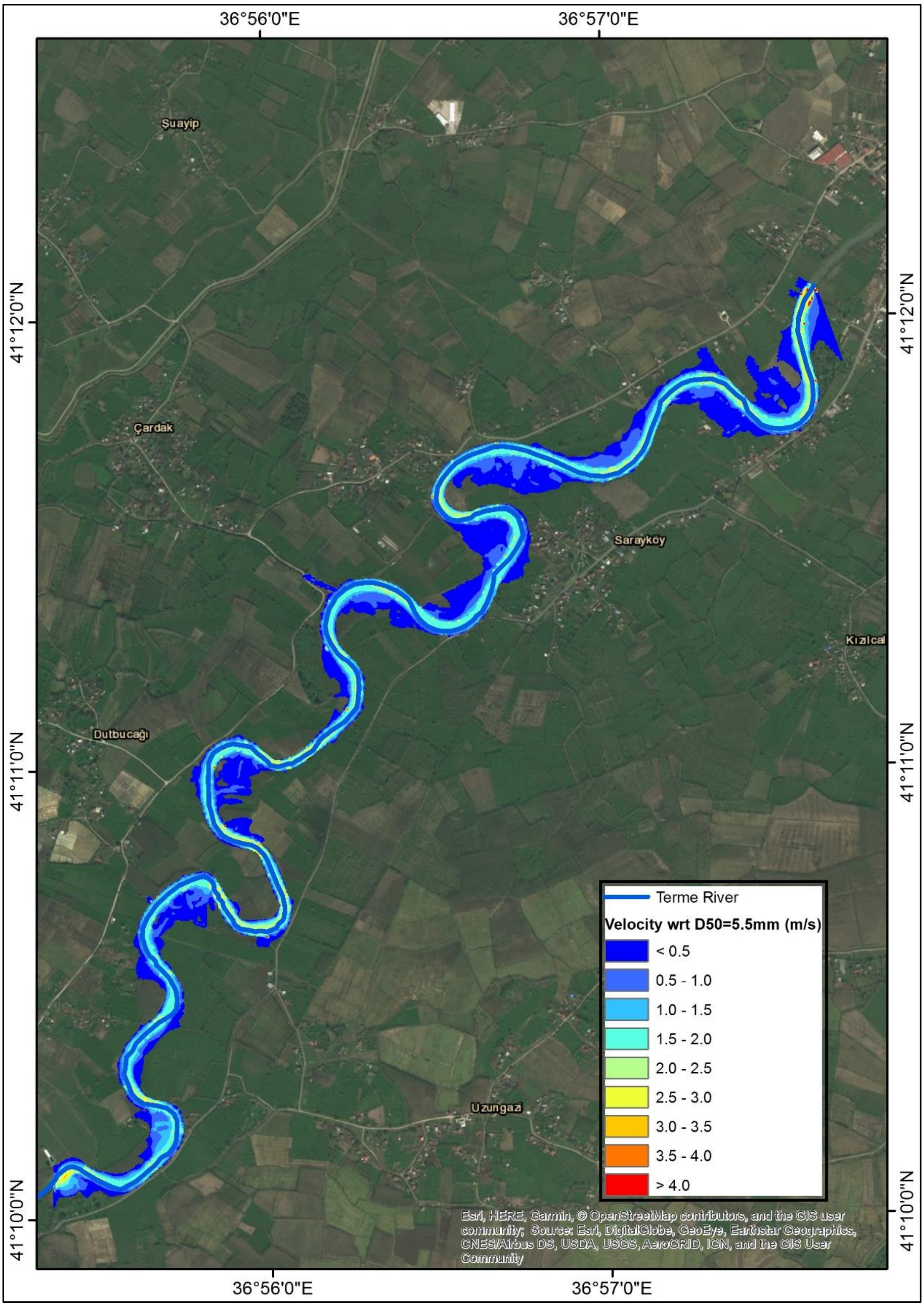


Figure 3-38 Velocity Map of 2D Coupled Hydrodynamic and Sediment Transport Model Having 5.5 mm Grain Size for Hydrograph of 22 November 2014

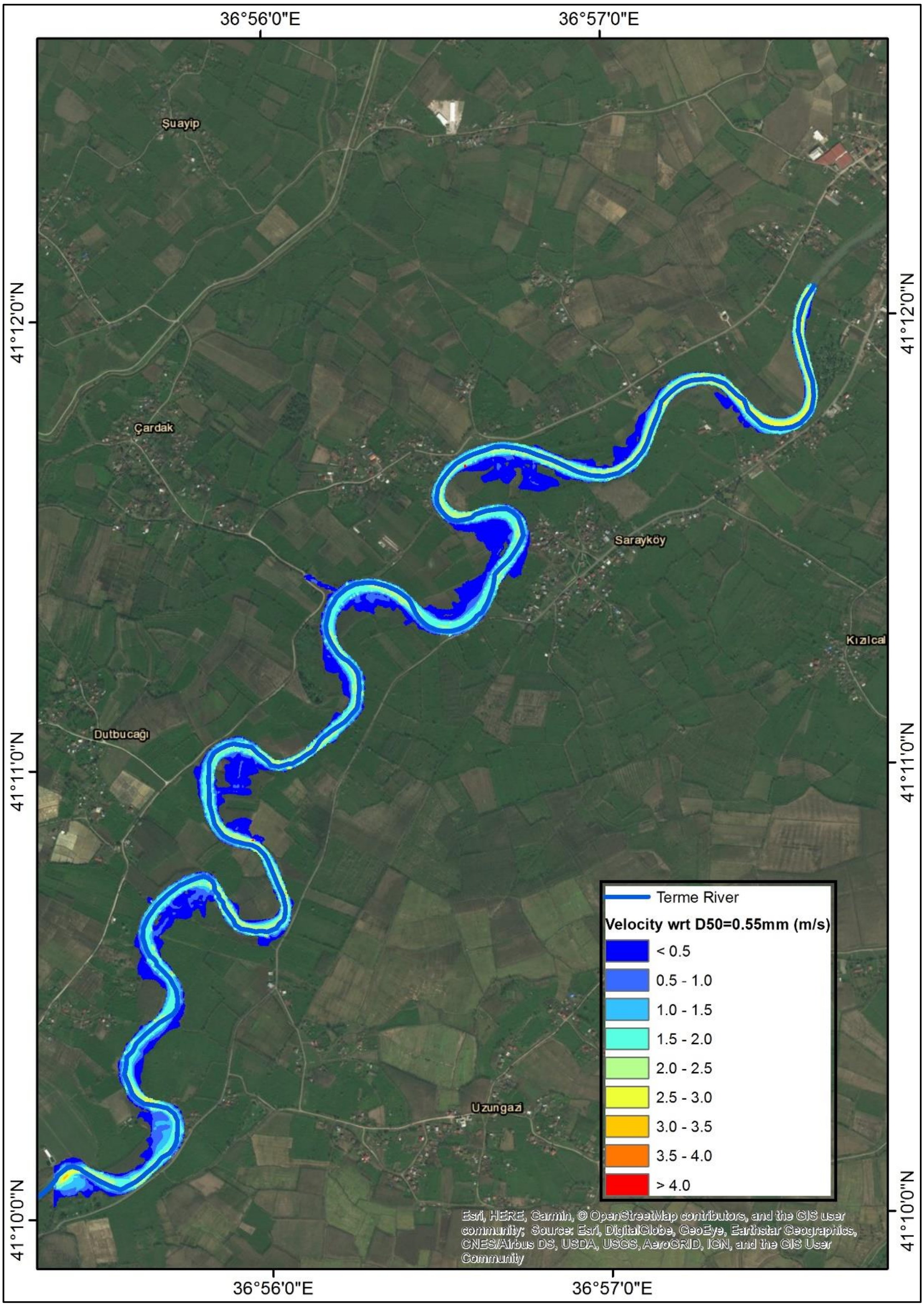


Figure 3-39: Velocity Map of 2D Coupled Hydrodynamic and Sediment Transport Model Having 0.55 mm Grain Size for Hydrograph of 22 November 2014

CHAPTER 4

DISCUSSION OF THE RESULTS

One of the most important input variables of 1D hydrodynamic models are cross sections since cross sections define a mean for morphology of the river. Therefore, it is important to choose appropriate cross section defining for the study area. In order to prevent cross section intersections and unrealistic water levels, large intervals can be used between cross sections but, river morphology could not be presented accurately.

Analyses show that sediment transport can affect hydrodynamic analyses due to morphological changes. River morphology changes based on sediment transport processes and rivers have a dynamic equilibrium as stated by Thomas and Chang (2008). In order to specify appropriate sediment transport formulation and bed level update method for study area, sensitivity analyses must be made. With respect to sensitivity analyses, bed level update methods and sediment transport calculation methods greatly affect calculations.

After selection of suitable bed level update method and sediment transport calculation method namely Engelund-Fredsoe (1976) for the study area, hydrographs of all flood frequencies are simulated by 1D modeling and results are presented in Table 4-1. In this table, maximum bed level change indicates the highest bed level change consisted through study area. Maximum water level change and maximum suspended sediment load rows are constructed by using highest values obtained through study area and simulation time. Calculations show that, flow capacity of the river part that was studied is around 400 m^3/s. Therefore, no overflow was seen for 2-year and 5-year flood frequency hydrographs. In addition, morphological changes and thus bed level changes and water level changes are limited. Morphological changes and their effects on hydrodynamics mostly take place for high hydrological regimes. This finding is similar to the results of Tu et al. (2017) where it is stated that magnitude of flow greatly affects morphological changes.

Table 4-1: 1D Coupled Hydrodynamic and Sediment Transport Model Results

Return Periods	**Q_2**	**Q_5**	**Q_{10}**	**Q_{25}**	**Q_{50}**	**Q_{100}**	**Q_{500}**
Overbank Flow	No	No	Yes	Yes	Yes	Yes	Yes
Max. Bed Level Change (m)	0.25	0.34	0.45	0.47	0.49	0.63	1.42
Max. Water Level Change (m)	0.13	0.24	0.3	0.34	0.36	0.41	0.75
Max. Suspended Sediment Load (m^3/s)	0.057	0.06	0.113	0.144	0.166	0.186	0.212

In addition to synthetic hydrographs calculated by using historical data, real flood event hydrographs are tested. These real flood event hydrograph analyses made by using 1D and 2D models indicate that bed level changes and hydrodynamic results differ for different river slope characteristics. As stated by Gharbi et al. (2016), 2D models give more precise results than 1D models. Therefore, both of the 1D and 2D models were performed.

Hydrograph observed for real flood event on 22 November 2014 is used in order to examine differences between 2D sediment transport modeling and 1D sediment transport modeling since the highest hydrological regime occurred in this event. In addition, three different grain size diameters were used as 0.55 mm, 3 mm and 5.5 mm in order to identify sensitivity of 2D model. In the study area, 0.55 mm and 5.5 mm grain size diameters were obtained by DSI for two different locations. Since these observations were made at only one point, representation of river bed characteristics is limited. In addition to observed values, sediment transport of 3 mm grain size diameter is also analyzed and results are given in Table 4-3. Results of model having 3 mm grain size diameter is closer to model having 5 mm grain size diameter.

Three of the cross sections having chainages 19650, 22825 and 25260 used in 1D modeling studies are chosen to compare with 2D modeling results. Locations of the cross sections are shown in Figure 3-33. Bed level, bed level change, water level and sediment load values are computed and given in Table 4-2 and Table 4-3 below.

Table 4-2: 1D Sediment Transport Model Results

<table>
<tr><th></th><th>Cross Section Chainage</th><th>19650</th><th>22825</th><th>25260</th></tr>
<tr><td rowspan="2">Hydrodynamic (1D)</td><td>Bed Level (m)</td><td>3.01</td><td>1.66</td><td>0.95</td></tr>
<tr><td>Max. Water Level (m)</td><td>10.22</td><td>7.94</td><td>4.72</td></tr>
<tr><td rowspan="4">Hydrodynamic + Sediment Transport (1D)</td><td>Bed Level (m)</td><td>2.96</td><td>1.64</td><td>0.98</td></tr>
<tr><td>Max. Water Level (m)</td><td>10.39</td><td>7.95</td><td>5.1</td></tr>
<tr><td>Sediment Load (m^3/s)</td><td>0.011</td><td>0.015</td><td>0.041</td></tr>
<tr><td>Bed Level Change (m)</td><td>-0.05</td><td>-0.02</td><td>0.03</td></tr>
</table>

Bed Level Change = $(\text{Bed Level})_{HD+ST}$-$(\text{Bed Level})_{HD}$

Results of 1D coupled sediment transport and hydrodynamic model indicate that bed level changes are very low and maximum water levels are not changed much when sediment transport is considered in flood modeling. However, changes of river bed elevation and maximum water level for 2D models are more than 1D model results. Calculations are limited with only cross section points for 1D modeling approach although, calculations are made for all meshes continuously for 2D modeling.

In areas where knowing erosion/sedimentation is crucial like at the sections of hydraulic structures, at the entrance of reservoirs, at the locations of rivers contributing to the sea/ocean, 2D sediment modelling must be considered. It is possible to obtain the change in the river bed in detail from 2D modeling whereas 1D models can give a lumped estimate for a section. Cross section at the upstream of the bridge located at 1345 shows the change of the river bed with respect to Q_5, Q_{50} and Q_{500} hydrographs. The cross section is at the 35 meters upstream of the bridge. The model results indicate that the river bed can be eroded about 50 cm at that cross section. This shows the importance of sediment transport modeling around bridge piers. From the analyses, it is clear that grain size affects the result directly, since flow velocity change affects the movement of the particles in terms of bed load transport or suspended load transport.

Table 4-3: 2D Sediment Transport Model Results

	Cross Section Chainage	19650	22825	25260
Hydrodynamic (2D)	Bed Level (m)	3.01	1.66	0.95
	Max. Water Level (m)	11	8.78	7.97
ST-2D (5.5 mm)	Bed Level (m)	3.06	1.77	0.88
	Max. Water Level (m)	10.82	8.44	6.94
	Sediment Load (m^3/s/m)	0.0013	0.0017	0.0018
	Bed Level Change (m)	0.05	0.11	-0.07
ST-2D (3 mm)	Bed Level (m)	3.06	1.79	0.86
	Max. Water Level (m)	10.79	8.38	6.81
	Sediment Load (m^3/s/m)	0.0023	0.0028	0.0018
	Bed Level Change (m)	0.05	0.13	-0.09
ST-2D (0.55 mm)	Bed Level (m)	3.07	1.89	-0.23
	Max. Water Level (m)	10.63	8.25	5.95
	Sediment Load (m^3/s/m)	0.0076	0.012	0.065
	Bed Level Change (m)	0.06	0.23	-1.18

Bed Level Change = $(\text{Bed Level})_{HD+ST}$-$(\text{Bed Level})_{HD}$

Chainage 19650

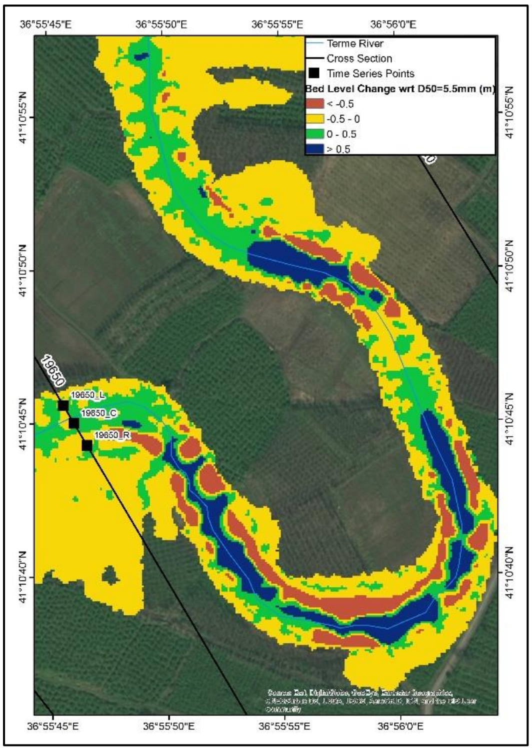
Changes on cross section for the chainage 19650 can be seen in graph below (Figure 4-1). Bed level change of 1D model result is obtained as 0.05 meters of erosion. Bed level results of 2D models are computed as 0.05 meters of deposition for 5.5 mm and 3 mm grain size diameter and 0.06 meters of deposition for 0.55 mm grain size diameter. However, erosion is determined for 2D models through cross section. Therefore, maximum water level computed with 2D models are lower than 1D model results.

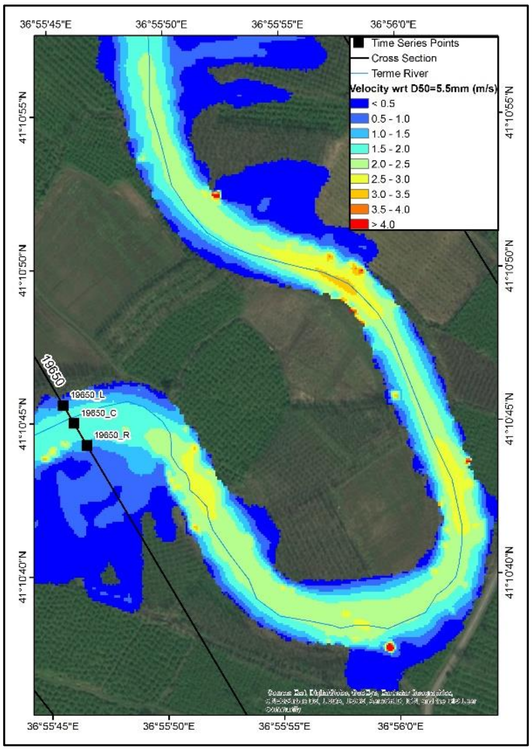
Figure 4-1: Cross Section Results Chainage 19650

At downstream of cross section for the chainage 19650, deposition is determined at the bed of river and erosion at banks with respect to analyses constructed by using grain size diameter as 5.5 mm and 0.55 mm. Especially in the meandering part, deposition is larger than straight parts due to low velocity at meanders. Analyses of 5.5 mm grain size diameter and 0.55 mm grain size show that deposition and erosion amount is larger for 0.55 mm grain size diameter. (Figure 4-2 (a) and Figure 4-3 (a)).

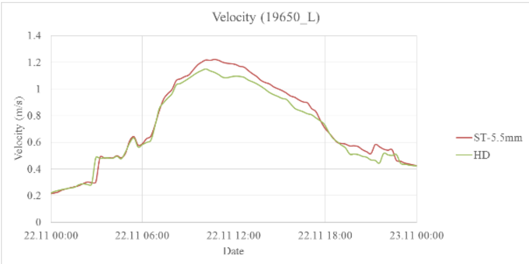
Velocity time series graphs that are given in Figures 4-2 (c), (d) and (e) and Figures 4-3 (c), (d) and (e) indicate that velocity is higher at the middle of the river than edges. Time of peak velocity values are almost the same for these three cross section points. Velocity values higher for 0.55 mm grain size diameter than the velocities of 5.5 mm grain size diameter at the cross section for the chainage 19650. Sediment transport models give greater velocity results than pure hydrodynamic models at this cross section.

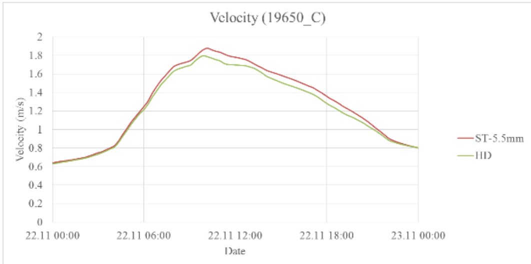
Although velocities are higher for 0.55 mm grain size at 19650, velocities are lower for that grain size at downstream part of 19650 due to smoother bed level (Figure 4-2 (b)).



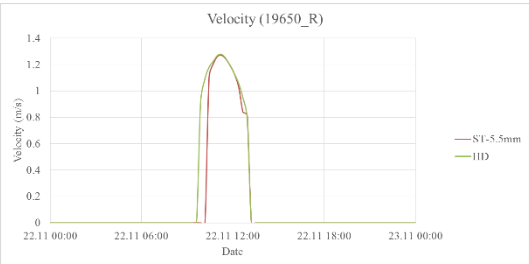


(a) **(b)**



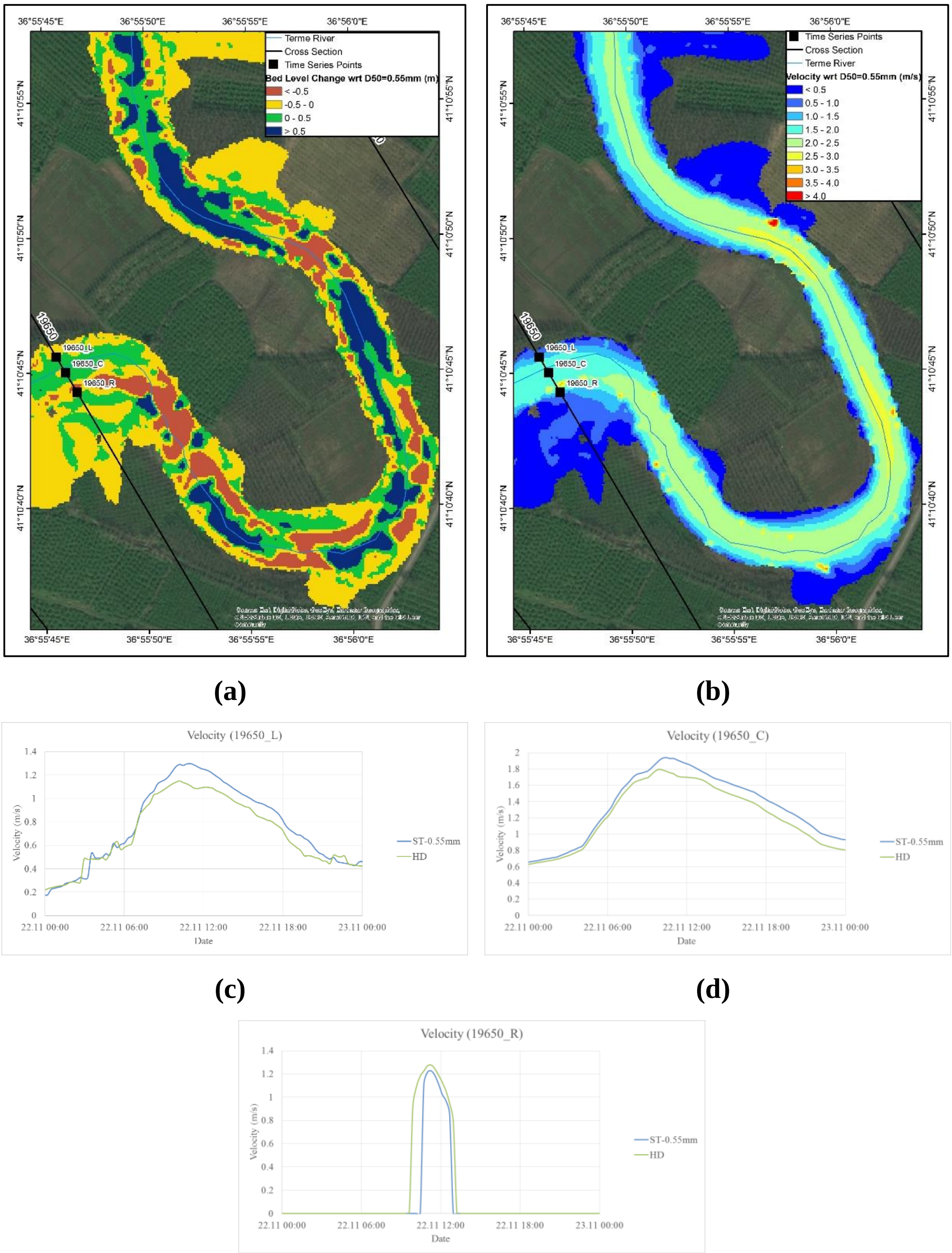


(c) **(d)**



(e)

Figure 4-2: Bed Level Change and Velocity Results at Chainage 19650 (D_{50}= 5.5 mm) **(a)** Bed Level Change, **(b)** Velocity, **(c)** Velocity Time Series at point 19650_L, **(d)** Velocity Time Series at point 19650_C, **(e)** Velocity Time Series at point 19650_R



(a) (b) (c) (d) (e)

Figure 4-3: Bed Level Change and Velocity Results at Chainage 19650 (D_{50}= 0.55 mm) **(a)** Bed Level Change, **(b)** Velocity, **(c)** Velocity Time Series at point 19650_L, **(d)** Velocity Time Series at point 19650_C, **(e)** Velocity Time Series at point 19650_R

Chainage 22825

Cross section at chainage 22825 is shown in graph below (Figure 4-4). With respect to 1D model results, 0.02 meters of erosion is obtained. 0.11 meters deposition is determined for 5.5 mm grain size diameter, 0.13 meters deposition is determined for 3 mm grain size diameter and 0.23 meters of deposition is determined for 0.55 mm grain size diameter. Due to erosion of cross section, maximum water level is larger for 1D modeling than 2D modeling.

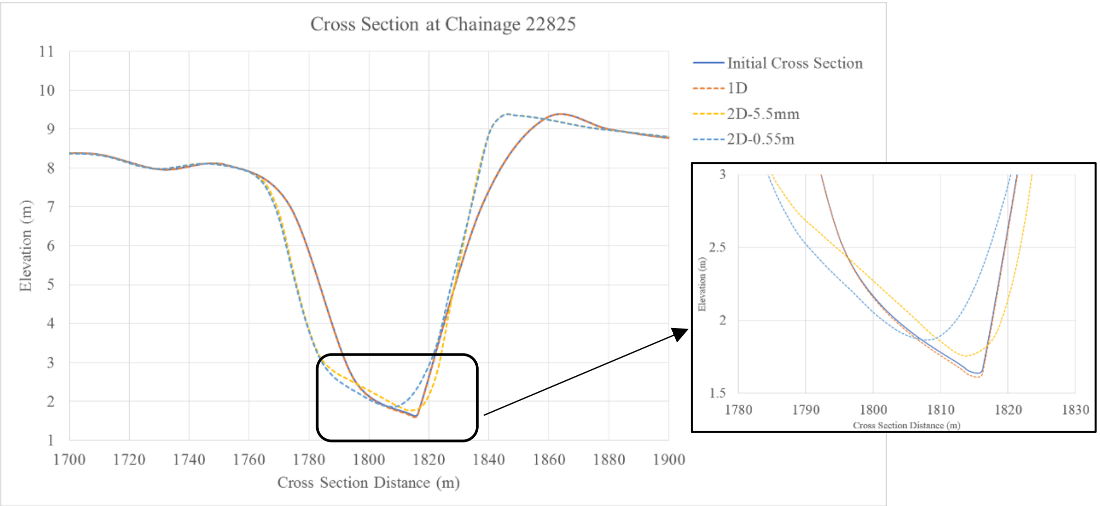
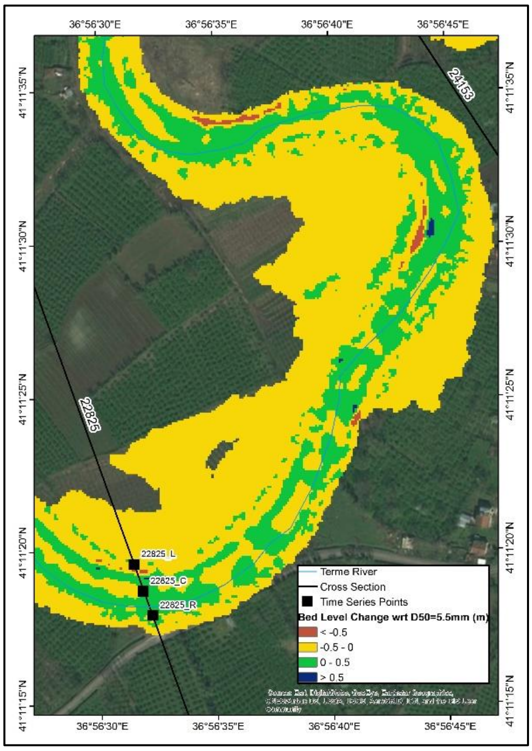


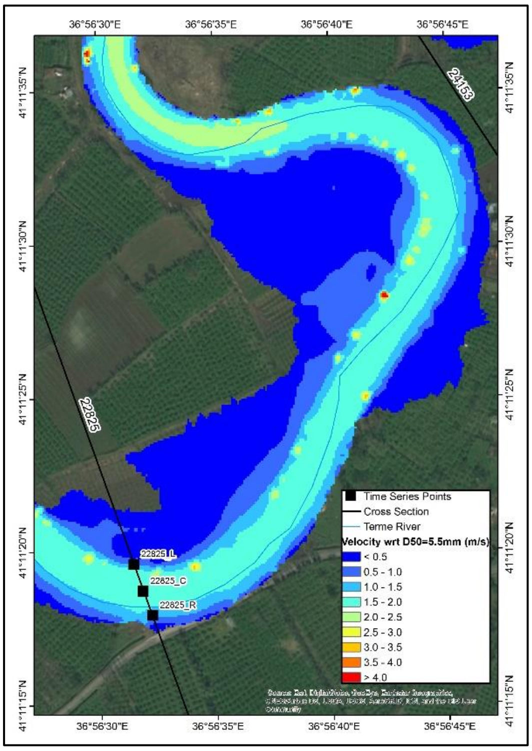
Figure 4-4: Cross Section Results Chainage 22825

At downstream of cross section 22825, bed level decrease is determined through river bed and bank elevations are increased due to deposition at the borders of the river. Therefore, river capacity increased. Since smaller grain size diameter is caused more erosion and deposition, river capacity is increased for the model having 0.55 mm grain size diameter than model having 5.5 mm grain size diameter (Figure 4-5 (a) and Figure 4-6 (a)).

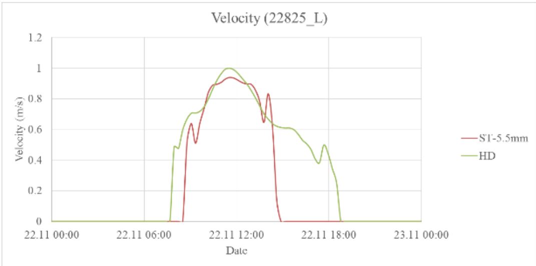
Figures 4-5 (c), (d) and (e) and Figures 4-6 (c), (d) and (e) introduce that velocities are higher at the middle part of the river cross section for the chainage 22825. Maximum velocities are generally higher for sediment transport models than pure hydrodynamic models. Time of peak velocity values are almost the same for these three cross section points.

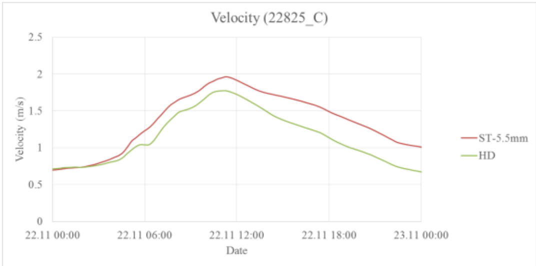
Velocity results are greater for smaller grain size for this part of the river (Figure 4-5 (b) and Figure 4-6 (b))



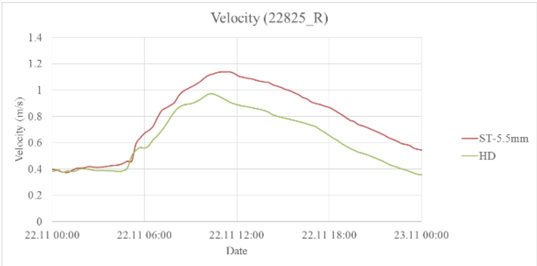


(a) **(b)**





(c) **(d)**



(e)

Figure 4-5: Bed Level Change and Velocity Results at Chainage 22825 (D_{50}= 5.5 mm) **(a)** Bed Level Change, **(b)** Velocity, **(c)** Velocity Time Series at point 22825_L, **(d)** Velocity Time Series at point 22825_C, **(e)** Velocity Time Series at point 22825_R

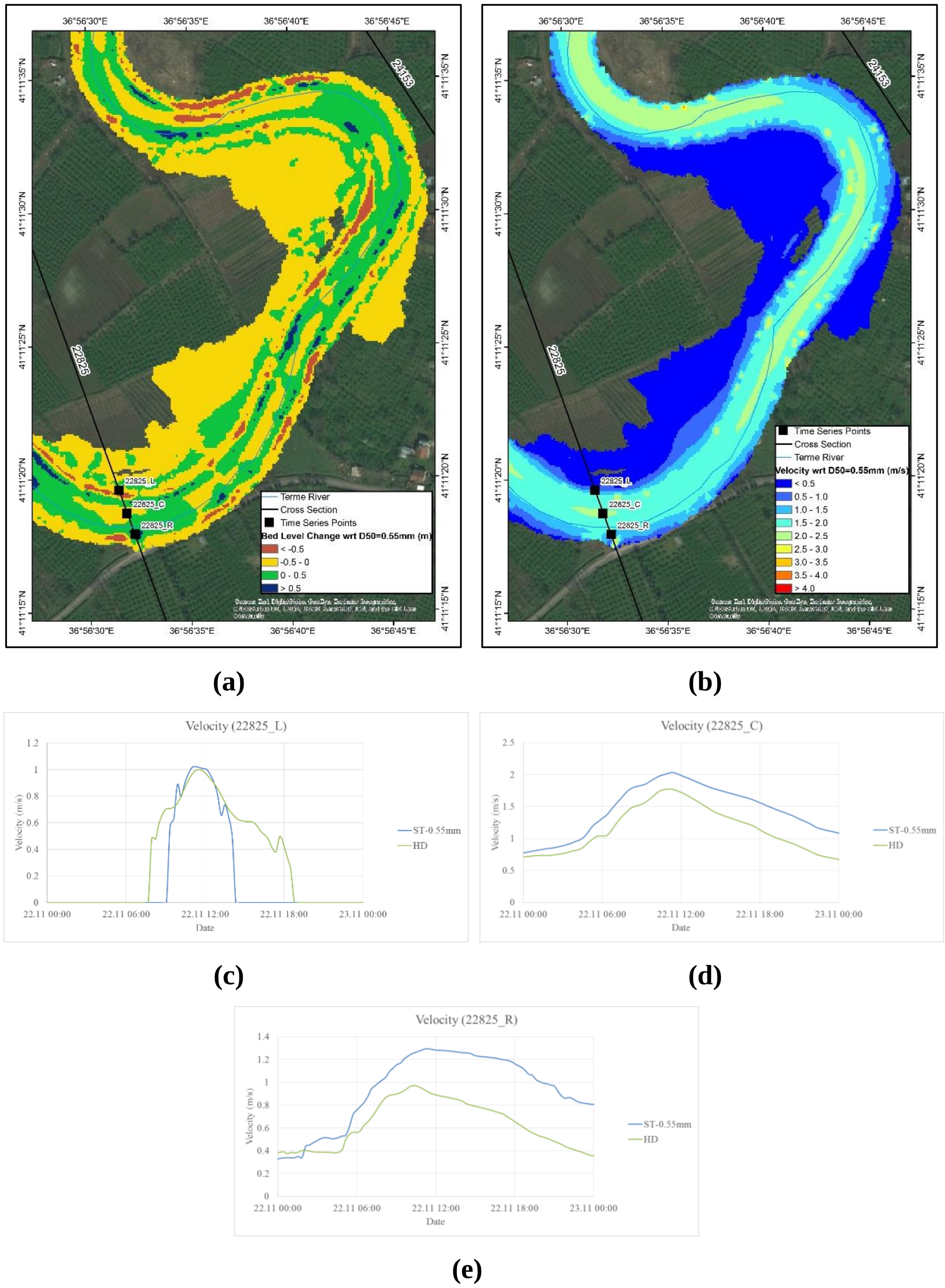


Figure 4-6: Bed Level Change and Velocity Results at Chainage 22825 (D_{50}= 0.55 mm) **(a)** Bed Level Change, **(b)** Velocity, **(c)** Velocity Time Series at point 22825_L, **(d)** Velocity Time Series at point 22825_C, **(e)** Velocity Time Series at point 22825_R

Chainage 25260

Cross section for the chainage 25260 can be seen in figure below (Figure 4-7). With respect to 1D model results, 0.03 meters of bed level increase is determined. 2D models give the bed level decrease as 0.07 meters, 0.09 meters and 1.18 meters for 5.5 mm grain size diameter, 3 mm grain size diameter and 0.55 mm grain size diameter respectively. Maximum water level is obtained as 5.1 meters for 1D model, 6.94 meters for 2D model having 5.5 mm grain size diameter and 5.95 meters for 2D model having 0.55 mm grain size diameter.

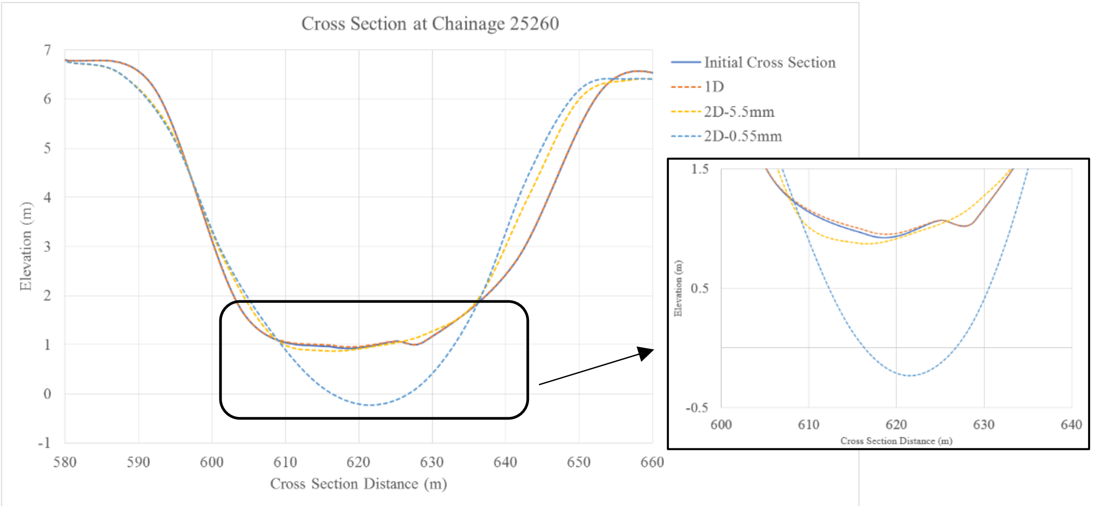
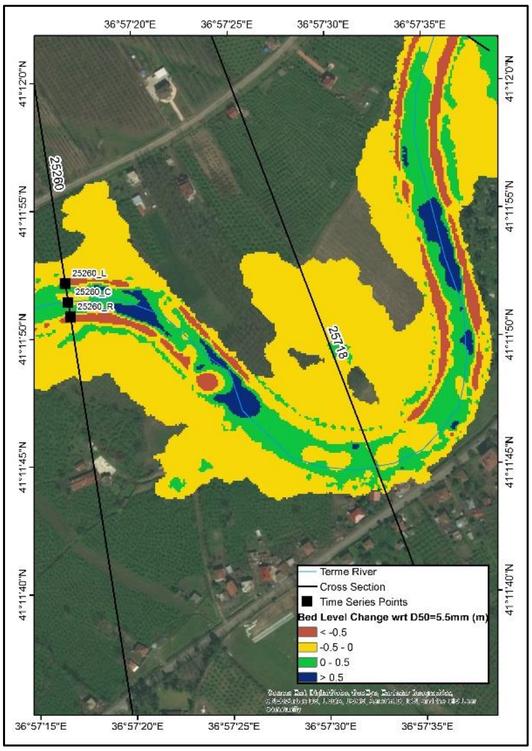


Figure 4-7: Cross Section Results Chainage 25260

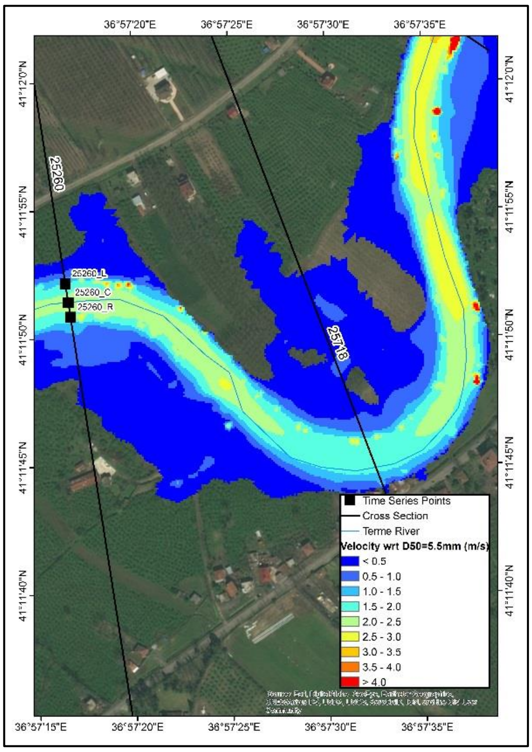
Bed level change results of the area between cross section having chainage 25260 and downstream of study area are different for 5.5 mm and 0.55 mm grain size diameter. Bed level generally increases and embankment elevation generally decreases for 5.5 mm grain size diameter. On the other hand, bank elevations are greater and bed level elevations are lower for 0.55 mm grain size diameter (Figure 4-8 (a) and Figure 4-9 (a)).

Figures 4-8 (c), (d) and (e) and Figures 4-9 (c), (d) and (e) demonstrate that velocity is higher at the middle part of the cross section compared to the edges. Maximum velocities are higher for sediment transport models than pure hydrodynamic models. Time of peak velocity values are almost the same for these three cross section points.

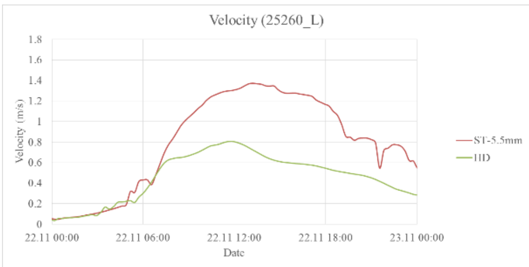
Velocity results are greater for smaller grain size for this part of the river that can be seen in Figure 4-8 (b) and Figure 4-9 (b).



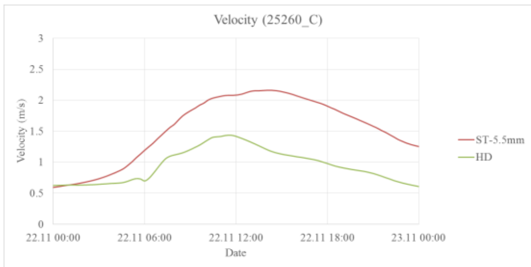
(a)



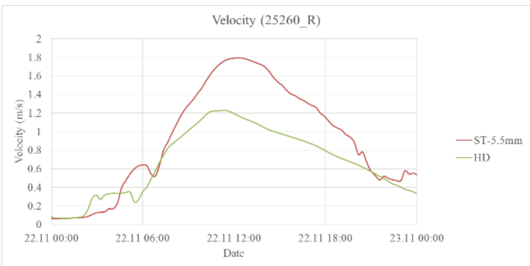
(b)



(c)

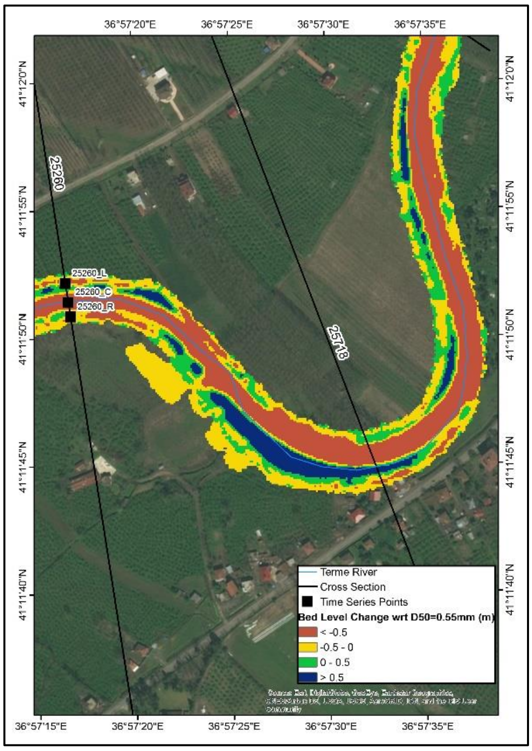


(d)

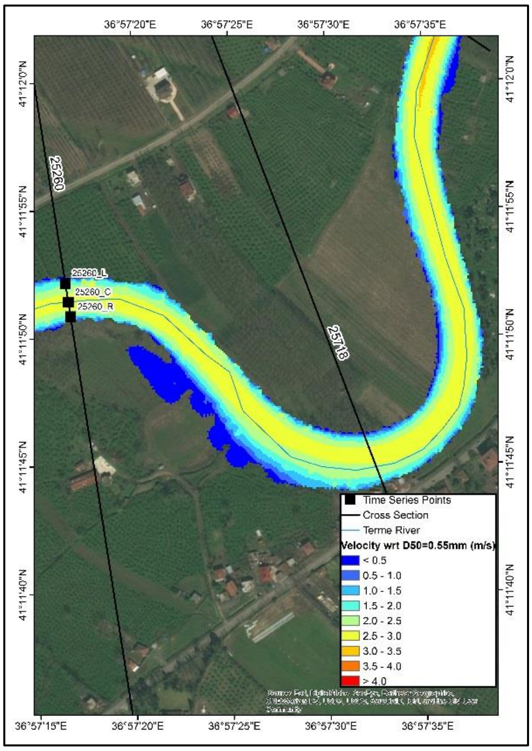


(e)

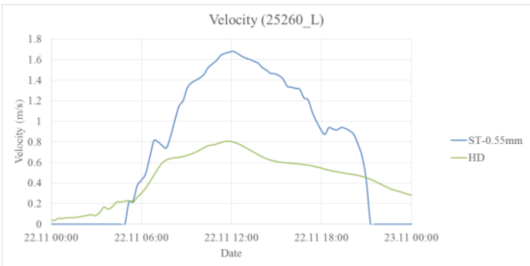
Figure 4-8: Bed Level Change and Velocity Results at Chainage 25260 (D_{50}= 5.5 mm) **(a)** Bed Level Change, **(b)** Velocity, **(c)** Velocity Time Series at point 25260_L, **(d)** Velocity Time Series at point 25260_C, **(e)** Velocity Time Series at point 25260_R



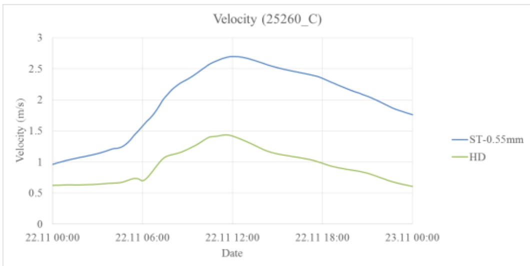
(a)



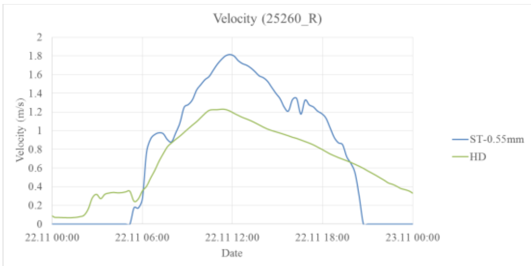
(b)



(c)



(d)



(e)

Figure 4-9: Bed Level Change and Velocity Results at Chainage 25260 (D_{50}= 0.55 mm) **(a)** Bed Level Change, **(b)** Velocity, **(c)** Velocity Time Series at point 25260_L, **(d)** Velocity Time Series at point 25260_C, **(e)** Velocity Time Series at point 25260_R

In addition to differences between 1D and 2D models, lower grain size diameter gives higher morphological changes and therefore maximum water level changes are greater for 2D models. Grain size difference can greatly affect sediment transport calculations and hydrodynamic calculations based on morphological changes.

In this study, Intel Xeon CPU E5-2665 @ 2.40 GHz, 2401 Mhz, 8 Cores, 16 Logical Processors with parallel processing is used and 2D coupled sediment transport and hydrodynamic model computations. Computation times are tabulated for 1D and 2D modeling practices in Table 4-4.

Table 4-4: Computation Time

<table>
<tr><th>Modeling Type</th><th>Computation Time</th><th>River Length (m)</th><th>Computation Nodes</th></tr>
<tr><td>1D - HD</td><td>11 seconds</td><td rowspan="2">26385</td><td rowspan="2">124 Cross Sections</td></tr>
<tr><td>1D - HD+ST</td><td>67 seconds</td></tr>
<tr><td>2D - HD</td><td>18.45 hours</td><td rowspan="4">8862</td><td rowspan="4">313840 Elements</td></tr>
<tr><td>2D - HD+ST (D_{50}=0.55 mm)</td><td>29.27 hours</td></tr>
<tr><td>2D - HD+ST (D_{50}=3 mm)</td><td>30.51 hours</td></tr>
<tr><td>2D - HD+ST (D_{50}=5.5 mm)</td><td>31.82 hours</td></tr>
</table>

From Table 4-4, it is clear that coupled 2D sediment transport and hydrodynamic modelling has a long computation time. 1D practices have shorter computation time than 2D practices. Since inundation area increases with grain size increasing, more computations are made and thus computation time is getting longer.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, effects of sediment transport on morphological changes of river bed and flood inundation are examined by using computational 1D and 2D models. Studies are performed for a part of Terme River, Samsun.

Analyses are performed as three main steps that are cross section defining analyses, sensitivity analyses and real event analyses.

Two different cross section defining techniques are used to determine the most suitable method. Firstly, cross sections are constructed with 50 meters of intervals and limited to river bed. Second approach considers cross sections as wide as possible with inconstant intervals.

After determining suitable cross sections, sensitivity analyses of sediment transport model are practiced. Engelund-Fredsoe Method and Van Rijn Method and two different bed level update methods are considered and following conclusions are obtained.

- The most fitted sediment transport method for study area characteristics should be chosen. Different calculation methods with the same input can produce different sediment transport and thus hydrodynamic results.
- Choosing suitable sediment transport method can be made by using the observed sediment amount to validate the best set of calculation method. Thus, sediment observations are crucial for calibrating the models.

- Bed level update method greatly affects morphological changes of cross sections. If bed level update is performed through whole cross section equally, morphological change can be underestimated. More detailed site observations would be helpful in deciding the bed level update method.
- With respect to analyses made, Engelund and Fredsoe Method and Bed Level Update Method – 2 that is deposition and erosion uniformly distributed over the whole cross section is determined as the most suitable set of calculation method for this study area.

Real flood events occurred in Terme River on 22 November 2014, 02 August 2015 and 28 May 2016 are modelled with 1D coupled hydrodynamic and sediment transport models. Effects of sediment transport on flood occurrence is also examined by hydrograph observed on 22 November 2014 that has highest flow among three events. For the analyses three different grain size diameters were used. Following conclusions can be made based on these analyses.

- High flow regimes cause more sediment transport and morphological changes due to high velocities.
- 2D models produce more detailed results than 1D models since 1D models can only use cross sections and cannot consider any data between cross sections.
- Changes on morphology and thus hydrodynamics are less in 1D models than 2D models. This can be caused by ignoring the areas between cross sections.
- Including sediment transport to hydrodynamic analyses may cause generally lower water levels at the parts having high velocity regime due to erosion and higher water levels at low velocity parts of the river due to deposition.
- 2D models indicate that flood occurrence can be greatly affected by sediment transport phenomena. Generally high velocity occurs at the middle of the river and thus erosion is dominant at bed thalweg and low velocity occurs at river banks and thus deposition is dominant at the embankments. Due to domination of erosion at river bed and domination of deposition at embankments, flow carrying capacity of the river bed increases. Since flow carrying capacity is higher, overbank flow is lower and thus flood tendency decreases.

- Grain size diameter of river bed material dramatically affects sediment transport calculations and hydrodynamics dependently. If grain size diameter is smaller, morphological changes become greater since sediment transport occurs intensively. Therefore, determination of bed material characteristics comprises major importance to have realistic sediment transport calculations. In this study, 2D models are performed for 0.55 mm, 3 mm and 5.5 mm grain size diameters separately.
- It is identified that if sediment transport calculations are included in the computation, flooded area is decreased. It is obtained that smaller grain size causes smaller inundation area for this study area.

Moreover to conclusions that are derived, following future recommendations are made in order to eliminate coarseness of computational model applications.

- More detailed digital elevation model may be used for modeling analyses since morphological information are used for both of the 1D and 2D models. 1D models can also be performed by using cross sections that are obtained from field.
- Calibration is one of the most important phenomena to get realistic results from modeling approaches. Therefore, inundation area with water level marks, flow and sediment transport respective to the flow data should be observed continuously.
- Bed roughness and bed material grain size must be obtained from several parts of the river. Sampling points should be increased and also non-erodible layers must be defined for the river bed.
- Slope failure at a certain angle of repose may be studied for banks and included in 2D modeling approach.
- Since the bridge is not defined in modeling studies, potential effects of deposition at the upstream of the structures are not examined. Choking risk of structures can greatly affect flood inundation.
- Instead of Central Processing Unit (CPU), Graphical Processing Unit (GPU) may be used for 2D modeling practices due to computation time concern.

- In order to obtain more realistic results, besides the suspended load and bed load must be observed and measured at least at some experimental sites. Obtaining bathymetry before and after a flood event would be helpful in modeling studies.

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