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Research Article

Comparative Analysis of HEC-RAS, SWMM, and THDH Approaches in Highway Culvert Design

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ABSTRACT

In this study, Hydrologic Engineering Center River Analysis System (HEC-RAS), Storm Water Management Model (SWMM) and Turkish Highway Design Handbook (THDH) approaches were examined in highway culvert design and the methods were compared on a sample highway culvert to show the differences in design calculations. A box type culvert, made of reinforced concrete and with dimensions of 3 meters in width and 2 meters in height, will be constructed at the intersection of the Kocaçay stream and the Nevşehir Avanos D302 highway at KM:800m. The culvert is designed to carry the 10-year and 100-year design flow rates calculated using the Rational method. The design flow conditions, and water levels of the culvert is originally designed according to THDH. The culvert along with the flow route up to a certain distance, upstream and downstream is modelled by using HEC-RAS and SWMM. The water levels obtained from the models were compared with the THDH design results. The hydraulic design of the culvert is conducted under inlet control conditions in all methods, however, with the discrepancies in the calculated headwater and tailwater depths. The nomogram method suggested in the THDH provides a practical means for determining headwater depth, tailwater depth and culvert dimensions. However, it does not adequately address the channel sections upstream and downstream of the culvert and the relevant flow conditions. To evaluate the environmental effects of the design flow rates of culverts, especially those located near residential areas, it is recommended to use HEC-RAS and similar GIS-supported modeling tools in hydraulic calculations.

Introduction

Culverts are tunnel-like structures that have been built since ancient times to cross roads and waterways and provide transportation over streams. Culvert structures, which are typically buried to be surrounded by soil, may consist of a pipe, or be made of reinforced concrete or another material. A culvert may cause an increase in upstream water surface elevations due to its restrictive cross-section forcing the upstream flood levels to be several meters higher than they would be without the culvert and the embankment [1].

The hydraulic design of culverts on highways is carried out with equations and nomograms obtained depending on the type of culvert and the upstream and downstream conditions created by the flow. The equations and nomograms are based on experimental data to estimate the flow characteristics of culverts. These equations and nomograms, such as those developed by Barr, Hydrologic Engineering Center (HEC), and Federal Highway Administration (FHWA), provided standardized methods for estimating flow capacity based on culvert size, shape, and other parameters. Hydraulic Design of Highway Culverts introduced by the Federal Highway Administration aims to provide information for the planning and hydraulic design of culverts. [2]. The FHWA has devised a methodical process for culvert analysis, which relies on different flow types as categorized by the U.S. Geological Survey. These flow types are determined by factors such as inlet and outlet submergence, flow regime within the culvert, and downstream brink depth [3]. The hydraulic design of culverts in Turkey is carried out according to the Turkish Highway Design Handbook (THDH) published by the General Directorate of Highways [4].

The HEC-RAS program operates on the principles of Saint-Venant hydraulic equations, which facilitate the estimation of floodplain dimensions, determination of water surface elevations, and distribution of flood velocities. The utilization of mathematical models is crucial and valuable in such hydrological simulations [5]. It can be inferred that HEC-RAS demonstrates a high degree of accuracy in forecasting water levels and areas impacted by flooding during extreme hydrological events, even when input data are relatively limited [6].

When it comes to creating safety and control during extreme flooding situations, HEC-RAS is a helpful tool [7]. Hydrodynamic models can be classified as one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D) models according to the size of the physical phenomenon.

In many applications of river flow modeling, a one-dimensional hydrodynamic modeling system is used. The Hydrological Engineering Center-River Analysis System (HEC-RAS) is a well-known model that simulates 1D and 2D unsteady flow in open channels and floodplains [8]. In 2016, Maharjan and Shakya [9] conducted one-dimensional and two-dimensional surface flow analyses in Nepal using HEC-RAS and other software. Wang performed a water surface profile analysis on an existing project using the HEC-RAS model in his study [10]. Model performance evaluation was conducted using observed data collected from five nested measurement sites in a mixed land-use watershed of the central United States by Zeiger J.S. et al. [11]. In their study, the authors used an integrated modeling approach to combine the Soil and Water Assessment Tool (SWAT version 2012) with the Hydrological Engineering Center's River Analysis System (HEC-RAS version 5.0.7).

Thalakkottukara et al. [12] mapped the flood inundation in Huron Creek watershed, Michigan, USA for an extreme rainfall event in 2018 (Father's Day Flood) using the Height Above Nearest Drainage (HAND) model and a synthetic rating curve developed from the Laser Imaging Detection and Ranging Digital Elevation Model (LIDAR DEM). The flood was evaluated as 1000-year return period flood and its inundation characteristics predicted by two hydrodynamic models, viz., HEC-RAS and Sedimentation and River Hydraulics 2 Dimensional Model (SMSSRH 2D).

The Storm Water Management Model (SWMM), on the other hand is used for planning, analysis, and design regarding storm water runoff, combined and sanitary sewers, and other drainage systems. SWMM calculates water profiles of unsteady flows of open and/or closed free-surface channel systems using dynamic flow routing [13].

Culverts are often engineered to accommodate a designated discharge without causing an excessively high depth of water upstream. Therefore, for an engineer to effectively design a culvert, they must be able to accurately forecast the depth of water upstream for the designated discharge. To achieve this, the design discharge and flow conditions are calculated through hydrologic and hydraulic analysis in the water collection area of the flow reaching the culvert. Since the 1980, computer programs and hydrodynamic models have begun to be used in culvert design, especially to obtain water surface profiles. The use of geographical information systems (GIS) has greatly simplified the development of input data necessary for most hydrologic and hydraulic calculations for the design of culverts. In this study, the methods were applied to an example of a highway culvert calculation in order to compare the HEC-RAS, SWMM, and THDH approaches in highway culvert design.

Materials and Methods

Study Area

The study area is located on a branch of the Kocacay stream, which is in the Kizilirmak basin in the Central Anatolia region and passes through the city center of Nevsehir province, Cappadocia, Türkiye. (Fig. 1). Nevsehir, located in Central Anatolia, lies between approximately 38-39° north latitude and 34-35° east longitude. Geographically, it is situated almost in the center of Turkey. The area of the city is 5,467 km². Brown soils, a common soil type in Central Anatolia, cover a wide range in Nevsehir. The Erciyes volcanic region is also positioned near the borders of this area. Nevsehir, located at the heart of Cappadocia, where nature, history, and culture come together, welcomes around 4 million tourists from all over the world annually [14].

Figure 1. Study area [15]

The Kocacay stream originates from a basin spanning 3688 ha area near the center of Nevsehir city. It flows during rainy seasons and remains dry during dry seasons. After passing through an open reinforced concrete channel and two culverts along Nevsehir city center, Kocacay stream merges with Karaagac stream near Nar district and reaches Kizilirmak river. General Directorate of Highways of the Republic of Turkiye is planning to build a reinforced concrete culvert with dimensions of 3m (horizontal) x 2m (vertical) at the point where the Kocacay stream intersects the Nevsehir - Avanos D302 highway at 800m (Fig. 2).

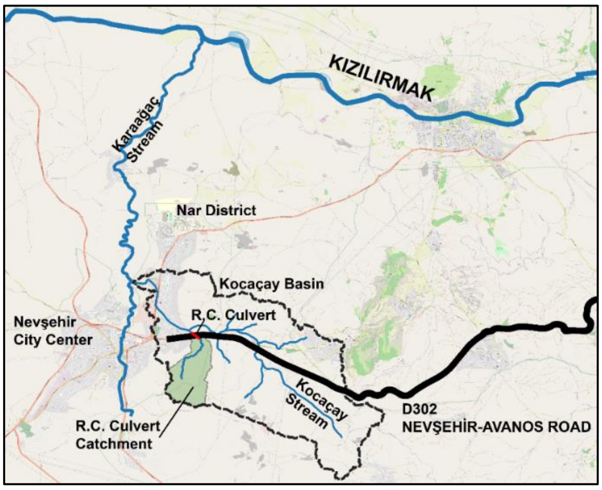


Figure 2. Kocacay stream and location of RC culvert

The sections upstream of the culvert are natural land sections. Downstream of the outlet of the culvert, the city municipality constructed an open channel with a trapezoidal cross-section, characterized by a concrete slab base with 2m width and side slopes covered with concrete grass stones (Fig. 3).

Figure 3. Culvert inlet (a), outlet (b) and open channel downstream of the culvert (c, d)

The elevation map of the study area was created using digital elevation maps (DEM) with globally 12.5m high resolution ALOS PALSAR (Advanced Land Observing Satellite Phased Array L-band Synthetic Aperture Radar) remote sensing tool, compiled by the Alaska Satellite Facility (ASF), using satellite radar interferometry within the scope of the Radiometric Terrain Correction Project [16]. According to the elevation map prepared by using QGIS 3.28.3 [17] geographic information system (GIS) software, the Kocaçay stream basin have a surface area of 3688ha. The hill formations are generally seen in the southern and eastern parts of the basin, where the drainage area of the culvert is located. (Fig. 4). Although the catchment of the culvert has a small surface area, the location of the culvert is sensitive to flood risks due to its proximity to Nevsehir central residential areas.

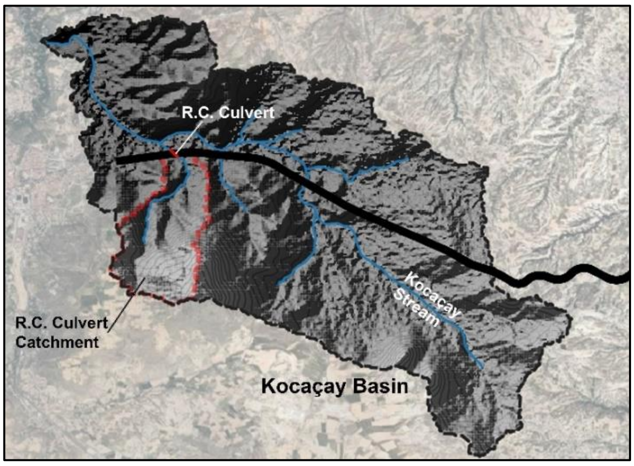


Figure 4. Elevation map of Kocacay stream basin

The lowest altitude is 1124m, the highest altitude is 1522m in the Kocacay basin, and the average altitude of the basin is 1314m. Surface runoff within the catchment area is channeled through densely packed hill formations to the lower regions in the north. The flow rate transmitted by the reinforced concrete culvert facing north consists of surface flow accumulated in a 278ha drainage area.

The culvert's drainage area is narrower downstream but widens significantly upstream. In such a configuration, the flood flow rate is higher compared to the reverse scenario, contrarily the time taken to reach the peak and sustain the flood is shorter [18].

In the culvert drainage area, which is mostly covered with a low permeable soil surface and small trees such as shrubs and fruit trees, the lowest altitude is 1207m, the highest altitude is 1634m and the average altitude is 1397m. In the Kocacay basin, the minimum slope was determined as 0%, the maximum slope was 38.00% and the average slope was 6.65%. In the drainage area of the culvert, the minimum slope was calculated as 0.61%, the maximum slope was 61.92% and the average slope was 20.63%. While a general slope of 0-10° is observed in the basin, when the reinforced concrete culvert and its surroundings are examined, it is seen that the slope values increase and are predominantly in the range of 20-30°.

Calculation of Design Flow Rate with Rational Method

When designing culverts, the initial step involves delineating the boundaries of the basin area and estimating the precipitation within these regions. The flow of floodwater triggered by precipitation can be computed using a selected method based on the basin area (drainage area). Typically, the Rational Method is suitable for rainfall basins up to 15 km2, while the synthetic unit hydrograph method is preferred for larger areas [18].

In both approaches, the 10-year, 100-year, and 500-year flood recurrence flows can be calculated based on meteorological data. The flow rates originating from the drainage area of the culvert for both the 10-year and 100-year recurrence intervals were determined using the Rational Method.

The maximum flow to the culvert is calculated using parameters such as the runoff coefficient (C, %), which shows the ratio of flow to precipitation, precipitation intensity according to recurrence years (i, mm/hour) and runoff area (A_r, km^2). According to the Rational Method, the flood flow rate (Q) that may occur as a result of the precipitation intensity (i) is calculated with the Eq.1 assuming that precipitation falls homogenously in every region of the basin [18], [19], [20]:

$$Q_{max} = \frac{\mathrm{Ci}A_r}{3.6} \quad (1)$$

The runoff coefficient (C) in Eq.1 varies depending on factors such as the topographic condition of the basin, the type of ground near the surface, and the density of vegetation [21]. While C takes values between 0.70-0.95 on impermeable surfaces, it takes values between 0.25-0.35 in gardens with heavy soil where the slope is higher than 7% [22]. The hydrological parameters of the drainage area of the culvert and the maximum flow rate calculated using the Rational Method are shown in Table 1.

Table 1. Hydrological parameters of culvert drainage area and design flow rate

Area (km^2)	Meteorological Station / No	I_{10} (mm/h)	I_{100} (mm/h)	Flow Coefficient C	Design discharge for 10year return period Q_{10} (m^3/s)	Design discharge for 100year return period Q_{100} (m^3/s)
2.780	Nevsehir/17193	27.00	41.00	0.60	12.51	19.00

The time of concentration (T_c) is the time that it takes for runoff to travel from the most remote upstream point in the drainage area to the downstream point and comprises two components: (1) the time taken for precipitation to travel from the catchment basin surfaces to the channel entrance at the top (t_0, in minutes), and (2) the time required for water within the channel to reach the outlet point at the bottom (Σt_i, in minutes). It is defined by the Eq. 2, 3 and 4 as outlined by Şen [20]:

$$T_c = t_0 + \Sigma t_i \tag{2}$$

$$t_0 = 60\left[0{,}87\frac{d^3}{dh}\right]^{0.385} \tag{3}$$

$$t_i = \frac{d_i}{60 v_i} \tag{4}$$

In Eq. 2, 3 and 4, d(km) is the longest distance that runoff water will travel until it enters the channel, d_h(m) is the altitude difference between the beginning and end of the flow path, d_i(m) is the drainage length, v_i(m/s) is the design velocity within the drainage area. When determining the time required to reach the outlet point at the downstream, it is necessary to calculate the total number of distinct channels within the drainage area based on the specific design velocity for each channel [20].

The topographic parameters of the runoff area are shown in Fig.5. The L_1, L_2 distances, H_1, H_2, H_3 elevations, average slope of each distinct channel, design flow velocity of the runoff and the collection time calculated according to the Rational Method are listed in Table 2.

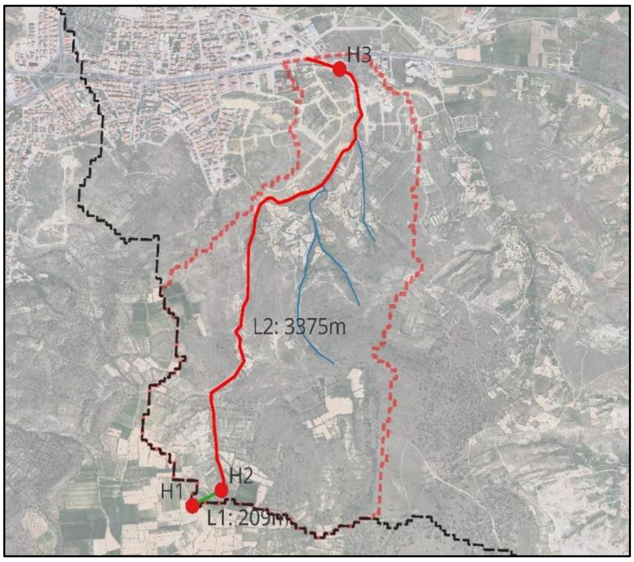


Figure 5. Topographic parameters of the Rational Method

Table 2 Topographical parameters of the drainage area and time of concentration

Elevation (m)			Distance (m)		Slope		Flow velocity (m/s)		Concentration time (min.)		Total concentration time (min.)
H_1	H_2	H_3	L_1	L_2	J_1	J_2	v_1	v_2	t_0	t_1	T_c
1570	1480	1210	209	3375	0.431	0.080	0.300	0.219	11.61	26.86	38

Application of the THDH Approach in Determining Culvert Dimensions

The culvert was originally designed according to the THDH [4]. To determine the culvert design dimensions, the culvert operating condition must be selected. Similar to Federal Highway Administration's Hydraulic Design of Highway Culverts two operating conditions are defined for culvert design [23]. These are:

- Inlet control: The culvert barrel is capable of conveying more flow than the inlet will accept.
- Outlet control: The culvert barrel is not capable of conveying as much flow as the inlet opening will accept.

The studied culvert was considered to be operated in inlet control conditions, and two types of operating conditions for inlet control are given in Fig. 6, namely unsubmerged and submerged inlet [4].

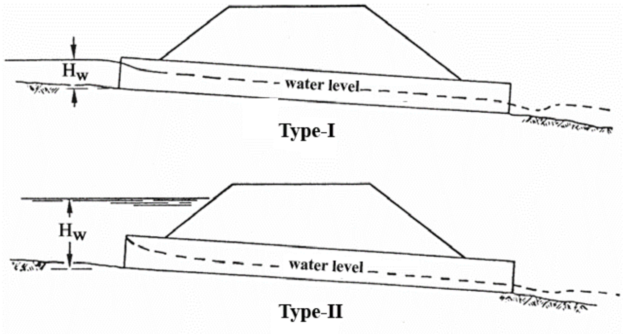


Figure 6. Operating conditions for inlet control (Type I and Type II) [4]

According to THDH [4], in Type I inlet control culverts, since the inlet water height (H_w) is less or equal to 1.2 times culvert height (a), no surge is to be considered at the inlet. This type of flow condition occurs when the natural stream bed is relatively low-sloping and wide and are the culvert dimensions are chosen to adequately accommodate the design flow. Critical velocity condition occurs at the outlet section of the Type I culvert. In Type II inlet control culverts, since the inlet water height (H_w) is greater than 1.2 times culvert height (a), the culvert is operating in submerged inlet condition. In both types of inlet-controlled culverts, the amount of surge at the inlet is calculated according to the Surge Determination Nomogram for inlet control culverts in the THDH [4].

Culvert dimensions are verified with the help of nomograms based on the culvert width (b). By using the design discharge (Q_{10}, Q_{100}), culvert slope (S_m) and critical slope (S_k) as variables in the nomograms, normal depth (D_n) and normal velocity (V_n) as well as critical depth (D_k) and critical velocity (V_k) are calculated. Manning's equation is used to verify the flow rate in selected culvert dimensions:

$$Q = \frac{1}{n}\ AR^{2/3}\ S^{1/2} \qquad (5)$$

where n is the Manning roughness coefficient, flow rate (Q), cross-sectional area (A), hydraulic radius (R), and slope (S). Critical velocity inside culvert is calculated by using Eq. 6:

$$Dk = \sqrt[3]{\frac{Q^2}{b}\,/g} \qquad (6)$$

The entry loss coefficient in reinforced concrete box culverts is determined from a table in THDH [4], according to the geometry of the culvert head wall and side walls.

Governing Equations of HEC-RAS and SWMM

HEC-RAS (Hydrologic Engineering Center's River Analysis System) and SWMM (Storm Water Management Model) are both widely used in hydraulic modeling, particularly in the field of water resources engineering. While they share some similarities in their purpose of simulating and analyzing hydraulic systems, they have different primary focuses and functionalities.

HEC-RAS is primarily designed for river hydraulics and is widely used for modeling steady and unsteady flow in rivers, channels, and floodplains. It's often used for tasks such as floodplain mapping, bridge and culvert design, and flood risk assessment. The HEC-RAS system encompasses four distinct one-dimensional river analysis components: (1) steady flow water surface profile computations; (2) unsteady flow simulation (one-dimensional and two-dimensional hydrodynamics); (3) Quasi unsteady or fully unsteady flow movable boundary sediment transport computations (1D and 2D); and (4) analysis of water quality [8].

On the other hand, SWMM is specifically designed for urban drainage systems, including stormwater runoff, sanitary sewers, and green infrastructure. It is used to simulate the quantity and quality of runoff within urban areas, helping with stormwater management, flood control, and pollution prevention [13]. The model idealizes the channel/conduit system to links connected to nodes or junctions, which transmit flow from node to node [24].

HEC-RAS and SWMM model uses the conservation of mass and momentum namely Saint-Venant equations. HEC-RAS model either uses one-dimensional (1D) unsteady flow routing (full Saint Venant equations), two-dimensional (2D) unsteady flow routing (Full Saint Venant equations or Diffusion wave equations); or level pool routing. SWMM uses gradually varied, one-dimensional unsteady flow equations to model unsteady flow ([24]; [25]). St Venan equations for gradually varied one-dimensional unsteady flow are shown in Eq. 7-8:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (7)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial\left(\frac{Q^2}{A}\right)}{\partial x}+gA\frac{\partial H}{\partial x}+gAS_f=0 \qquad (8)$$

where, Q = AV, V: average velocity, A: cross-sectional area, t: time, x: length of the channel or conduit, Q: flow rate, g: gravitational acceleration, H: hydraulic head, S_f: friction slope. The bottom slope is incorporated into gradient of H.

HECRAS and SWMM uses the Manning equation (Eq.1) to model steady uniform flow, expressing the relationship between flow rate, cross-sectional area, hydraulic radius, and slope.

HEC-RAS uses implicit finite differences and solve one-dimensional equations of motion numerically using the Newton-Raphson iteration technique [25]. SWMM v.5 uses an implicit backwards Euler method to provide stability, whereas previous versions are based on explicit twostep

Modified Euler method to calculate the continuity and momentum equations [24].

HECRAS can handle a full network of channels, a dendritic system, or a single river reach by modeling subcritical, supercritical, and mixed flow regime water surface profiles, considering the effects of various obstructions such as bridges, culverts, dams, weirs, and other structures in the flood plain [8].

The roughness within an irregular, natural channel section is changes according to the type and size of materials that compose the bed and banks of a channel and the shape of the channel. HEC-RAS determines the value of Manning's n of a channel by using Cowan's (1956) procedure [26]:

$$n=(n_0+n_1+n_2+n_3+n_4)m \tag{9}$$

Where, n_0 is base value for a straight, uniform channel, n_1 is the additive value to account for the effect of cross-section irregularity, n_2 is the additive value to account for the variations in size and shape of the channel, n_3 is the additive value to account for the effect of obstructions, n_4 is the additive value to account for the type and density of vegetation and m is the adjustment factor for the degree of channel meandering; determined by the ratio of channel meander length (L_m) to valley or straight channel length (L_s).

For determination of Manning coefficient for an irregular open channel, both model uses equivalent roughness coefficient n_c [27] as shown in Equation 10 [24], [25].

$$n_c = \left[\frac{\sum_{i=1}^{N}\left(P_i n_i^{1.5}\right)}{P}\right]^{2/3} \tag{10}$$

where nc is the composite coefficient of roughness, ni Manning roughness for subdivision i, P is the wetted perimeter of the channel and P_i is the wetted perimeter of subdivision i.

Culvert Hydraulics in HEC-RAS and SWMM

HEC-RAS is equipped to model nine widely utilized culvert geometries, including circular, rectangular, arch, pipe arch, low profile arch, high profile arch, elliptical, semi-circular, and Con/Span shapes. These culverts can be configured individually, in groups, or in combination with weirs, gates, rating curves, and time series outlets. Additionally, culverts can be assigned to specific station points along a river reach as defined within HEC-RAS or can be georeferenced [8].

The head losses due to the contraction and expansion of flows upstream and downstream of a culvert are calculated by user-defined loss coefficients. Typical lateral cross section of a culvert is shown in Fig 7 [25].

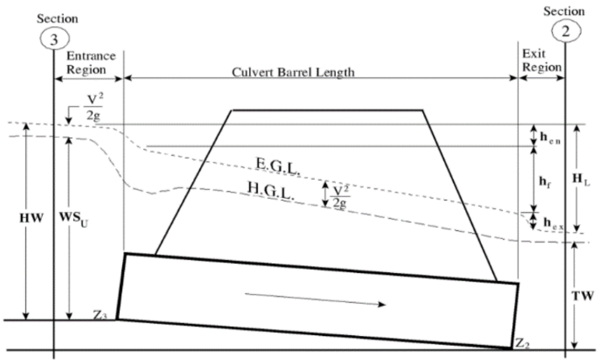


Figure 7. Typical lateral cross section of a culvert [25]

Headwater (HW in Figure 6) is the depth from the culvert inlet invert to the energy grade line, in Section (3), where Tailwater (TW in Figure 6) is the depth on Section (2). Upstream water surface (WSU in Figure 6) is the water depth at the entrance of the culvert. The flow type through a culvert can be defined as "inlet control" or "outlet control". Inlet control culvert flow occurs when the flow capacity of the culvert entrance is less than the flow capacity of the culvert barrel, contrarily outlet control flow occurs when the culvert flow capacity is limited by downstream conditions (high tailwater) or by the flow carrying capacity of the culvert barrel [25].

The inlet control equations for submerged and unsubmerged inlet conditions are developed according to the laboratory tests by the National Bureau of Standards, the Bureau of Public Roads, and are the basis of the Federal Highway Administrations inlet control nomographs HEC-RAS provide solutions for inlet control computations for submerged and unsubmerged and carries the water surface profile through the structure and maintains the approach velocity [2].

For outlet control culvert flow, HEC-RAS uses s Bernoulli's equation to compute the change in energy through the culvert [25]:

$$Z_3+Y_3+\frac{a_3V_3^2}{2g}=Z_2+Y_2+\frac{a_2V_2^2}{2g}+H_L \tag{11}$$

Where, Z_3: upstream invert elevation of the culvert, Y_3: the depth of water above the upstream culvert inlet, V_3: the average velocity upstream of the culvert, a_3: the velocity weighting coefficient upstream of the culvert, g: the acceleration of gravity, Z_2: downstream invert elevation of the culvert, Y_2: the depth of water above the downstream culvert inlet, V_2: the average velocity downstream of the culvert, a_2: the velocity weighting coefficient downstream of the culvert, HL. total energy loss through the culvert (from section 2 to 3).

In SWMM, a culvert designation is assigned to any conduit link by specifying its shape, which may be circular, rectangular, ellipsoidal, or arch. During each time step of a simulation, the flow through the culvert is initially computed using the standard dynamic wave method, which represents the outlet control condition. Subsequently, an inlet-controlled flow is computed to assess whether it imposes a flow rate limitation. Under inlet control, a rating curve establishes the relationship between culvert flow rate and inlet head [24].

Under inlet control conditions, a rating curve defines the relationship between the flow rate through a culvert and the inlet head, influenced by the culvert's shape, material, and the geometry of its inlet opening. When the inlet is submerged, the culvert functions as an orifice, whereas it operates as a weir when unsubmerged. Similar to the procedures employed in HEC-RAS, SWMM utilizes equations delineated in Hydraulic Design of Highway Culverts [23] to determine the flow under unsubmerged inlet control conditions [24].

Results and Discussion

THDH Approach to Culvert Design

Design discharges (Q_{10}, Q_{100}), dimensions (a, b) and other design parameters for the culvert at D302 KM:800 are shown in Table 3.

Table 3. Design parameters of the culvert

Design discharge for 10year return period Q_{10} (m^3/s)	Design discharge for 100year return period Q_{100} (m^3/s)	**Design Parameters of Inlet-Controlled Box Type Culvert**					
		Cross-sectional width b (m)	Cross-sectional height a (m)	Unit discharge for 10y.r.p. q_{10} (m^3/s /m)	Unit discharge for 100y.r.p. q_{100} (m^3/s /m)	Manning's roughness coefficient n	Culvert slope S (%)
12.51	19.00	3.00	2.00	4.17	6.33	0.016	4.10

The culvert hydraulic values calculated for Q10 and Q100 with the nomogram method defined in the THDH [4] are used to calculate the headwater (HW) and tailwater (TW) depths. The design results calculated for the selected culvert dimensions are given in Table 4. Since the calculated water height inside the culvert is less than the critical flow height, it is not necessary to perform surge control at the culvert outlet.

Table 4. Culvert design results by THDH approach

Design discharge (m^3/sn)	Normal water depth inside the culvert D_n (cm)	Normal velocity inside the culvert V_n (m/sn)	Critical depth D_k (cm)	Critical velocity V_k (m/s)	HW depth (m)	TW depth (m)
Q_{10} =12.51	80	7.8	121	3.4	1.80	0.80
Q_{100}=19.00	109	8.7	160	4.0	2.40	1.09

According to Table 4, at Q_{10} discharge, a 1.80m HW is expected to occur at the culvert inlet, and at Q_{100} discharge, a 2.40m HW is expected to occur at the culvert inlet. Following the nomogram method proposed in the THDH, while the water depth at the inlet does not exceed the culvert height at the 10-year flow, it does at the 100-year design flow. Still, both flow scenarios are still categorized as Type-I (unsubmerged) inlet control flow as stated in the handbook, given that the headwater level remains within 1.2 times the culvert height.

Application of HEC-RAS in Culvert Design

To simulate the culvert in the HEC-RAS software, the stream sections encompassing the water collection area, as well as the natural cross sections of the stream upstream and downstream of the culvert are also included to the model. RAS Mapper v.2 software was used to perform these operations in the GIS environment. Using digital maps compiled by ALOS PALSAR [16], natural stream sections in areas close to the culvert were transferred to the model. The flow path line and bank lines to define the main channel banks for the cross sections are prepared using RAS Mapper. The cross-sections were taken every 100m along the flow route on the Kocacay stream, starting 850m upstream of the culvert and continuing to 450m downstream of the culvert. To analyze the variations in water levels at the entrance and exit of the culvert, the model was executed with link lengths of 5 meters over a distance ranging from 400 to 500 kilometers. Flow path line, bank lines and the cross-sections of Kocacay stream prepared using RAS Mapper is shown in Fig. 8.

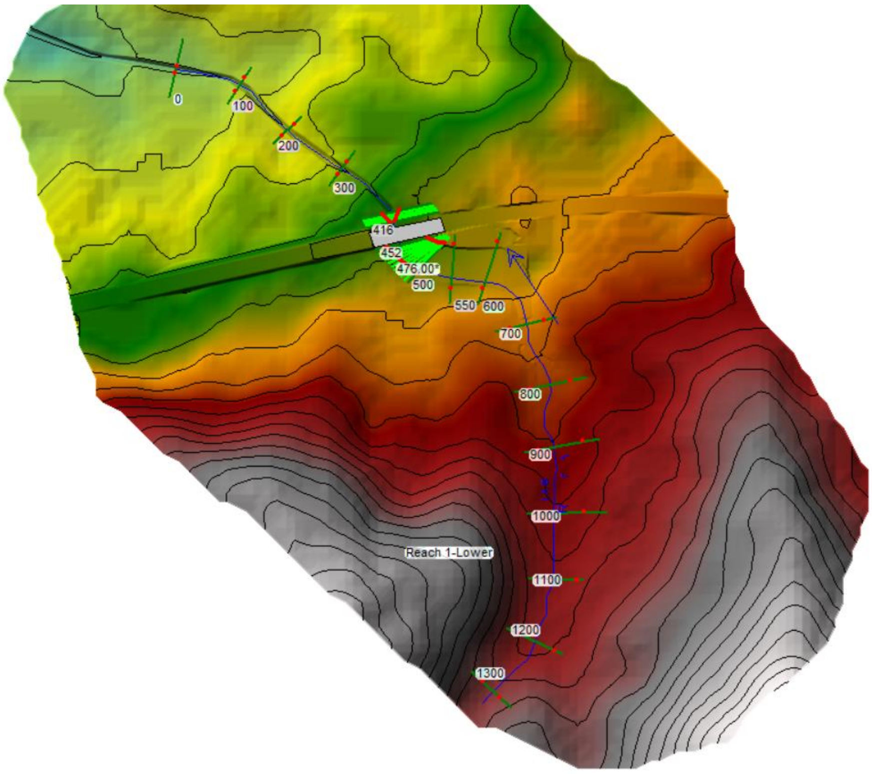


Figure 8. Flow path line, bank lines and the cross-sections of Kocacay stream

Between KM: 0 and KM: 416m are the flow path downstream of the culvert which is an open channel with a trapezoidal cross-section. The sections upstream of the culvert (KM:452 to KM:1300) are natural land sections. Manning roughness coefficients of the sections defined in the model are shown in the Table 5. The culverts centerline is positioned at KM: 435 along the streamline, designated as a reinforced concrete box-type culvert with specified dimensions of 3 meters in width, 2 meters in height, and a length of 30 meters. The inlet loss coefficient was determined as 0.5, as recommended by FHWA [2], and the outlet loss coefficient was determined as 0.5, taking into account the outlet conditions of the culvert.

Table 2 Manning coefficients used for cross-sections [26], [27]

STKM	Channel Type	Manning Coefficient		
		Right Bank n_1	**Channel Bed** n_2	**Left Bank** n_3
0-438	Concrete bed & grassstone banks	0.035	0.016	0.035
438-468	Reinforced concrete rectangular culvert	0.016	0.016	0.016
468-3750	Natural irregular riverbed	0.035	0.035	0.035

The upstream and downstream boundary conditions in the model are set to the normal depth according to the natural bed ream slope at those sections (Table 6). The model was run in steady condition with Q_{10} and Q_{100} design flow rates estimated according to the Rational Method, and the hydraulic conditions that may arise according to the topographic model and the culvert section are determined with the HEC-RAS model.

Table 6 Upstream and downstream boundary conditions

StKM	Channel Type	Boundary Condition	
		Type	**Slope (J)**
0	Concrete bed & grassstone banks	normal depth	0.04
1300	Natural irregular riverbed	normal depth	0.03

The water levels formed with Q_{10} discharge in the cross-sections at the upstream and downstream and in the cross-sections at the inlet and outlet of the culvert are shown in Fig. 9. The water levels formed with Q_{100} discharge at same cross-sections are shown in Fig. 10. The water surface profiles along the culvert for Q_{10} and Q_{100} discharges are shown in Fig. 11.

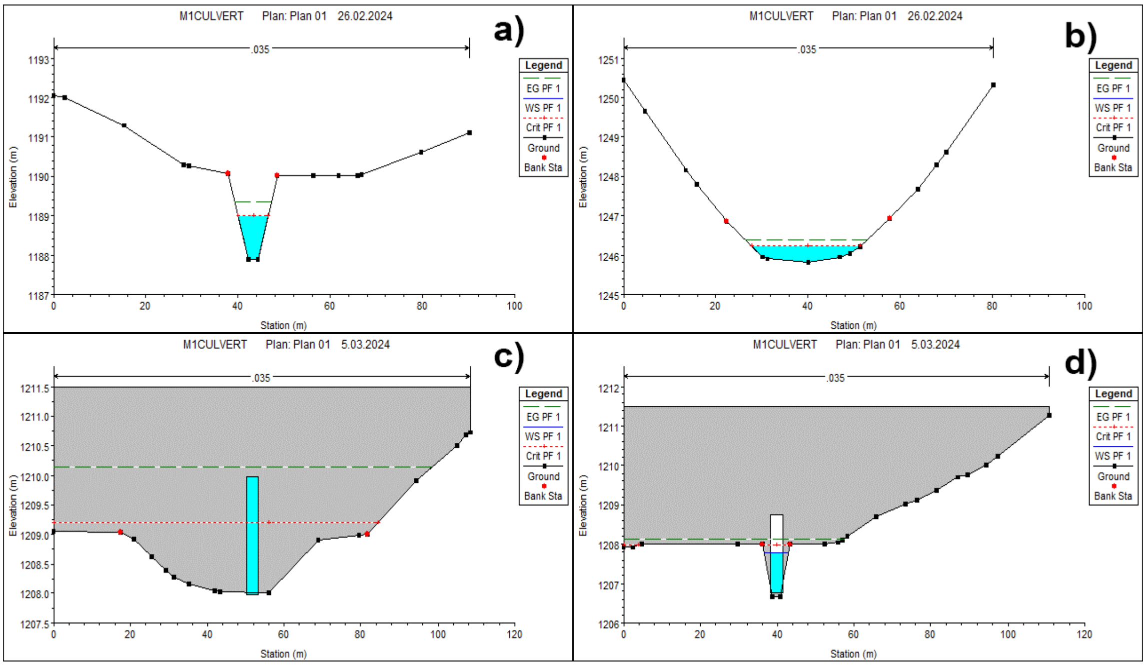


Figure 1. Channel cross-section and water level at the downstream (a), upstream (b) of the channel and culvert inlet (c) and outlet (d) for Q10 discharge

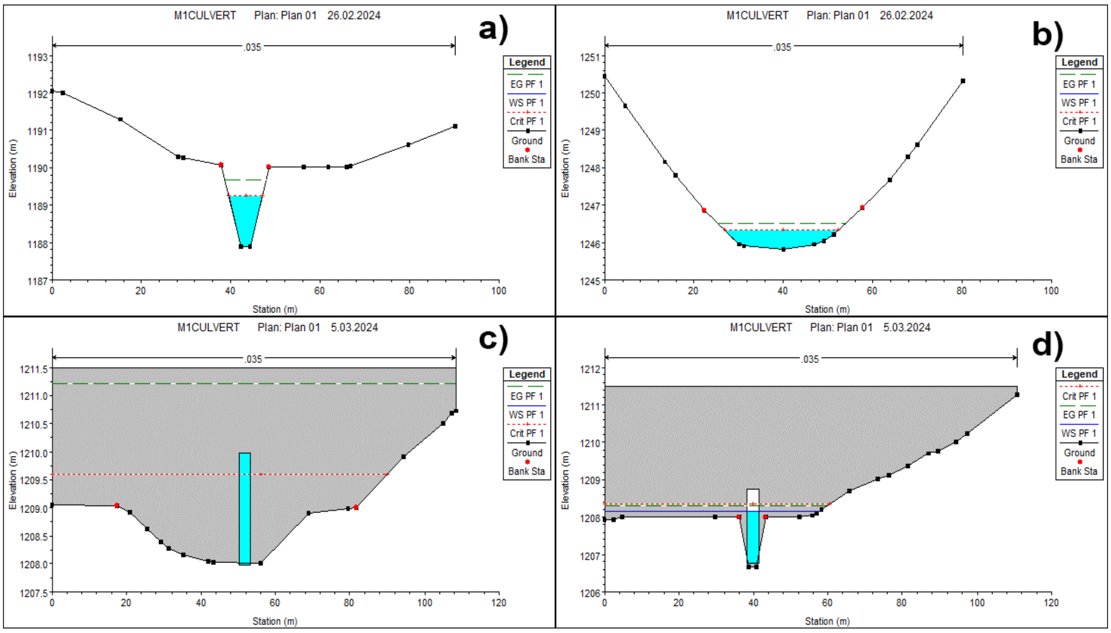


Figure 10. Channel cross-section and water level at the downstream (a), upstream (b) of the channel and culvert inlet (c) and outlet (d) for Q100 discharge

Upon examining the profiles and sections in Figures 9, 10 and 11, it becomes evident that the culvert can convey both Q_{10} and Q_{100} discharges and both flow type can be classified as inlet control USGS Type 5 flow since the headwater depth (HW) exceeds culvert height in both cases (submerged inlet) [3]. In the natural stream section preceding the culvert entrance, characterized by a higher roughness value, HW surpasses the culvert height. The inlet end is submerged and the outlet end flows freely. The control section of the culvert is located just inside the entrance and near this location critical depth occurs. Subsequently, within the culvert featuring a lower roughness and a steep bottom slope, the flow persists at a depth below the critical depth for both discharge conditions and the flow regime downstream is supercritical. Figure 11's profiles indicates that the flow, corresponding to the Q_{10} and Q_{100} discharges, the flow approaches normal depth at the culvert outlet end. Hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity. In both instances, a higher headwater level results in ponding at the upstream side of the culvert, particularly pronounced during Q_{100} discharge conditions. The perspective view of the hydraulic sections for Q_{100} flow rate by the model is shown in Fig. 12.

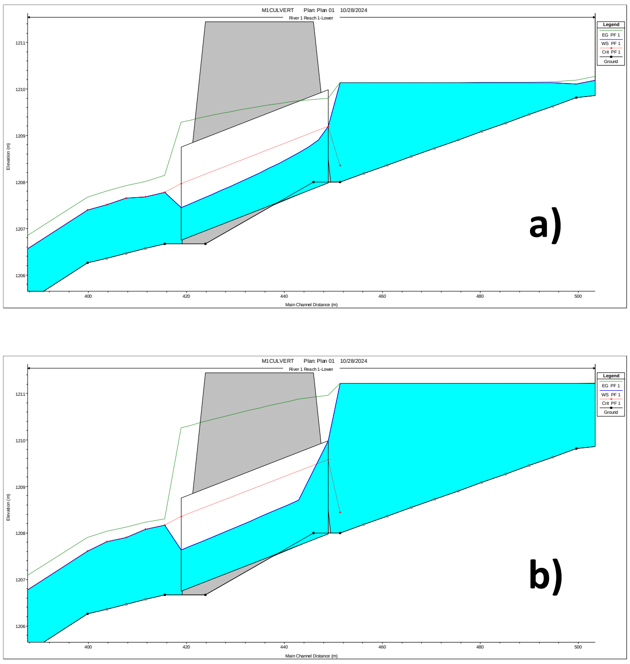


Figure 11. The water surface profiles along the culvert for Q_{10} (a) and Q_{100} (b) discharge

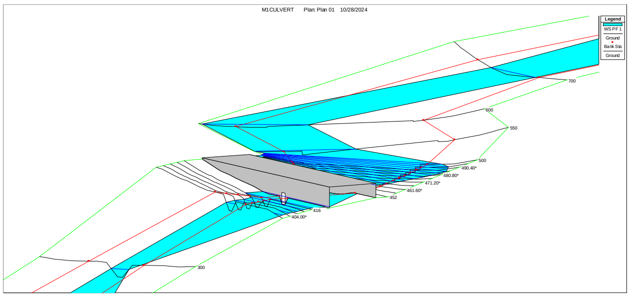


Figure2. Perspective view of culvert for Q_{100} discharge

Fig. 13 displays the ponding area at the culvert entrance, generated by RAS-Mapper based on the water surface profile computed in the HEC-RAS model. Upstream from the culvert entrance, the natural stream bed forms a sharp bend, with several public buildings situated along the right edge of the ponding area. It's crucial to acknowledge that such sharp turns in the natural stream bed can lead to erosion and potentially increase sediment deposition, posing a flood risk to the nearby buildings.

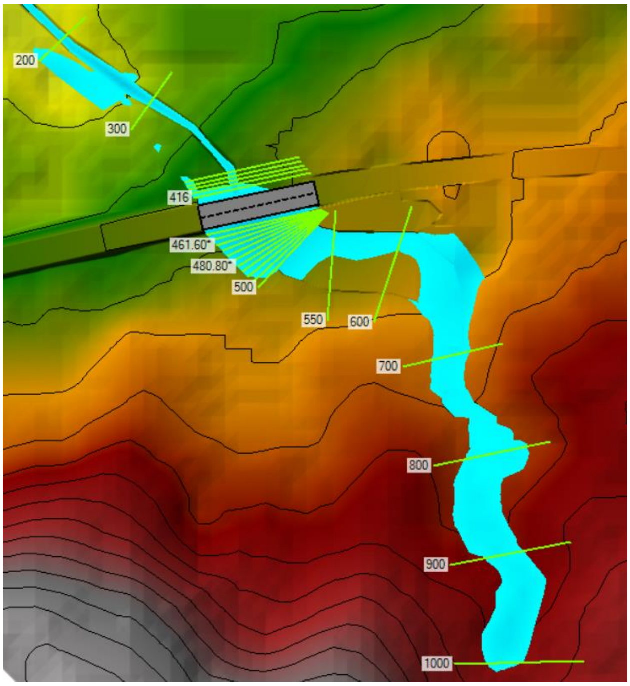


Figure 13. Ponding area for Q_{100} discharge

Application of SWMM in Culvert Design

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. Typical applications of SWMM include design and sizing of drainage system components for flood control and sizing of detention facilities and their appurtenances for flood control. SWMM can generate profile plots showing how water surface depth varies across a path of connected nodes and links [24].

The cross-sections obtained from DEM every 100 m along the route were transferred to the SWMM model and defined as nodes. The lines between these calculation points defined along the route are defined as links. The links and nodes defined along the stream route in the SWMM model are shown in Fig. 14.

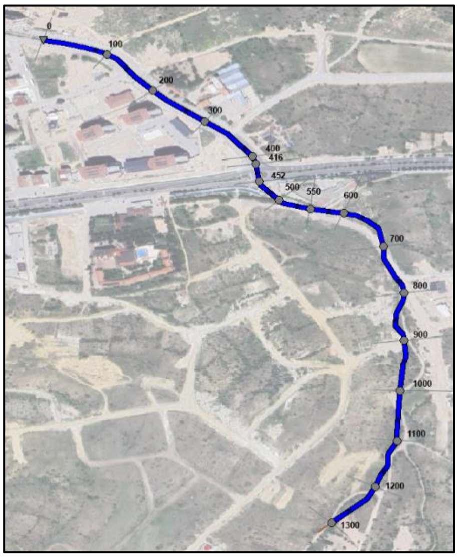


Figure14. Stream centerline, links, and nodes of Kocacay

The cross-section of each link was calculated based on the cross-sections defined at the node and obtained from the DEM. The lowest point of the sections at the node points is defined as the channel talweg/base point in the model, and the invert elevation is defined at the calculation points. In the model created in SWMM, natural stream sections at the upstream and the downstream of channel, at the inlet and the outlet of the culvert are shown in Fig. 15.

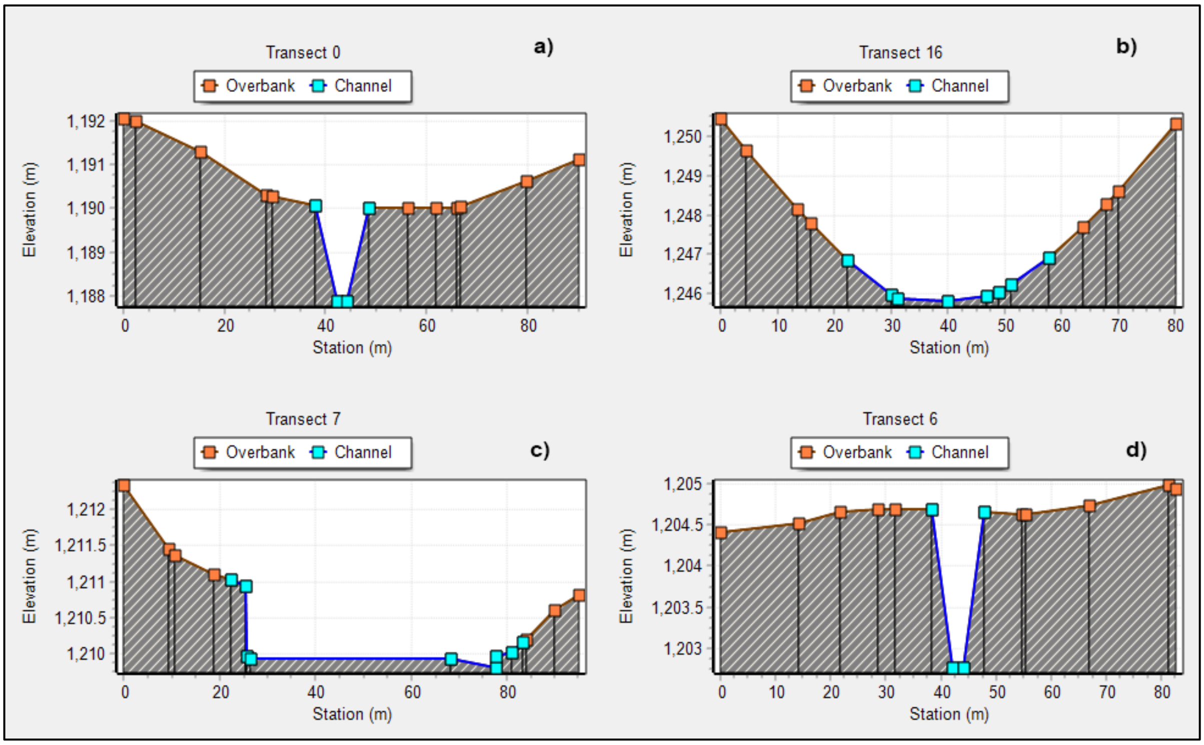


Figure 15. Channel cross-sections at the upstream (a), downstream (b) of the channel and culvert inlet (c) and outlet (d) in SWMM

The link section from KM:416 to KM:452 was designated as a reinforced concrete box culvert with a rectangular cross-section and 30-75 deg. flared wingwalls. The dimensions, roughness coefficients for the walls and foundation of the culvert, and inlet-outlet loss coefficients were configured to match the parameters in the HEC-RAS model. Subsequently, the model was simulated under steady flow conditions for both Q_{10} and Q_{100} discharges. Fig. 16 displays the water surface profiles recorded upstream and downstream of the culvert.

When utilizing the SWMM model for Q_{10} and Q_{100} flow rates, the Figure 16 reveals that the culvert functions under both inlet control. For Q_{10} flow, a surge is evident at the entrance of the culvert, attributed to changes in cross-section and inlet losses. However, according to the model's calculations, the surge height is determined to be lower than the culvert height for Q_{10} discharge. On the other hand, for Q_{100} flow the HW surpasses the height of the culvert and the inlet is submerged. In both cases the flow regime inside the culvert is supercritical. SWMM model results shows USGS Type-1 flow through an unsubmerged inlet control culvert for Q_{10} and USGS Type-5 flow through a submerged inlet control culvert for Q_{100} discharge.

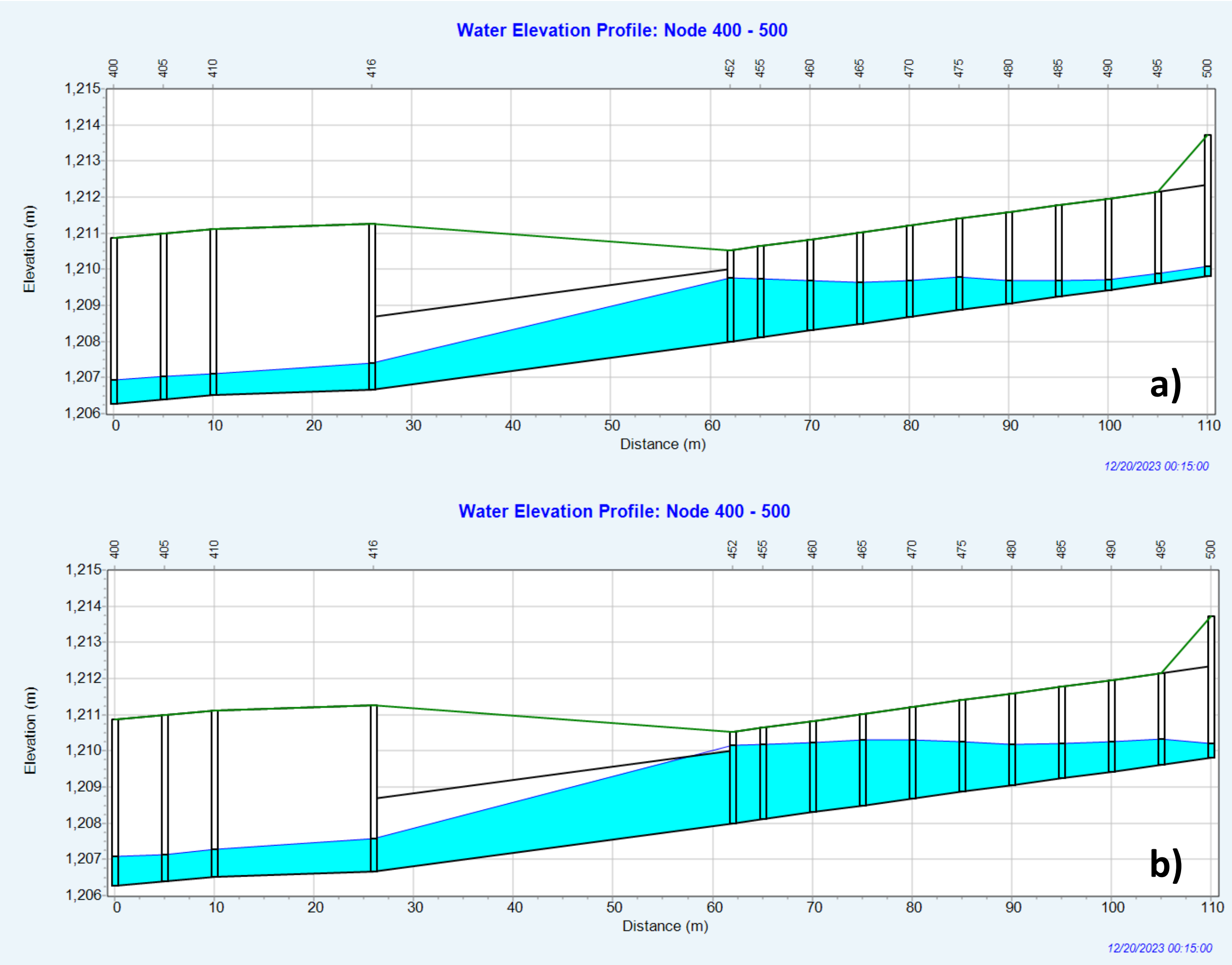


Figure 16. Water surface profile for flow rates Q10 (a) and Q100 (b)

Comparison of the Results

The hydraulic calculations made using nomograms in the THDH [4] for the culvert to be built in the Kocaçay stream on Nevsehir Avanos highway were compared with HEC-RAS and SWMM models, and the water depths calculated at the culvert inlet and outlet for Q_{10} and Q_{100} discharges are shown in Table 7.

Table 3. Headwater (HW) and tailwater (TW) depth of the culvert

Flow (m^3/s)	Calculated water depth (m)					
	THDH		HEC-RAS		SWMM	
	HW	TW	HW	TW	HW	TW
Q10 (12.51)	1.80	0.80	2.14	1.10	2.13	0.86
Q100 (19.00)	2.40	1.09	3.21	1.50	3.31	1.06

Upon reviewing Table 7, the assessment of culvert flow focuses on inlet control across all calculation methods. As per the methodology outlined in the THDH [4], at Q_{10} discharge, an unsubmerged inlet condition is observed. However, at Q_{100}, the calculated headwater depth (HW) surpasses the culvert height. Despite this variation, both flow scenarios are still categorized as Type-I (unsubmerged) inlet control flow as stated in the handbook, given that the HW remains within 1.2 times the culvert height. Unlike the calculations according to THDH, in both conditions the headwater level exceeds culvert height according to HEC-RAS model calculations. The flow is considered as inlet control USGS Type 5 flow as submerged inlet occurs in both Q_{10} and Q_{100} discharge conditions.

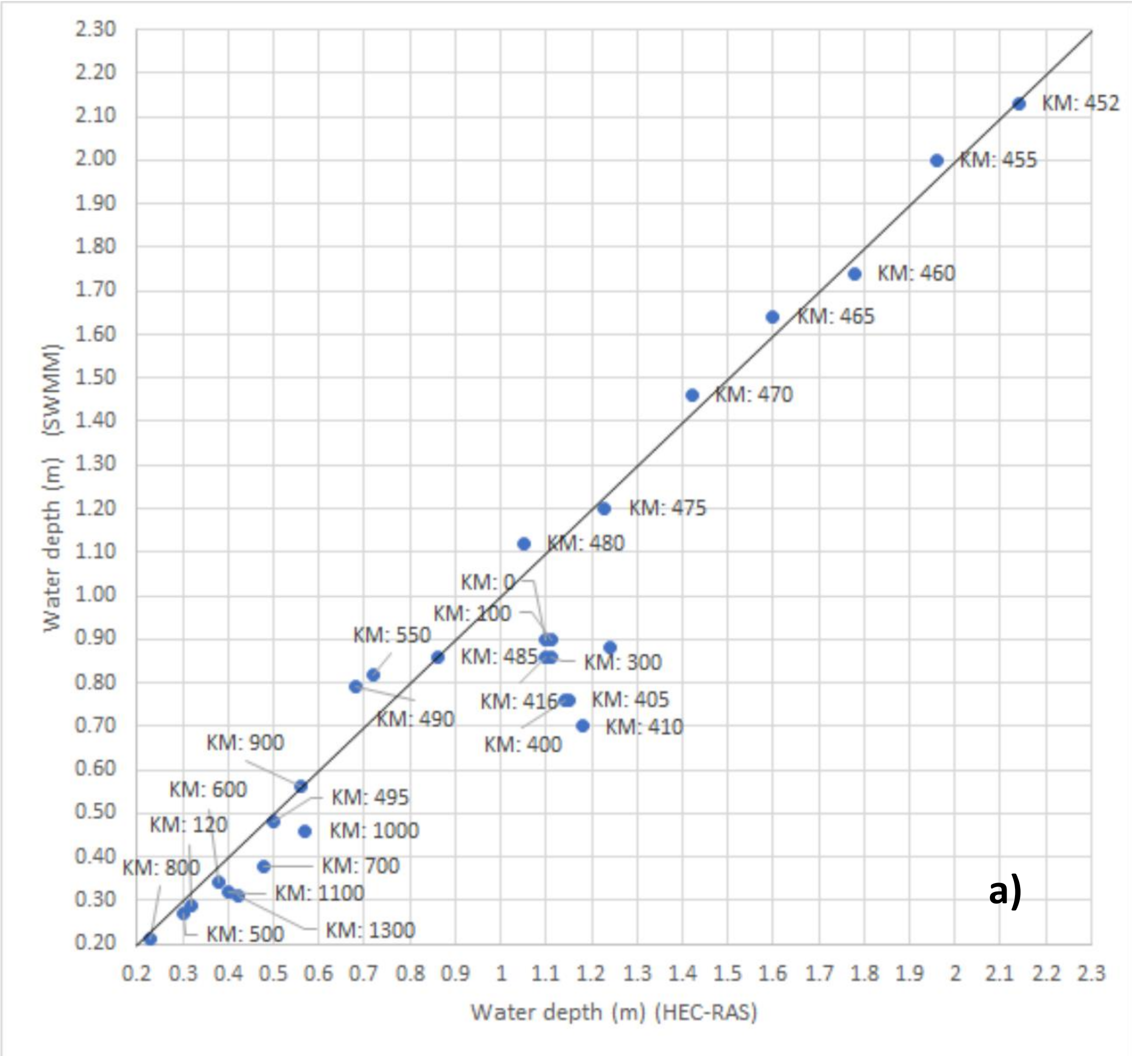
SWMM model results for Q_{10} shows an unsubmerged inlet control culvert with supercritical USGS Type-1 flow inside the culvert. On the other hand, for Q_{100} flow the HW surpasses the height of the culvert and the inlet is submerged. The flow inside the culvert is supercritical matching USGS Type-5 flow conditions.

Although all calculation methods yield relatively similar results for water depths at the tailwater, the methodology outlined in the THDH produces higher values for tailwater depths compared to the model results. Notably, discrepancies in the method utilized, result in more significant differences in water heights calculated at the headwater. The THDH method yielded the lowest headwater depth for both discharge cases, which could lead to inaccuracies in determining culvert dimensions and surge levels. While THDH and SWMM give relatively closer results to each other, HEC-RAS produces significantly higher depth values at headwater than the other two methods.

While according to THDH, hydraulic calculations can only be made for the culvert inlet and outlet by using formulas and nomograms, in HEC-RAS and SWMM models, hydraulic calculations can be made up to the desired distance upstream and downstream, apart from the culvert entrance and exit.

In HEC-RAS and SWMM models, water depths were calculated at cross-sections every 100 m on a 1300 m route on the Kocaçay stream. In both models, the geometries, roughness coefficients of the naturally irregular sections were kept identical to constitute a comparison between the water depth results for both models.

Fig. 17 compares the water depths calculated by HEC-RAS and SWMM models at each cross-section for Q_{10} and Q_{100} discharges. The comparison excludes water depths at the headwater and tailwater, where calculation methods differ between the models, as well as at KM:0 and KM:1300, where boundary conditions influence the results.



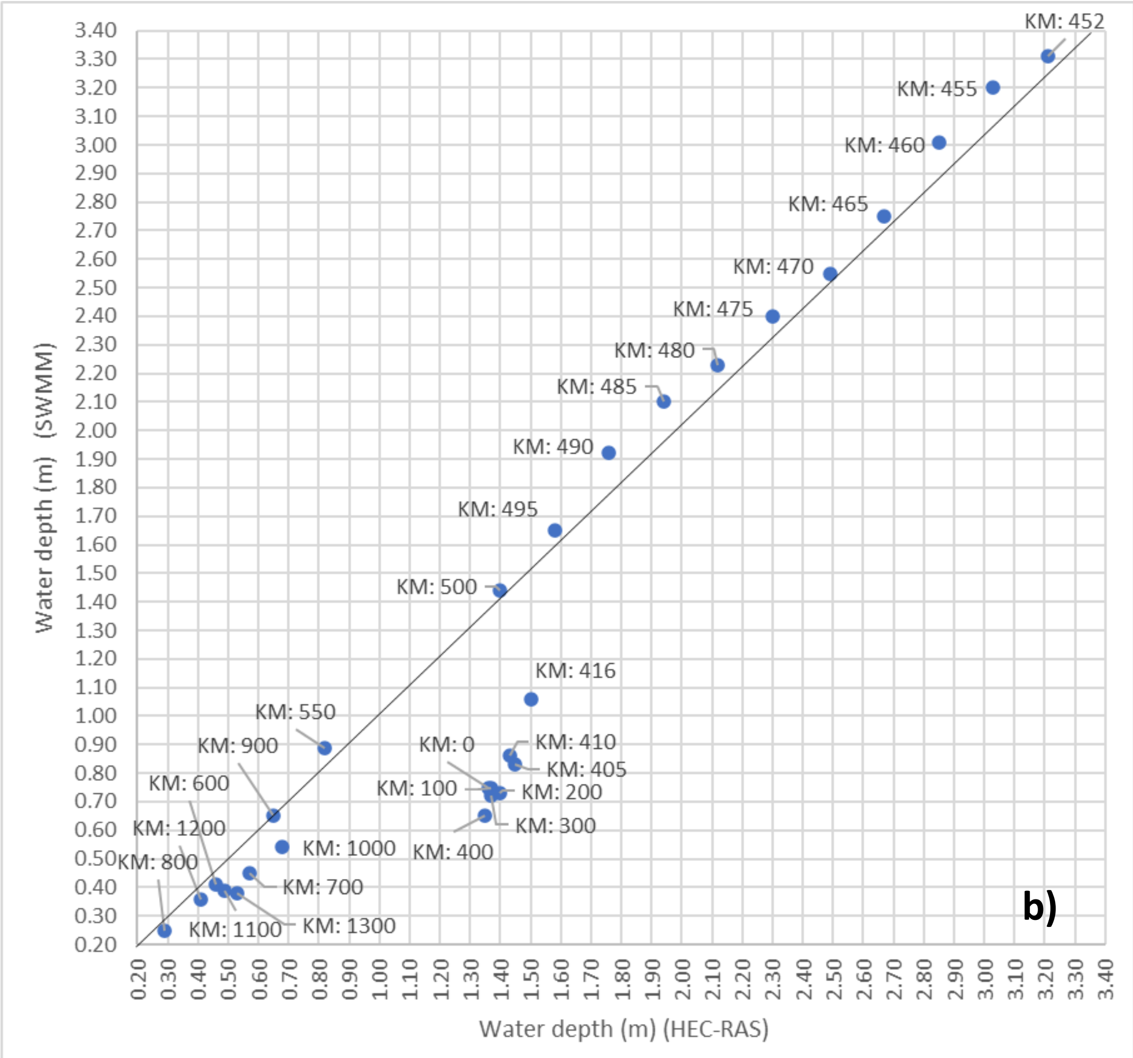


Figure 17. Water depths calculated for Q_{10} (a) and Q_{100} (b) discharge in the HEC-RAS and SWMM models

Although the water depths calculated by the HEC-RAS and SWMM models were close to each other at the calculation points upstream of the culvert along the Kocaçay Stream, except the ponding area close to the inlet of the culvert, the water depths calculated by the HEC-RAS model were generally higher than those calculated by SWMM at the same cross-section.

While both models utilize the same fundamental equations, the HEC-RAS model incorporates the meander effect into hydraulic calculations by considering reach lengths for the left and right overbank and channel between two cross-sections. In cases where the distances between cross sections for both the channel and overbanks vary, HEC-RAS determines a discharge-weighted reach length. [25]. Conversely, in SWMM, floodplain access distances are not computed by the model, and users must define the meander effect in natural sections [24]. Additionally, HEC-RAS and SWMM utilize different numerical methods and algorithms to simulate hydraulic behavior, which leads to variations in results.

The difference between SWMM and HEC-RAS results increases with increasing water depth at the cross-sections downstream from the station point where the culvert is located and downstream of the culvert outlet. The presence of the culvert itself introduce complexities in flow dynamics downstream, such as changes in flow velocity, turbulence, and water surface profiles. SWMM and HEC-RAS handle these effects differently, leading to discrepancies in predicted water depths. This situation is observed in the model results, especially between KM: 416, and KM: 0 at the downstream of the culvert.

Conclusions

After reviewing the water depths calculated using three distinct methods at the culvert entrance, exit, and nearby points along the channel, it becomes apparent that while the nomogram method suggested in the THDH provides a practical means for determining headwater depth, tailwater depth and culvert dimensions. However, it does not adequately address the channel sections upstream and downstream of the culvert and the relevant flow conditions. This oversight leads to an underestimation of culvert headwater depth during design flow conditions and may cause the water to surge to undesirable levels during floods.

With the model made with SWMM, an urban infrastructure modeling tool, it was observed that the flow conditions at the culvert inlet and outlet and in the natural sections at the upstream and downstream were taken into consideration, but it was observed that the flow conditions did not fully reflect the flow conditions since the effect of some river features such as meanders on the flows was not directly calculated by the model.

It has been determined that HEC-RAS, can model many hydraulic features of a natural stream and reflects the flow conditions on the channel more accurately, both at the inlet and outlet of the culvert and at the upstream and downstream of the culvert. With the GIS tools in HEC-RAS, the water collection areas created by the design flow rates around the culvert can be shown on the map and the regional effect of the flow can be evaluated with this tool.

To evaluate the environmental effects of the design flow rates of culverts, especially those located near residential areas, it is recommended to use HEC-RAS and similar GIS-supported modeling tools in hydraulic calculations.

In summary, While the THDH and SWMM methods have their useful insights, HEC-RAS integrates comprehensive modelling and GIS tools for better accuracy and reliability of culvert performance assessment and flood management, in particular for complex and residential areas. It is therefore suggested that future studies should focus on prioritizing and integrating HEC-RAS and GIS based technologies to enhance detailed flow dynamics and environmental impacts.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person / institution in the article prepared

Authors' Contributions

Cebe K: Writing the main manuscript text, assessing and preparing the data for the models, constructing models, and assessing their performances. Reading and approving the final manuscript.

Bilhan O: Field works, study conception and design, interpretation of data, drafting of manuscript. Reading and approving the final manuscript.

Balci RS: processed, curated and stored the original data used in this study. Reading and approving the final manuscript.

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