

**DETERMINING LANDSLIDE DRAIN
MAINTENANCE AND OPERATION
MANUALS**

Final Report

PROJECT SPR-834



Oregon Department of Transportation

DETERMINING LANDSLIDE DRAIN LIFECYCLE FOR DEVELOPMENT OF MAINTENANCE AND OPERATION MANUALS

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16. Abstract In this project, numerical models are proposed to evaluate the (1) mechanisms and transient drawdown from horizontal drains for a wide range of geometric conditions using simplified design charts, (2) siltation mechanisms and timing for various drain geometries and grain sizes as a means of determining "time until failure" using simplified design charts, and (3) a simple machine learning model to estimate transient drawdown using an ArcGIS toolbox. Further, hydrologic data from the HWY20 Pioneer Mountain-Eddyville realignment was analyzed and used to develop robust observation-based criteria for evaluating drain performance at a systems level, explored through proposed hazard matrices that guide actions regarding inspection and intervention. These criteria are intended for less frequent, but more robust evaluation of performance. Simple criteria for individual, more frequent drain monitoring is provided in a checklist form, along with template inspection guidelines and examples of satisfactory or unsatisfactory drain performance. Lastly, in collaboration with the OpenS lab at Oregon State University, a low-cost, open-source flowmeter system was designed and developed as a future means of monitoring discharge from horizontal drain systems.			
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SI* (Modern Metric) Conversion Factors

Approximate Conversions to SI Units

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	n	inches	25.4	millimeters	mm
Length	ft	feet	0.305	meters	m
Length	yd	yards	0.914	meters	m
Length	mi	miles	1.61	kilometers	km
Area	in ²	square inches	645.2	square millimeters	mm ²
Area	ft ²	square feet	0.093	square meters	m ²
Area	yd ²	square yard	0.836	square meters	m ²
Area	ac	acres	0.405	hectares	ha
Area	mi ²	square miles	2.59	square kilometers	km ²
Volume	fl oz	fluid ounces	29.57	milliliters	mL
Volume	gal	gallons	3.785	liters **	L
Volume	ft ³	cubic feet	0.028	cubic meters	m ³
Volume	yd ³	cubic yards	0.765	cubic meters	m ³
Mass	oz	ounces	28.35	grams	g
Mass	lb	pounds	0.454	kilograms	kg
Mass	T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
Temperature (exact degrees)	oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	oC
Illumination	fc	foot-candles	10.76	lux	lx
Illumination	fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
Force and Pressure or Stress	lbf	poundforce	4.45	newtons	N
Force and Pressure or Stress	lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa

*SI is the symbol for the International System of Measurement

** Volumes greater than 1000 L shall be shown in m³

SI* (Modern Metric) Conversion Factors
Approximate Conversions from SI Units

Physical Quantity	Symbol	When You Know	Multiply By	To Find	Symbol
Length	mm	millimeters	0.039	inches	in
Length	m	meters	3.28	feet	ft
Length	m	meters	1.09	yards	yd
Length	km	kilometers	0.621	miles	mi
Area	mm ²	square millimeters	0.0016	square inches	in ²
Area	m ²	square meters	10.764	square feet	ft ²
Area	m ²	square meters	1.195	square yards	yd ²
Area	ha	hectares	2.47	acres	ac
Area	km ²	square kilometers	0.386	square miles	mi ²
Volume	mL	milliliters	0.034	fluid ounces	fl oz
Volume	L	liters	0.264	gallons	gal
Volume	m ³	cubic meters	35.314	cubic feet	ft ³
Volume	m ³	cubic meters	1.307	cubic yards	yd ³
Mass	g	grams	0.035	ounces	oz
Mass	kg	kilograms	2.202	pounds	lb
Mass	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
Temperature (exact degrees)	oC	Celsius	1.8C+32	Fahrenheit	oF
Illumination	lx	lux	0.0929	foot-candles	fc
Illumination	cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
Force and Pressure or Stress	N	newtons	0.225	poundforce	lbf
Force and Pressure or Stress	kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

For More Information see: <https://www.fhwa.dot.gov/publications/convtabl.cfm>

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1.0 LITERATURE REVIEW

1.1 PROBLEM STATEMENT

Horizontal drains stabilize unstable slopes by decreasing the quantity of water in the ground. These drains are the only practical method for mitigating excessive slide movement for many of the large landslides impacting ODOT infrastructure. Effective design and performance criteria are limited for horizontal drains, resulting in rare delivery of Operations and Maintenance (O&M) manuals and associated budgets to Maintenance teams who are ultimately responsible for their upkeep. Frequently, drain systems are installed with limited means of estimating or measuring how long they will effectively function. Maintenance of horizontal drains is critical for maintaining the integrity of these landslide mitigation systems. Without maintenance, these systems will cease to function, and excessive slope movement will resume. To ensure long-term slope stability and driver safety on ODOT right-of-way, development of drain design criteria to inform maintenance operations and projected design life is essential.

The timing and extent of repair and maintenance of horizontal drains is currently an arbitrary process that requires use of expensive equipment, creation of access roads, highway closures, and a cleaning process that could potentially impair drain function if improperly performed. Without an understanding of long-term performance of horizontal drains with an associated maintenance plan, progressive loss of function could lead to potential failure of the hillslope—resulting in loss of connectivity, impaired driver safety, and the expensive removal of large quantities of debris. Using recent advances in landslide drain monitoring systems, such as discharge weirs and flowmeters, together with precipitation, piezometer and groundwater data, drain performance can be measured, modeled, and predicted. This research will leverage existing ODOT data and sponsored research (SPR807 and SPR808), including extensive drain data from ODOT’s Pioneer Mountain-Eddyville (PME) project, together with targeted instrumentation of horizontal drains and evaluation of maintenance records to generate horizontal drain design and performance criteria, which will in turn be used to inform maintenance schedules and methodologies. Horizontal drains stabilize unstable slopes by decreasing the quantity of water in the ground. These drains are the only practical method for mitigating excessive slide movement for many of the large landslides impacting ODOT infrastructure. Effective design and performance criteria are limited for horizontal drains, resulting in rare delivery of Operations and Maintenance (O&M) manuals and associated budgets to Maintenance teams who are ultimately responsible for their upkeep. Frequently, drain systems are installed with limited means of estimating or measuring how long they will effectively function. Maintenance of horizontal drains is critical for maintaining the integrity of these landslide mitigation systems. Without maintenance, these systems will cease to function, and excessive slope movement will resume. To ensure long-term slope stability and driver safety on ODOT right-of-way, development of drain design criteria to inform maintenance operations and projected design life is essential.

1.2 BACKGROUND

1.2.1 Introduction to Landslides

Landslides are driven by a variety of disturbances, including seismic activity, in-situ weathering of soil and rock, and predominantly, precipitation. Landslides and subsequent mass movement of soil and rock on slopes occurs all over the world leading to loss of life and destruction to property and infrastructure (Froude and Petley, 2018; Petley, 2012). The international Disaster Database (EM-DAT) suggests that between 1990 and 2015 landslides were 4.9% of all natural disaster events and 1.3% of all natural hazard fatalities and that 54% of all of these events occurred in Asia (Froude and Petley, 2018; Guha-Sapir et al., 2015). However, the impact of landslides on society has been underestimated by global multi-peril databases (Froude and Petley, 2018). The number of fatal landslide events has been underestimated in EM-DAT database by ~2000% and fatalities by 430% between 2004 and 2010 (Petley, 2012). The most important reason for this underestimation is the perception of landslides as a secondary hazard, often being incorporated into larger primary hazards such as earthquakes, wildfire, and heavy rainfall rather than actual cause of death (Froude and Petley, 2018). Consequently, many landslide fatalities are classified as being the result of an earthquake or other larger hazard, with landslide fatalities and human losses underestimated (Kjekstad and Highland, 2009; Petley, 2012). Beside damages, injuries, and fatalities, landslide events may sever critical infrastructure, causing long term economic disruption (Geertsema et al., 2009; Highland and Bobrowsky, 2008). In Oregon, landslides cause highway closures every year, resulting in impacts to commerce, particularly in isolated communities directly reliant on limited routes for access.

Landslide processes can be categorized based on the types of movement (flows, topples, slides, spreads, and deformations), velocities of movement (<16 mm/year to >5 m/s; (Hungr et al. 2014)), and the hydrological and geomechanical processes acting upon landslide materials (Whiteley et al. 2019). Based on geographically collected datasets, more than 90% of landslides are unevenly distributed as: flows (40%, especially debris flows and earth flows), slides (33%, mainly rock slides, rotational and translational slides), and rock avalanches (22%). Only a few percent of mass movement cases are deep-seated gravitational slope deformation and rock falls and topples (Pánek, 2019).

Human activities can initiate destabilization processes, including activities such as: disturbing or changing drainage patterns, destabilizing slopes, removing vegetation, draining reservoirs, leaking pipes, and improper excavating or grading on slopes (Highland and Bobrowsky, 2008). However, natural causes commonly induce destabilization, including seismic events, progressive toe erosion from wave runup or river scour, and heavy rainfall, which may be more widespread due to global climate change (Highland and Bobrowsky, 2008; Leshchinsky et al., 2019). These failures are further intensified by adverse geological conditions (e.g. bedding planes, weak seams and weathering) (Anbalagan, 1992). Significant studies were performed to characterize and evaluate the destabilizing effects of seismic events (Hess et al., 2017; Li et al., 2019; Liang and Knappett, 2017; Newmark, 1965; Zhao et al., 2017), human activities such as construction (Stark et al., 2005; Luo et al., 2019; Shuo et al., 2020; Wang et al., 2014), and more recently heavy rainfalls (Damiano, 2019; Fan et al., 2017; Greco et al., 2019; Piciullo et al., 2017). Other factors such as weathering, erosion, hydrological changes, and human activities are difficult to measure, but their influence on stability of slopes is fundamental to assessing landslide activity.

1.2.2 Landslides Climatic and Geological Drivers

Slope failure occurs when the effective friction and cohesion of the weak section of the soil or bedrock is insufficient in resisting gravitational shear stresses, generally most problematic from increases in groundwater levels or seismic excitation. A traditional measure for the stability of the slope is expressed as the ratio of resistance parameters of the soil or bedrock to driving shearing force, factor of safety, FS:

$$FS = \frac{c + \sigma' \tan \varphi}{\tau_{dr}} \quad (1.1)$$

where c is cohesion, σ' is the effective normal stress, θ is the failure plane angle, φ is the angle of internal friction of the failure plane material, and τ_{dr} is the mobilized shear stress. When FS becomes less than one, failure occurs. Instability can be triggered frequently by seismic, climatic, and geological forcing conditions and cause different types of movements (e.g. rotational or translational slide). Horizontal drains are typically used to stabilize failures driven by climatic conditions (e.g. precipitation or snow melt).

Climatically triggered landslides have recently been more widespread due to global warming influence on precipitation, snow melt, and temperature (Crozier, 2010; Dhakal and Sidle, 2004; Gariano and Guzzetti, 2016). Increase in total precipitation results in potentially higher groundwater levels, reducing shear resistance and increasing the weight of the slope materials making slope instability more probable (Tacher and Bonnard, 2007). More abundant precipitation may increase river discharge resulting in erosion of the river banks and removal of basal slope support and potential slope instability (Gariano and Guzzetti, 2016). Another impact of increase in rainfall intensity is higher infiltration (decrease in matric suction and shear strength of the soil) and subsurface drainage, that contributes to buildup of perched water tables, soil piping (Jones, 2010), erosion (Verachtert et al., 2011) and surface runoff that initiates debris flow and enlargement (Hung et al., 2005; Iverson et al., 2011). On the other hand temperature increase may result in more stable slopes through more evapotranspiration (Gariano and Guzzetti, 2016; Senatore et al., 2011). However, with increased climate variability the likelihood of extreme precipitation events increases, and with an intense short-duration rainfall, the infiltration of water in upper layers may cause shallow landslides (Rahardjo et al., 2001, 2011).

Geological factors including composition, structure of the soil and underlying bedrock, rock weathering, and clay mineralogy often control the geometry and deformation of slope instabilities. Weak or sensitive, weathered, sheared, jointed or fissured materials, adversely oriented discontinuities (bedding, schistosity, fault, unconformity), and contrast in permeability and/or stiffness of materials are amongst geological landslide drivers (Von Huene et al., 2016). Geological condition of the deposits and bedding govern the geometry of the slip surface in a way that the presence of bedding planes, weak seams, or old sliding surface can create circular, spiral shaped, straight, or combination of various failure surface shapes. Also, high pore water pressures in sand or silt seams can cause translational failures in clays, especially if the seams dip toward an excavation. Sloughing may be a further problem if the seams are exposed at the toe of the slope (Fang, 2013). In addition to adverse bedding conditions, localized discontinuity

in rocks, which result in reduction in shearing resistance and consecutive modification in shape and size distribution of particles, change the mechanical behavior of the rock material, and hence, are likely responsible for long-term changes in creep movement (Federico et al., 2012; Lebourg et al., 2011; Pánek and Klimeš, 2016). Subcritical crack growth in rocks without pre-existing discontinuity (Brueckl and Parotidis, 2001), repeated changes in groundwater pressure (Vallet et al., 2016), and weathering are among other reasons for strength reduction in rocks and changing fracture properties of rock mass (Lebourg et al., 2011; Pánek and Klimeš, 2016). Landslides themselves can introduce disturbances and may have impact on potential landslide reactivation or recurrence in the same location (Mirus et al., 2017). There are many reasons for a landslide to be reactivated in the same location where steep convergent topography is a well-known contributor as pore pressure buildup evacuates colluvium-filled bedrock hollows (Ebel et al., 2008; Montgomery and Dietrich, 1994; Wu and Sidle, 1995). Another possible landslide recurrence is wave action or bank erosion that can undermine the toe of previous landslides (Ebel et al., 2008; Montgomery and Dietrich, 1994; Wu and Sidle, 1995). Also, abrupt disturbances in subsurface properties by wildfire, deforestation, earthquake, or volcanic eruptions can alter porous media properties, resulting in hydrological storage capacity and flow path connectivity changes that enable catastrophic future failure (Ebel and Mirus, 2014; Mirus et al., 2017).

1.3 LANDSLIDE MITIGATION

Landslide hazard is a function of site characteristics (topography, geology, drainage), type of activity, and frequency of past landslides. Avoidance of construction on hazardous steep slopes is the simplest method to prevent landslides. However, avoidance is not always a possible solution, and appropriate mitigation techniques must be determined based on the controlling process that is causing instability for the slope to reduce its effects. Excavation and unloading, strengthening the slope (such as plastic mesh reinforcement, rock-fill buttresses, anchors, piles), installing retaining structures, stabilization using vegetation, and biotechnical protection are common landslide mitigation techniques. Drainage systems are critical mitigation techniques as groundwater is the most important contributor to landslide initiation. Drainage can be either surface or subsurface. Surface drainage design prevents erosion and infiltration of water into soil and requires minimum cost and effort. Subsurface drainage design and installation is relatively expensive and requires thorough study of slope conditions to identify groundwater as the main cause of landslide (Highland and Bobrowsky, 2008).

1.4 HORIZONTAL DRAINS

Since the presence of water in hillslopes is a major problem contributing to slope failure, draining water is a common solution to improve stability. Installation of horizontal drains decreases the elevation of the water table surface and reduces pore water pressure (i.e. increases shear strength of the soil). This method is beneficial due to its rapid implementation and generally being less expensive than other methods. However, in comparison to other stabilization methods, there are limited design approaches available for drain systems and their lifecycles are often overdesigned or designed qualitatively. Another issue is the lack of information regarding the long-term performance of drains where efficiency can be reduced with siltation and sediments, thus requiring frequent maintenance (Carroll and Badger, 2013; Kleppe, 1984; Weng Long et al., 2017).

The effectiveness of horizontal drain systems is governed by several factors like soil/rock type, slope geometry, drain type, location, number, length, and spacing (Martin et al., 1994; Prellwitz, 1978; Rahardjo et al., 2011). Long-term drain functionality is also affected by clogging of the pipe by soil sediments which can reduce drain efficiency and increase the risk of slope failure (Weng Long et al., 2017). Monitoring and evaluation of long-term behavior may improve existing design and maintenance procedures.

One important factor of consideration is the response efficiency of horizontal drain systems to short duration high-intensity rainfall and how fast drains can reduce the pore water pressure in the slope. In unsaturated and residual soils, matric suction in the surface of the soil can become as high as 100 kPa resulting in higher shear strength. Following a heavy rainfall the shear strength of the soil will be reduced, with shallow landsliding as a possibility (e.g. Brand, 1995; Liew et al., 2004). Using a numerical finite element analysis, modeling of horizontal drain efficiency for lowering groundwater levels due to infiltration of rainfall into the slope was investigated by Rahardjo et al. (2011). It has been shown that the factor of safety of the slope with horizontal drains is higher at all times than a slope without drains. In this study the piezometers, tensiometers and inclinometers installed in the slope to monitor the groundwater level, matric suction, and movement of the slope with the horizontal drains demonstrated good agreement with the numerical model for controlling slope stability (Rahardjo et al., 2011). However, while the general effectiveness of horizontal drains was investigated by numerical modeling and field data, the influence of each parameter controlling drain performance such as the drain size, drain spacing, etc., is still poorly characterized.

Critical parameters of drains including configuration, arrangements, and filters that can affect drain efficiency were studied in a small-scale experimental design (Weng Long et al., 2017). In this experiment, rainfall was introduced to a model box of 0.8m*0.8m*0.6m homogenous soil with horizontal drains oriented at 5 degrees from the horizontal. An HDPE pipe was placed with center-to-center spacing of 70 mm and was covered by a geotextile and filter material around it and in addition to another material with larger opening over the filter. Weng Long et al. (2017) found that sediment discharge was limited in most experiments, but most notable in lateritic, fine-grained soils. Further, wrapping drains in a geotextile reduced sediment discharge in all cases. However, the drains assessed do not necessarily represent typical design conditions used in practice.

The efficiency of horizontal drains has also been studied through case studies such as a shallow landslide caused by typhoon Morakot along Shangyu-Sanmen express highway in Zhejiang, China. Field monitoring data and software modeling by GeoStudio indicated the important role of horizontal drains in slope stabilization. In this study, the effect of drains was obtained during and after rainfall. The results showed that the factor of safety was recovered for both the original slope and slope with horizontal drains for the first three hours and then the increase slowed down over the next 36 hours. The factor of safety for the slope with horizontal drains was 21.5% higher than original condition (Tang et al., 2011). Three hours after the rain stopped the calculated discharge rate from one drain was 88.83 L/h and the monitored discharge rate was 66.67 L/h. Afterward the discharge rate decreased gradually and calculated discharge rate was faster than the monitored rate, but still the values were on the same level. After 36 days of draining, the monitored flow rate was 27.08 L/h and calculated flow rate was 23.29 L/h (Tang et al., 2011, Figure 3 within publication).

Cai et al. (1998) performed three-dimensional elasto-plastic shear strength reduction finite element method analysis to investigate the effect of horizontal drains on slope stability during rainfall. Three sets of van Genuchten model parameters of hydraulic characteristics for the Glendale clayey loam (GCL) (Ugai and Leshchinsky, 1995), the Uplands silty sand (USS) (Russo and Bresler, 1980), and the Bet Degan loamy sand (BLS) (Staple, 1969) were chosen for modeling. The changing parameters under study were drain length, spacing, and direction. Spacing and length of the drains were found to be critical design parameters for drain efficacy. When the length of the drain is 7.5 m, slope stability exhibits a limited increase with close drain spacing. However, when the length of the drain increases (e.g. $L = 15$ m) the effect of smaller spacing is more pronounced and stability increases more significantly. They found an interplay between drain length and spacing, suggesting that length may be a more critical factor, but spacing between drains became more important with longer drains.

Rahardjo et al. (2003) performed a numerical study using Seep/W to investigate the significance of drain location within a slope profile. The drains were located at three different heights in the slope, one at top, one at the middle, and one at the toe. They concluded that the least beneficial location is at the top and the most beneficial location was at the toe. When all three conditions are combined, only a 3% increase in factor of safety was observed compared to the condition of only the drain at the bottom. The reason for this is the bottom drain removes the most water in the system (Rahardjo et al., 2003). When the three drain locations are used, the top and middle zone show approximately two orders of magnitude less flow than the bottom drain. This again demonstrates that drains at lower elevations tend to be most efficient for dewatering and maintaining the stability of the slope (Rahardjo et al., 2003). There is no discussion of long-term drainage performance, however.

To analyze horizontal wells (drains) temporally three components should be assessed: (a) the flow process within the aquifer, (b) flow from the aquifer into the horizontal well, and (c) the hydraulic condition in the horizontal well (Mohamed and Rushton, 2006). As the wells distribute fluid by perforations in different sections of the pipe, the discharge, head loss and pressure distribution of perforated pipes are different from non-perforated pipes (Liu et al., 2017). Many horizontal well analytical studies seek for solutions using constant head or uniform flux boundary while hydraulic condition within the pipe is largely ignored (Mohamed and Rushton, 2006). The hydraulic condition within the pipe is crucial in the study of design of horizontal wells for slope stabilization because siltation and clogging of the pipe are serious problems affecting the service life of the drain and can result in catastrophic damage to infrastructure due to lack of serviceability with time. The hydraulic behavior of perforated pipes has been studied by many researchers such as Siwoń (1987) and Kirkkala et al. (2012), though study on discharge characteristics and spatial and temporal groundwater drawdown is still limited. One widely used method in the literature is proposed by Hooghoudt (1940) in which spacing between two parallel drains is simply specified by an expression based on the Boussinesq equation and Dupuit-Forchheimer (DF) assumptions (Shokri and Bardsley, 2015). To obtain a solution for non-steady state moving water table above the drains based on the Hooghoudt equation, Youngs (1985) proposed a more convenient approach based on specific yield assuming a continuous succession of steady states. However, it is not as accurate as the exact solution that can be achieved by numerical techniques.

By considering each slot on the pipe as a pumping point source, a semi-analytical solution was developed to investigate the drawdown in both horizontal and slanted wells in an unconfined anisotropic aquifer (Samani et al., 2006; Zhan and Zlotnik, 2002) and an analytical solution for the same problem for confined aquifer (Zhan et al., 2001). The fully three-dimensional solution derived equations for instantaneous drainage and delayed yield in Laplace domain. Numerical Laplace inversions made it possible to obtain results of drawdown in real time which indicated three stages in type curves: rapid increase at early time, middle flat stage, and rapid increase in later timepoints (Zhan and Zlotnik, 2002). Zhan and Zlotnik (2002) solved this equation first for the point source problem and then integrated the solution along the well axis to calculate the solution for horizontal or slanted wells.

A horizontal drain can be defined as a horizontal well on the periphery of which the head or drawdown is uniform and steady (Samani et al., 2006). Samani et al. (2006) proposed a drain as a uniform flux well in a way that the total flow to the uniform flux well is equal to total flow rate to the drain in order to make the problem computationally cheaper than assuming spatial and temporal distribution of flow along the drain. By modifying Zhan and Zlotnik (2002) solution for horizontal wells in an unconfined aquifer and Rosa and Carvalho (1989) solution for finite length uniform head horizontal wells to predict the total flow rate, Samani et al. (2006) obtained the Laplace domain solution for a horizontal drain. Similar to the results of horizontal wells, the drawdown curves of horizontal drains in unconfined aquifers have three parts: first, increase of drawdown with time; second, constant drawdown with time; and third, increase again of drawdown with time (Samani et al., 2006). The difference between first and last stage is the controlling mechanism of discharge which is storativity, S_s , and specific yield, S_y , respectively (Samani et al., 2006).

Another important factor necessary for long-term design of horizontal drains is the change of discharge rate during design life. Discharge is not only affected by the groundwater level above the drain but also the cross-section variation of the pipe due to siltation. Based on the groundwater drawdown, Samani et al. (2006) calculated the discharge from horizontal drains. Similar to drawdown curves, the discharge showed three stages including steep decrease at the beginning, intermediate horizontal decrease, and again decrease in slower rate for the later time period. This descending slope at the late time is due to the reduction in difference between the head level and groundwater level (Samani et al., 2006). The semi-analytical method of Samani et al. (2006) can provide an accurate three-dimensional water table surface, drain discharge, and aid in stability analysis and design of size and length of drain arrays. However, this method can become complicated and computationally expensive when an array of drains is simulated.

One of the most critical issues for designing the horizontal drains is when and where sedimentation inside the pipe occurs and consequently the time required before the drain can no longer convey water due to sedimentation and clogging. In order to have guidelines for drain maintenance to ensure continuous water yield, it is crucial to know how suspended soil particles in the flow of water move and settle and evaluate the possibility of particle transportation after settlement. Therefore, the problem first consists of analysis of suspended particle transport and settlement, followed by bedload transport analysis along the pipe or entrainment of sediment into suspension at the solid-fluid interface. Upon drain installation the surrounding soil will be washed out by flow of water entering the holes and bringing cohesive and noncohesive suspended particles inside the pipe. Several factors are effective on a pipe flow of suspension,

such as properties of the particle (size, density, etc.), properties of the fluid, parameters of the fluid, turbulence, gravity effect, inclination of the pipe with respect to direction of gravity, electric charges, etc. (Soo and Tung, 1971). Electric charge effects are more prominent in gas particle suspension in pipe flow, and their effects are not significant in sand in water that is mostly controlled by gravity and flow regime (Soo and Tung, 1971). Based on the flow regime (laminar or turbulent), the distribution of particles inside the pipe is different (Soo, 1969). Soo and Tung (1971) categorized particle transport by turbulent fluid in three states: (a) dilute suspension in which particle spacing are at least two diameters, resulting in unaffected fluid motion by the presence of particles, (b) the state that particle spacing is about one diameter, the perturbation of fluid motion by particles cannot be neglected, but steady flow is still possible, and (c) the state whereby particle density is such that packed bed can occur both by electrostatic effect, or gravity, or both; whereby transport can be a result of repeated formation and blowing away of deposition or traveling dunes, so that steady flow is no longer possible.

In order to predict the spatial and temporal accumulation of sediments in pipes, a mass conservation equation of suspended sediments of noncohesive uniform size and constant material density in turbulent flow can be used to simply solve the question (Garcia and Parker, 1991). This equation, which is similar to advection equation, is valid only for dilute suspensions (i.e. concentration $\ll 1$) of particles that are finer than 0.5 mm (Garcia and Parker, 1991).

$$\frac{\partial c}{\partial t} + \frac{\partial F}{\partial x} = 0 \quad (1.2)$$

That c is the volume suspended sediment concentration and F is a function of averaged turbulent fluid velocity and turbulent fluctuations. Although solving this equation shows consistency with experimental results, it does not include source and sink points; which in reality for horizontal drains, several holes along the pipe length act as source points for incoming volume of particle concentration.

Advection is an appropriate physical process for many problems such as transport of pollutants (Bernard et al., 2006; Horvat et al., 2015; Zamani and Bombardelli, 2014) and disciplines of oceanography (Di Lorenzo et al., 2013; Rypina et al., 2010). Corrigan et al. (2020) solved 1D and 2D advection equations both numerically and analytically with spatially varying velocity field. They suggested an exact solution based on a simple transformation for the case of a linearly varying velocity field which is:

$$\rho(x, t) = \frac{1}{(1 + ktx)^2} \quad (1.3)$$

Where ρ is density and k are some constant. Multiple combinations of initial density and initial velocity were compared to numerical solutions and showed that methods with slope limiting techniques are most applicable for an accurate solution for most cases (Corrigan et al., 2020). Having an analytical solution to advection equation is advantageous, making the calculations

more accurate and easier. However, adding sink and source points with different locations along the pipe, and different densities of particles entering the system from each, will make the analytical solution not desirable, in which case the numerical solution will be the only option. Therefore, the general form of the advection equation can be:

$$\frac{\partial c}{\partial t} + \frac{\partial(uc)}{\partial x} = Q(x, t) \quad (1.4)$$

Where $Q(x, t)$ indicates the flow of water with specific concentration of material as function of location and time. In order to calculate the volume of particles settled at each time step a trajectory of particles can be used. A theoretical model was suggested by Fadel and Baumann (1990) to explain the performance and a design guideline developed for tube settlers in sedimentation facilities. Based on this model, a particle settles based on the ratio of particle settling velocity, flow velocity and inclination of the pipe (Fadel and Baumann, 1990). This method will be further discussed in methodology section.

1.5 OPPORTUNITIES AND CURRENT LIMITATIONS

Repairs of landslides are expensive, require road closures and delays, and may require extensive instrumentation and extended periods of monitoring. More quantitative, generalizable means of designing horizontal drains and understanding long-term drain performance would help reduce repair times, delays, and expense associated with installation and maintenance. As reviewed above, literature on horizontal drains is limited, and there is very limited information regarding long-term performance. By adding inexpensive weir systems to the numerous, expensive drain arrays already being used for landslide repairs, designers may better ensure that drain design is sensibly conservative, and most importantly – effective. To monitor the efficiency and lifecycle of each drain individually, a monitoring system and database would be required to measure the outflow consistently and compare changes due to seasonal groundwater level variation or siltation and clogging inside the pipe.

The monitoring system may include discharge weirs, flowmeters, piezometers, thermometers (measuring outflow temperature), and turbidity sensors. Together this quantitative data assists in designing and capturing long-term performance. Using inexpensive monitoring systems in various field conditions, improved guidelines can be a basis for decision making regarding maintenance schedules for enhanced long-term efficiency. This can reduce the need for unnecessary closures of highways and roads, facilitate improved objective allocation of maintenance resources, and preclude the worst outcomes - failure of the drains and catastrophic slope failure.

2.0 METHODOLOGY

2.1 GROUNDWATER DRAWDOWN MODEL

2.1.1 Transient Drawdown

The drawdown of drain systems is considered using Darcian flow in three dimensions. In order to characterize drawdown, the continuity equation is considered, where:

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} = 0 \quad (2.1)$$

where h is total hydraulic head and is $h = h_p + h_e$, where h_p and h_e are pressure and elevation head, respectively; K_x, K_y and K_z are hydraulic conductivity of the soil in x, y and z directions, respectively. The given hillslope domain is considered as a slope with length L_y , a width between drains of S , and an aquifer thickness H . Symmetric boundary conditions are considered for a single drain to reflect the influence of multiple drains that are approximately parallel. While many drain systems are installed in a fan shape, this approximation is reasonable considering the relative length of the drain systems and their general proximity to one another. The aquifer is considered to be in a slope-parallel flow condition at an angle β from the horizontal. A schematic of the domain is shown in Figure 2.1.

The boundary conditions of the problem are a fixed head condition at the toe of slope and a steady recharge flux at the upper boundary. The recharge boundary condition at the head of the slope is determined as a back-calculated constant recharge rate necessary to keep the steady state, slope-parallel flow conditions in the absence of a drain and may be calculated as:

$$Q \sqrt{(K_z \sin \beta)^2 + (K_y \cos \beta)^2} \frac{\partial h(x, L_y, z, t)}{\partial y'} \Big|_{Re} \quad (2.2)$$

where Q_{Re} is recharge rate; and $\partial y'$ is the corrected form of ∂y which is defined as:

$$\partial y' = \sqrt{(\partial y \tan \beta)^2 + \partial y^2} \quad (2.3)$$

The recharge flux and steady state groundwater head obtained at this step are used as boundary and initial conditions, respectively, prior to the next step where the drain is added to the system.

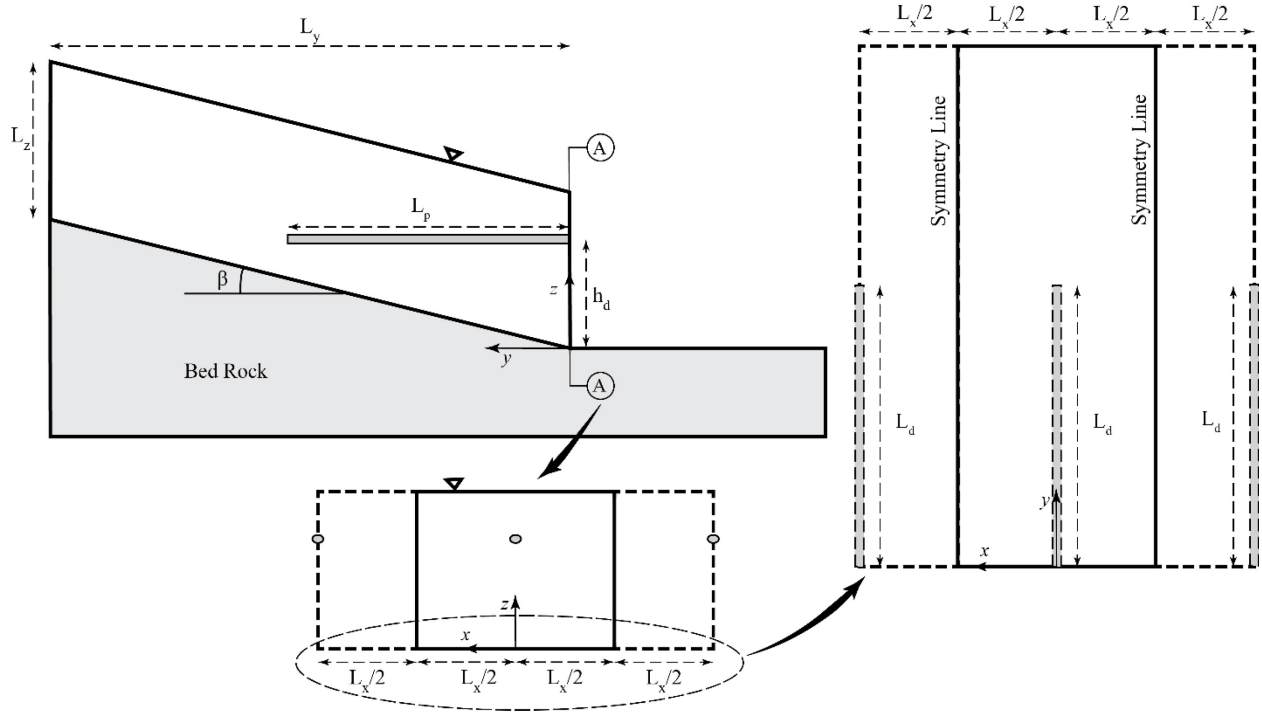


Figure 2.1. Schematic of domain considered for drawdown analyses.

2.1.2 Flow to Drains

Upon drain installation, there is a transient gravity-driven drawdown behavior that manifests as a decrease in head (specifically pressure head) that is a function of drain geometry and placement. Upon modeling drawdown from parallel drains, drawdown conditions are considered for a horizontal drain with length L_p that is located at the center of the xy plane (Figure 2.1). The physics governing transient drawdown are the three-dimensional nonlinear transient groundwater flow equations for an anisotropic, unconfined aquifer, presented in most general form as:

$$S_s \frac{\partial h}{\partial t} = K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} + Q \quad (2.4)$$

the initial condition which is obtained from the steady state condition prior to installation is:

$$h(x, y, z, 0) = h_0 \quad (2.5)$$

where no-flow impermeable boundary conditions at the base are considered as:

$$\frac{\partial h(x, y, 0, t)}{\partial z} = 0 \quad (2.6)$$

and an instantaneous drainage boundary condition is considered at the top of the aquifer as:

$$K_z \frac{\partial h(x, y, L_z, t)}{\partial z} + S_y \frac{\partial h(x, y, L_z, t)}{\partial t} = 0 \quad (2.7)$$

The boundary condition at the toe of slope is a fixed head condition similar to that used to determine initial steady state conditions in absence of a drain as:

$$h(x, 0, z, t) = z_{drain} \quad (2.8)$$

and similarly, a recharge boundary condition at the top of the slope that would maintain slope-parallel, steady-state flow in absence of a drain as:

$$\frac{\partial h(x, L_y, z, t)}{\partial t} = Q \sqrt{(K_z \sin \beta)^2 + (K_y \cos \beta)^2} \frac{\partial h(x, L_y, z, t)}{\partial y'} \quad Re \quad (2.9)$$

where t is time; h_0 is initial head; Q is pumping rate (considered to be zero for gravity-driven drawdown). The domain dimensions are L_x , L_y and L_z in x , y and z directions, respectively; S_s is specific storage; S_y is specific yield; z_{pipe} is vertical distance of the drain from the bottom boundary; and Q_{Re} is the recharge rate obtained from previous step. Groundwater is drawn into the drain through perforations on the periphery of the pipe by gravity and a gradient in pressure. The volume of groundwater flowing into the drain is dependent on the elevation of the drain and the head surrounding it. Thus, a boundary condition of fixed elevation head based on the location of the drain is chosen to represent the drain in the system as:

$$h(x_d, y_d, z_d, t) = h_{ed} \quad (2.10)$$

where x_d , y_d and z_d represent spatial location of perforations on the drain with respect to the origin; and h_{ed} is elevation head of the drain perforations. It should be noted that for simplicity the head loss due to entrance resistance is neglected in this analysis, as it is unlikely to have a large effect for closely-spaced drains under long-term conditions. As the drains tend to be installed in arrays with different layouts, the two lateral boundaries that are parallel to drain length are considered symmetrical, thus reflecting uniform spacing of distance S . Hence, the

boundaries represent drawdown not only due to the drain located at the center of the domain but also reflect a virtual drain located at the same distance from the side boundary as the one actually considered in the model.

The inflow rate of discharge entering the drain through each perforation can be calculated through evaluating head at each time step and perforation size. The following equation reflects discharge into the drain at a given node:

$$Q_{in} = \sqrt{(K_x i_x)^2 + (K_y i_y)^2 + (K_z i_z)^2} A_{perf} \quad (2.11)$$

where A_{perf} is the perforation area; and i_x , i_y , and i_z are hydraulic gradients in x , y and z directions, respectively, as follows:

$$i_x = \frac{\partial h(x_d, y_d, z_d, t)}{\partial x} \quad (2.12)$$

$$i_y = \frac{\partial h(x_d, y_d, z_d, t)}{\partial y} \quad (2.13)$$

$$i_z = \frac{\partial h(x_d, y_d, z_d, t)}{\partial z} \quad (2.14)$$

Total outflow to the drain can be obtained by summation of the discharge from each perforation along the drain length.

Applying a forward time central space method of discretization of finite difference approach to Equation (2.4), the partial differential equation of 3D transient groundwater is solved numerically. A constant uniform spatial discretization was chosen for all dimensions to approximate the changes in total head for each time step. Time steps were limited to a calculated minimum based on spatial discretization and hydraulic conductivity to maintain numerical stability (e.g. a Courant number). To simplify the number of dimensions that need to be evaluated for generating output results, domain geometry, soil properties, and time can be made dimensionless. Through dimensionless parameters, type curves can be derived to provide specific solutions. Considering d as the thickness of the aquifer, the dimensionless parameters are defined as:

$$L_{xD} = \frac{L_x}{d} \quad L_{yD} = \frac{L_y}{d} \quad L_{zD} = \frac{L_z}{d} \quad h_d = \frac{h}{d} \quad L_{pD} = \frac{L_p}{d} \quad (2.15)$$

$$T_D = \frac{K}{S_s d^2} t \quad (2.16)$$

$$K = (K_x K_y K_z)^{\frac{1}{3}} \quad (2.17)$$

$$Q_D = \frac{Q_{in}}{K d^2} \quad (2.18)$$

where subscript “D” indicates dimensionless form of their corresponding counterparts introduced previously.

2.1.3 Drawdown Effects on Slope Stability

To evaluate changes in stability stemming from drawdown, the mobilized friction angle is evaluated for the duration of the drawdown phase. By calculating the total head in the previous step and knowing elevation head at all locations, pore water pressure can be translated to a three-dimensional slope stability analysis, reflecting increased effective stresses and consequently decreased mobilized friction. As the cone of depression from drawdown is inherently three-dimensional, particularly at wider drain spacing, a three-dimensional stability analysis provides a more realistic and potentially conservative estimate of overall increased slope stability. To perform three-dimensional slope stability analyses, we use the force equilibrium method proposed by Hung et al. (1989) and shown in Figure 2.2, defined as:

$$F = \frac{\sum (cA \cos \alpha_y + (N - uA) \tan \phi \cos \alpha_y)}{\sum N \cos \gamma_z \tan \alpha_y + \sum kW + E} \quad (2.19)$$

where F is the factor of safety; c is soil cohesion; A is true base area; α_y inclination of sliding surface; u is pore water pressure; ϕ is friction angle; γ_z is the local dip of the sliding block; k is horizontal earthquake acceleration; W is the total weight of the sliding block; E is the resultant of all horizontal components of applied point loads; and N is normal force acting at the base of the block and is derived from vertical force equilibrium as:

$$N = \frac{W - \frac{cA \sin \alpha_y}{F} + \frac{uA \tan \phi \sin \alpha_y}{F}}{m_\alpha} \quad (2.20)$$

where $m_\alpha = \cos \gamma_z \left(1 + \frac{\sin \alpha_y \tan \phi}{F \cos \gamma_z}\right)$. The mobilized friction angle, ϕ_{mob} , is then

calculated for every time step by implementing the pore water pressure obtained in previous step and setting factor of safety to 1. A more detailed description of the three-dimensional slope stability analysis can be found in Hunger et al. (1989). Neglecting cohesion, which is reasonable for active landslides in a residual state, the time-dependent factor of safety of the slope owing to drawdown can be described as:

$$F(t) = \frac{\tan(\phi)}{\tan(\phi_{mob}(t))} \quad (2.21)$$

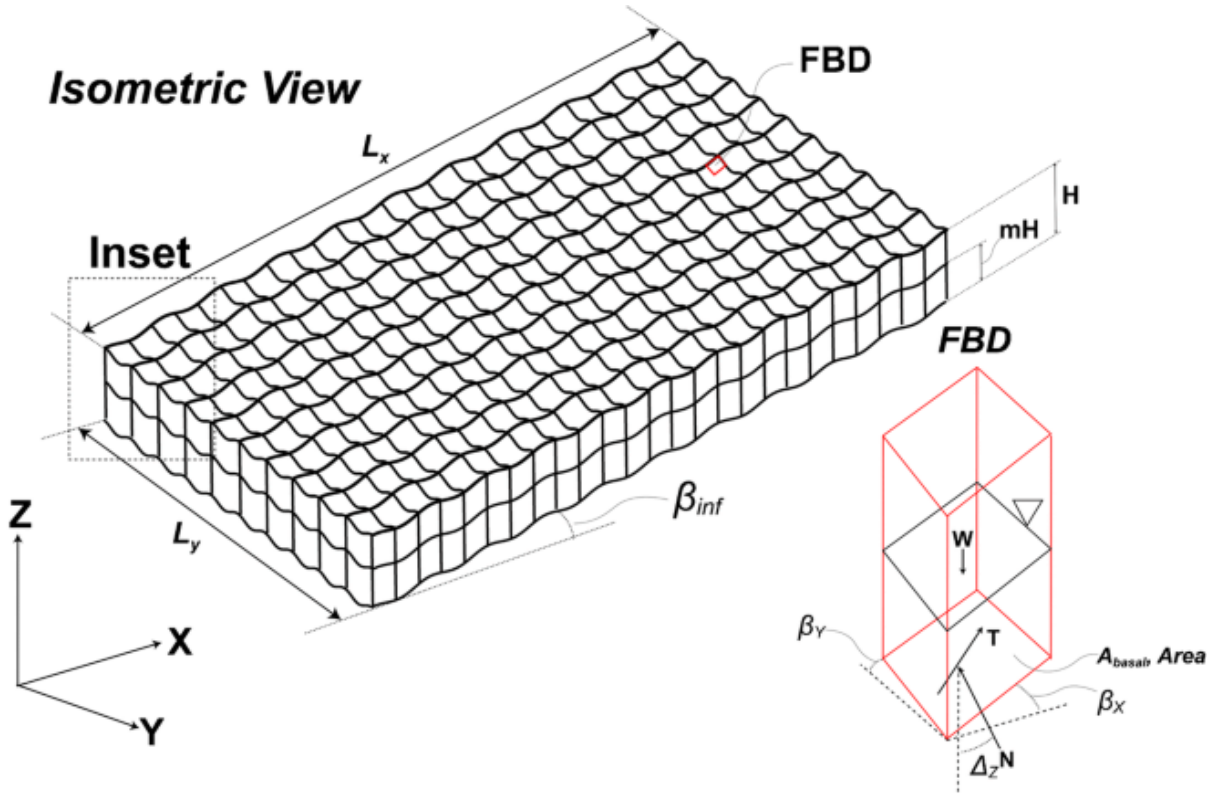


Figure 2.2. Schematic of ‘method-of-columns’ approach to slope stability used to characterize three-dimensional increase in transient slope stability from horizontal drain installation. The aquifer thickness is a proportional height of mH .

2.2 PREDICTIVE MODEL OF DRAWDOWN

Numerical solutions could potentially incur high computational costs, therefore having a predictive model for estimating drawdown for simple site conditions likely has value. For convenience, we have developed a regression technique using Artificial Neural Networks (ANN) to estimate the transient drawdown resulting from horizontal drains, for any drain and aquifer conditions of interest. It is important to highlight that Artificial Neural Networks (ANN), a supervised machine learning algorithm, are employed here for the classification of drawdown, as modeled through the proposed numerical methodology in this particular project.

ANNs are made up of artificial neurons arranged in a specific pattern, with the most common and preferred structure being the Multi-Layer Feed-forward NN, which consists of one input layer, one output layer, and one or more hidden layers between the input and output layer. The number of neurons in the input and output layer is determined by the application, whereas the number of hidden layer neurons are decided by trial and error (Gong, 1996). Data provided to the input layer is multiplied by connection weights and summed to derive the net input for the next layer's neurons. An activation function is then applied to approximate the neuron's output as well as to provide non-linearity, thresholding, and differentiability. The optimization of connection weights is defined as learning or training, and it is achieved by updating the weights to minimize the error between the predicted output and actual output through backpropagation. The connection weight with the least error is stored as the weight for the inputs of the dataset being processed, and the NN is considered as trained. The trained NN will be tested with another dataset of known output to assess the generalization capability. If the testing accuracy is acceptable, the obtained weights can be used to simulate the output of an unseen dataset. In this analysis, the Rectified Linear Unit (ReLU) has been chosen as the activation function and the gradient descent algorithm has been considered as the back-propagation algorithm considering the regression nature of the problem.

The ReLU activation function can be expressed as:

$$O_j = \varphi(\text{net}) = \max\left(0, \sum_{i=1}^n w_{ij}x_i + b_j\right) \quad (2.22)$$

where O_j is the output of the j th neuron; $\varphi(\text{net})$ is ReLU activation function; w_{ij} is the weight connecting the i th input to the j th neuron; x_i is the i th input value; b_j is the bias term for the j th neuron; and N is the total number of input values. The gradient decent algorithm can be expressed as:

$$\mathbf{w}_{\text{new}} = \mathbf{w}_{\text{old}} + \Delta \quad (2.23)$$

$$\Delta w = -\eta \times \left(\frac{dj}{dw} \right) \quad (2.24)$$

where w_{new} is the new weight; w_{old} is the old weight; Δw is the change in weight; η is the learning parameter; and j is error. These predictions and tools developed to predict transient drawdown are presented in the Results section of this report.

2.3 SILTATION

Water flowing into the horizontal drain annulus carries particles of the inflowing soil that settle on the pipe wall and/or flush out of the pipe system. The transport, deposition, and suspension of dispersed particles can be described with the continuity equation for particle concentration, obtained by a mass balance on a differential element which can be written as:

$$\frac{\partial C}{\partial t} + (\mathbf{v} \cdot \nabla C) = D_f \nabla^2 C \quad (2.25)$$

Where C is the sediment concentration (m^3 of sediment/ m^3 of water), D_f is diffusivity, t is time, and $\mathbf{v}$ is velocity. Development of a mathematical convection-dispersion model for particle dispersion flowing inside a horizontal cylinder (pipe) of radius R and length L_p introduces the following equation:

$$\frac{\partial C}{\partial t} + \left(v_r \frac{\partial C}{\partial r} + v_\theta \frac{1}{r} \frac{\partial C}{\partial \theta} + v_z \frac{\partial C}{\partial z} \right) = D_f \left(\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial C}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 C}{\partial \theta^2} + \frac{\partial^2 C}{\partial z^2} \right) \quad (2.26)$$

Since in horizontal drains steady flow rates (v_z) increase in axial direction (length of the drain), particle concentration is a function of position of the particle in cross-section and axial direction and time, i.e. r , θ , z and t directions. The settling velocity of the particle is dependent on size and density of the particle and viscosity and density of the medium and achieved equilibrium of the forces acting on the particle as follows:

$$v_s = \frac{g(\rho_p - \rho_L)d_p^2}{18\mu_L} \quad (2.27)$$

Therefore, the particle sedimentation velocity in radial and angular direction is expressed as:

$$v_r = v_s \cos \theta \quad (2.28)$$

$$v_\theta = v_s \sin \theta \quad (2.29)$$

where C is particle concentration; t is time; v_r , v_θ and v_z are particle velocity in radial, angular and axial directions, respectively; g is gravity acceleration; ρ_p is particle density; ρ_L is liquid density; d_p is particle diameter; and μ_L is the viscosity of the liquid medium, assumed to be water at 20°C. The source of the incoming material is defined as a constant incoming flux of sediment scaled to groundwater inflow (dQ/dz) at a concentration of C_0 which enters the pipe through perforations over time, defined as:

$$C(r, \theta, z, t) = C_0 \frac{dQ}{A_0 dz} dt, \quad r = R, \quad \alpha_1 \leq \theta \leq \alpha_2 \quad (2.30)$$

At $\theta = 0$,

$$\frac{\partial C}{\partial \theta} = 0, \quad 0 \leq r \leq R \quad (2.31)$$

As radial conditions are considered, particle concentrations are not considered to change at the center of the cylinder ($r = 0$) with respect to the radius in all angles:

$$\frac{\partial C}{\partial r} = 0, \quad 0 \leq \theta \leq 2\pi \quad (2.32)$$

The wall of the pipe is required to be modeled as a boundary without mass exchange and represent the deposition of all the particles on the wall. This means there is no convection or dispersion occurring on the inner pipe wall ($r = R$), therefore, the boundary is represented by deposition flux boundary defined as:

$$-D_f \frac{\partial C}{\partial r} + v_r C = 0, \quad 0 \leq \theta \leq 2\pi \quad (2.33)$$

A finite difference approach is employed to address the second-order parabolic partial differential equation of the convection-dispersion equation, along with its corresponding initial and boundary conditions. The main objective is to determine the concentration of particles adhering to the pipe walls and to develop a time series depicting the buildup of material and potential pipe clogging. Pipe clogging occurs once the material concentration reaches a specific

threshold with a defined void ratio (e) for the particles. It is worth noting that the transport and entrainment of settled material are not considered, which is a conservative assumption. The settling void ratios for suspended sand, silt, and clay are reported as 0.6, 1.1, and 2.5, respectively, according to studies conducted by Lu and Likos (2004), Lade et al. (2009), and Fredlund and Houston (2013).

2.4 ANALYSIS OF PIONEER MOUNTAIN-EDDYVILLE DATA

The Pioneer Mountain-Eddyville (PME) realignment began in 2005, and during early construction there were observed slope movements which indicated that the paleolandslides present were active. In 2011 and 2012, additional landslide and groundwater monitoring instrumentation was installed to attempt to characterize landslide movement and hydrologic behavior. Plans for installing mitigation systems were adjusted in 2012 to reflect the use of the observational method for guidance of embankment construction. The design team used a combination of the observational approach (Peck, 1969) with traditional slope stability to oversee movement of the slides during the construction period. This monitoring system needed instrumentation, including piezometric, inclinometer and weir data. These data are used to analyze the PME response to horizontal drain installation, explored in more detail in Jones et al. (2023). Time series of piezometric data are interpolated to provide insight towards the overall water balance and response of four paleolandslides at PME. Kriging was used as an interpolation technique as it enables spatial weighting of observations, and allows for distinct comparisons of site groundwater data, both before and after horizontal drain installation. To use kriging to interpolate a groundwater model, a semivariogram defining spatial autocorrelation between piezometers must be created. The semivariogram relates Euclidean distance (lag) and semivariance between observations such as inferred groundwater depth. Semivariance (SV) is described as:

$$SV = 0.5 * (GW_1 - GW_2)^2 \quad (2.34)$$

where GW is the observed groundwater depth for a given location. In order to characterize the relationship between observation distance and semivariance, GW pairs are grouped in bins representative of distance. The mean lag and semivariance for each bin was then plotted to create a semivariogram (Figure 2.3), a fit of the observed pairs enables calculation of semivariance at any distance from a groundwater observation (i.e. a piezometer). Kriging relationships were updated yearly to reflect changing site conditions up until 2018, such as the installation and loss of piezometers and the implementation of mitigation measures during project progress. September 1st was chosen as the start date for each semivariogram as it commonly marks the end of the dry season at the site.

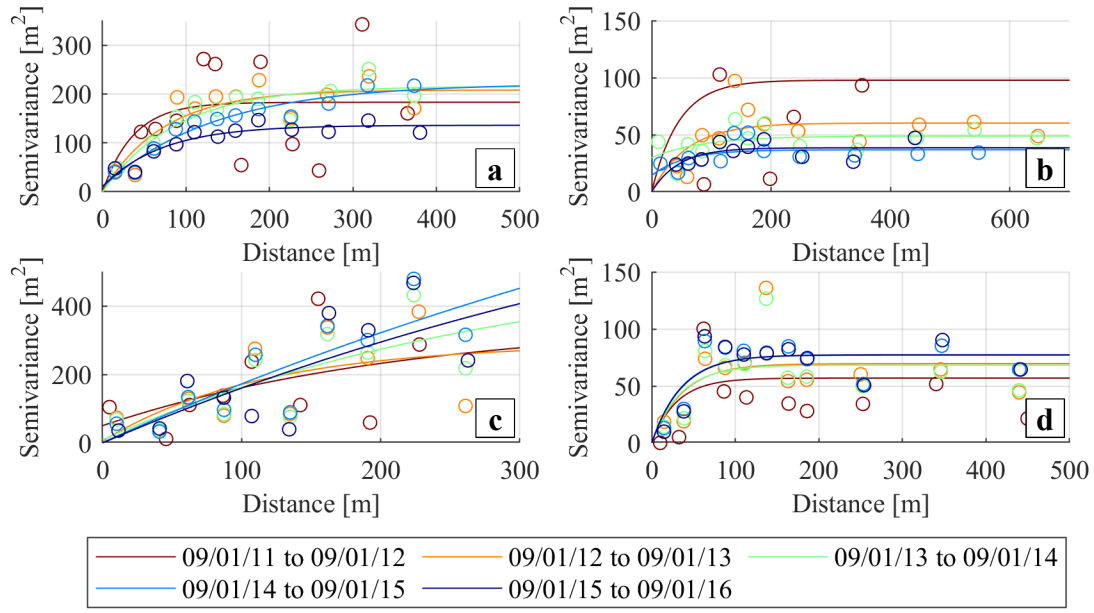


Figure 2.3. Semivariograms for landslide AOIs with kriging models used. (a) Cougar Creek. (b) Crystal Creek. (c) Eddy AB. (d) Eddy CD.

Through characterizing yearly semivariance relationships for measured piezometric data for each landslide site, interpolation of a groundwater profile may be performed. These interpolations were performed at each four-hour interval where piezometric data were recorded, enabling three-dimensional characterization of groundwater change over time. For a given location of interest, the groundwater depth can be estimated through solving the semivariance matrix, A , which is symmetric and defined as (Jones et al., 2023):

$$A = \begin{bmatrix} SV_{11} & SV_{21} & SV_{31} & \dots & SV_{n1} & 1 \\ SV_{12} & SV_{22} & SV_{32} & \dots & SV_{n2} & 1 \\ SV_{13} & SV_{23} & SV_{33} & \dots & SV_{n3} & 1 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ SV_{1n} & SV_{2n} & SV_{3n} & \dots & SV_{nn} & 1 \\ 1 & 1 & 1 & \dots & 1 & 0 \end{bmatrix} \quad (2.35)$$

where each SV_{ij} represents model semivariance between each pair of groundwater observations. The semivariance vector (b) at the given point of interest, m , is defined as:

$$\mathbf{b} = \begin{bmatrix} SV_{m1} \\ SV_{m2} \\ SV_{m3} \\ \vdots \\ SV_{mn} \\ 1 \end{bmatrix} \quad (2.36)$$

where each SV_{mn} represents the model semivariance associated with the distance from the point of interest to each of the n observed groundwater depths. To establish the interpolative relationship between all observed groundwater points, n , and the point of interest, m , the vector of weights from each observed point, λ , must be solved along with a Lagrange multiplier (ϕ). This is performed through taking the dot product of $\mathbf{b}$ and the inverse of $\mathbf{A}$ (Burrough et al., 2015), defined as:

$$\mathbf{A}^{-1} \cdot \mathbf{b} = \begin{bmatrix} \lambda \\ \phi \end{bmatrix} \quad (2.37)$$

By doing this, the resulting vector will have a length of $n+1$, with the first n values being weights for interpolation at the point of interest (λ), and the last value being the Lagrange multiplier (ϕ). Thereafter, the groundwater depth at the point of interest (Z_m) is determined as:

$$Z_m = \sum_{i=1}^n \lambda_i * Z_i \quad (2.38)$$

Further, the variance estimation at the point of interest (σ) is defined as:

$$\sigma = \phi + \sum_{i=1}^n \lambda_i * b_i \quad (2.39)$$

The interpolative relationship is repeated for every grid cell in the given landslide AOI. This process is repeated at four-hour intervals to characterize the change in the three-dimensional groundwater profile through time.

3.0 RESULTS AND DISCUSSION

3.1 GRAVITY-DRIVEN GROUNDWATER DRAWDOWN USING HORIZONTAL DRAINS

3.1.1 Model Validation

3.1.1.1 Comparison against Experimental Tests

Lakruwan et al. (2021) performed experiments with physical models evaluating the performance of horizontal drains in terms of drawdown, head loss, and discharge. The test consisted of a horizontal drain placed within the center of a tank filled with sand and water. A pressurized air supply was used to saturate sand and apply a constant head level at the top of the physical model (Lakruwan et al., 2021). The sand tank was instrumented with piezometers at five different locations within the middle section of the tank and discharge was measured at the pipe outflow. Steady state conditions were achieved upon convergence to constant piezometric levels and discharge values (Lakruwan et al., 2021). A schematic of the experimental setup is shown in Figure 3.1. To validate the applicability of the proposed approach, the experimental setup is modeled numerically. For this purpose, boundary conditions are modified to a constant head condition at the soil surface of 2 m, and a no flow boundary condition ($\partial h/\partial x=0$) on all other sides of the tank.

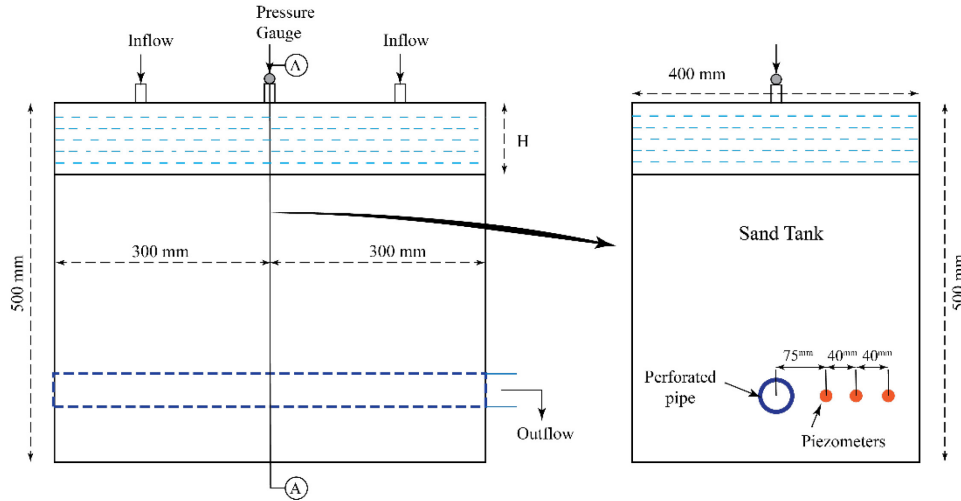


Figure 3.1. Schematic of experimental setup (after Lakruwan et al., 2021 and Abed and Leshchinsky, 2023)

Figure 3.2a shows modeled transient head level for a cross section of the tank. As shown, there is an evident formation of a cone of depression, which is most drastic at the onset of drain installation, and thereafter becomes more modest, but still pronounced at steady-state conditions. The steady state is achieved in approximately one second as the hydraulic conductivity and hydraulic gradient were high, which also was observed during

experimental testing (Lakruwan et al., 2021). For the numerical solution, a steady-state condition was reached when the change in head levels were less than a defined tolerance of head change less than 10^{-8} m. Steady-state head levels from the experiments of Lakruwan et al. 2021 compare favorably to numerical solution, as evidenced by the steady-state cone of depression (yellow line) and black points where piezometric levels were measured.

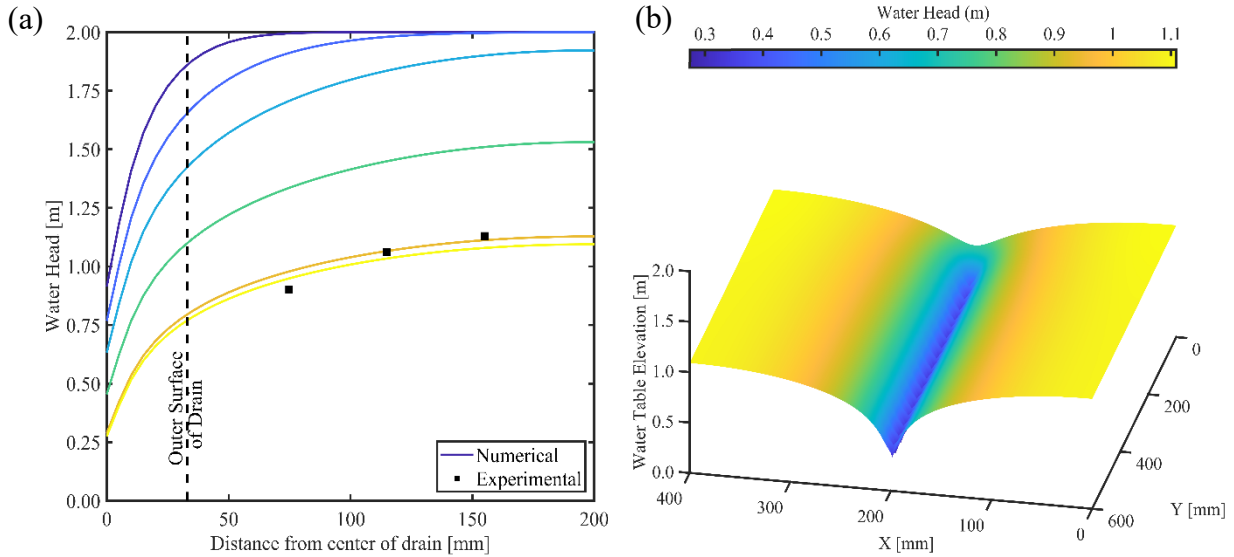


Figure 3.2. (a) Transient cone of depression at section A-A (Figure 3.1) from Abed and Leshchinsky (2023), comparison to piezometer water head of tank test by Lakruwan et al. (2021) (b) 3D cone of depression at drain depth after reaching steady state conditions (Abed and Leshchinsky, 2023)

3.1.1.2 Comparison against Semi-analytical model

Zhan and Zlotnik (2002) suggested an analytical solution for a horizontal well with a predefined pumping rate in an unconfined aquifer. By applying Laplace transform, Zhan and Zlotnik (2002) solved the transient three-dimensional groundwater flow in an anisotropic medium near a point source with a pumping rate, Q , and obtained the closed-form analytical solution by Stehfest (1970) numerical Laplace transform inversion. To validate the suggested numerical solution proposed in this report, the boundary and drain conditions are modified to present Zhan and Zlotnik (2002). Figure 3.3a compares the numerical and analytical solution (Zhan and Zlotnik, 2002) results for the piezometers shown in Figure 3.3b. Initially, the numerical solution underestimates the drawdown for P1 by an average of 20% and for P3 by an average of 12%. However, for P2, the underestimation is relatively low, at an average of 3%. As the drawdown process continues and reaches its final stages, the disparity between the two methods diminishes. The numerical method becomes more accurate and shows drawdown values within 1% for P1 and P2, and within 0.6% for P3 compared to solution of Zhan and Zlotnik (2002). Overall, the comparison demonstrates reasonable agreement, especially for longer timescales relevant to the functionality of horizontal drain systems.

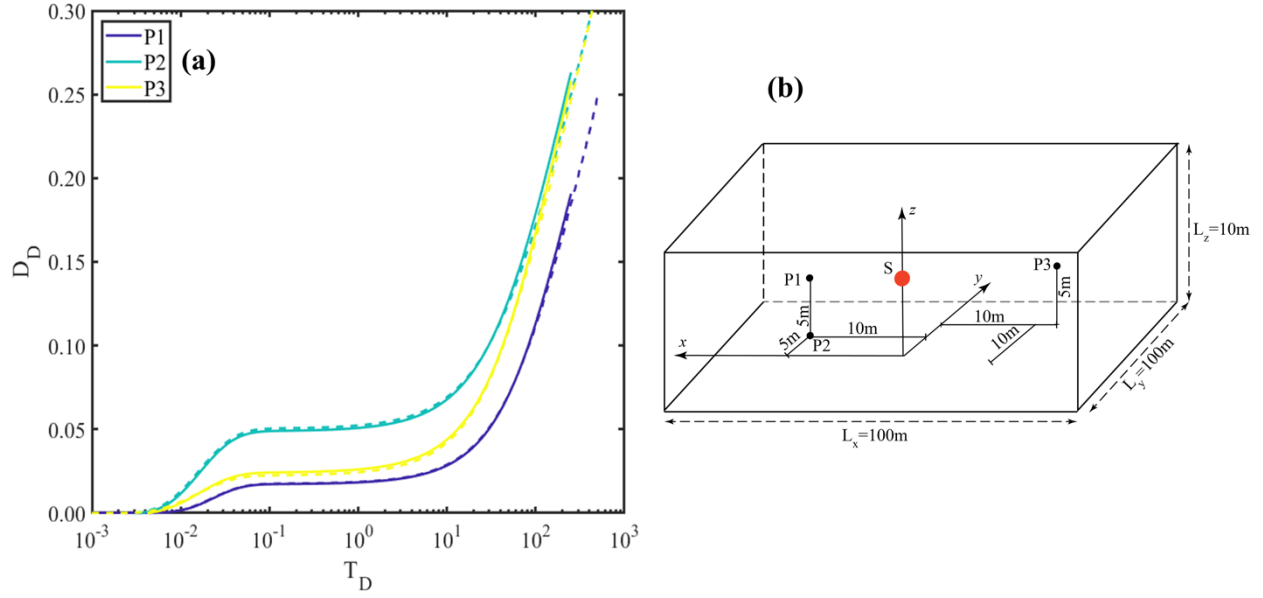


Figure 3.3. (a) Comparison of semi-analytical solutions of transient dimensionless groundwater drawdown, DD, from Zhan and Zlotnik (2002) (dashed line) and numerical solution proposed in this study (solid line) (b) Schematic of the aquifer and sink point and location of piezometers at points P1(10m,5m,5m), P2 (10m,5m,0m), and P3 (10m,10m,5m) (Abed et al., 2024)

3.1.2 Results of Numerical Model Groundwater Drawdown

The effectiveness of horizontal drain (HD) systems in decreasing pore pressures through lowered groundwater and enhancing slope stability is influenced by various design parameters such as drain length, drain spacing, inclination, and recharge domain size. The drawdown time is reported in dimensionless form to generalize the solution for any material with different values of hydraulic conductivity and specific storage. Since the spacing and length of the drain are considered dominant parameters for design, we provide drawdown time series for different pipe lengths, and for drains installed in hillslopes/aquifers with 10° , 20° , 30° , and 40° inclinations. The length of aquifer (L_y) parallel to the pipe length is 50m and 100m, but the overall drawdown for larger areas can be considered through superposition of drawdown.

Figures 3.4 to 3.23 show the transient mean drawdown on slip surface, which is assumed to be at the base of aquifer, for drain length of 10m, 20m, 30m, 40m and 50m, respectively. It is important to mention that in this analysis, there is minimal sensitivity of the drain inclination on drawdown. These are reasonable assumptions as these inclinations would not significantly affect hydraulic conductivities within the aquifer; however, they are likely to reduce siltation and deposition of sediment within the drain system. Therefore, drains are modeled with zero degrees of inclination, meaning they are positioned horizontally. The geometry shown in Figure 2.1 applies to all analyses presented, the landslide is assumed to be fully saturated, the drain is placed at the toe of landslide, i.e. $h_d = L_z = d$, and symmetric conditions are used to reflect drain spacing. The drawdown was computed by taking the difference between the initial head and the water head level obtained from the proposed numerical model at each time step ($D =$

$h_0 - h$). As the drawdown exhibited variations across the entire landslide area, we simplify the model time series for further discussions by presenting the mean drawdown over the entire slip surface.

Figures 3.24 to 3.43 show the changes in mobilized friction angle on the slip surface due to reduction of pore water pressure as a result of groundwater drawdown. As expected, change in mobilized friction for stability follows similar trends to average drawdown; whereas the stabilizing effects of dewatering are rapid at first and sustained at slower rates over a longer period. As described in section 2.1.3, the change in mobilized friction can be used as a comparison to evaluate the overall change in stability versus an initial friction angle. Figures 3.44 to 3.63 represent the total outflow discharge of each drain, which results from the accumulation of gravity driven water into the drain through circumferential perforations extending longitudinally along the pipe.

The behavior of transient drawdown is notably nonlinear owing to the stages in which hydraulic gradients evolve. Typically, there are three distinct stages of drawdown, and changes in drain length, spacing, and aquifer size can influence the duration of each drawdown stage as well as the amount of water drawn into the system. The three stages of drawdown indicate different phases in the process including: an initial rapid drawdown that occurs with the formation of a “trough of depression”, resulting from the proximity of standing water to the drain; an intermediate stage where the trough of depression expands both between parallel drains and upslope, influencing a larger area of the aquifer, where the head contours and the distribution of head along the drain demonstrate the nonlinear behavior of groundwater drawdown caused by horizontal drains; and the third stage representing a sustained drawdown phase where the groundwater upslope of the drain system is significantly lowered compared to the previous stages where drawdown continues until a balance is achieved between upslope recharge and the flow of water into the drain, leading to steady-state conditions.

Figures 3.4 to Figure 3.63 can be used to predict the average drawdown, mobilized friction angle, and total discharge outflow of the drain using the hydraulic conductivity of the aquifer, specific storage, depth, length, and angle of the slope, drain length and drain spacing. Herein, a simple example leveraging these design charts is posed. For example, installation of a 40m long drain in a saturated slope with 10m depth, 10° slope angle and 50m length, lowers the ground water 4.2m if the drain spacing is 2m. Similarly, mean drawdown is 3.7m if the drain spacing is 18m (Figure 3.7). Ideally, the time to achieve steady state conditions is a function of hydraulic conductivity, specific storage, and aquifer depth (Eq. (3.1)); consequently, assuming a hydraulic conductivity of $K = 10^{-5} \text{ m/s}$, specific storage $S_s = 8.64 \times 10^{-4} \text{ m}^{-1}$ and depth of $d = 10\text{m}$, it takes 16.3 days and 27 days to reach steady-state conditions (Figure 3.7) for drain spacing of 2m and 18m spacing, respectively. Figure 3.27 shows upon achieving steady state conditions, the mobilized friction angle of the slope is decreased 5.8° and 5.4° for drain spacings of 2m and 18m, respectively. Based on the geometry of aquifer and drain installation conditions, Figure 3.47 demonstrates that at the steady state condition for $K = 10^{-5} \text{ m/s}$ and $d = 10\text{m}$, expected observations of total outflow discharge approximate $115 \text{ m}^3/\text{day}$ for drain spacing of 2m and $417 \text{ m}^3/\text{day}$ for 18m drain spacing (using Eq. 3.2). These examples demonstrate sensitivity (or lack thereof) as related to various drain design parameters posed in Figures 3.4 to Figure 3.63.

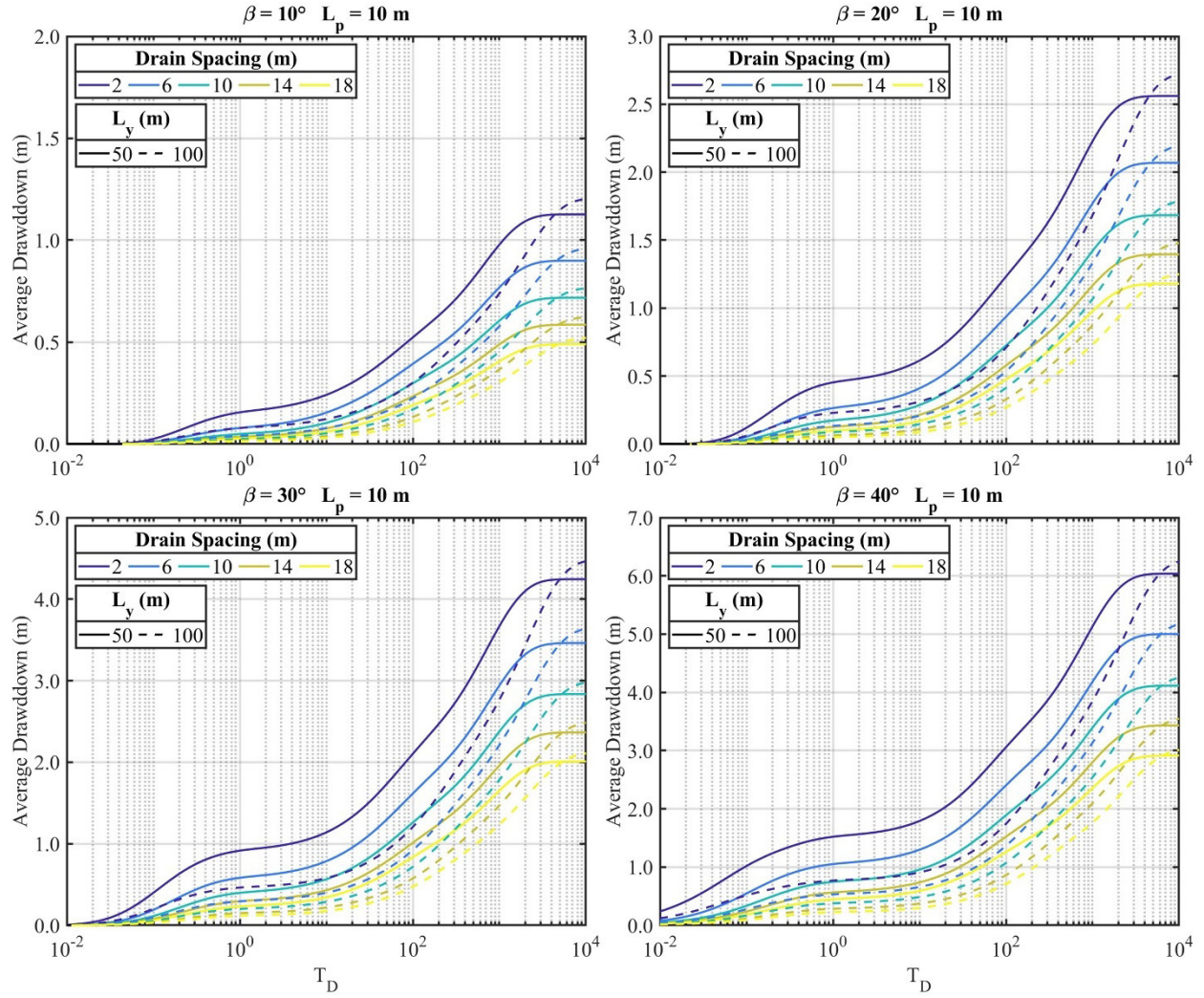


Figure 3.4. Transient average drawdown for drain length of $L_p = 10$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

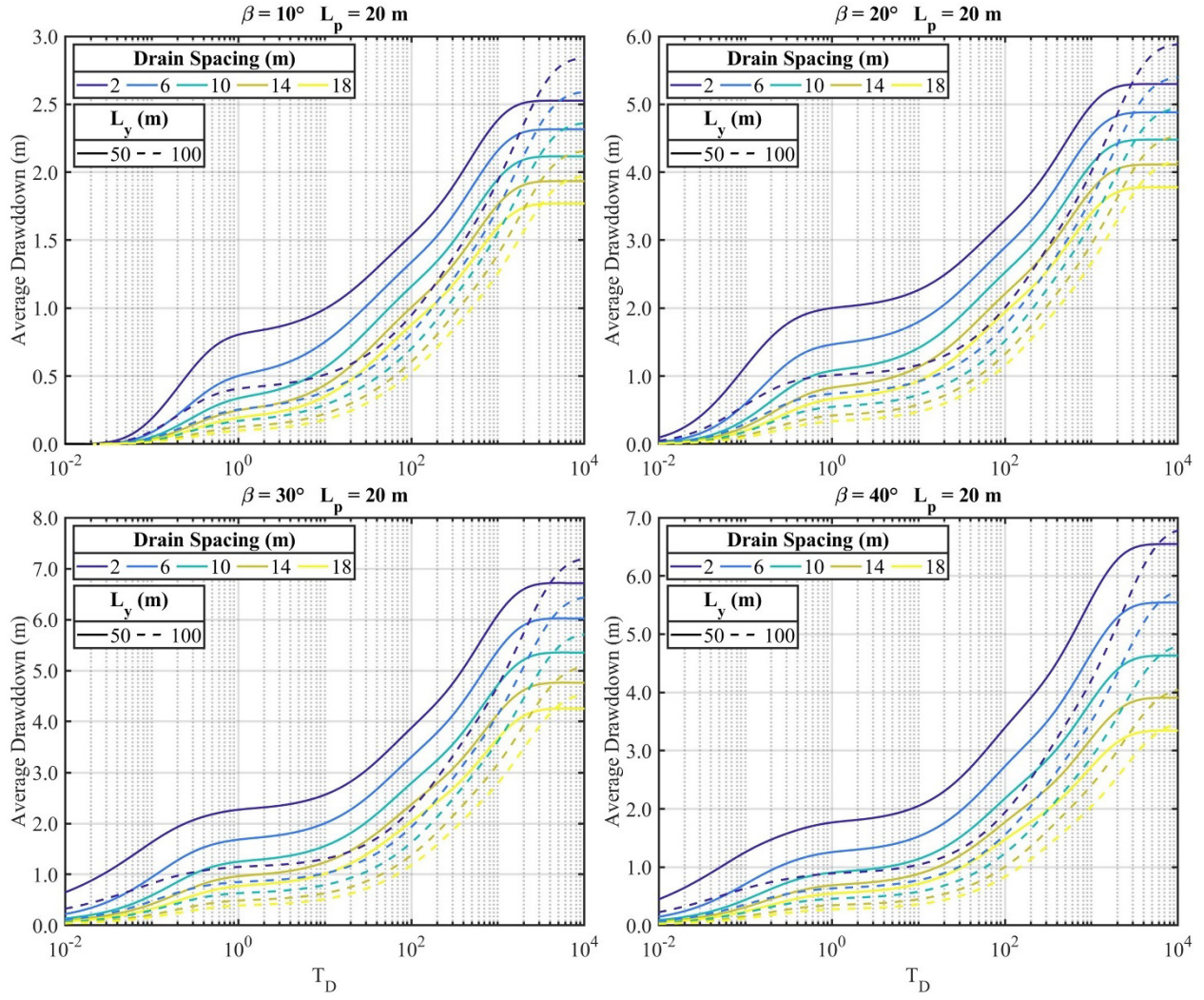


Figure 3.5. Transient average drawdown for drain length of $L_p = 20$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

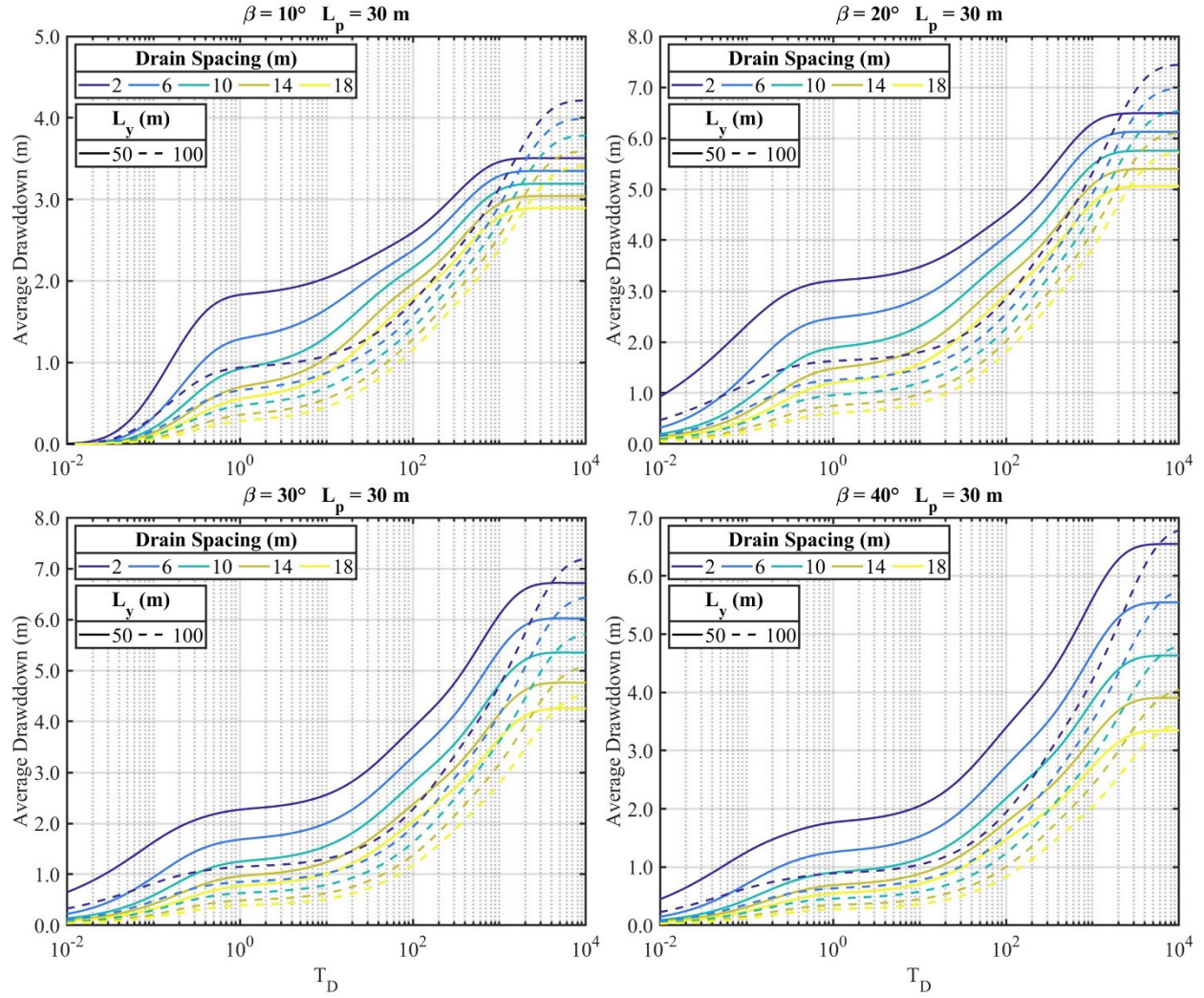


Figure 3.6. Transient average drawdown for drain length of $L_p = 30$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

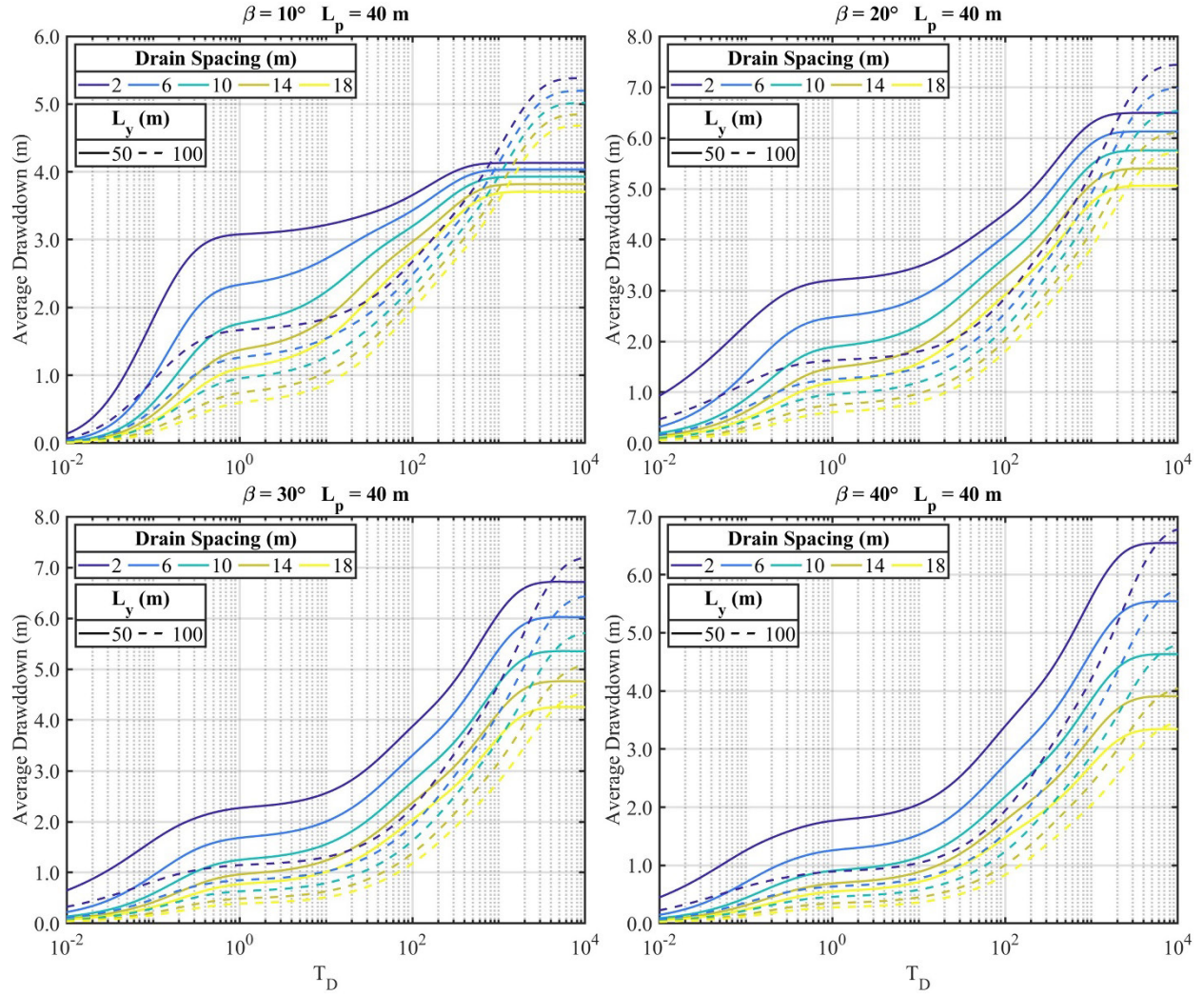


Figure 3.7. Transient average drawdown for drain length of $L_p = 40$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

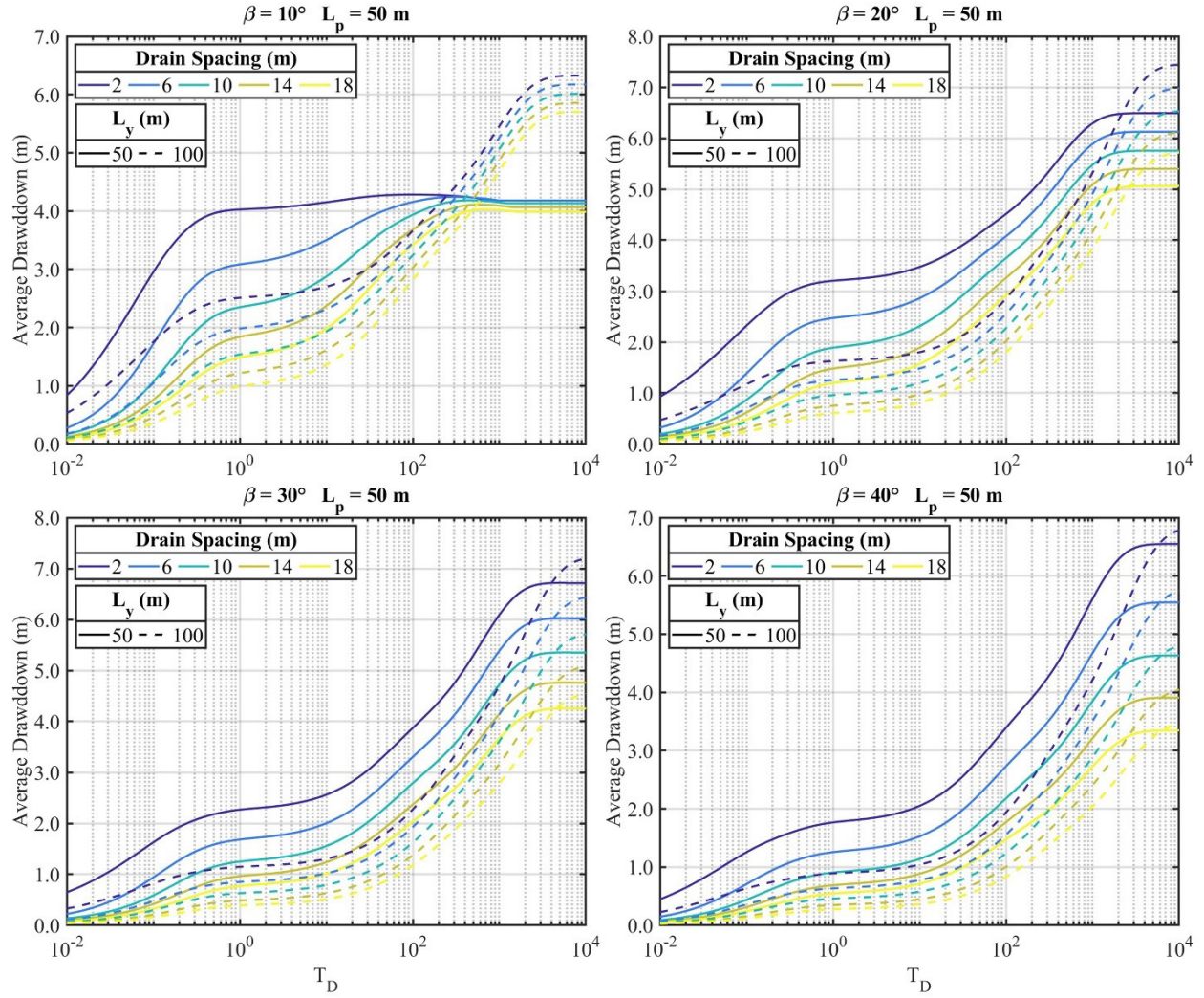


Figure 3.8. Transient average drawdown for drain length of $L_p = 50$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

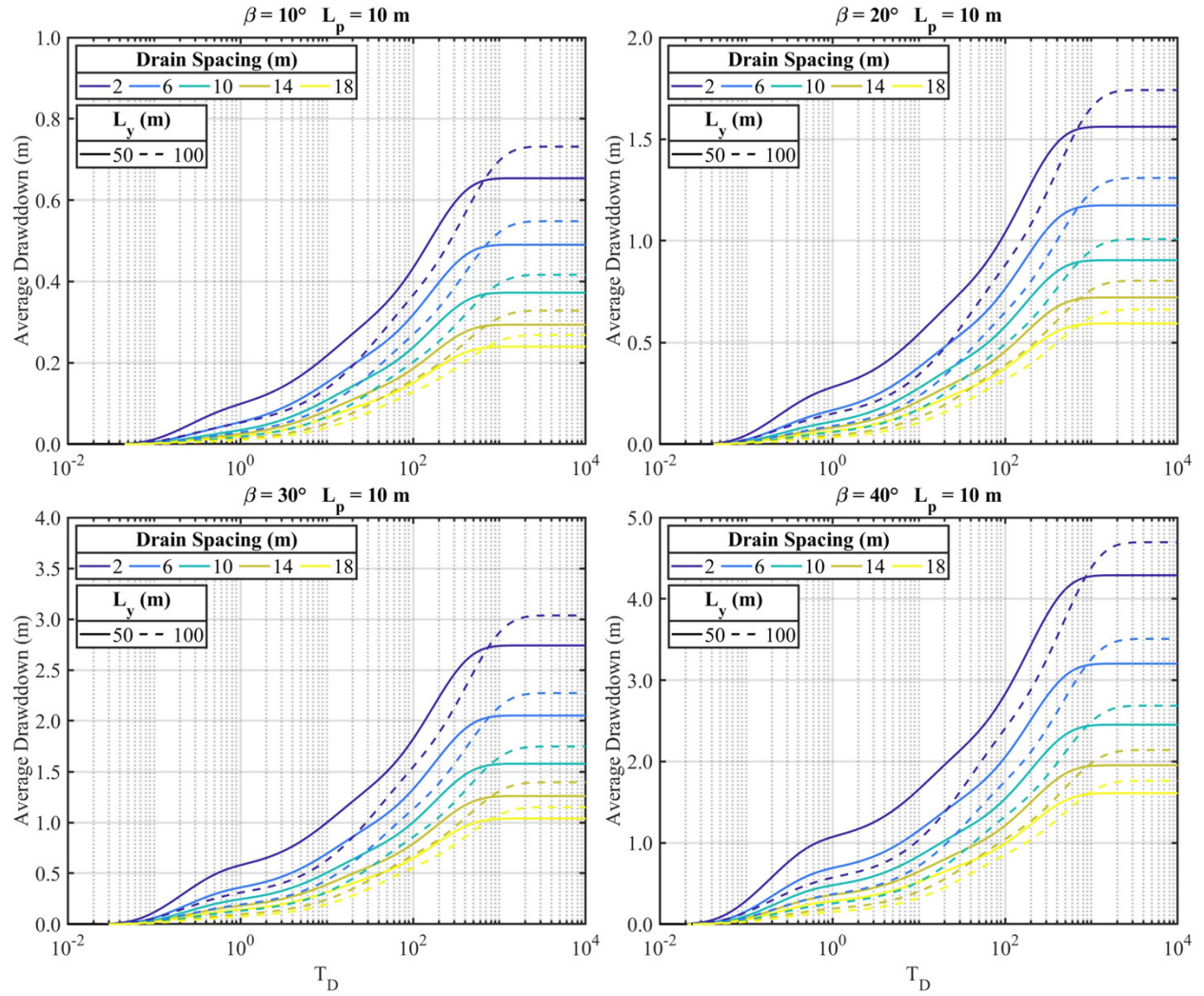


Figure 3.9. Transient average drawdown for drain length of $L_p = 10$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

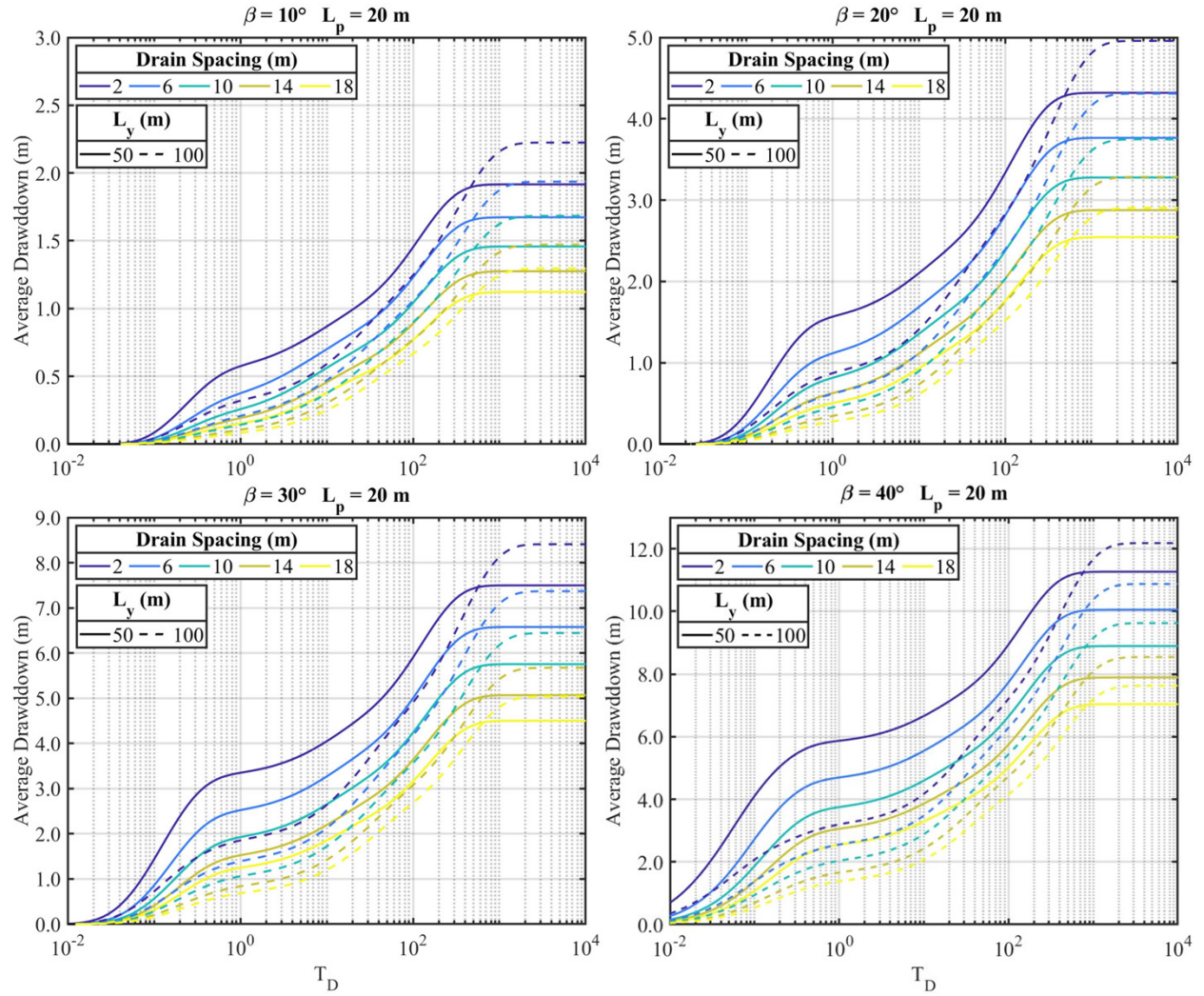


Figure 3.10. Transient average drawdown for drain length of $L_p = 20$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

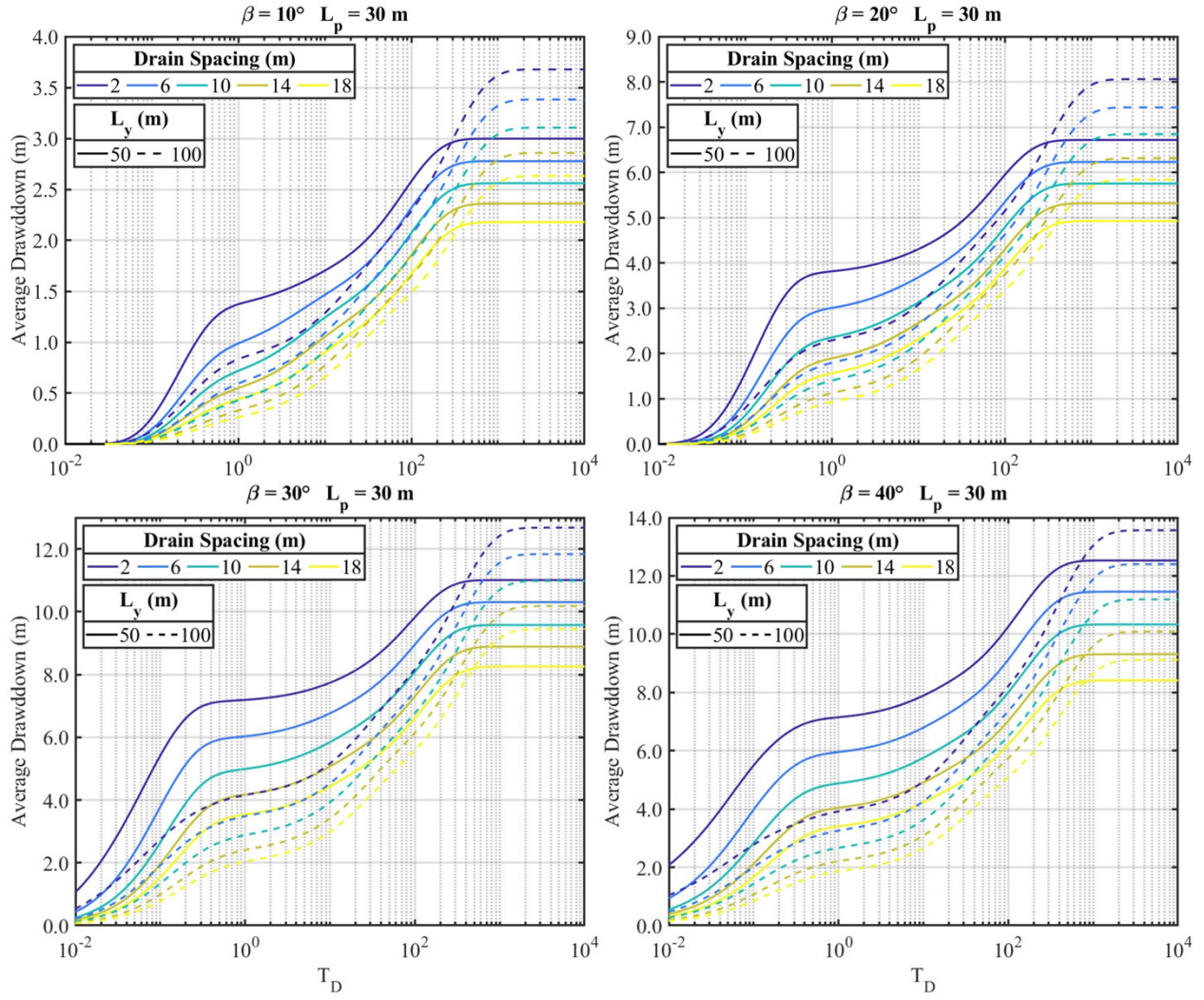


Figure 3.11. Transient average drawdown for drain length of $L_p = 30$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

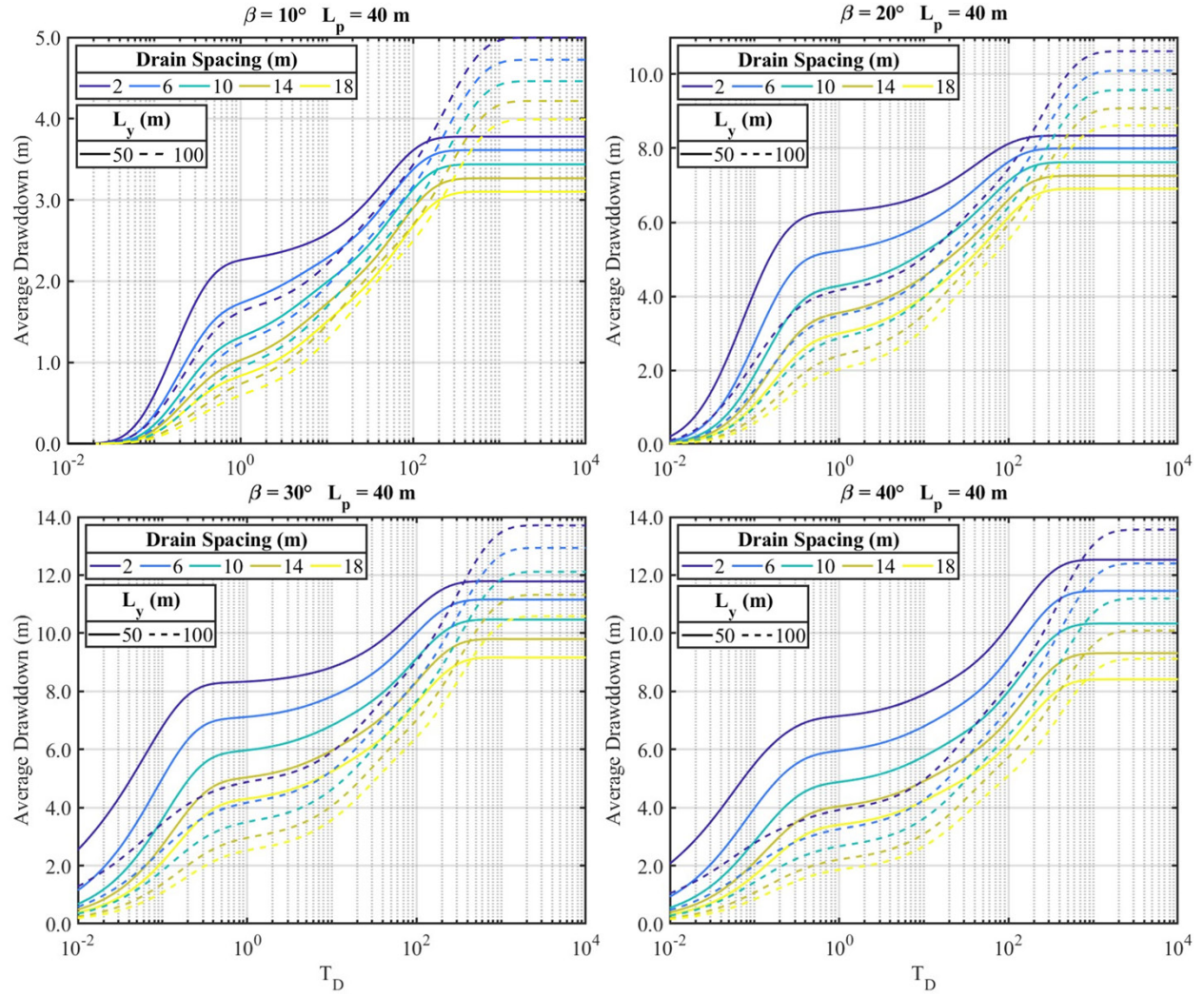


Figure 3.12. Transient average drawdown for drain length of $L_p = 40$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

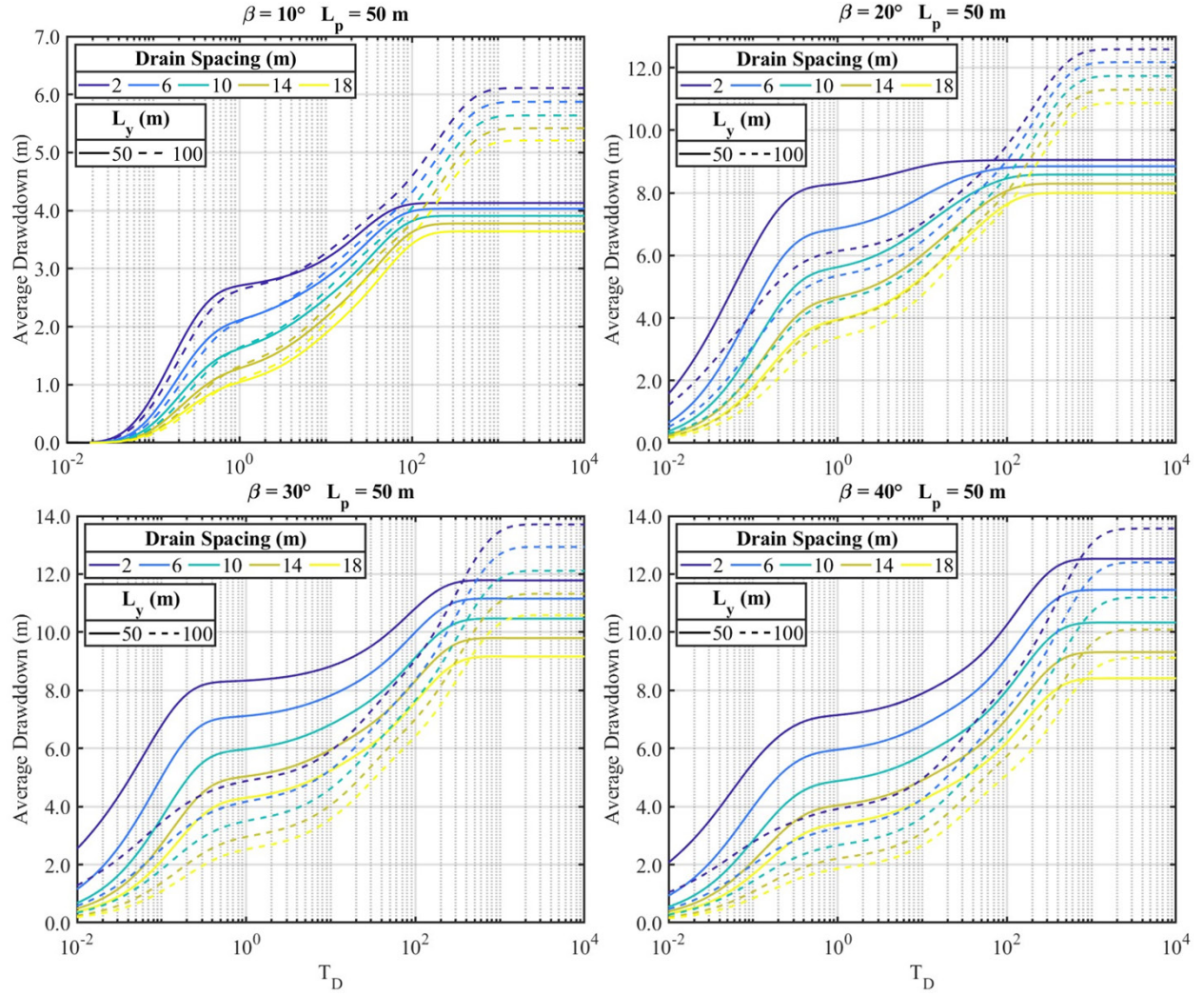


Figure 3.13. Transient average drawdown for drain length of $L_p = 50$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

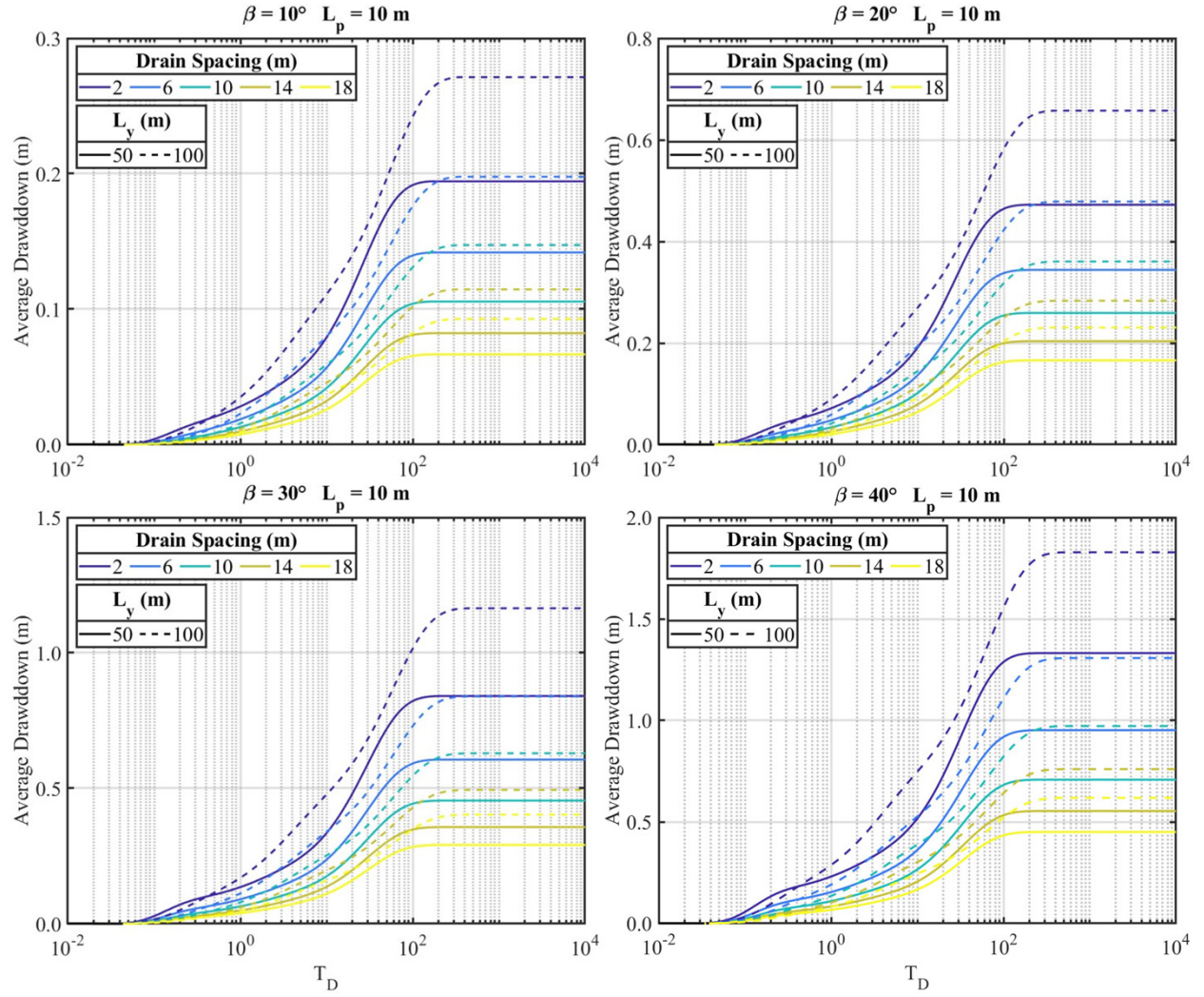


Figure 3.14. Transient average drawdown for drain length of $L_p = 10$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

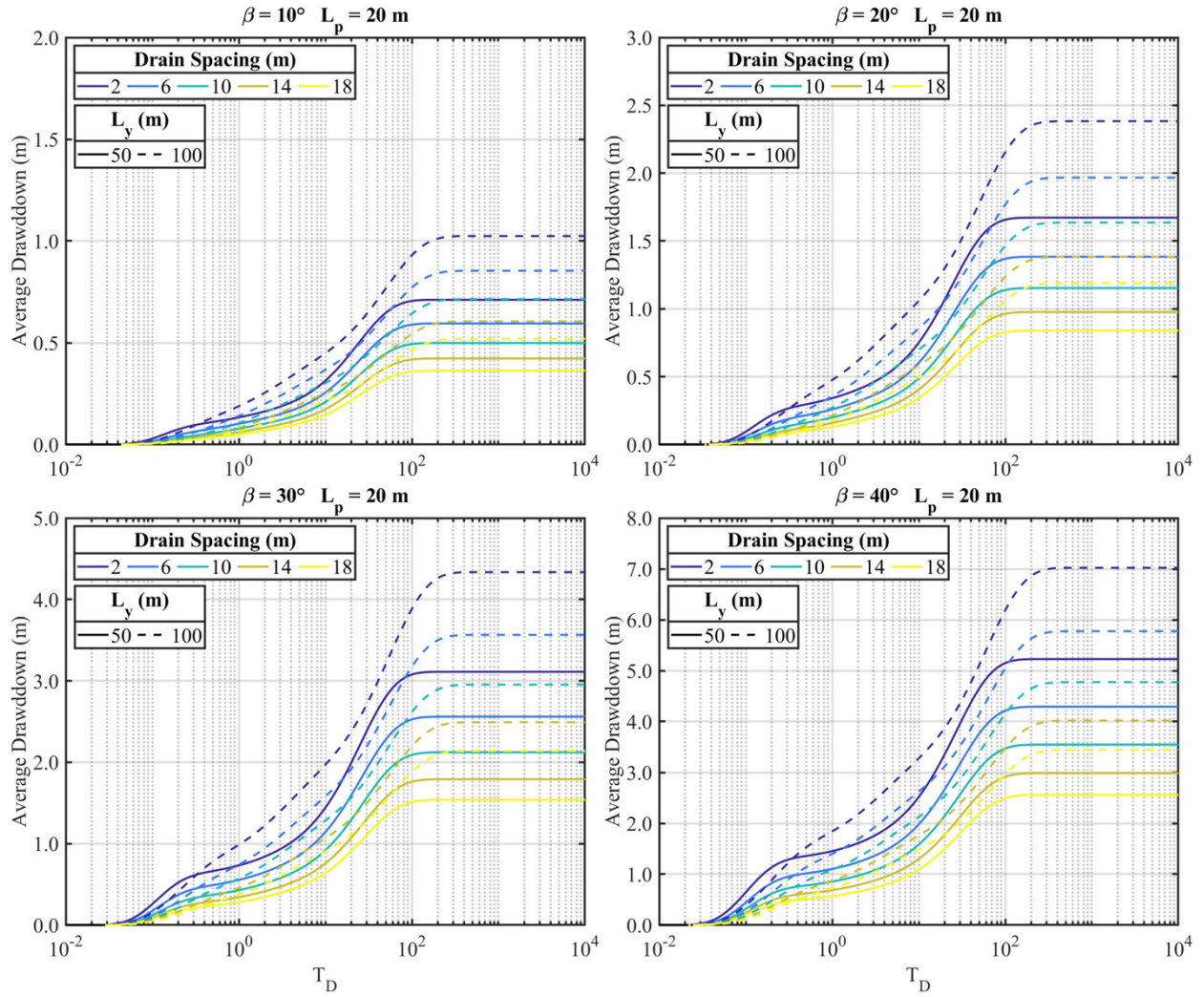


Figure 3.15. Transient average drawdown for drain length of $L_p = 20$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

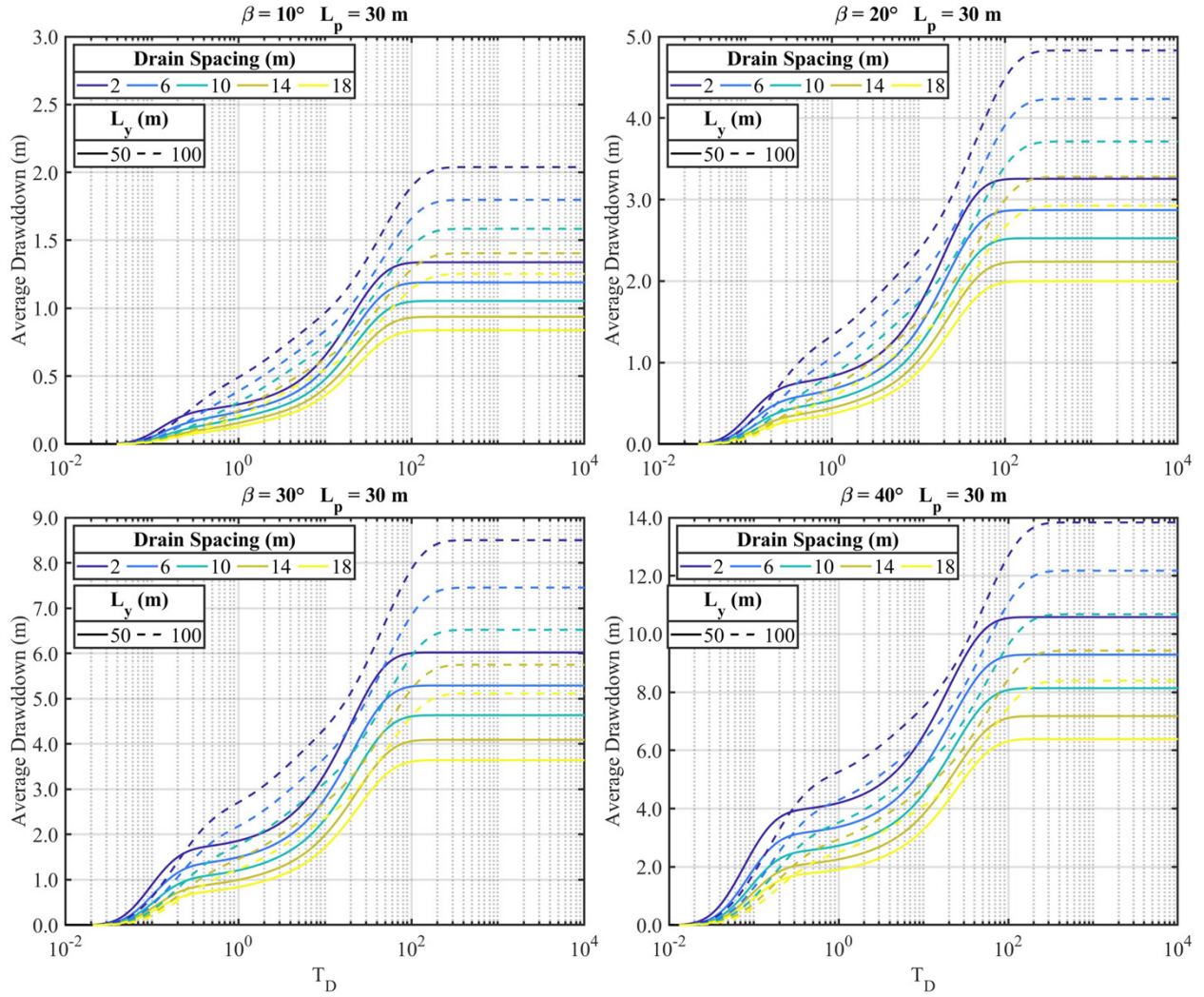


Figure 3.16 Transient average drawdown for drain length of $L_p = 30$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

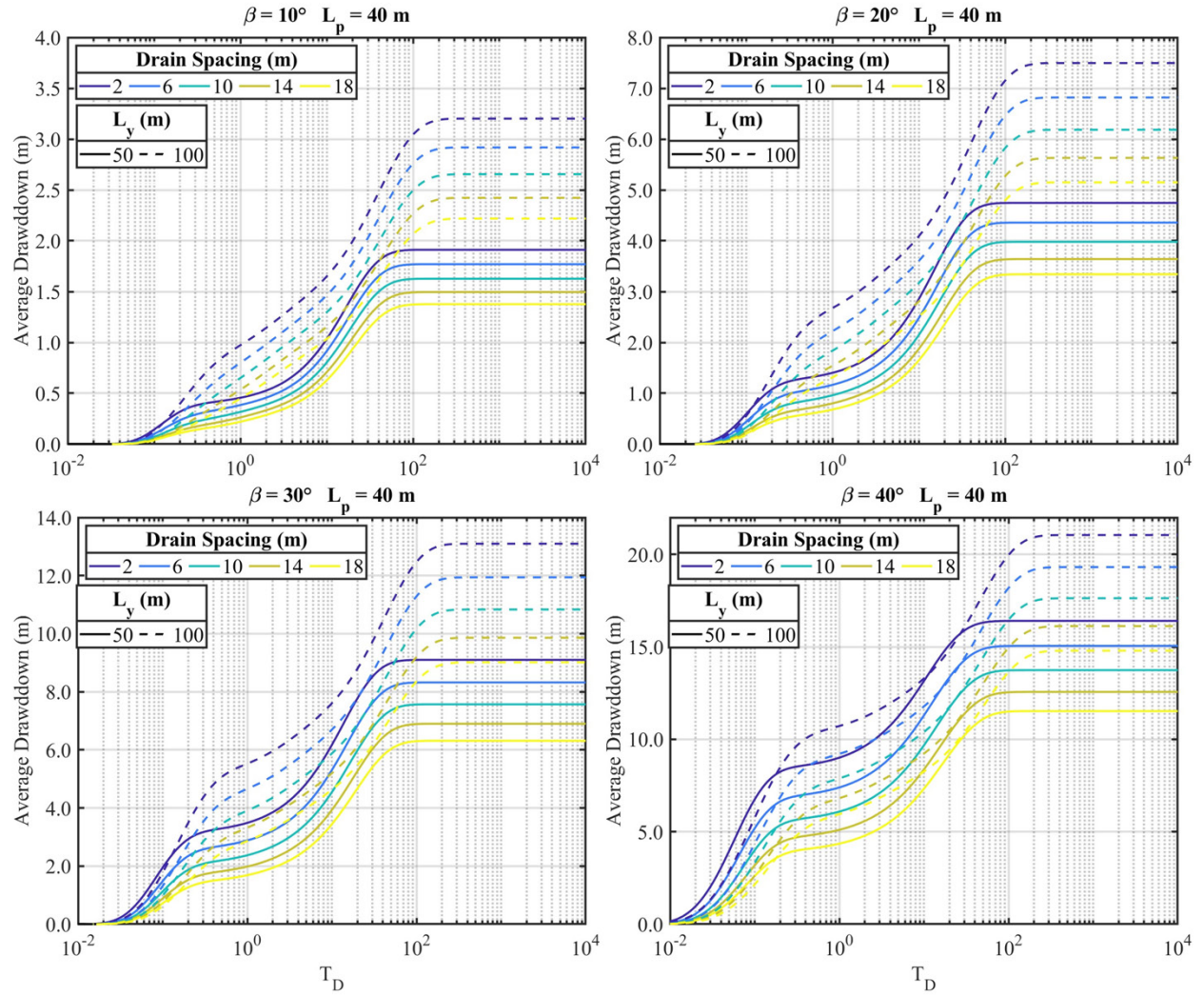


Figure 3.17. Transient average drawdown for drain length of $L_p = 40$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

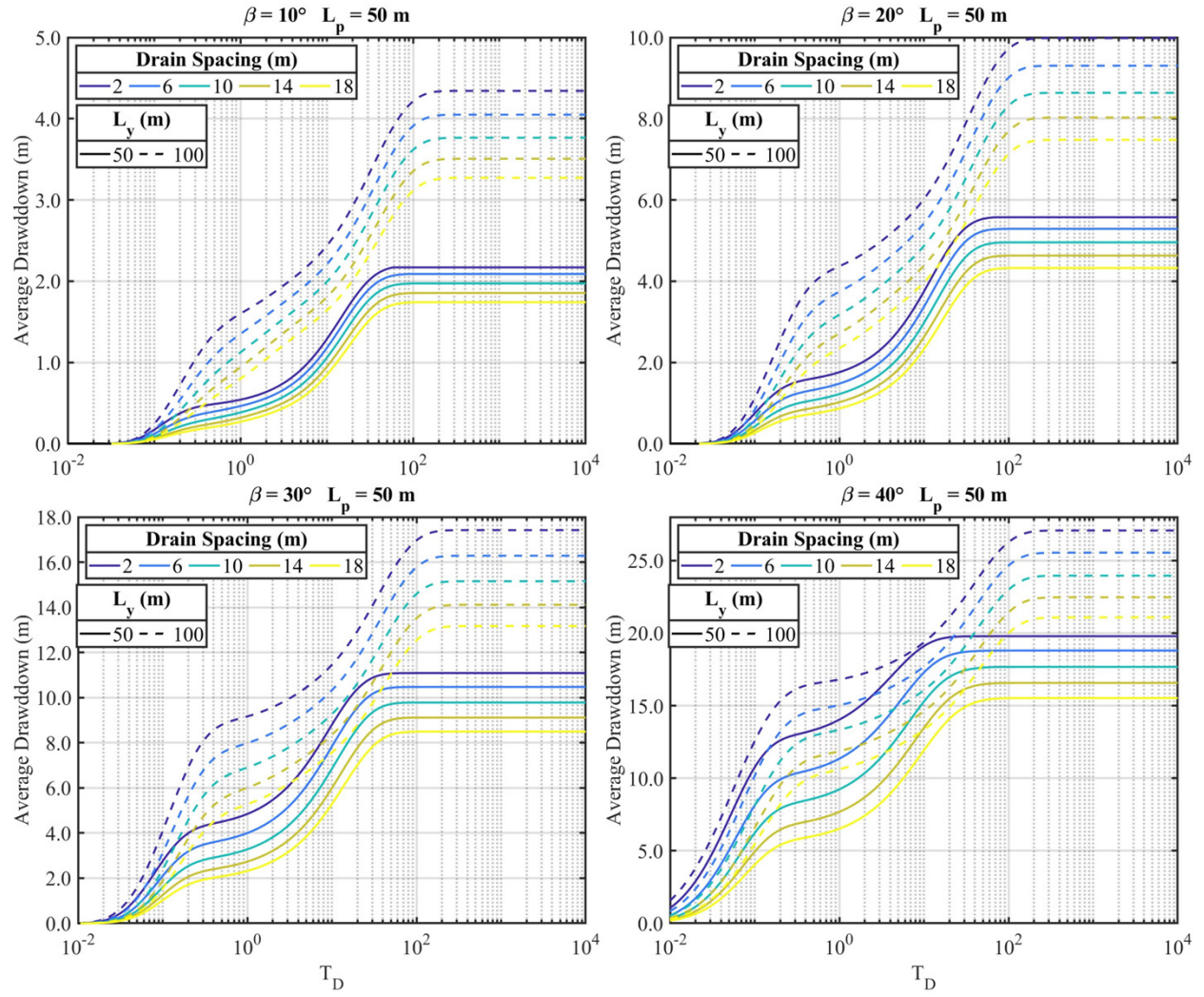


Figure 3.18. Transient average drawdown for drain length of $L_p = 50$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

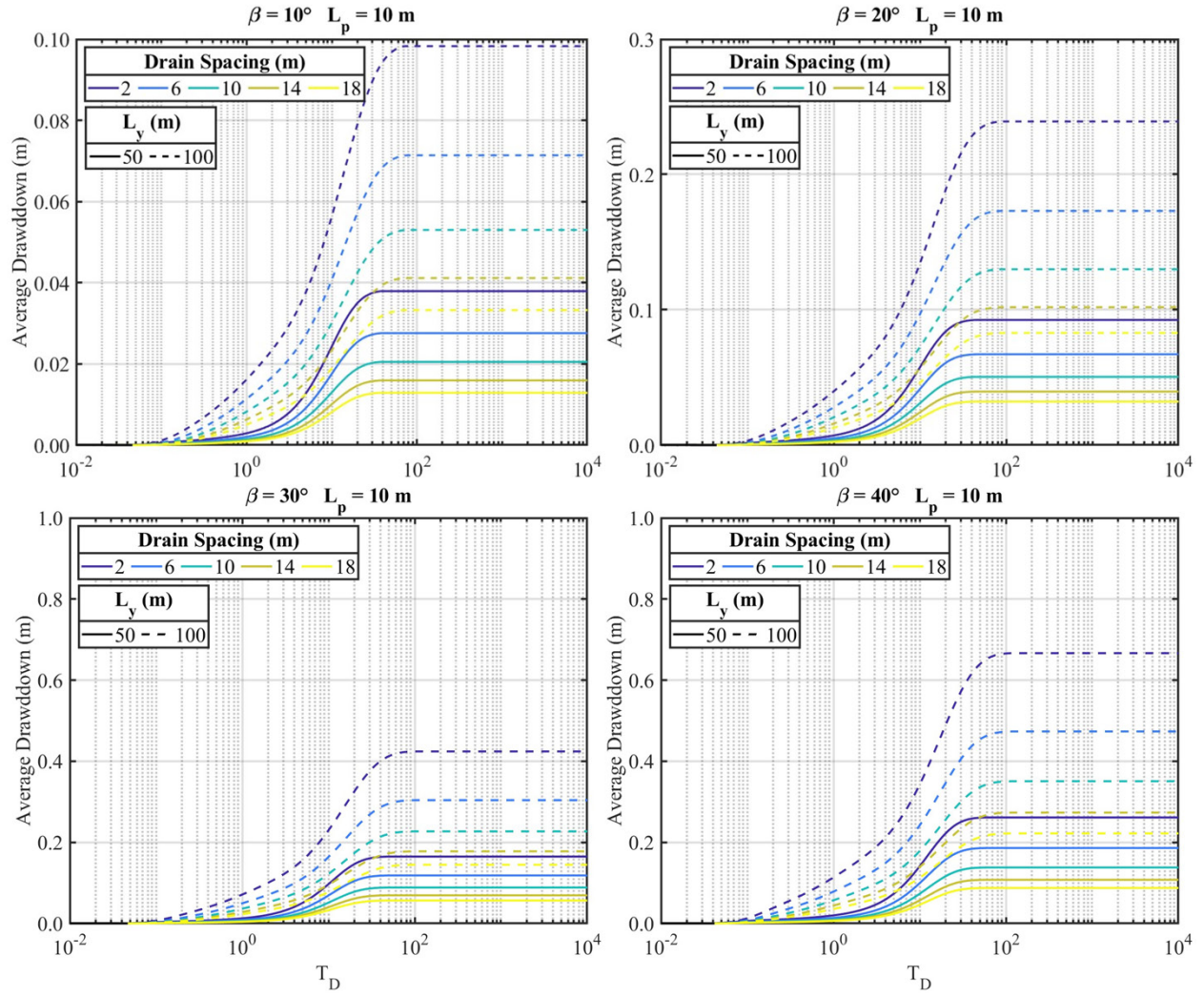


Figure 3.19. Transient average drawdown for drain length of $L_p = 10$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

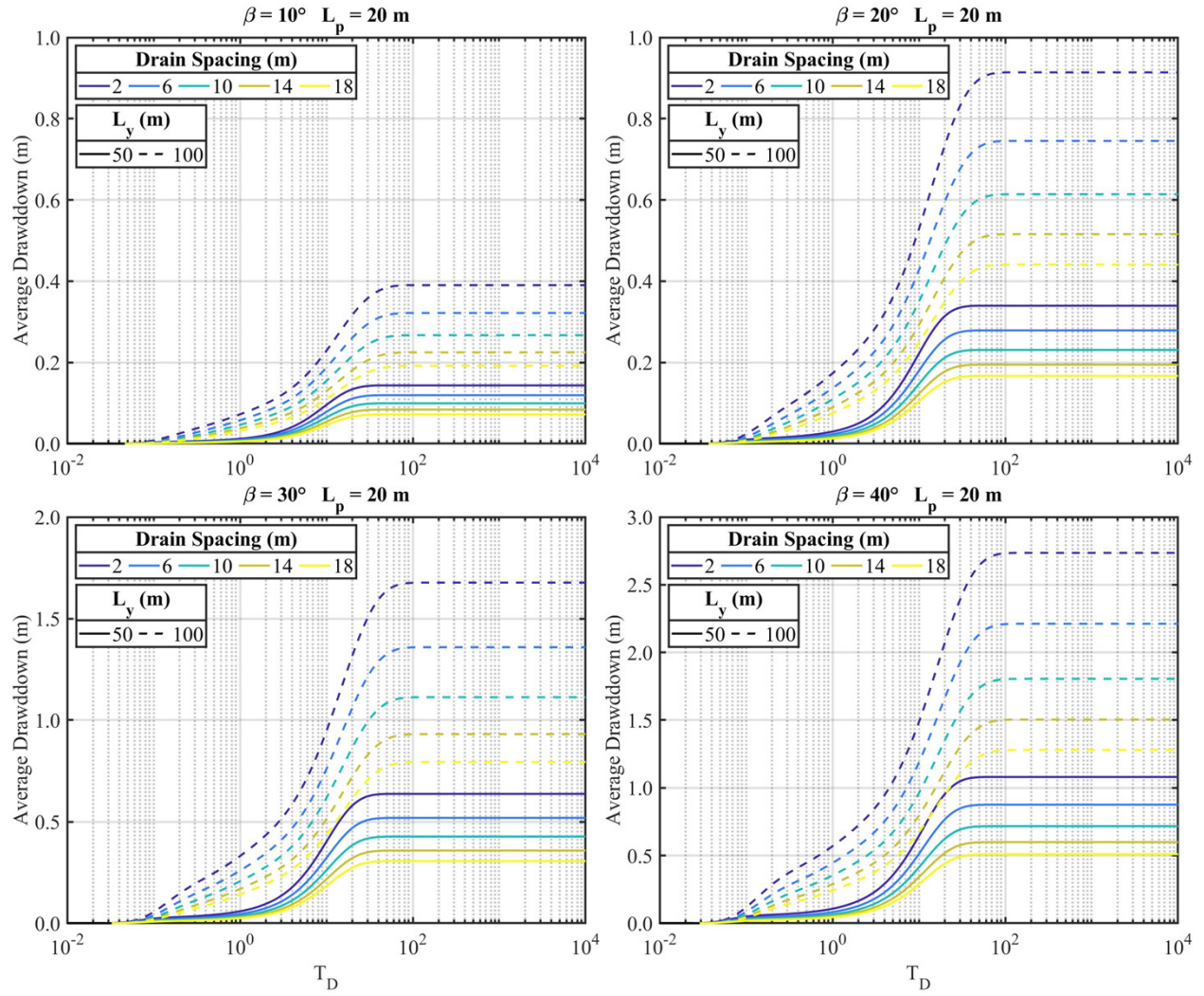


Figure 3.20. Transient average drawdown for drain length of $L_p = 20$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

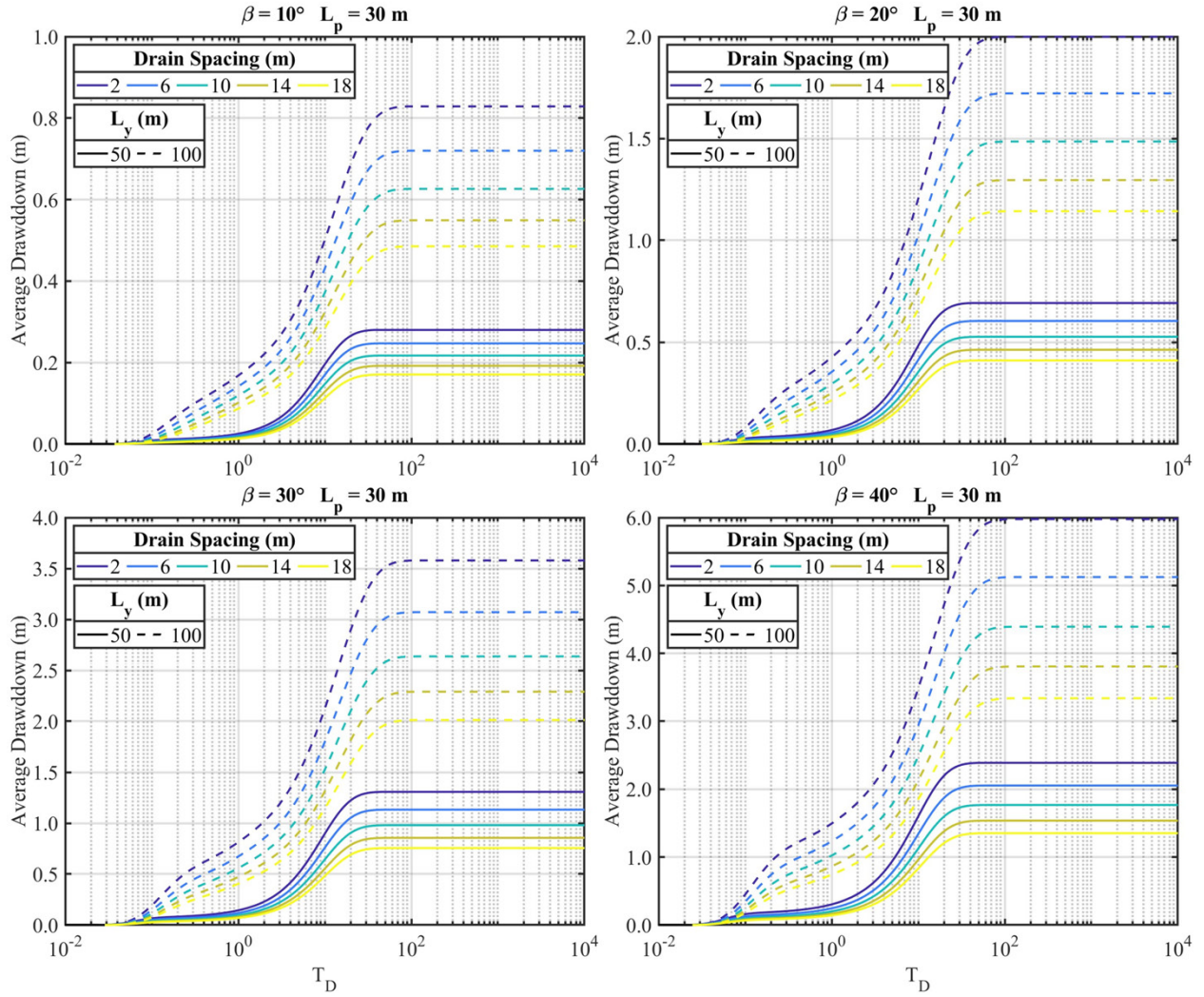


Figure 3.21. Transient average drawdown for drain length of $L_p = 30$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

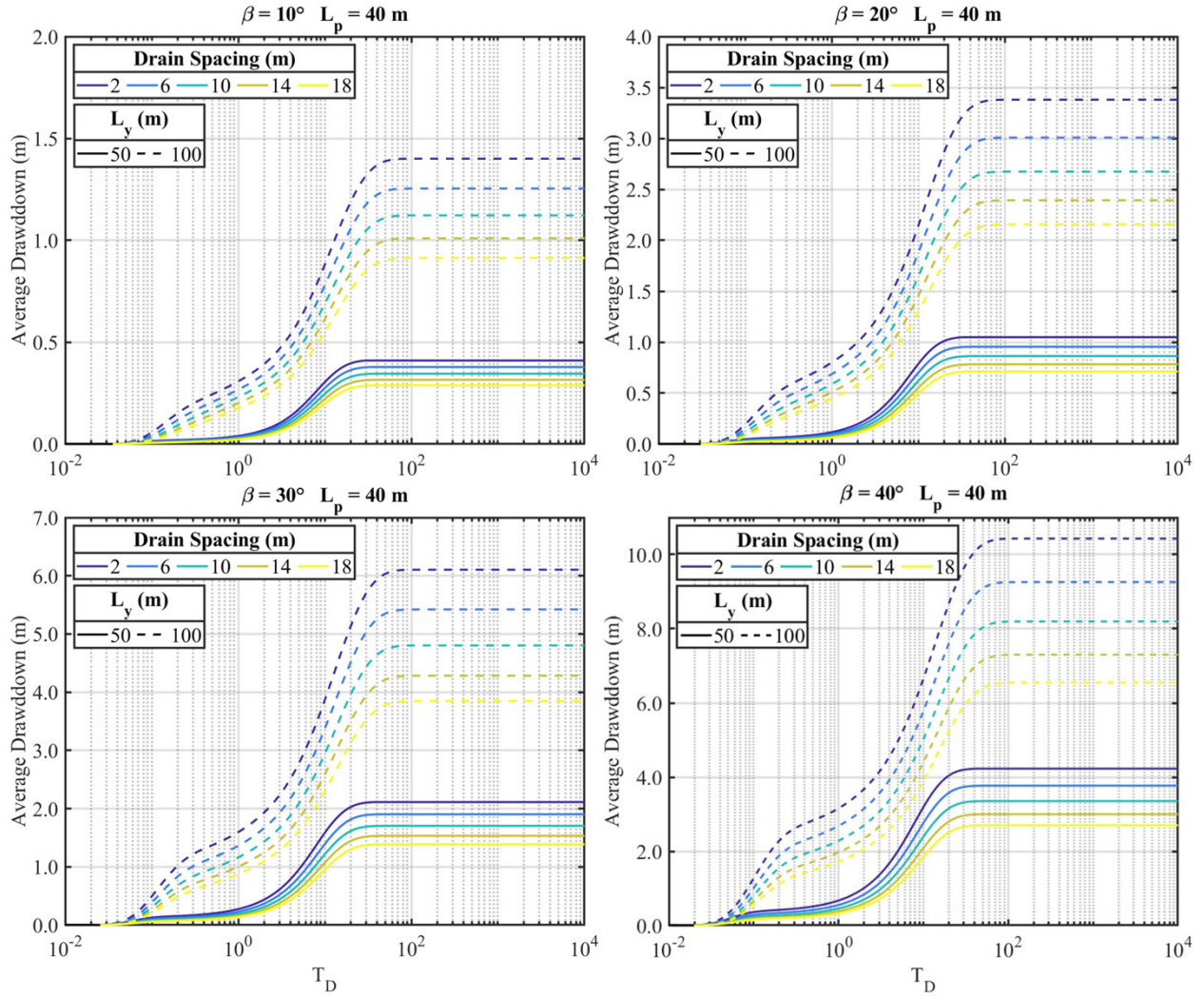


Figure 3.22. Transient average drawdown for drain length of $L_p = 40\text{m}$ on the failure surface of $L_z = 100\text{m}$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

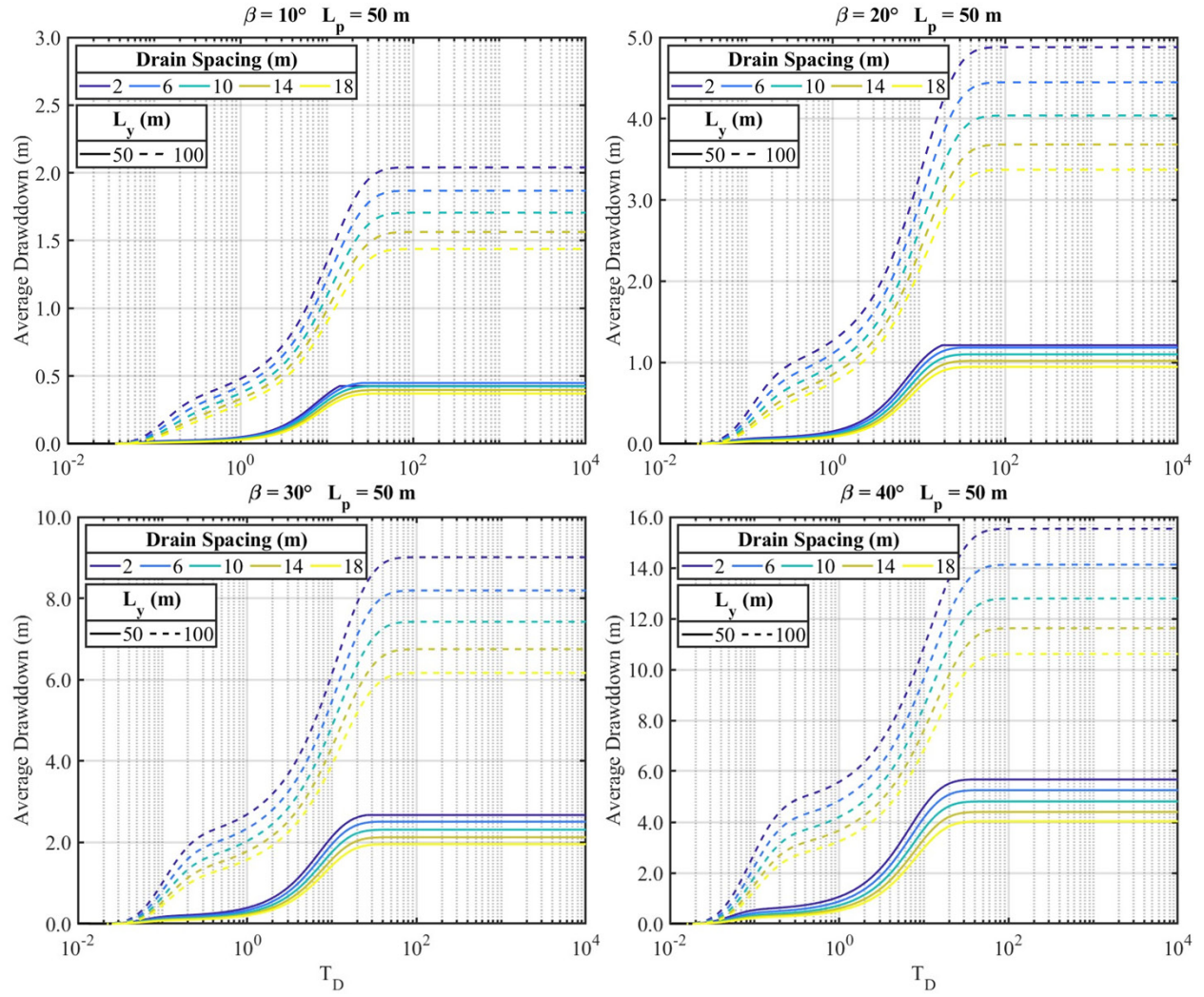


Figure 3.23. Transient average drawdown for drain length of $L_p = 50m$ on the failure surface of $L_z = 100m$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

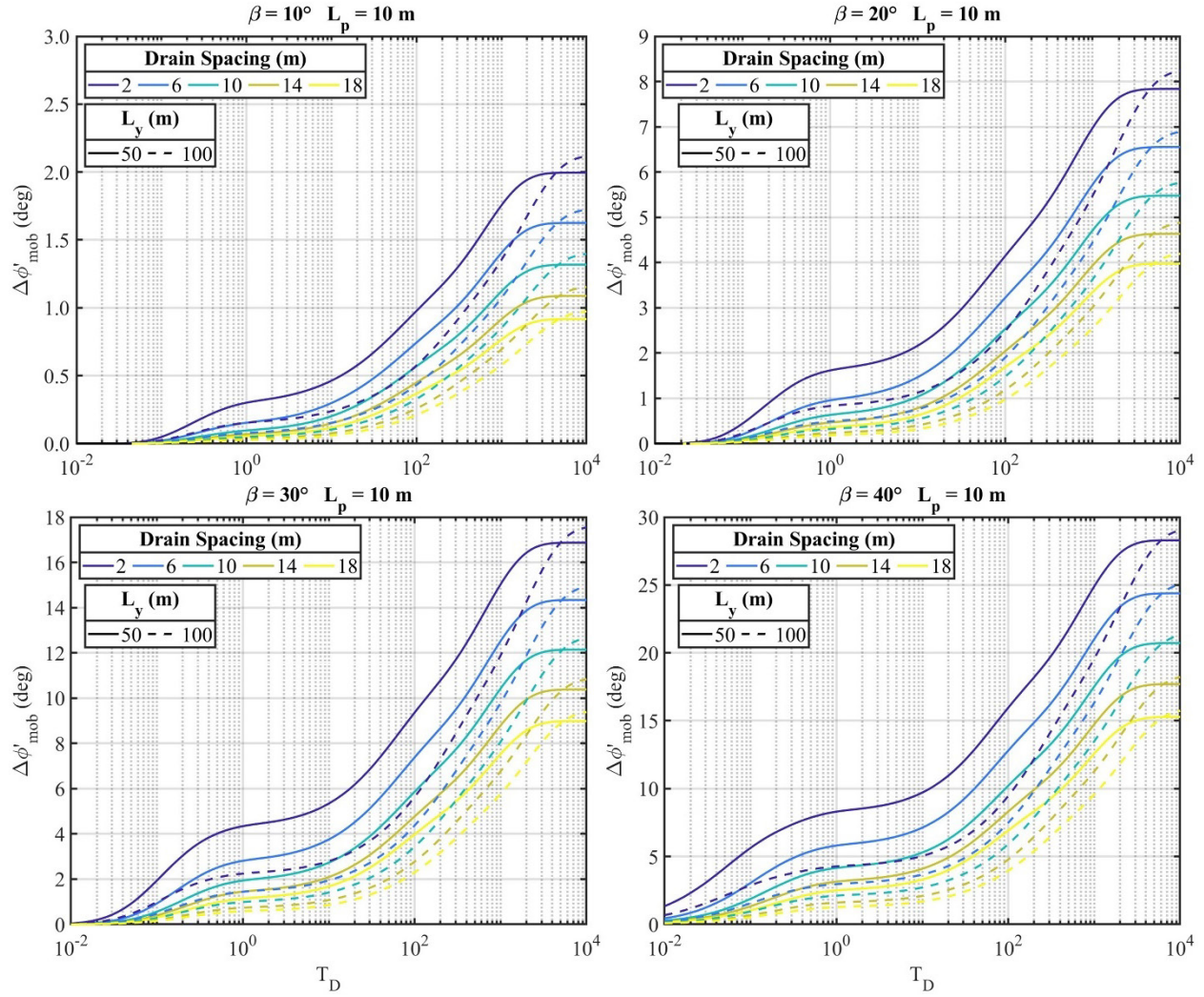


Figure 3.24. Mobilized friction angle at the failure surface for drain length of $L_p = 10$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

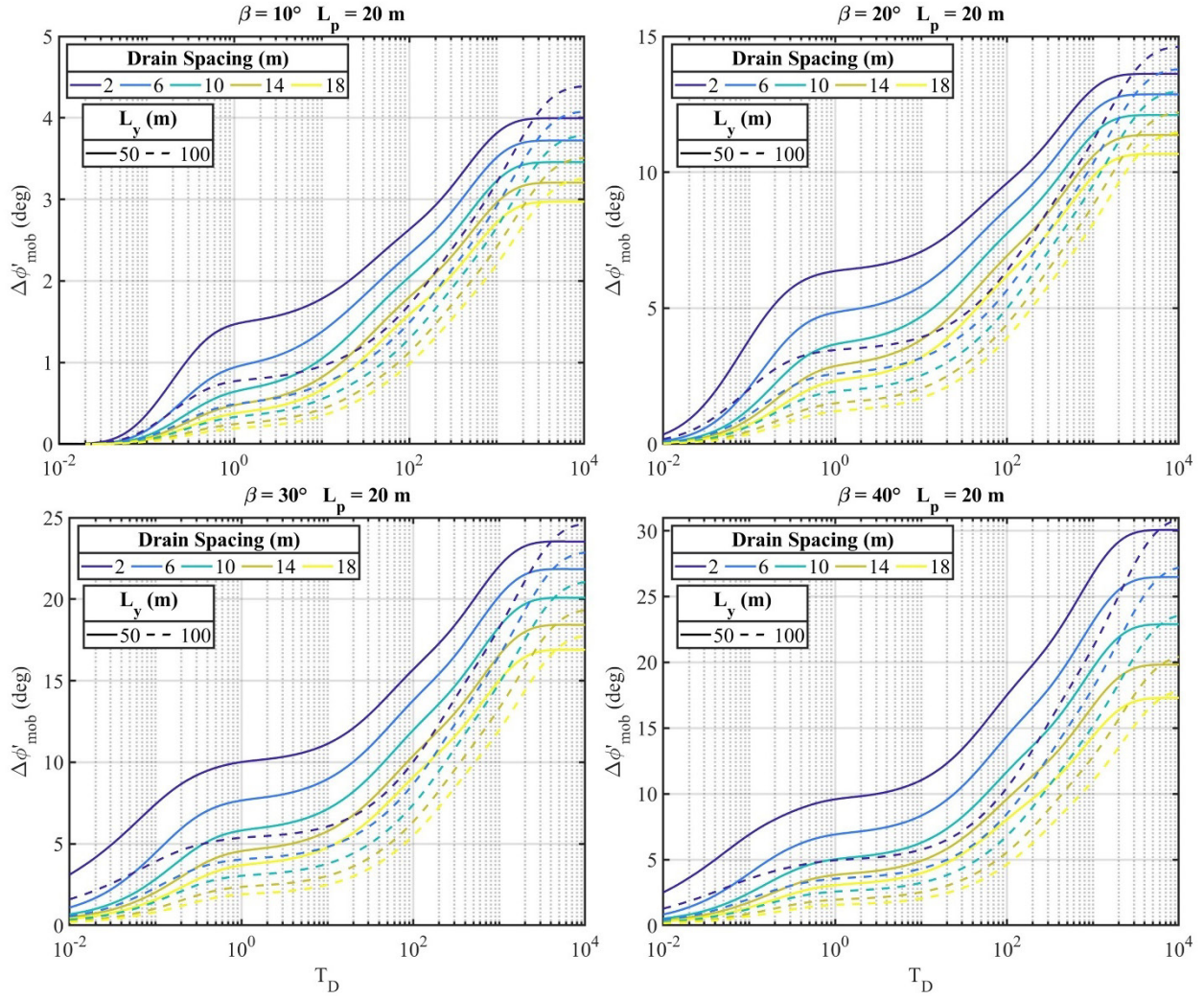


Figure 3.25. Mobilized friction angle at the failure surface for drain length of $L_p = 20$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

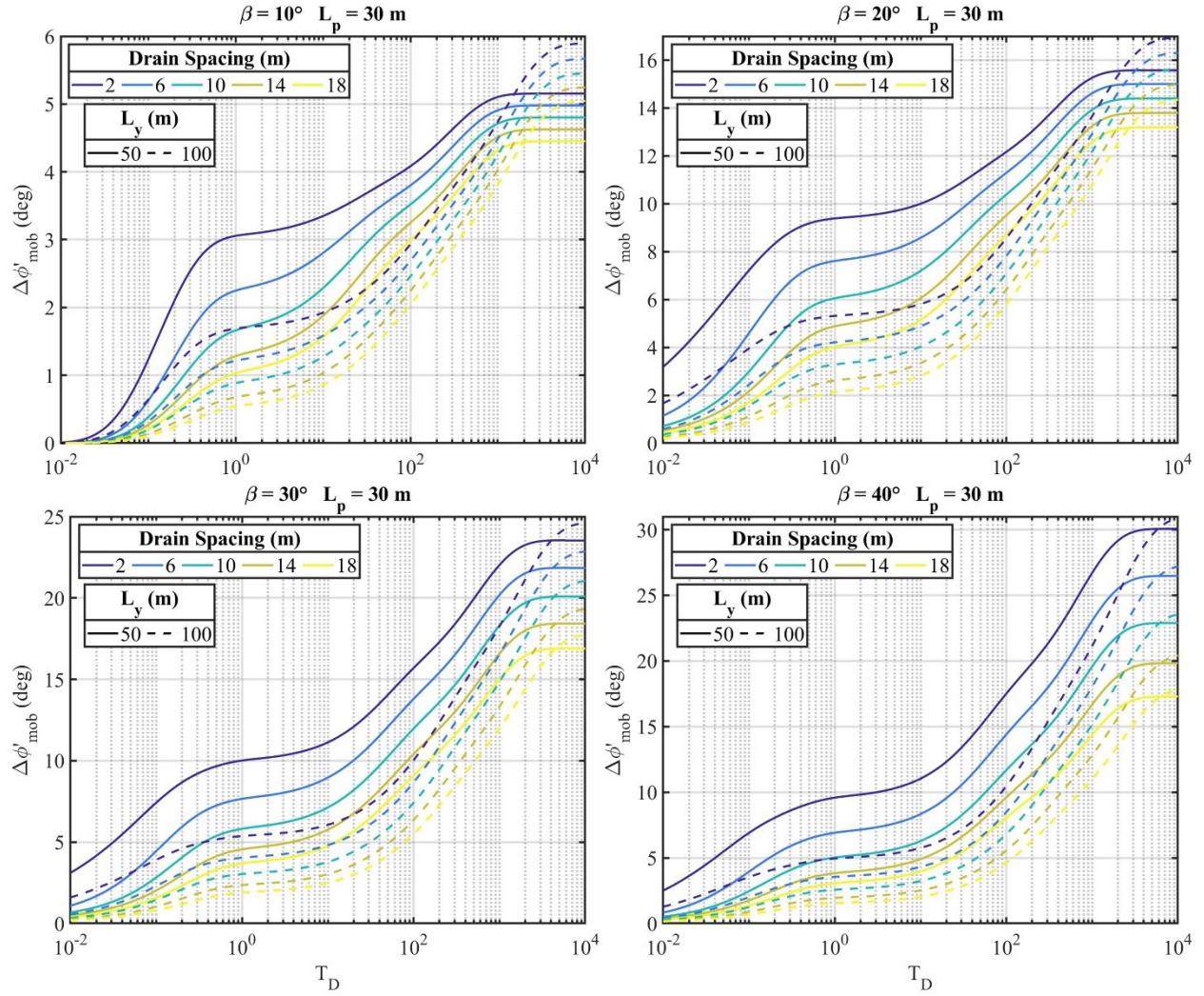


Figure 3.26. Mobilized friction angle at the failure surface for drain length of $L_p = 30m$ on the failure surface of $L_z = 10m$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

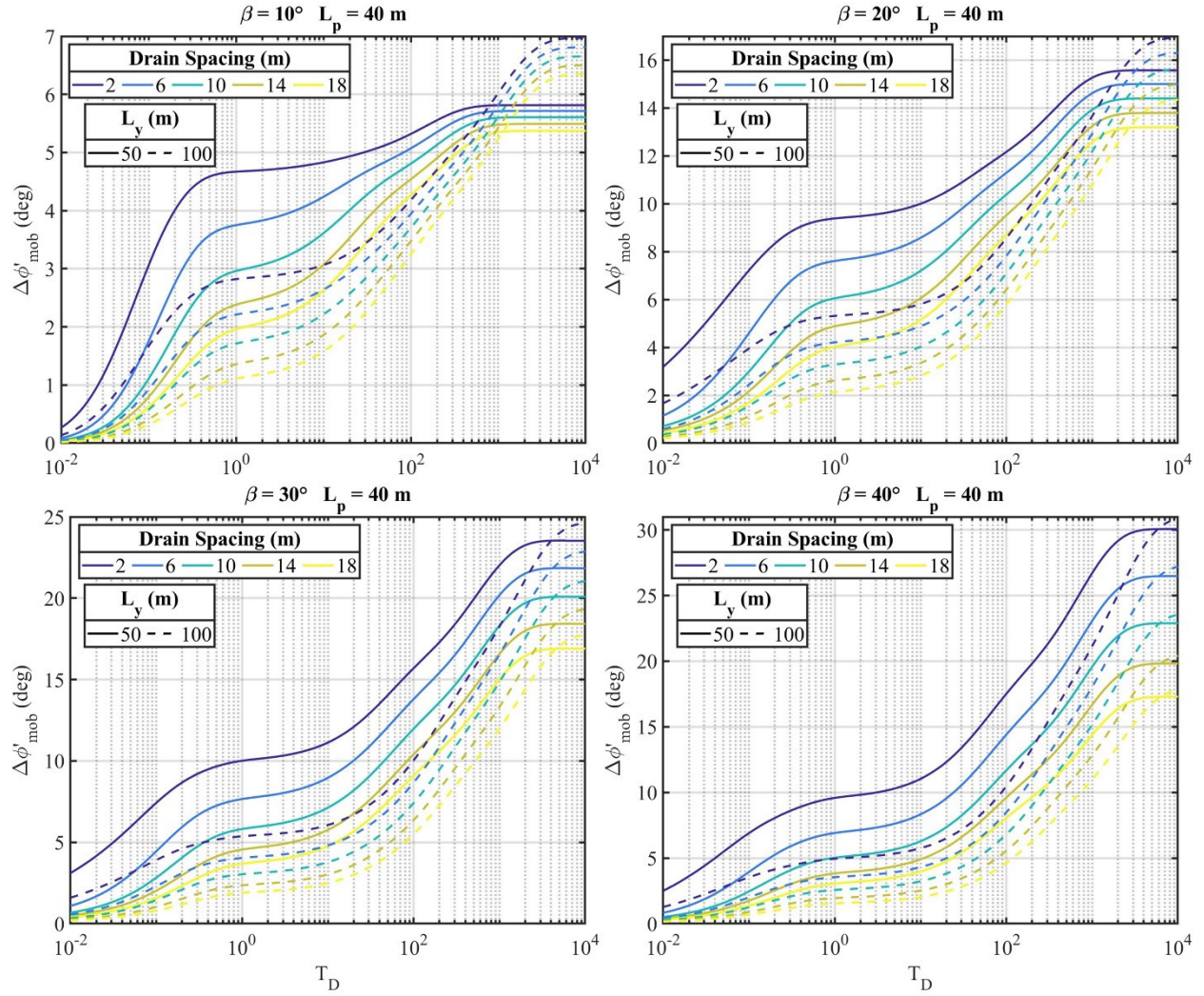


Figure 3.27. Mobilized friction angle at the failure surface for drain length of $L_p = 40m$ on the failure surface of $L_z = 10m$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

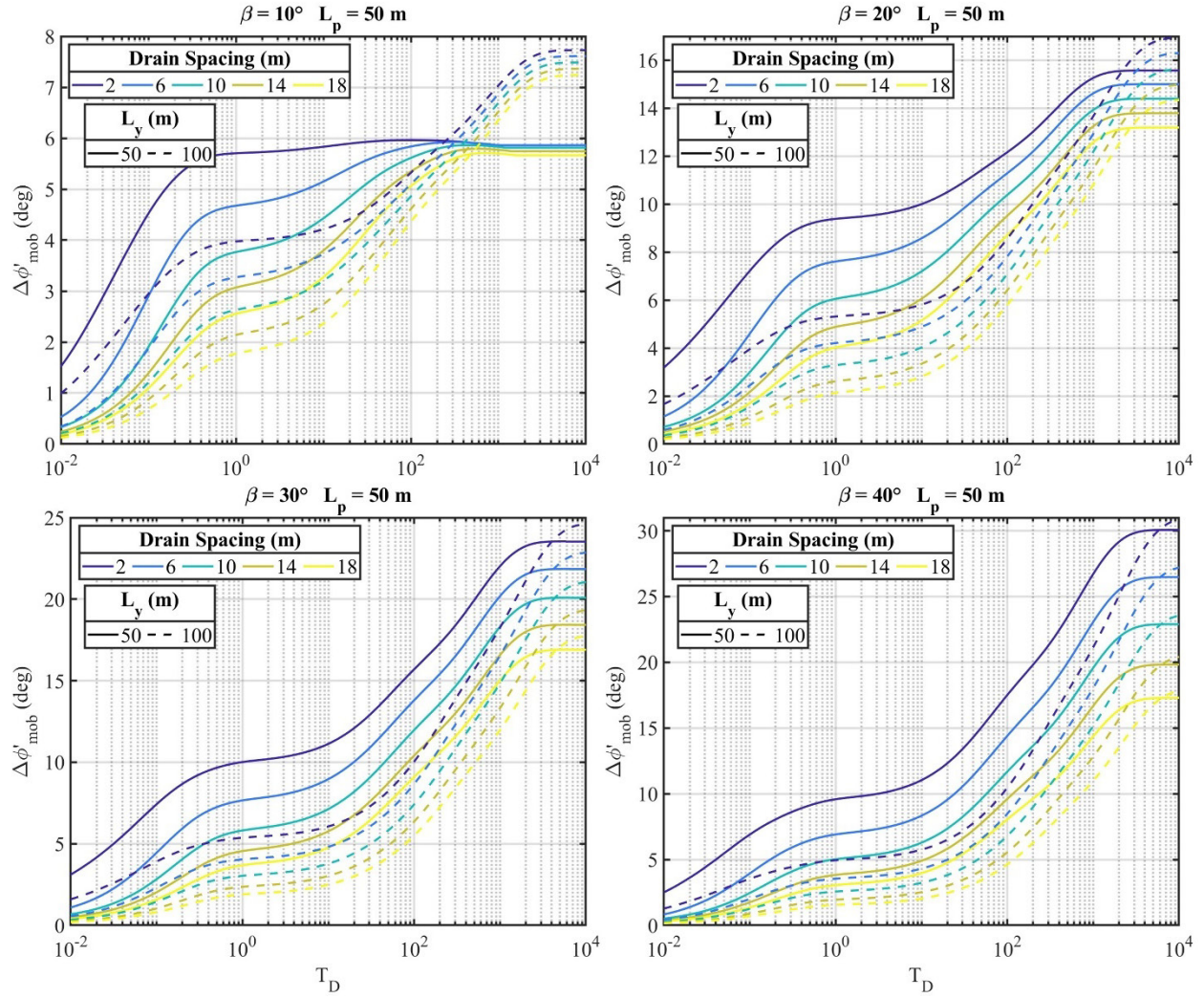


Figure 3.28. Mobilized friction angle at the failure surface for drain length of $L_p = 50$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

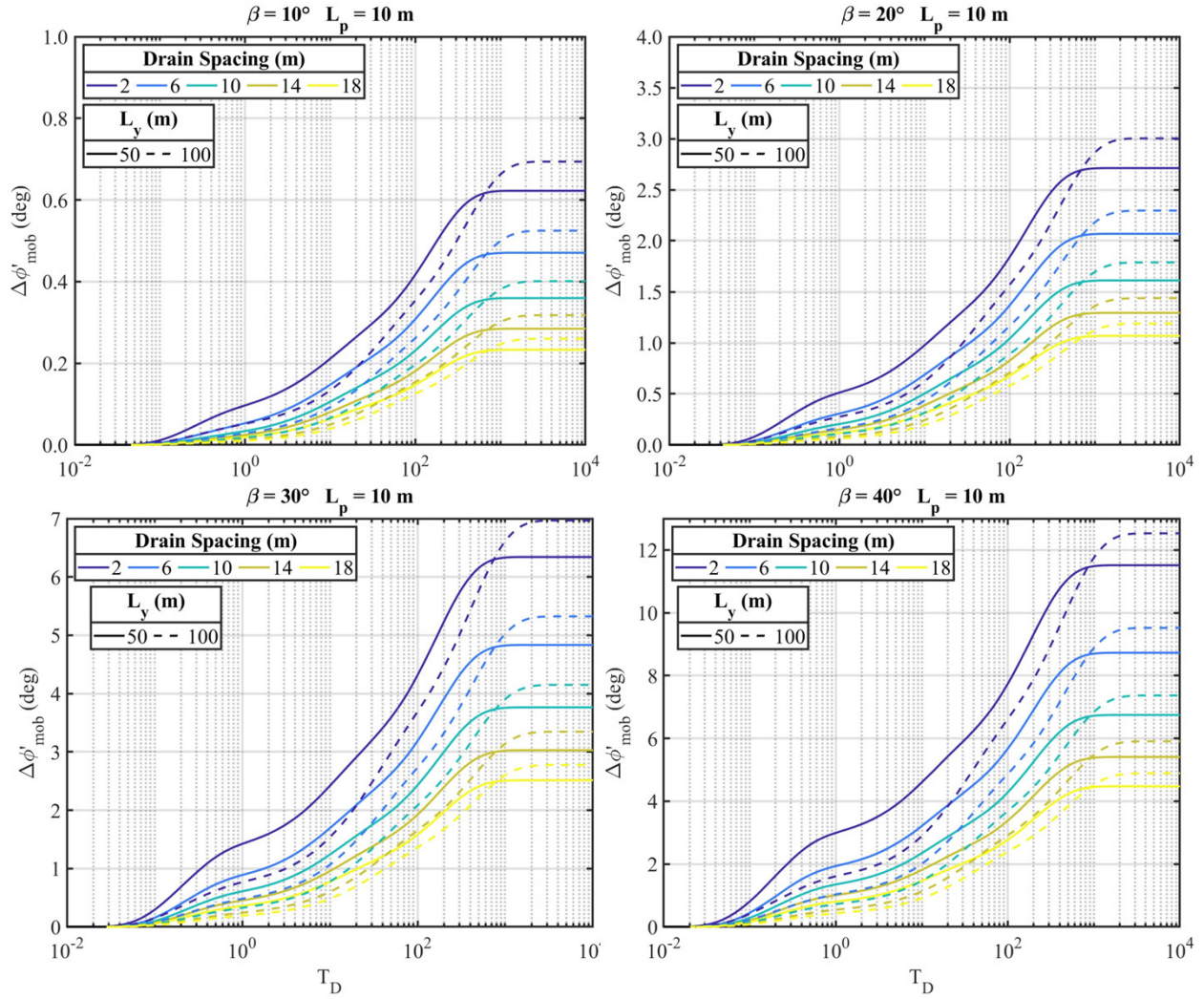


Figure 3.29. Mobilized friction angle at the failure surface for drain length of $L_p = 10$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

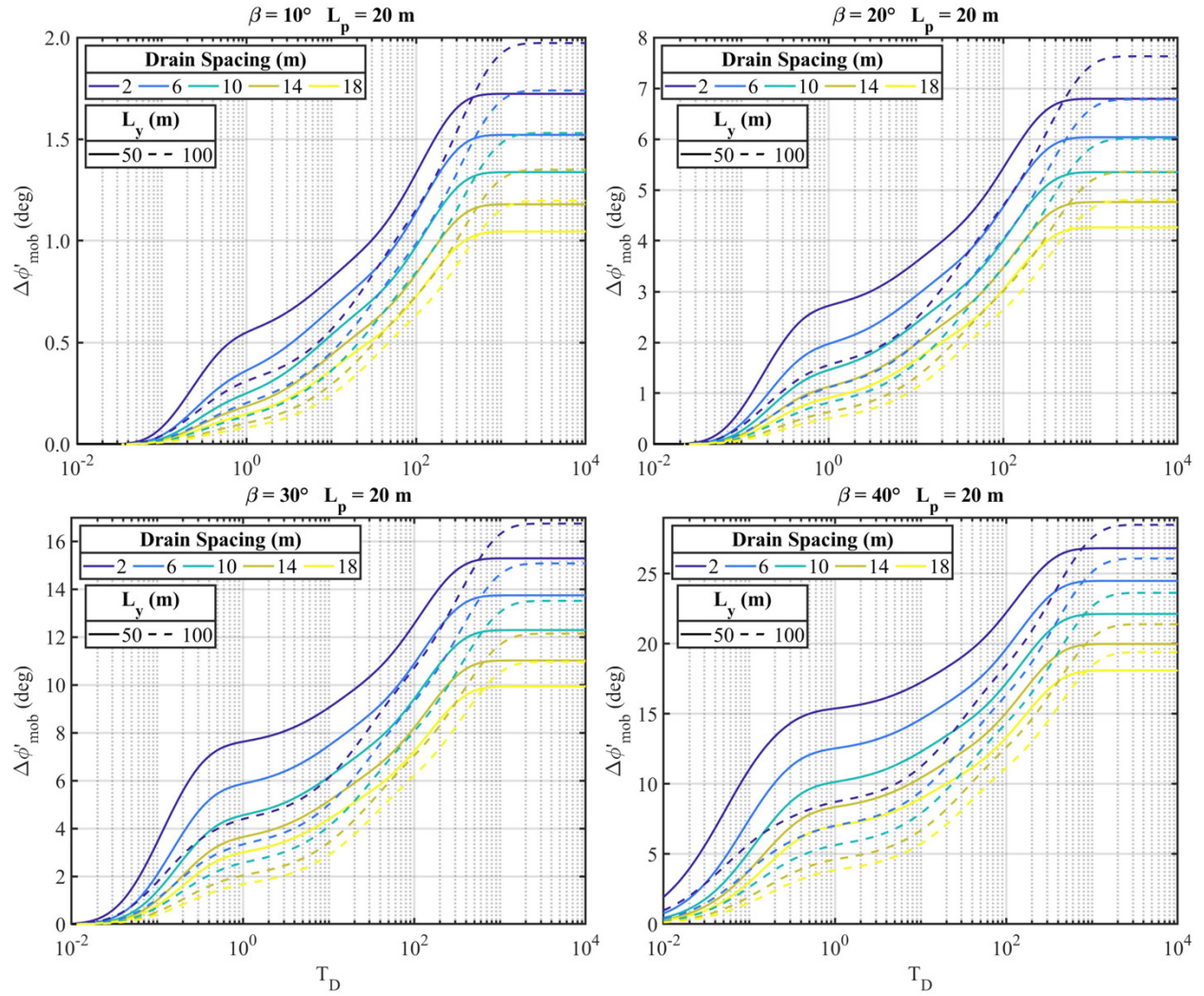


Figure 3.30. Mobilized friction angle at the failure surface for drain length of $L_p = 20m$ on the failure surface of $L_z = 20m$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

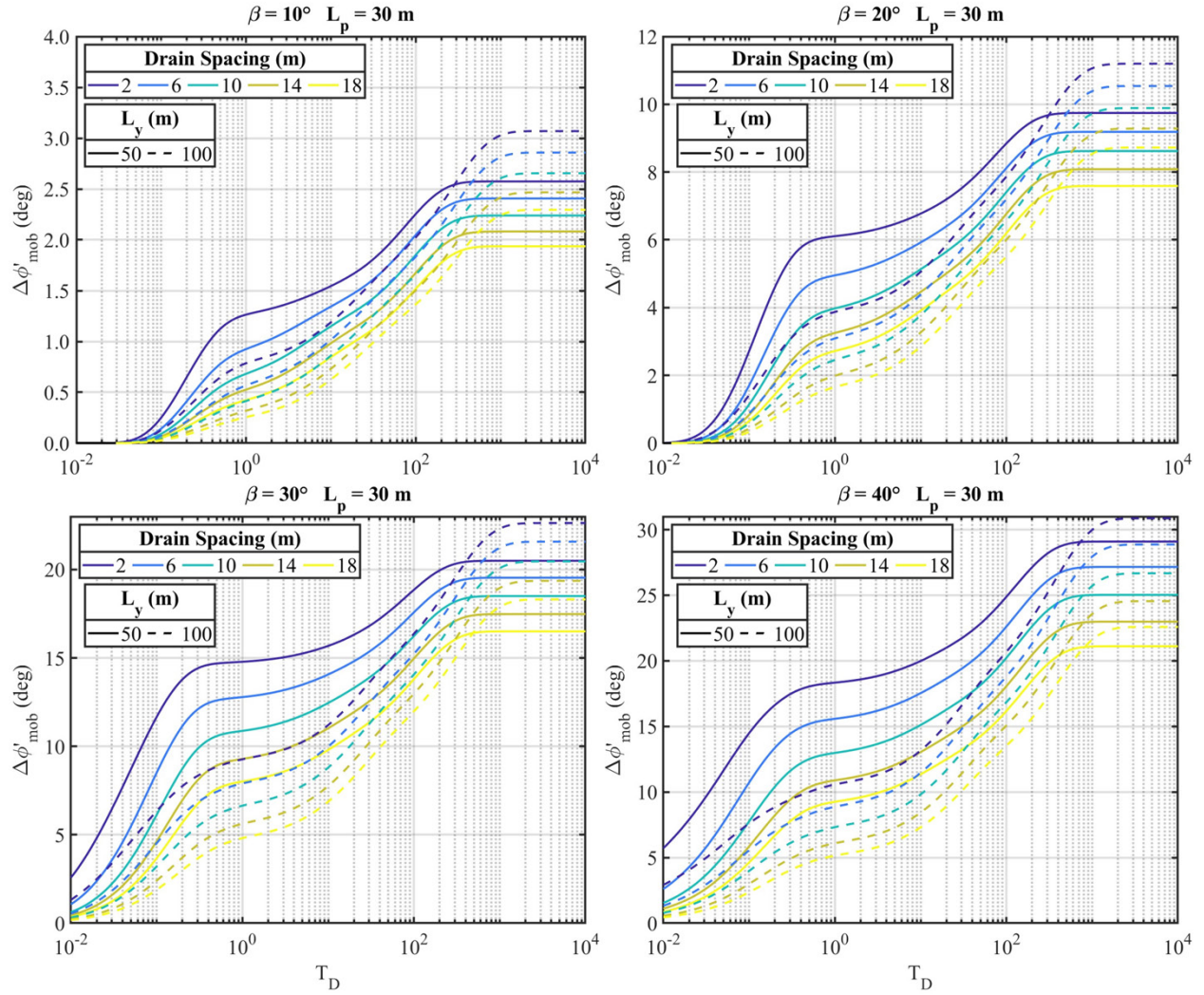


Figure 3.31. Mobilized friction angle at the failure surface for drain length of $L_p = 30$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

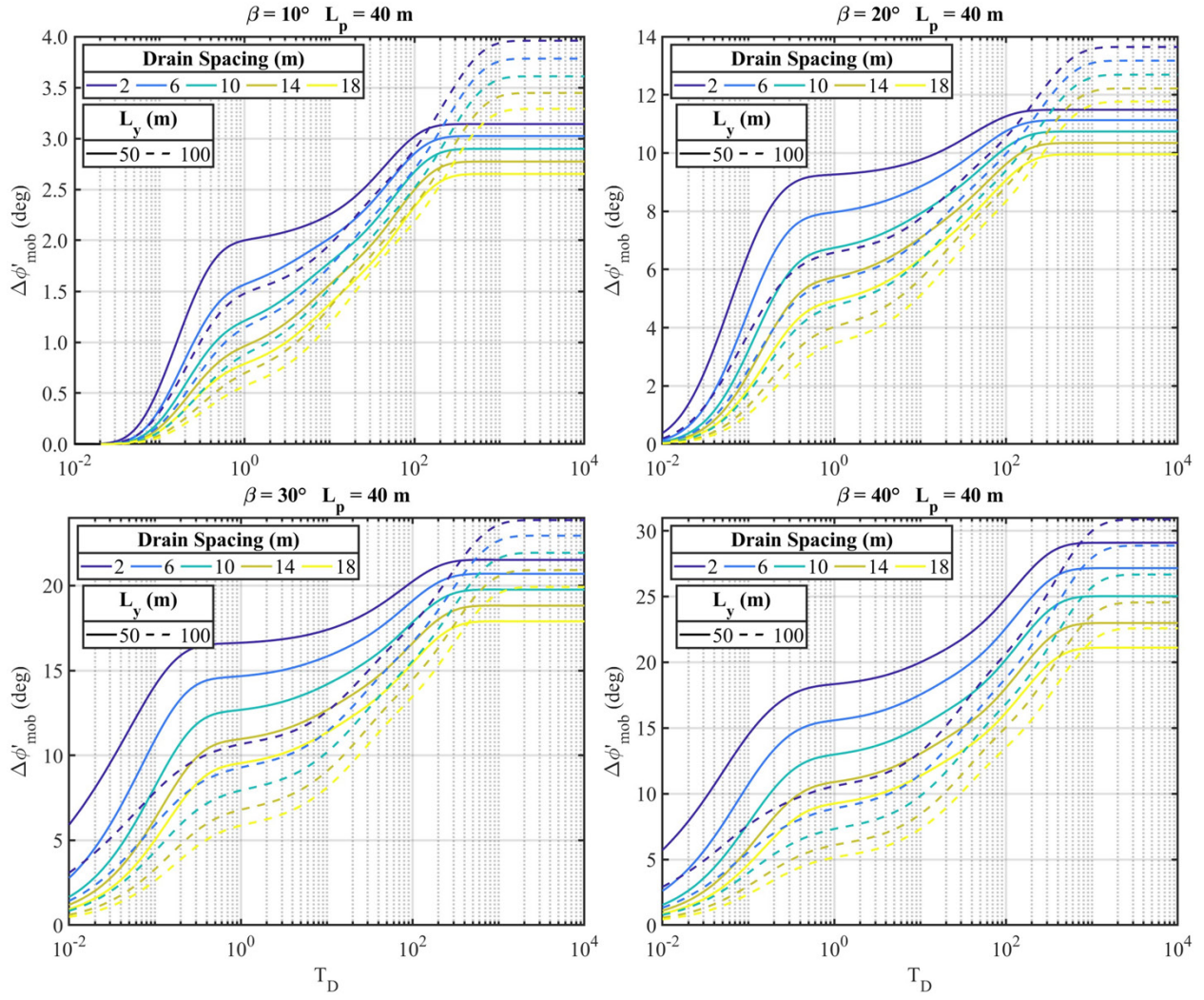


Figure 3.32. Mobilized friction angle at the failure surface for drain length of $L_p = 40$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

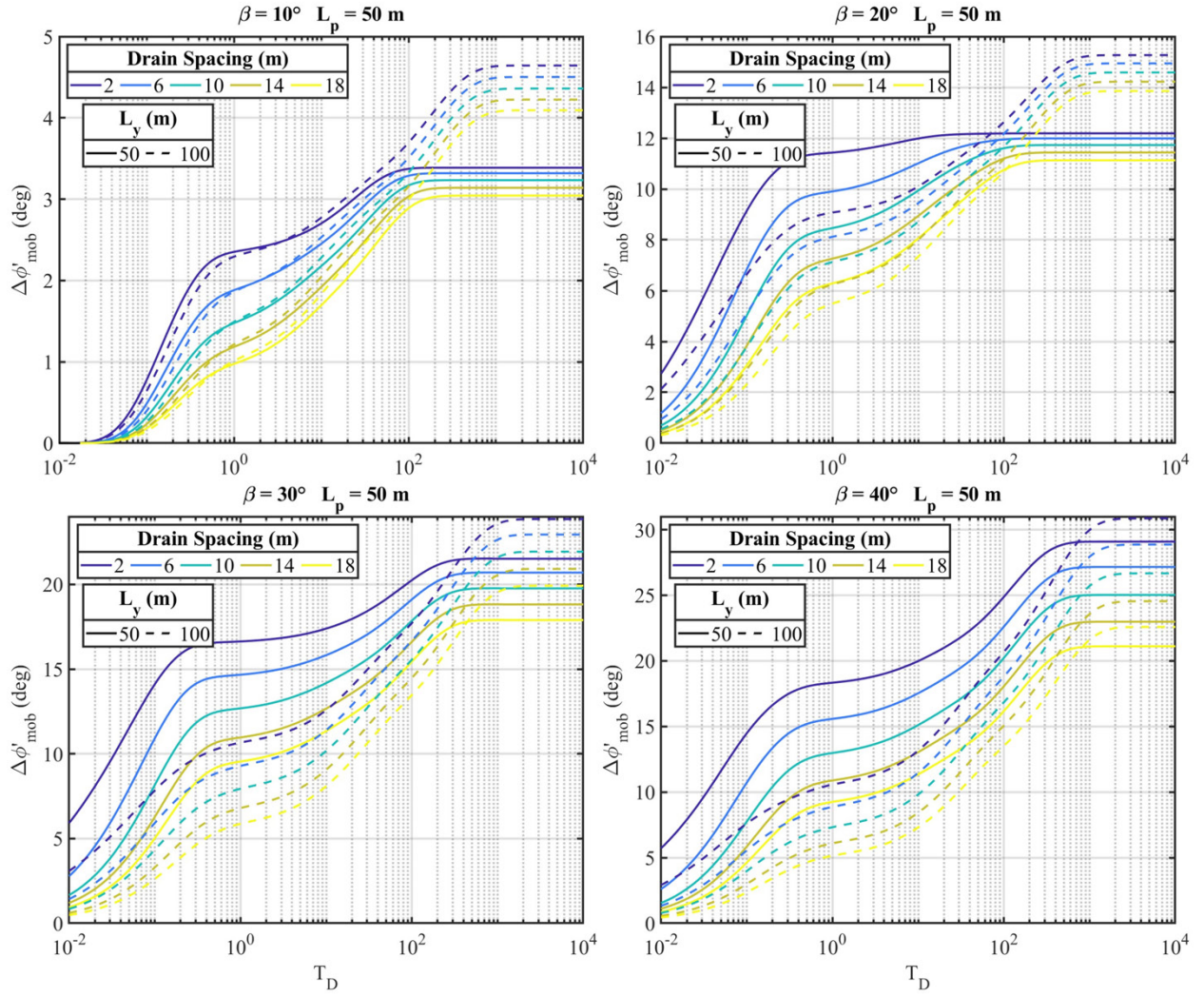


Figure 3.33. Mobilized friction angle at the failure surface for drain length of $L_p = 50$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

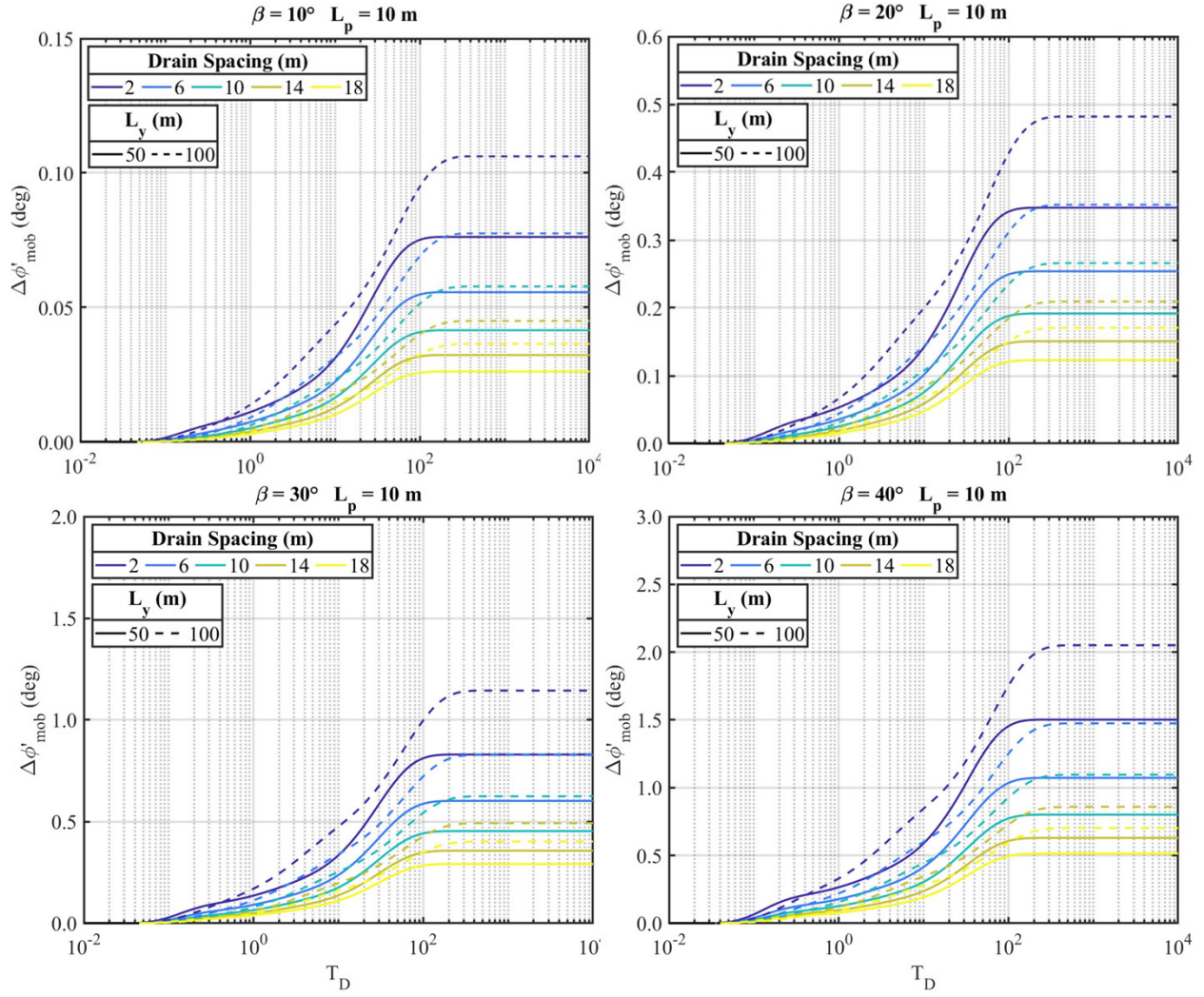


Figure 3.34. Mobilized friction angle at the failure surface for drain length of $L_p = 10$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

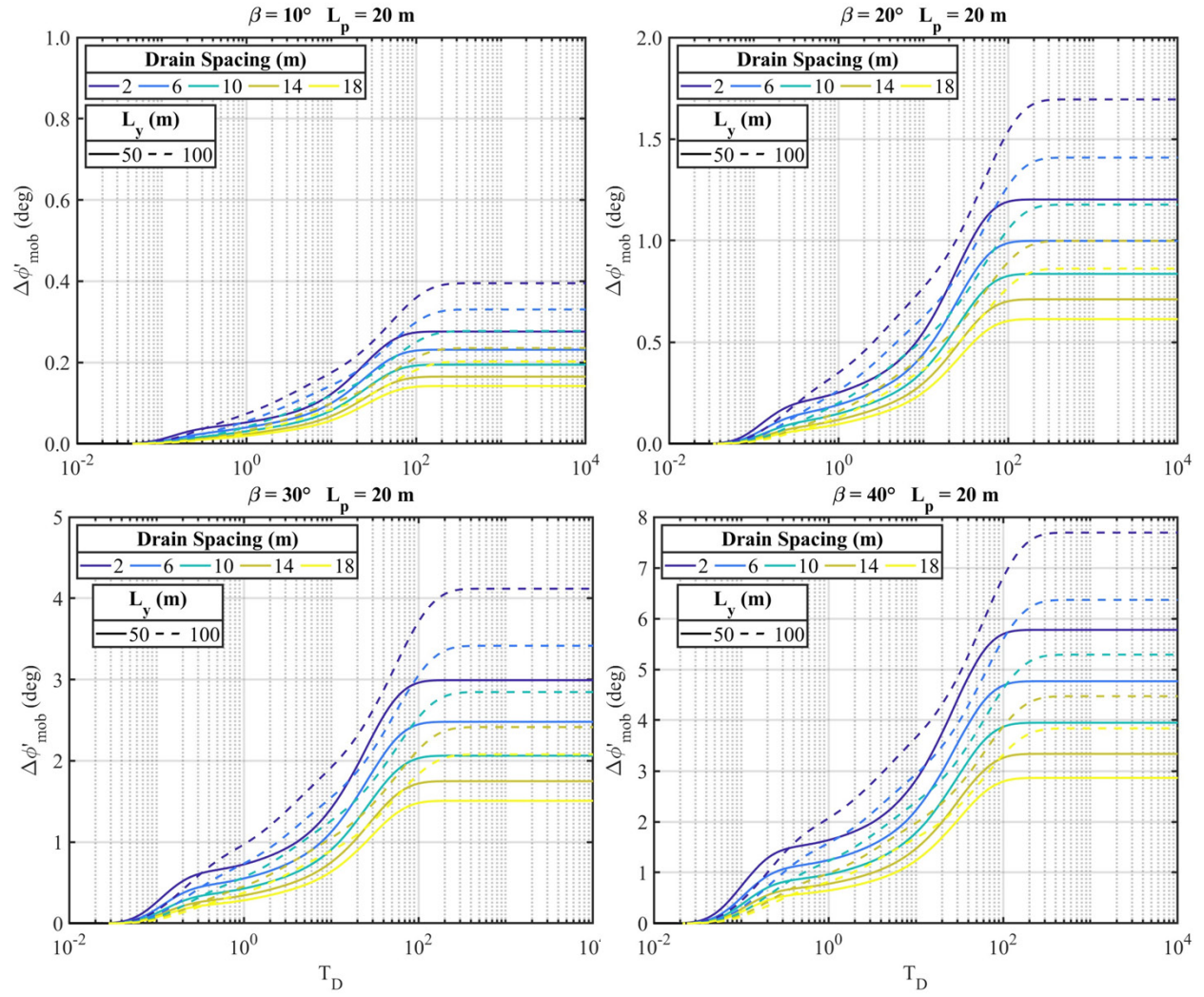


Figure 3.35. Mobilized friction angle at the failure surface for drain length of $L_p = 20$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

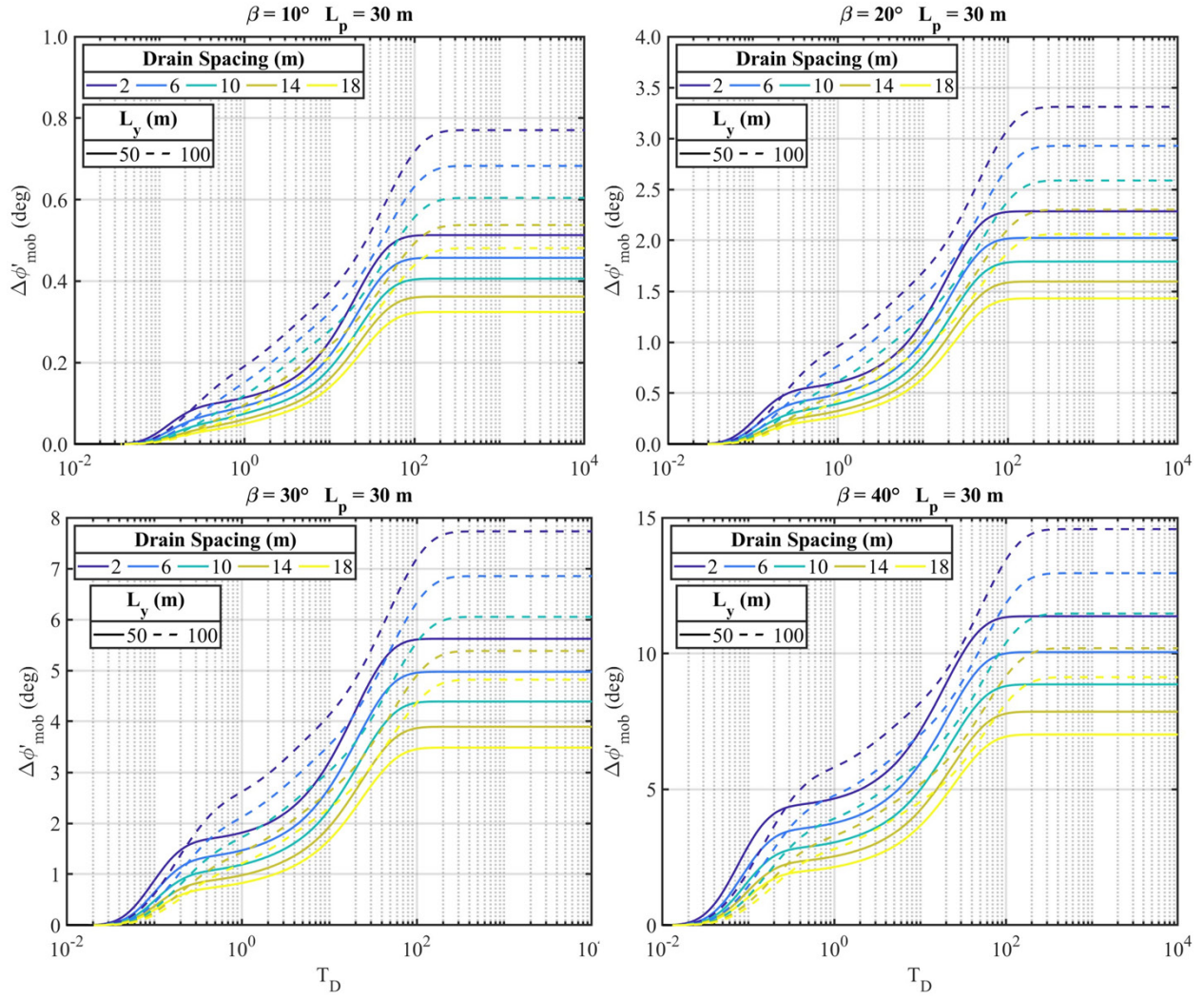


Figure 3.36. Mobilized friction angle at the failure surface for drain length of $L_p = 30m$ on the failure surface of $L_z = 50m$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

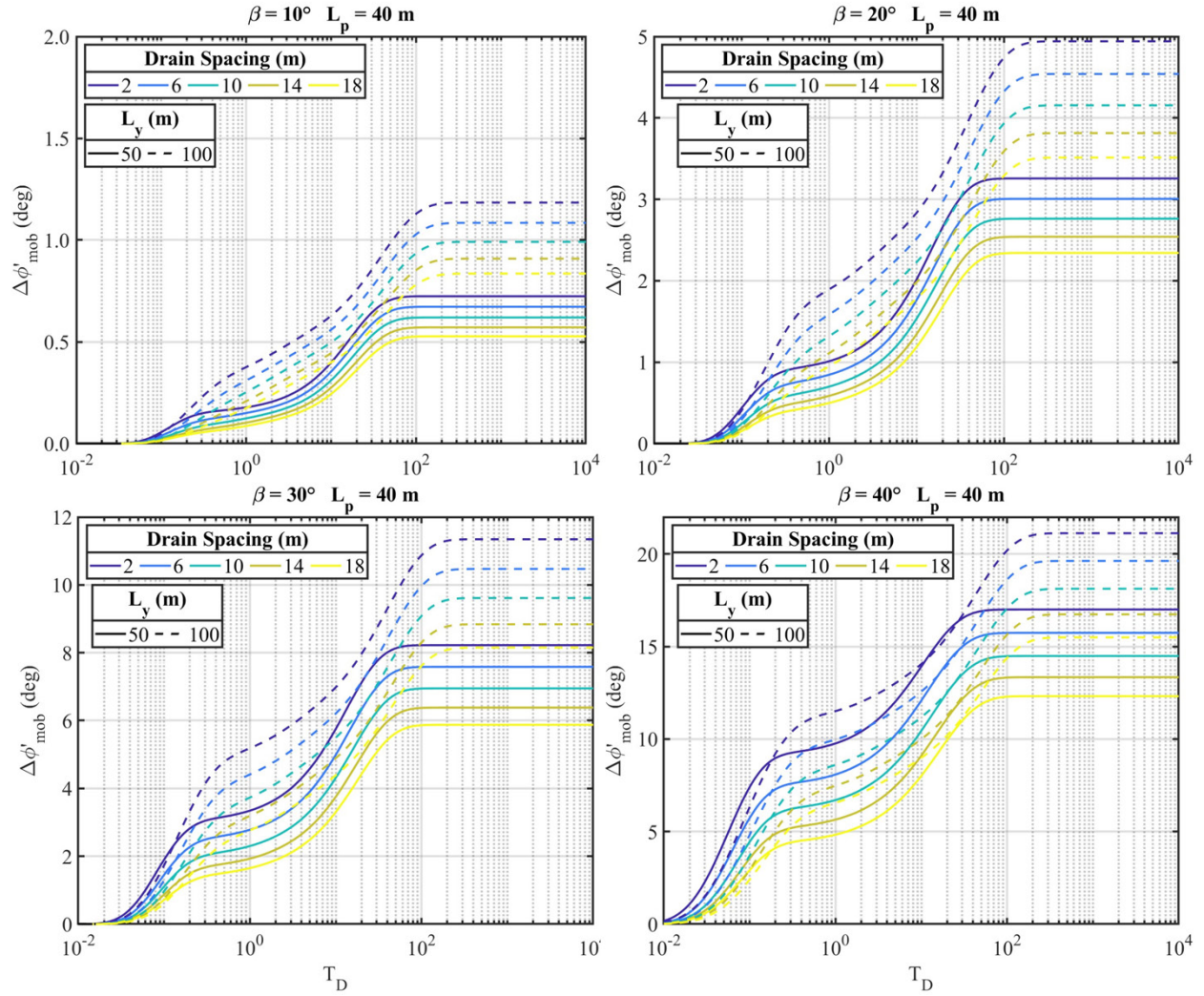


Figure 3.37. Mobilized friction angle at the failure surface for drain length of $L_p = 40$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

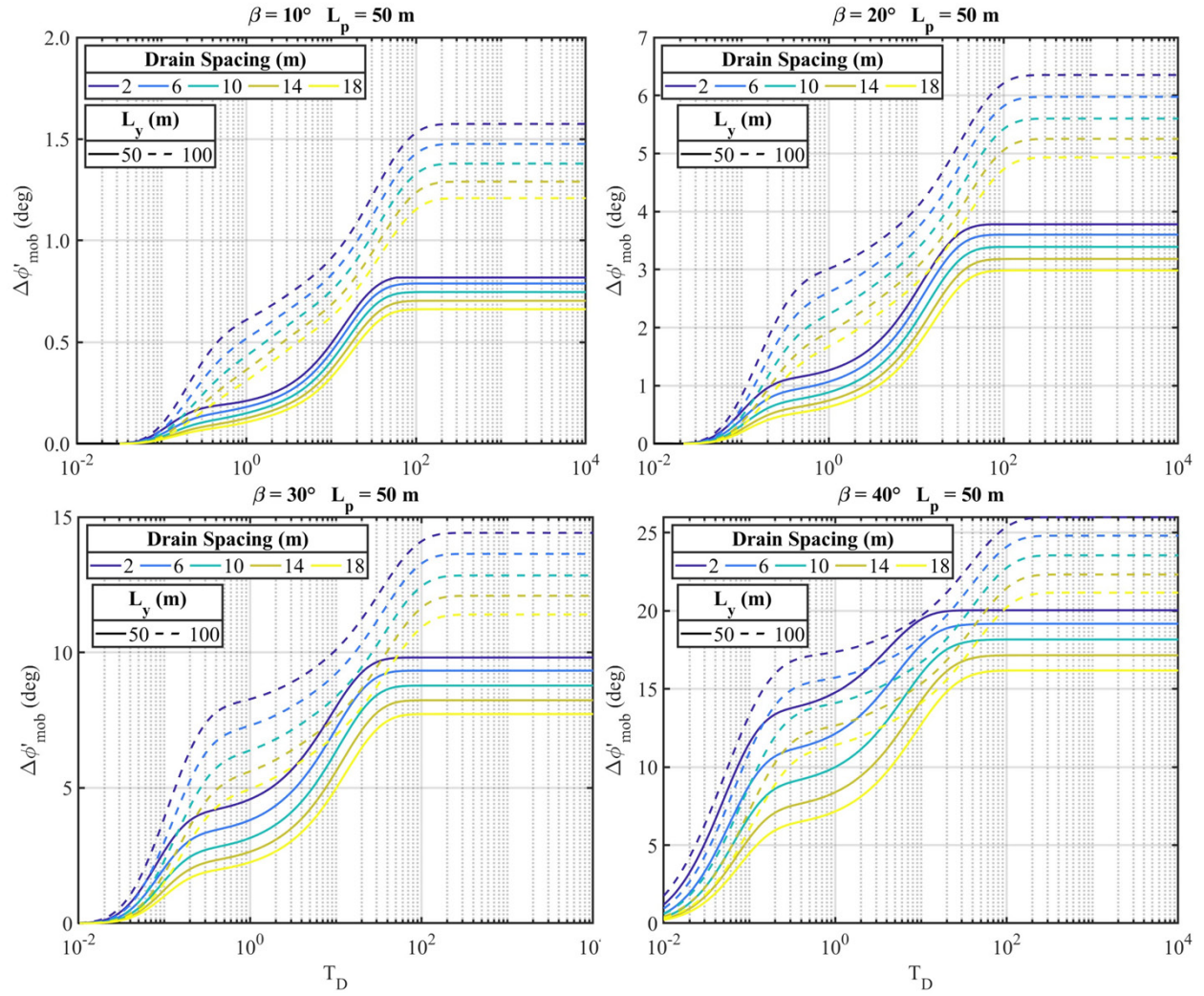


Figure 3.38. Mobilized friction angle at the failure surface for drain length of $L_p = 50$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

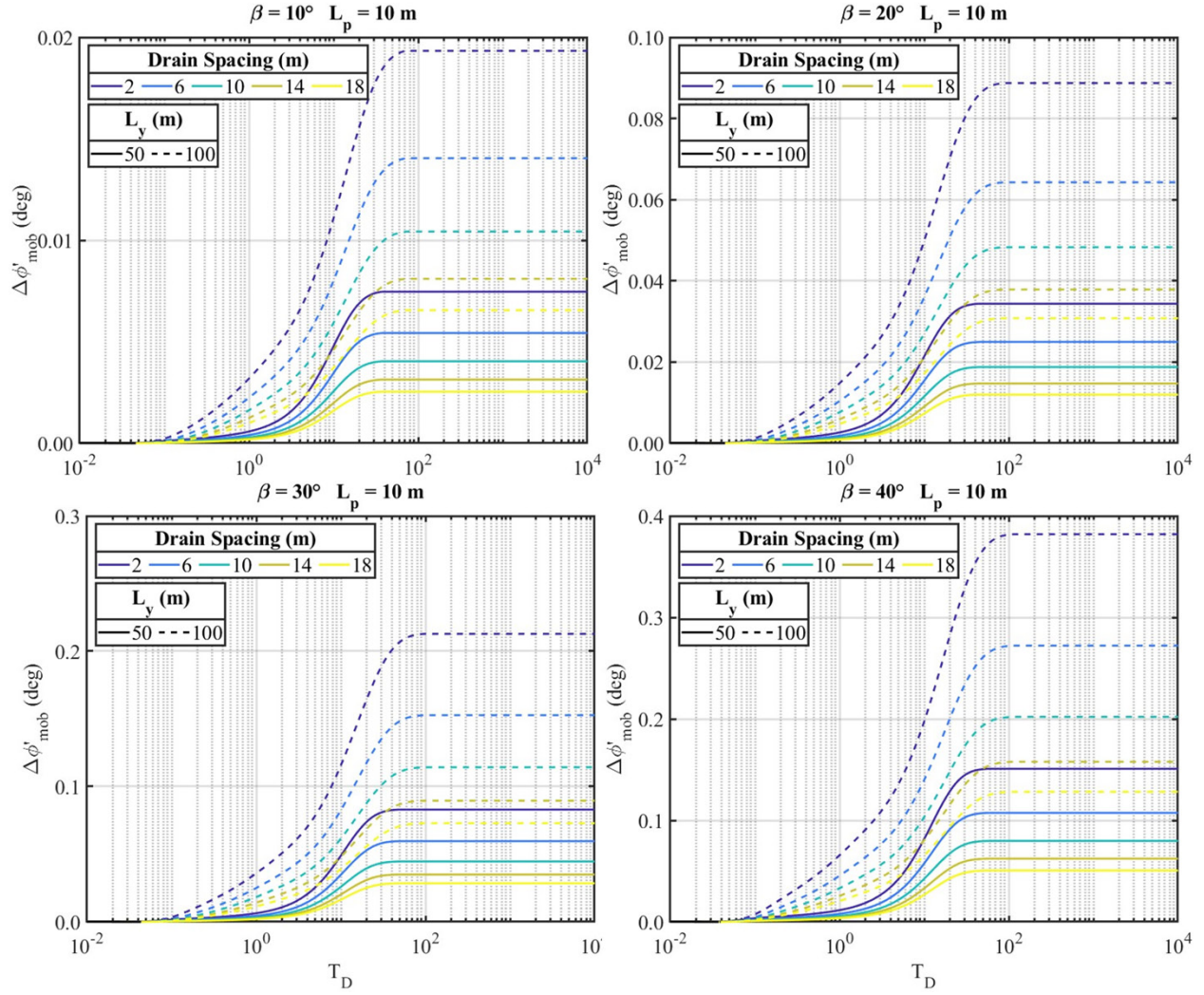


Figure 3.39. Mobilized friction angle at the failure surface for drain length of $L_p = 10$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

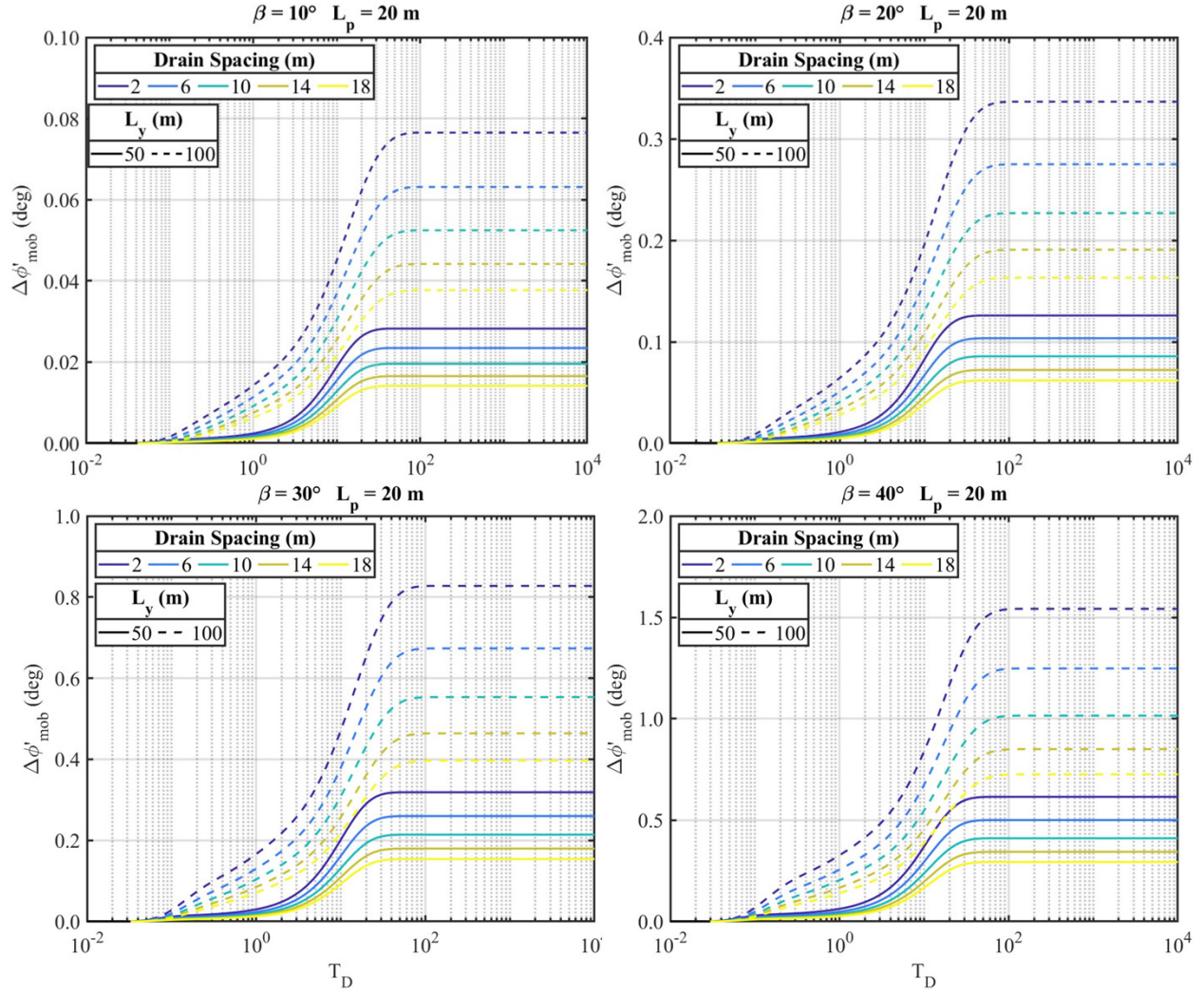


Figure 3.40. Mobilized friction angle at the failure surface for drain length of $L_p = 20$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

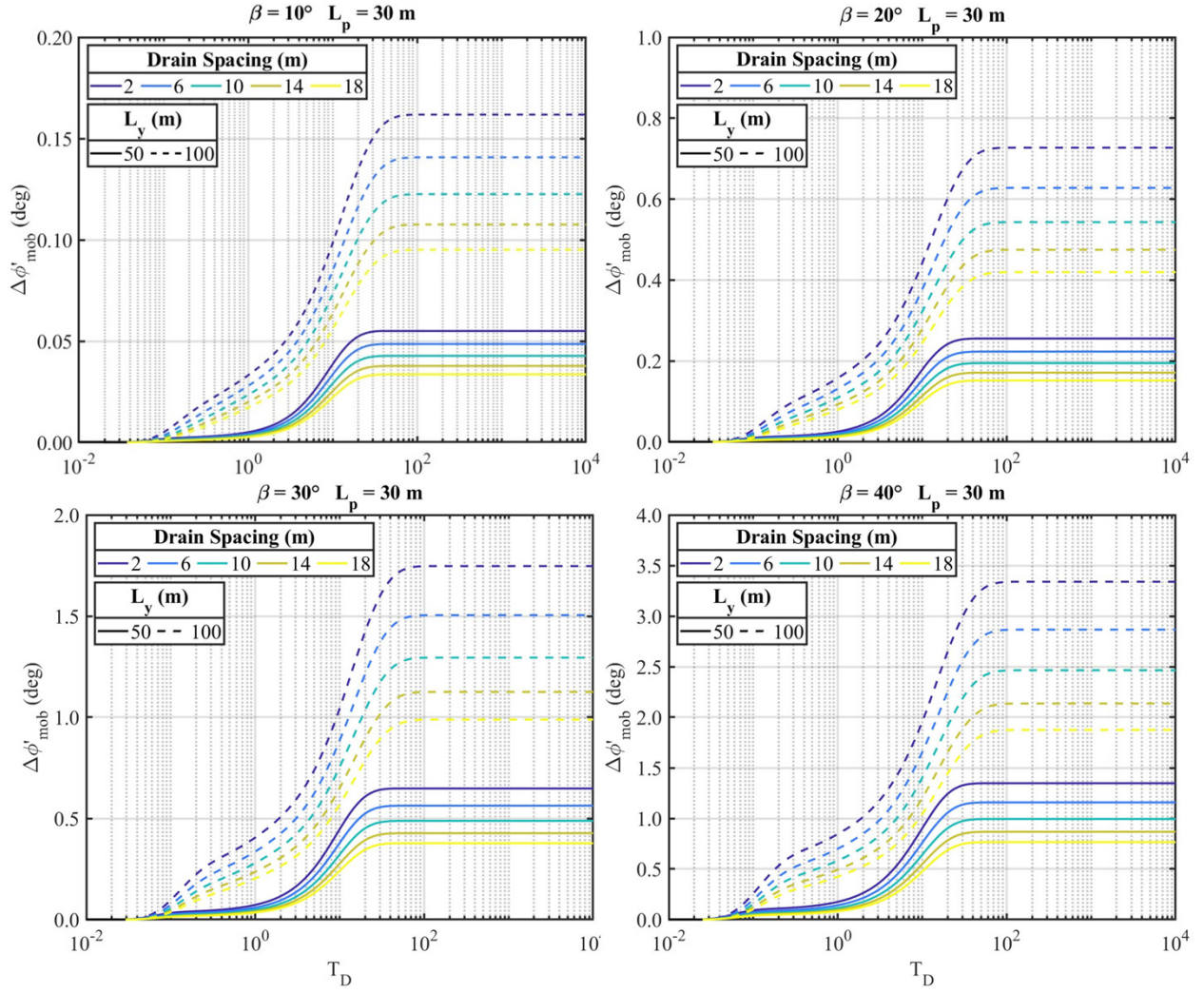


Figure 3.41. Mobilized friction angle at the failure surface for drain length of $L_p = 30$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

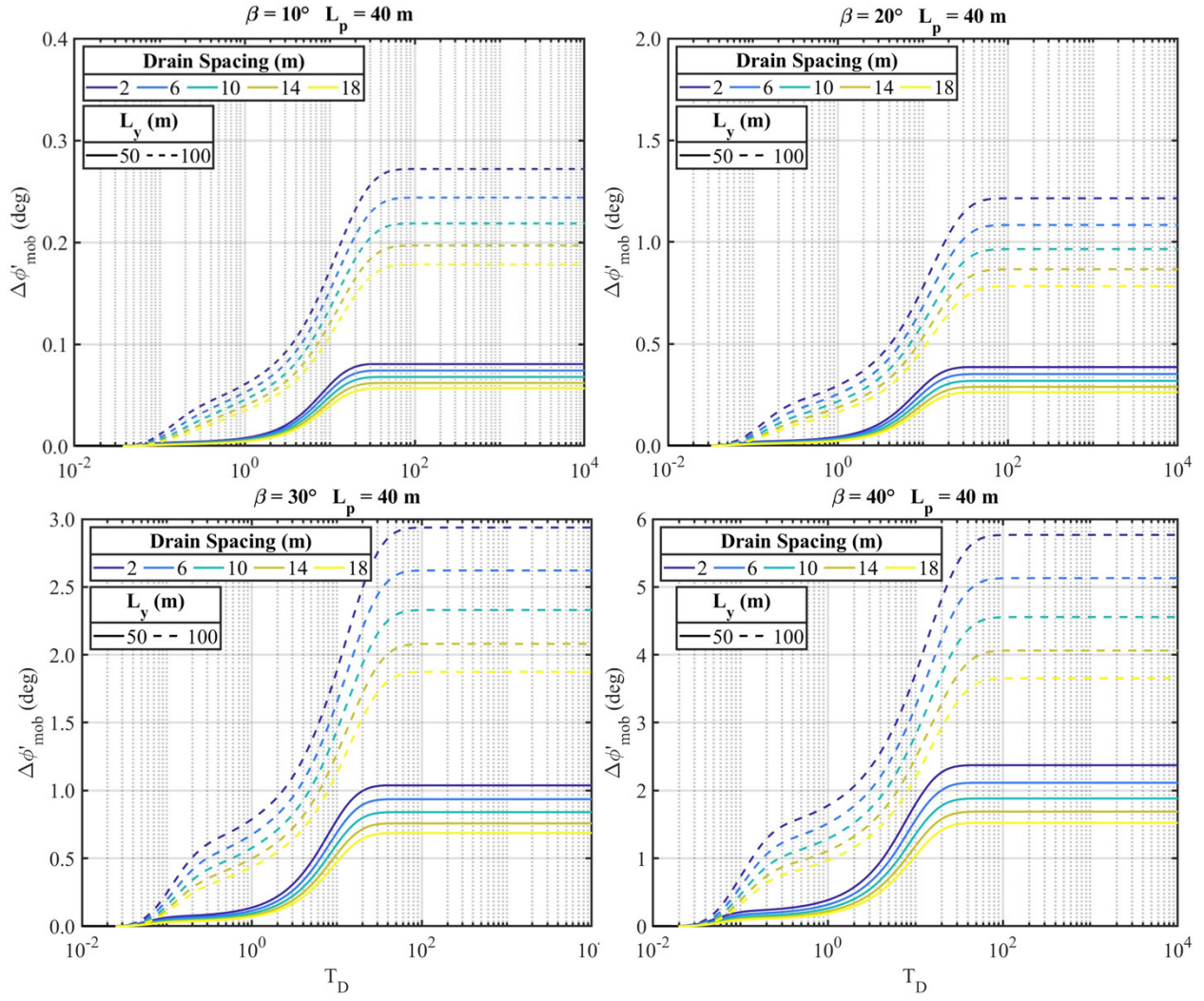


Figure 3.42. Mobilized friction angle at the failure surface for drain length of $L_p = 40$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

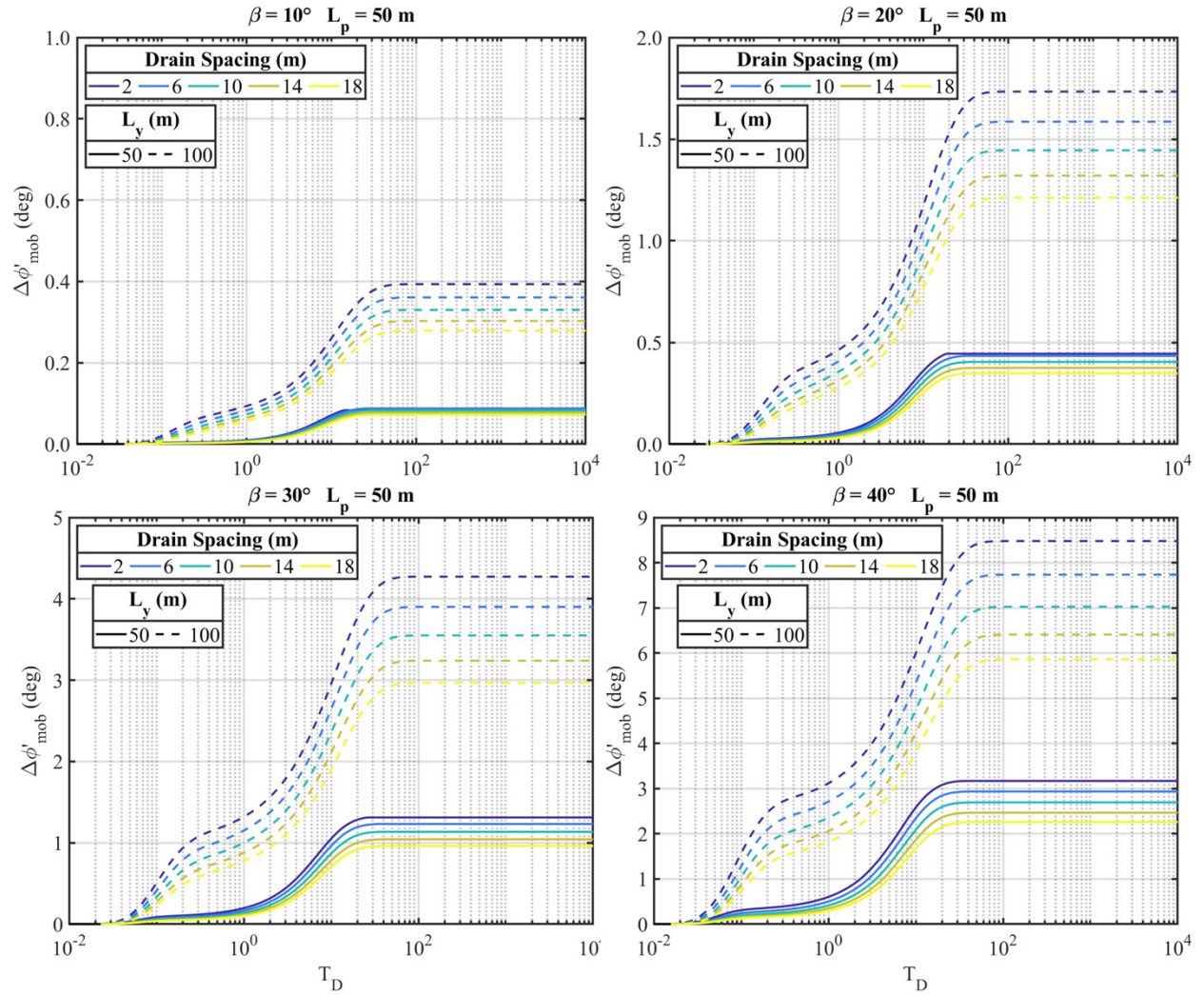


Figure 3.43. Mobilized friction angle at the failure surface for drain length of $L_p = 50$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

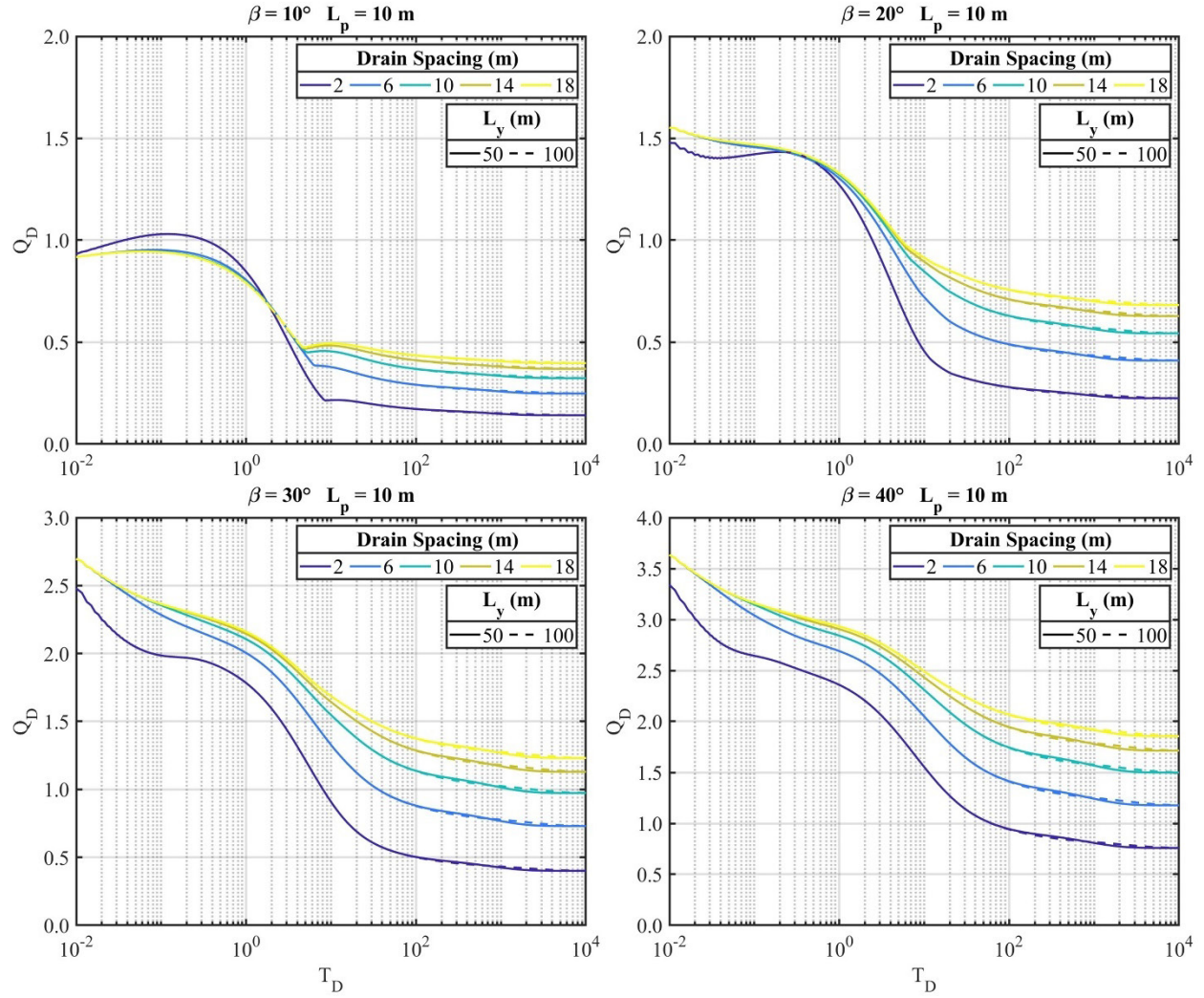


Figure 3.44. Total dimensionless outflow discharge for drain length of $L_p = 10$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

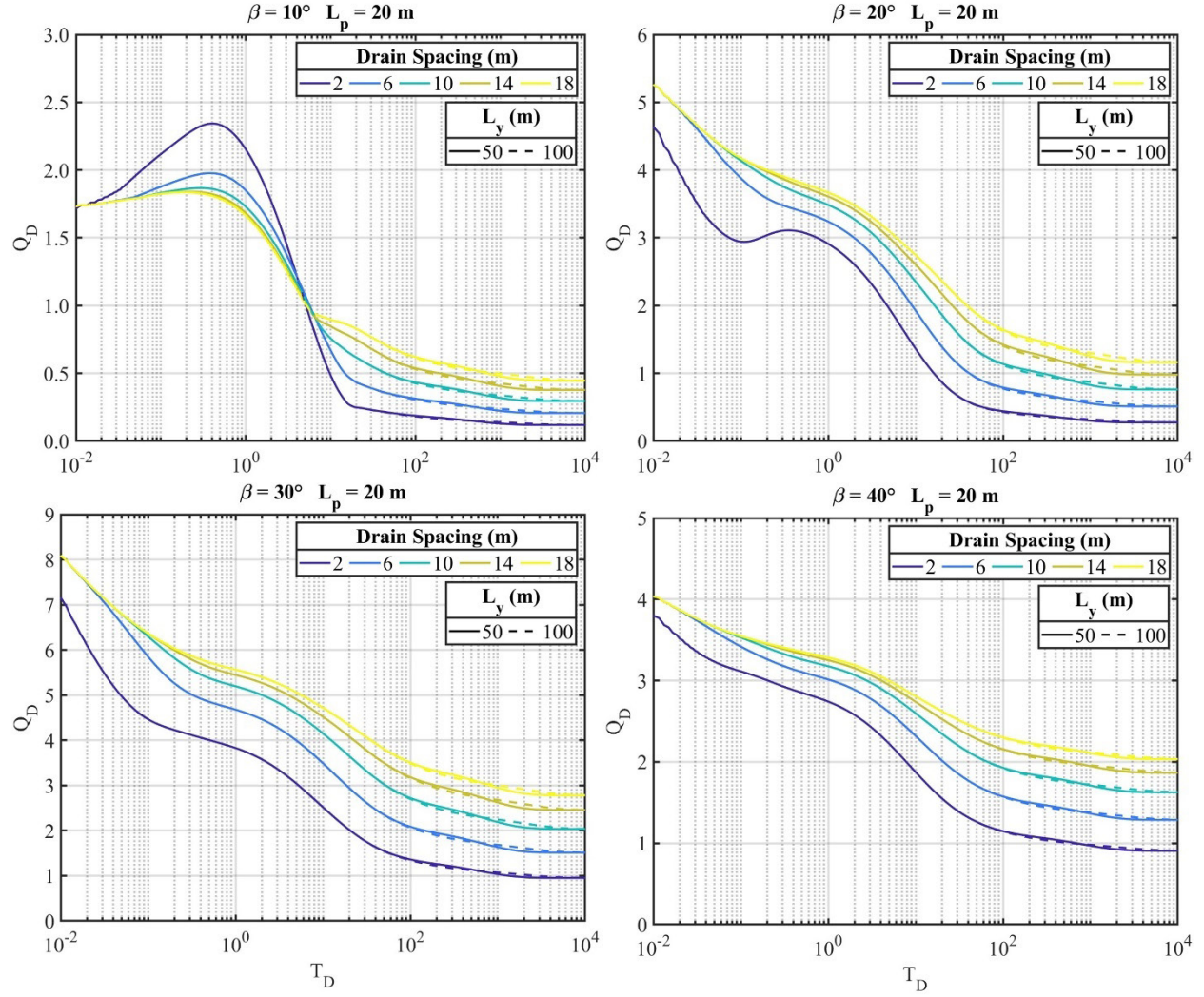


Figure 3.45. Total dimensionless outflow discharge for drain length of $L_p = 20$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

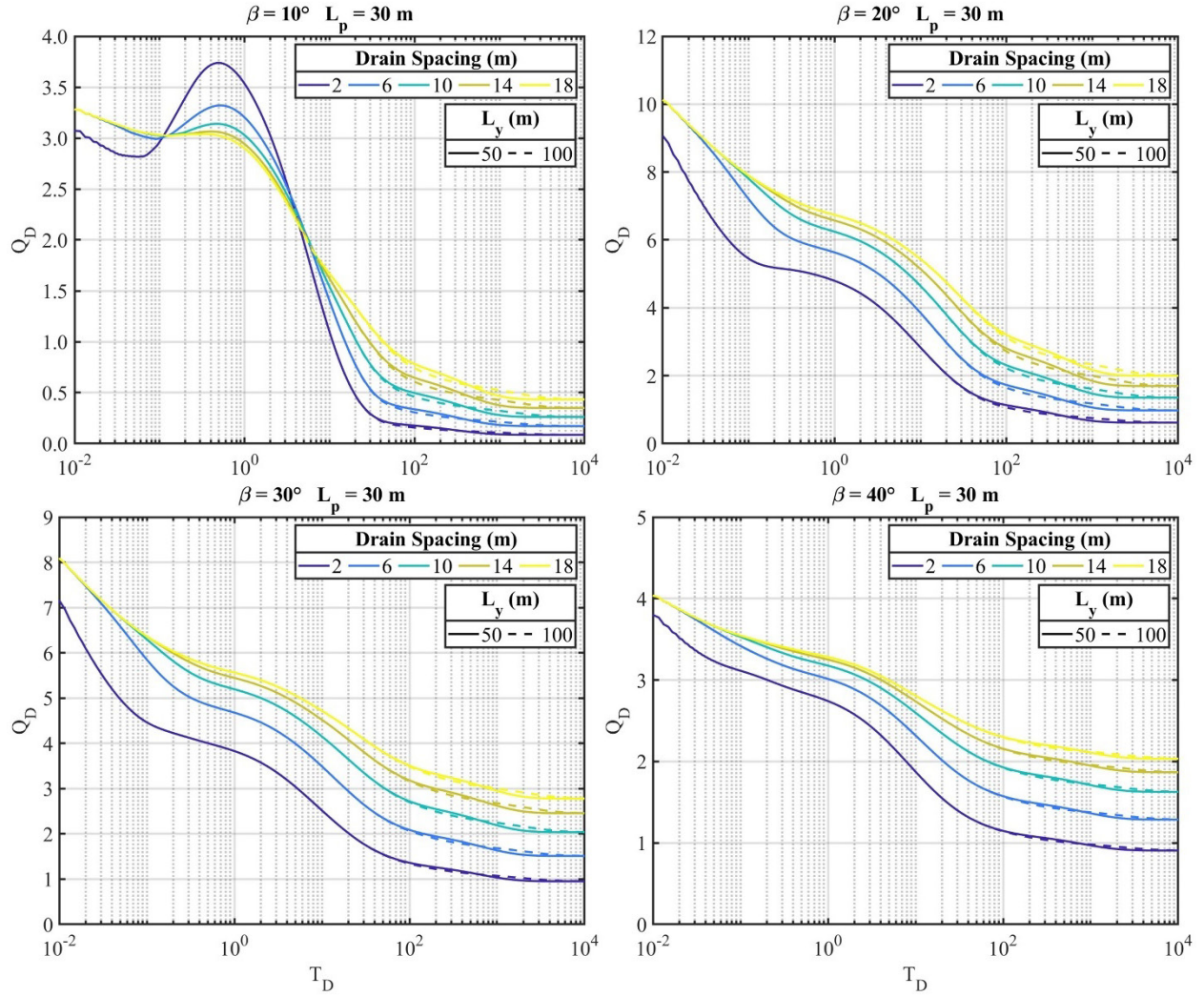


Figure 3.46. Total dimensionless outflow discharge for drain length of $L_p = 30$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

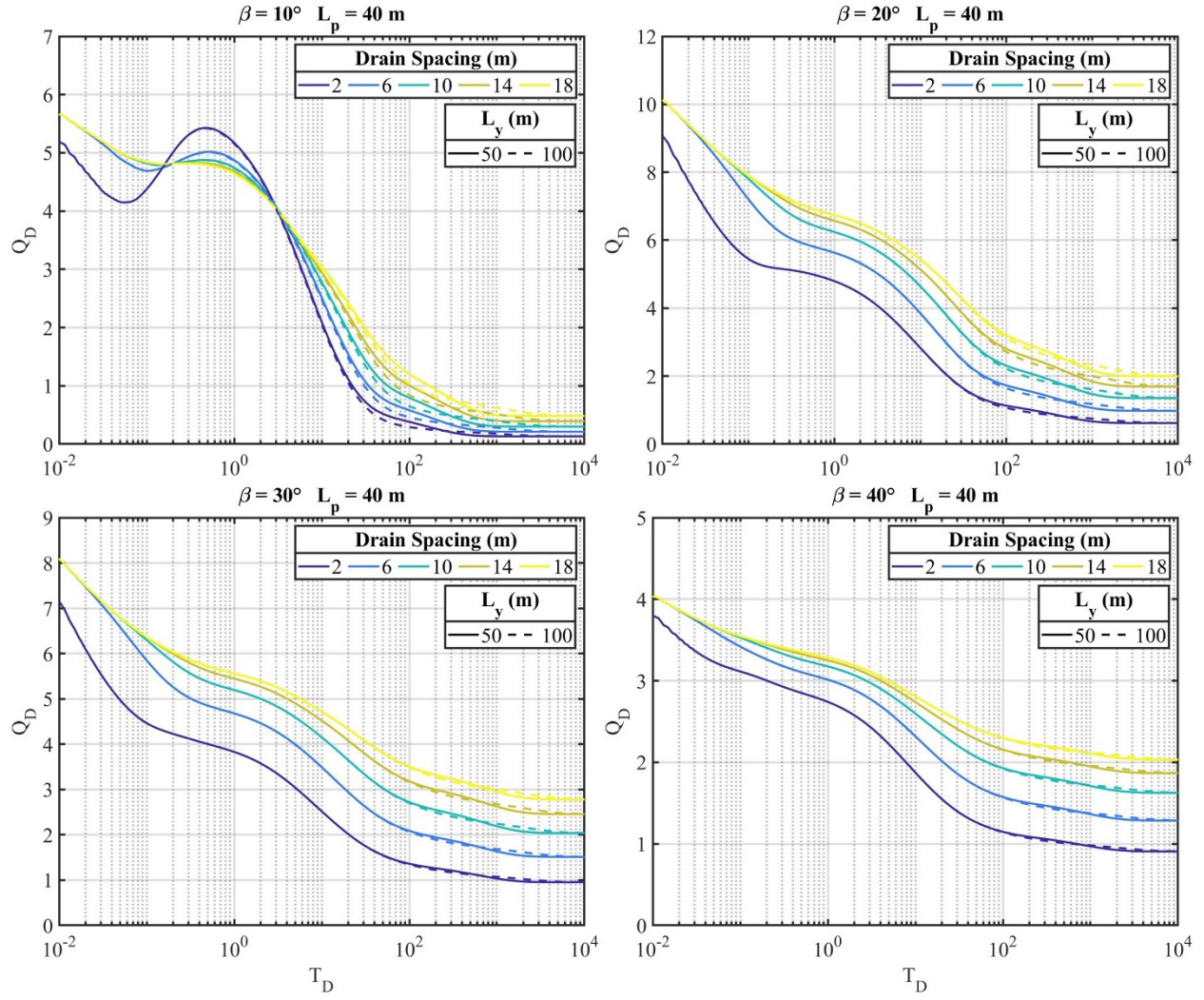


Figure 3.47. Total dimensionless outflow discharge for drain length of $L_p = 40$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

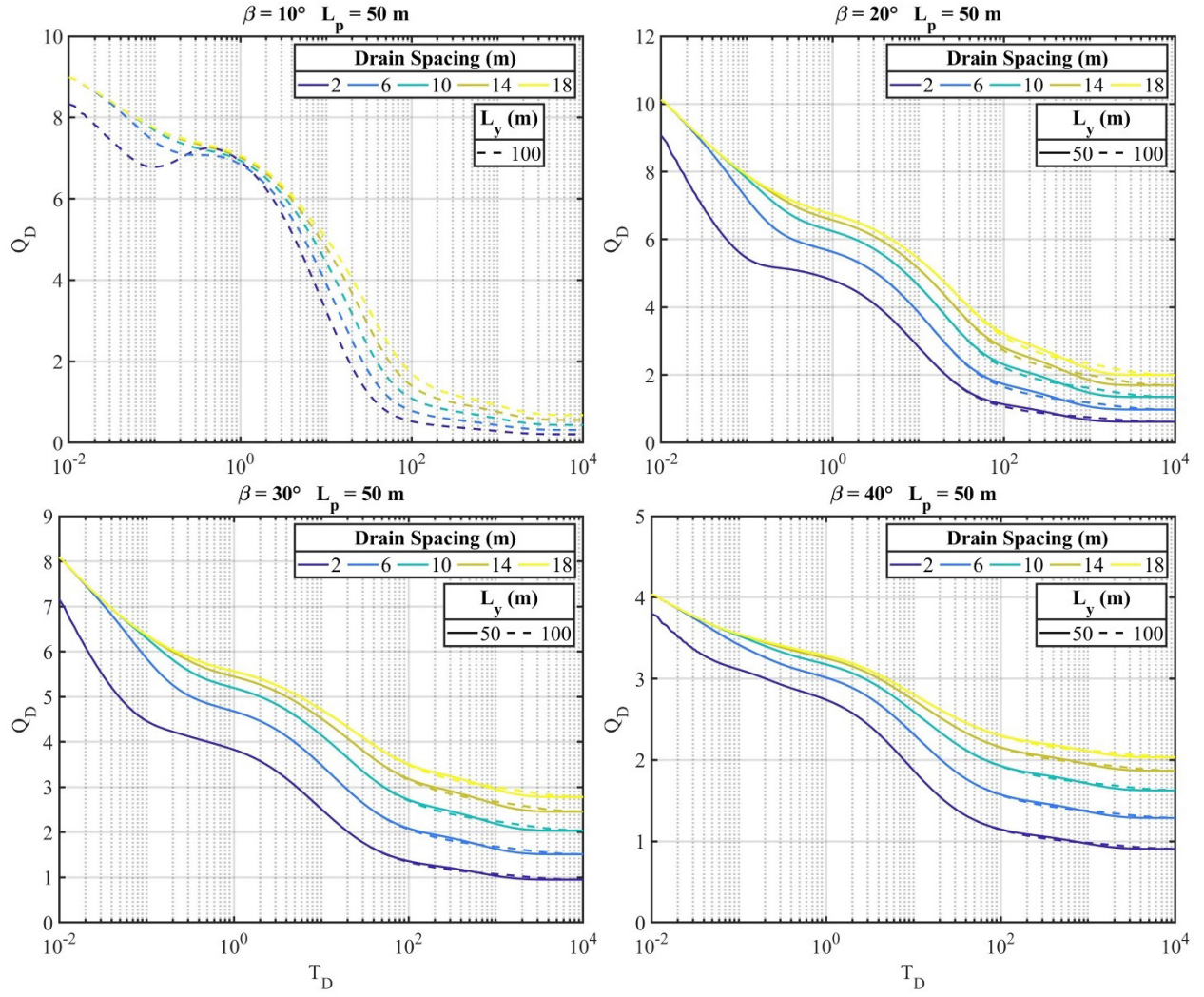


Figure 3.48. Total dimensionless outflow discharge for drain length of $L_p = 50$ m on the failure surface of $L_z = 10$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

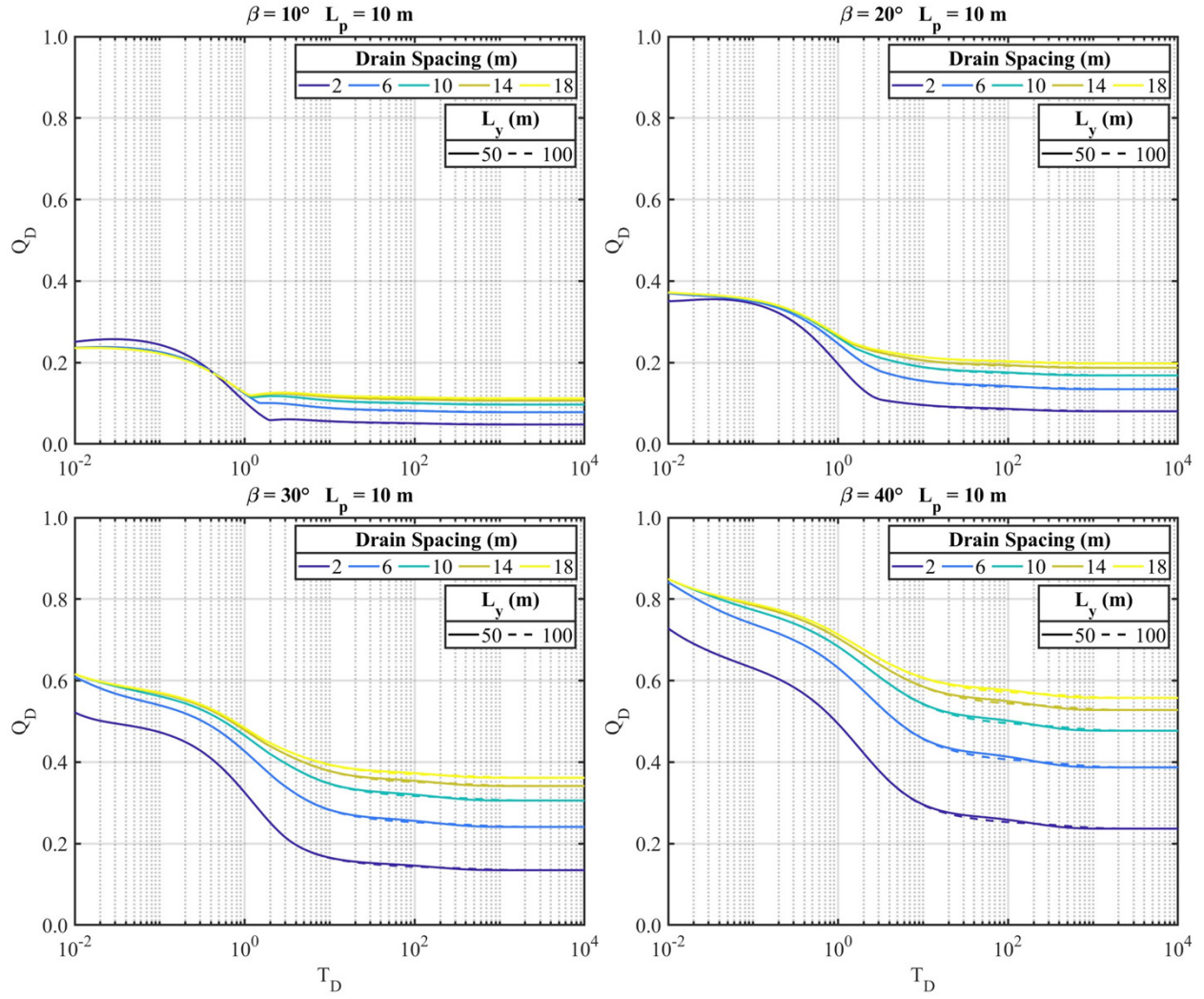


Figure 3.49. Total dimensionless outflow discharge for drain length of $L_p = 10$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

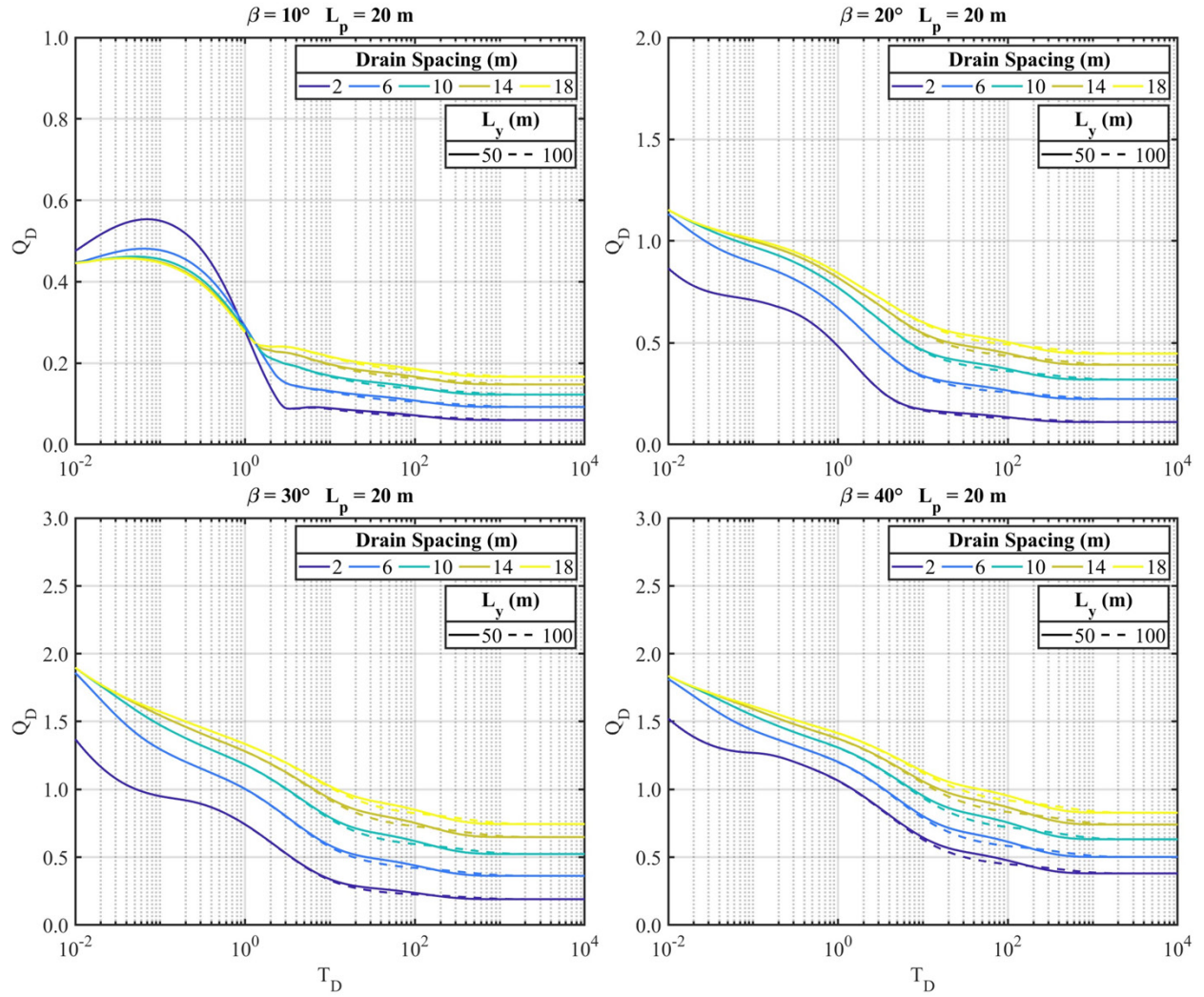


Figure 3.50. Total dimensionless outflow discharge for drain length of $L_p = 20$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

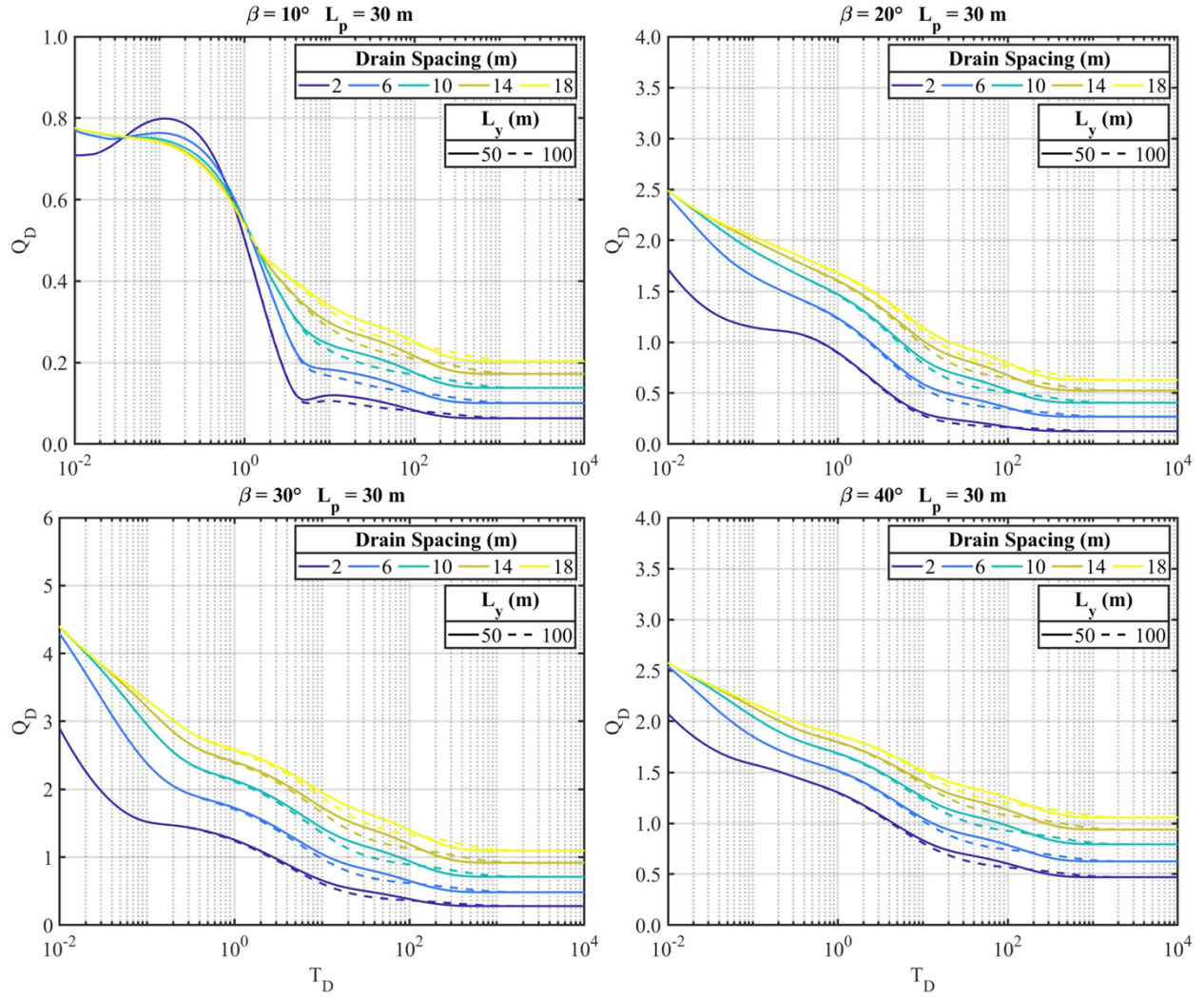


Figure 3.51. Total dimensionless outflow discharge for drain length of $L_p = 10$ m on the failure surface of $L_z = 30$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

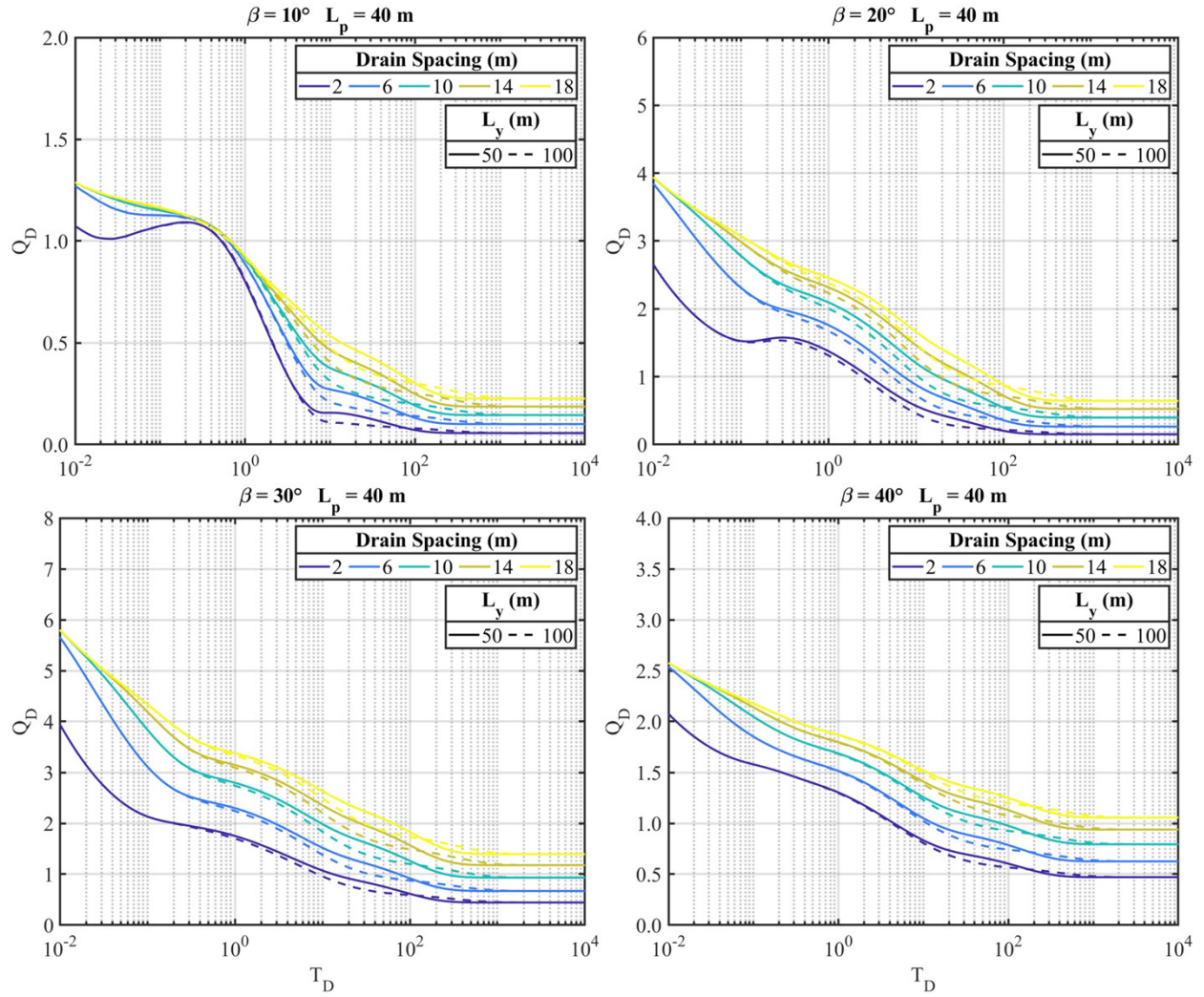


Figure 3.52. Total dimensionless outflow discharge for drain length of $L_p = 40$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

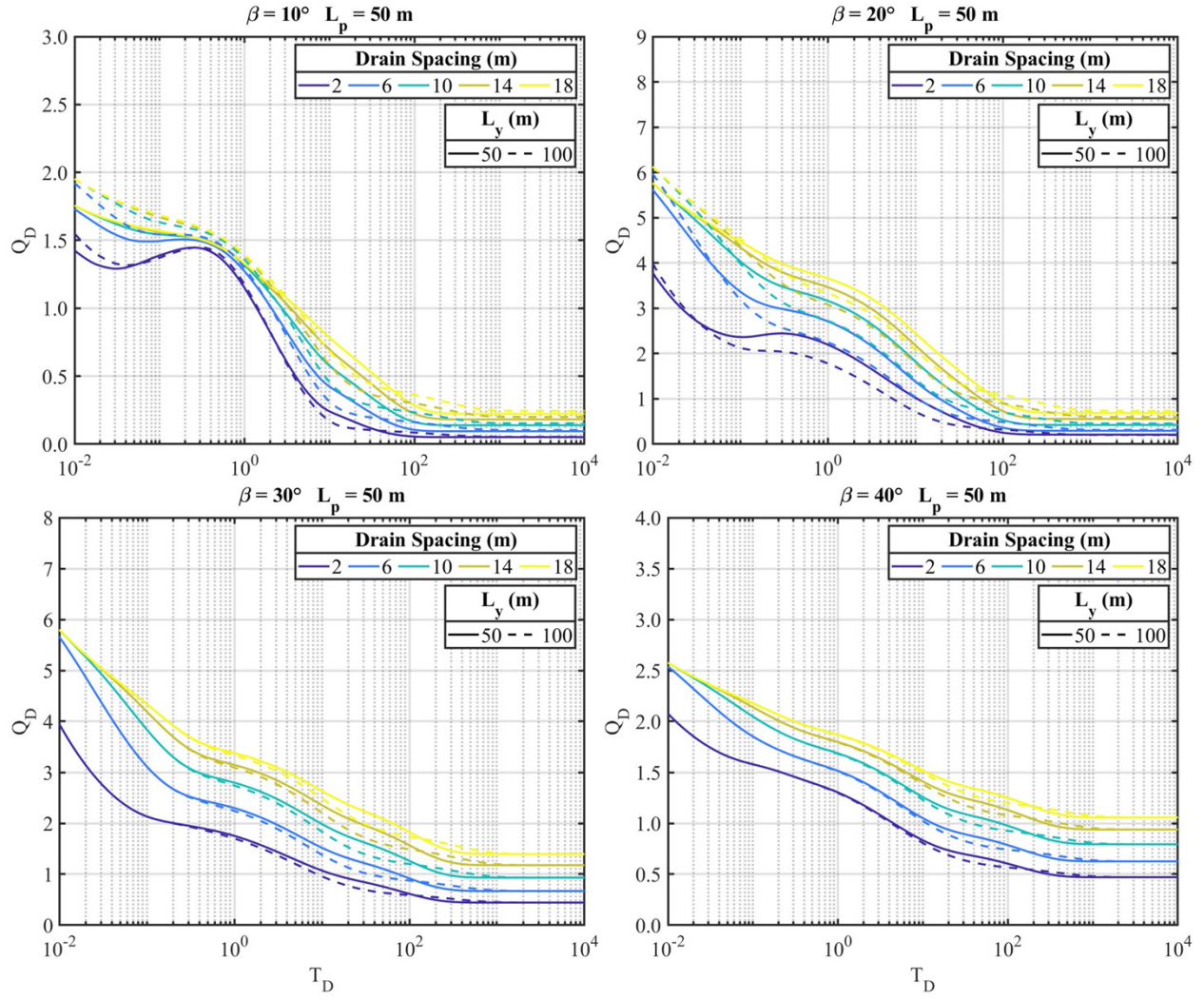


Figure 3.53. Total dimensionless outflow discharge for drain length of $L_p = 50$ m on the failure surface of $L_z = 20$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

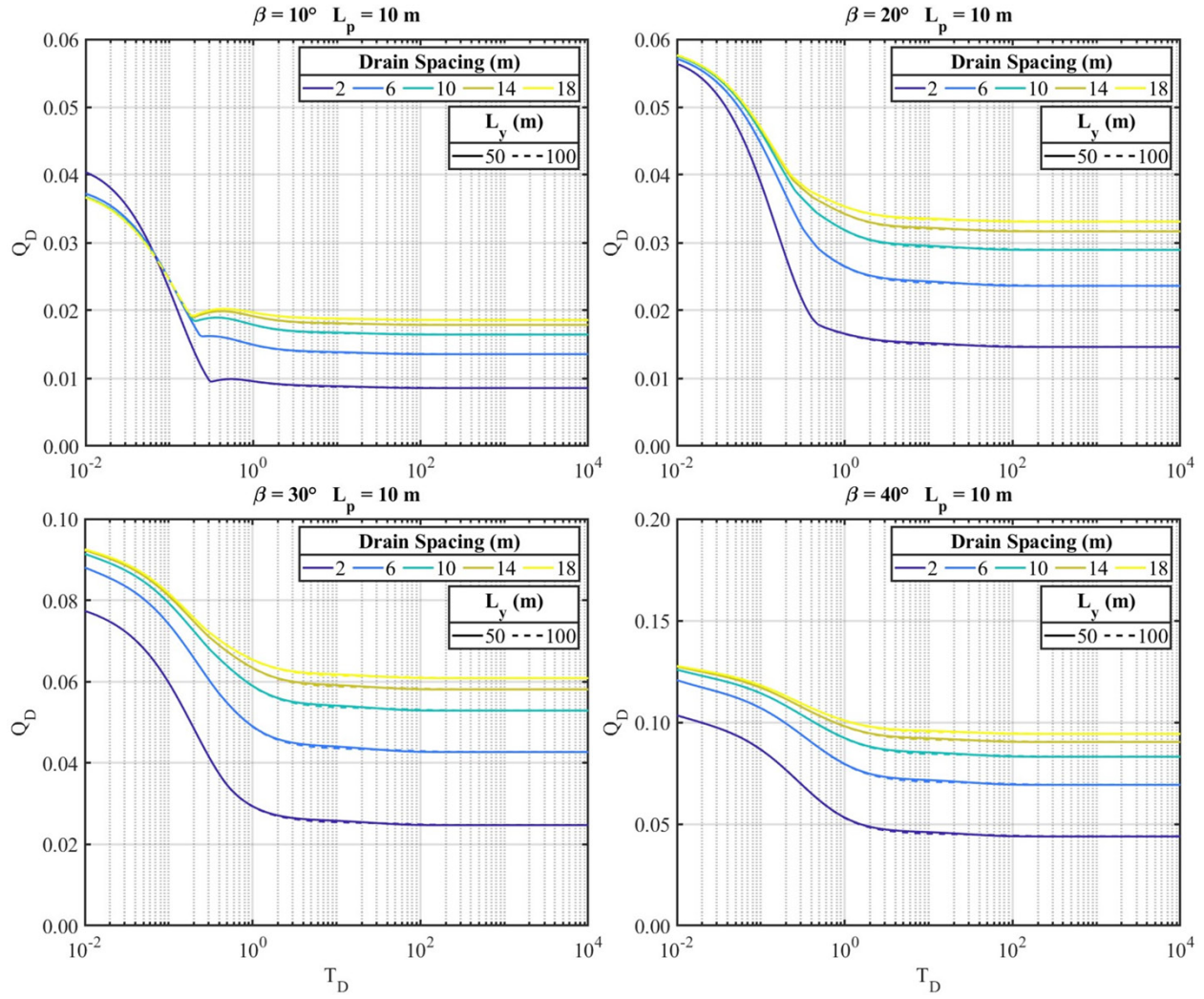


Figure 3.54. Total dimensionless outflow discharge for drain length of $L_p = 10$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

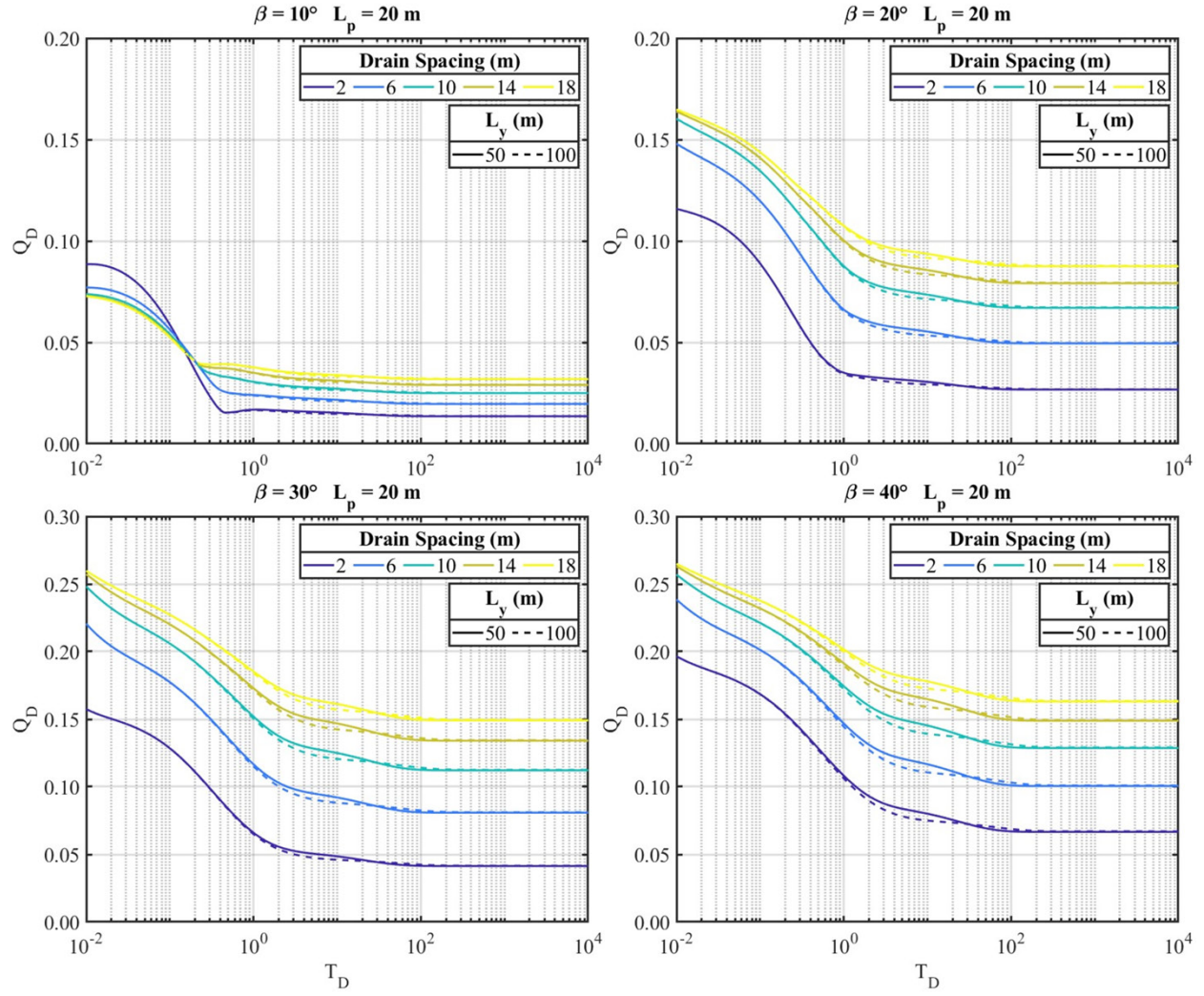


Figure 3.55. Total dimensionless outflow discharge for drain length of $L_p = 20$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

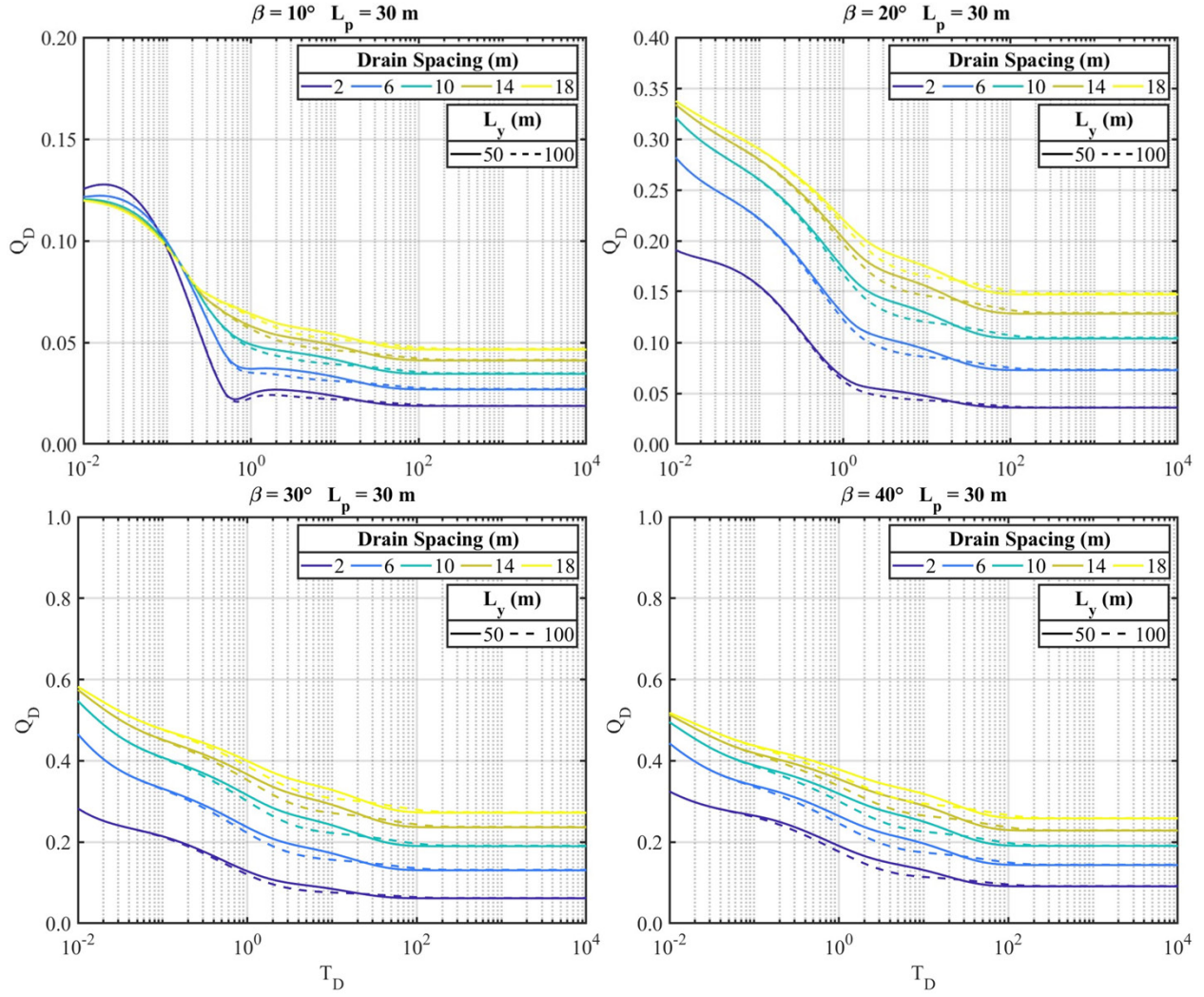


Figure 3.56. Total dimensionless outflow discharge for drain length of $L_p = 30$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

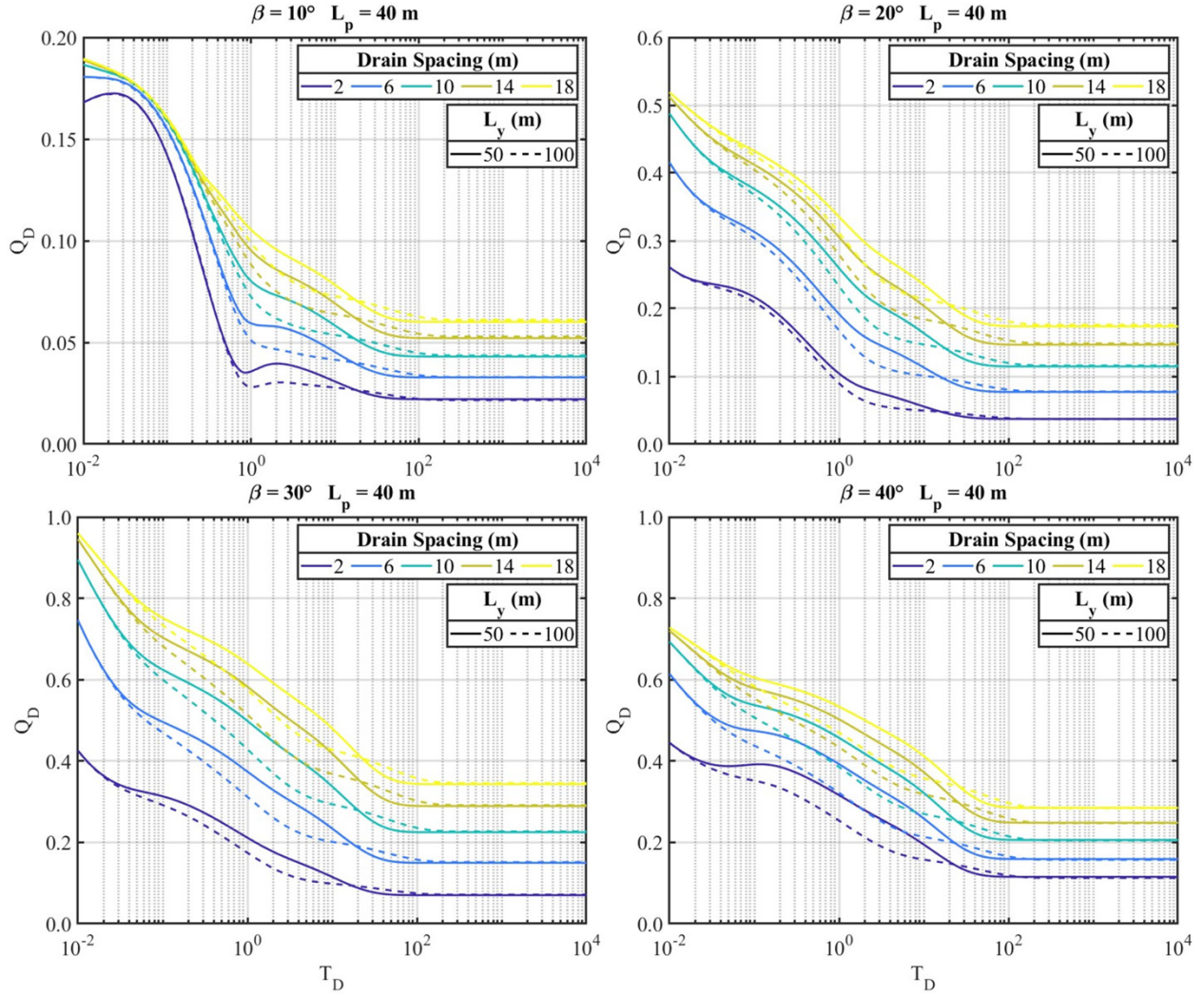


Figure 3.57. Total dimensionless outflow discharge for drain length of $L_p = 40$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

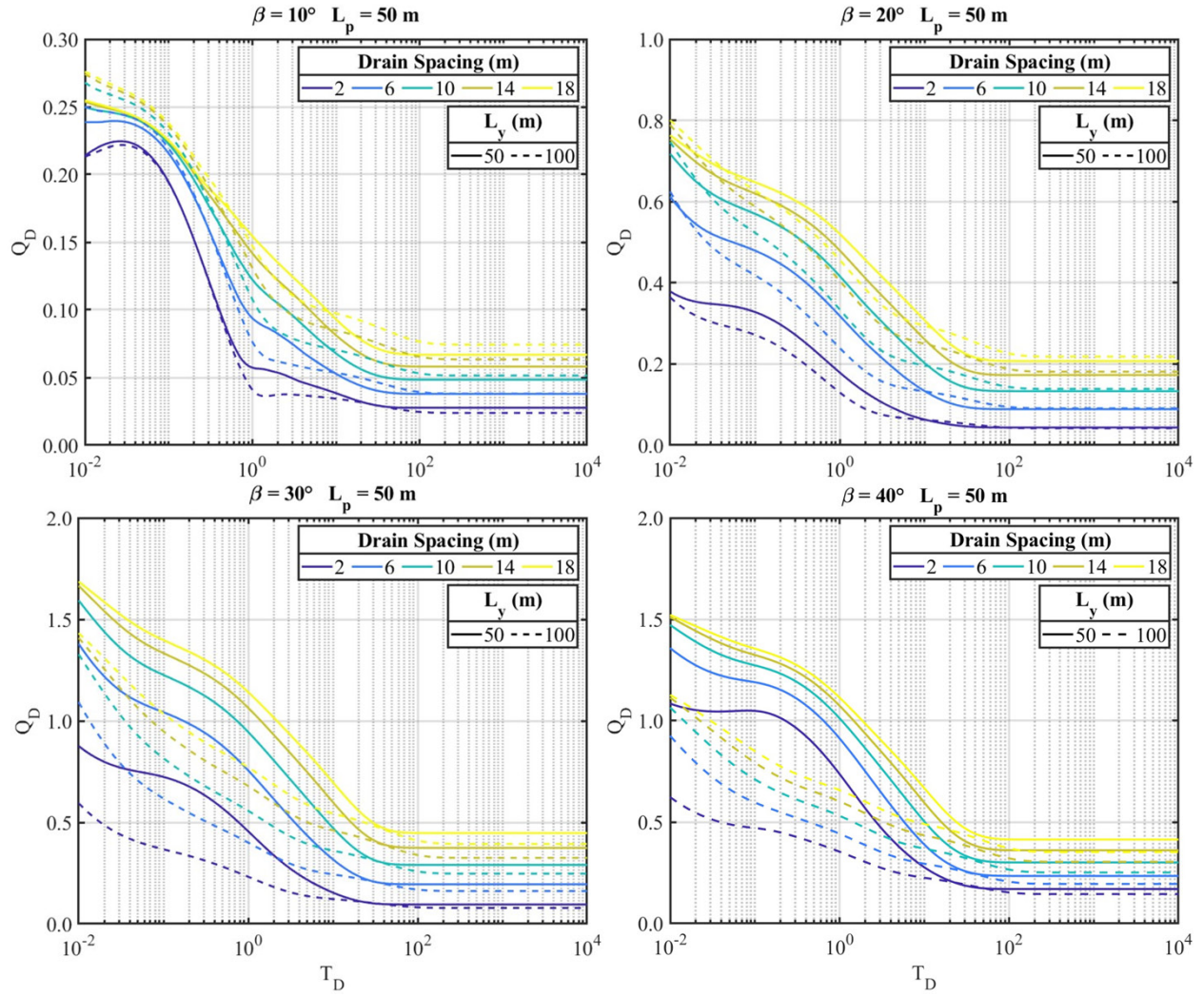


Figure 3.58. Total dimensionless outflow discharge for drain length of $L_p = 50$ m on the failure surface of $L_z = 50$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

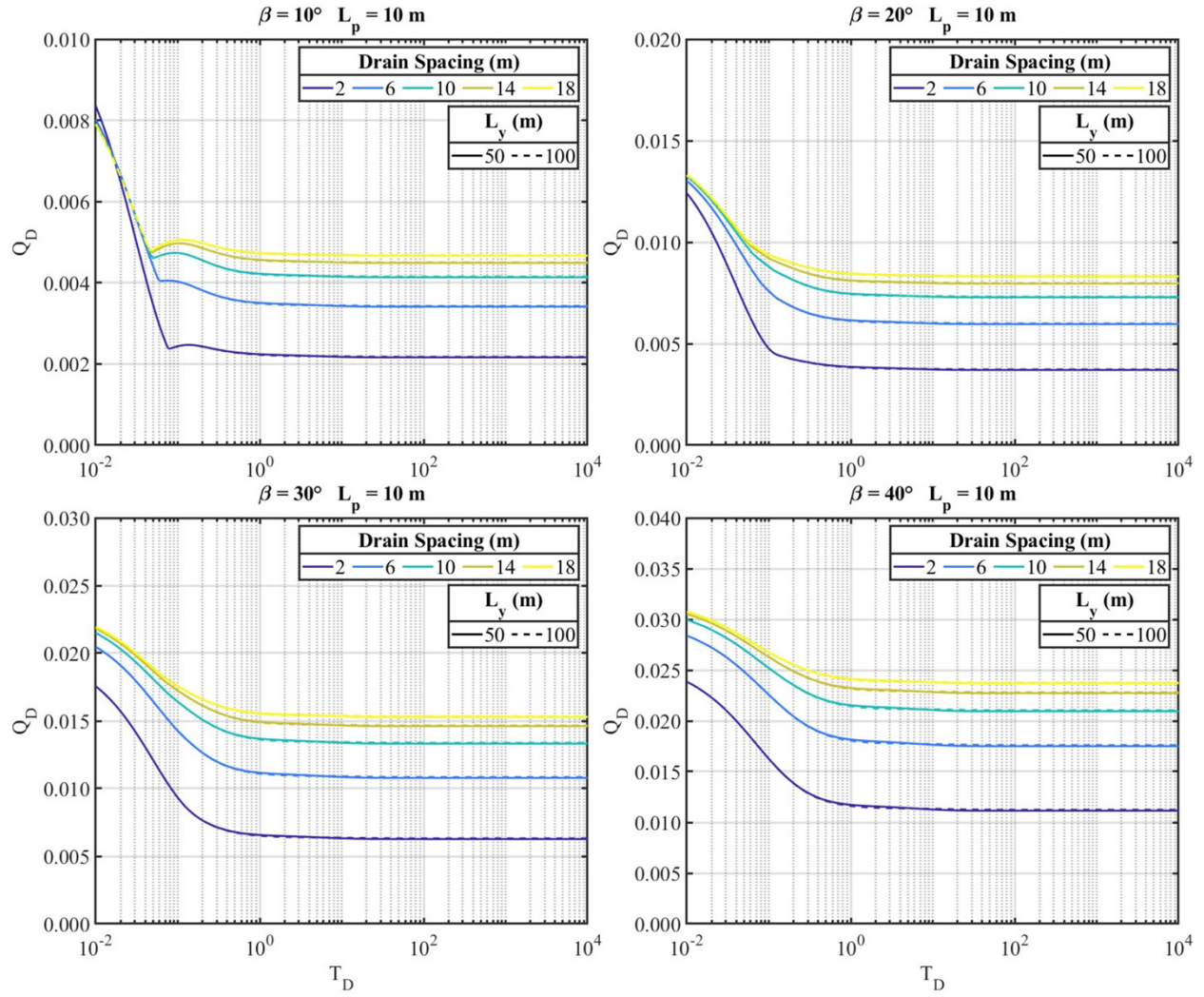


Figure 3.59. Total dimensionless outflow discharge for drain length of $L_p = 10$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

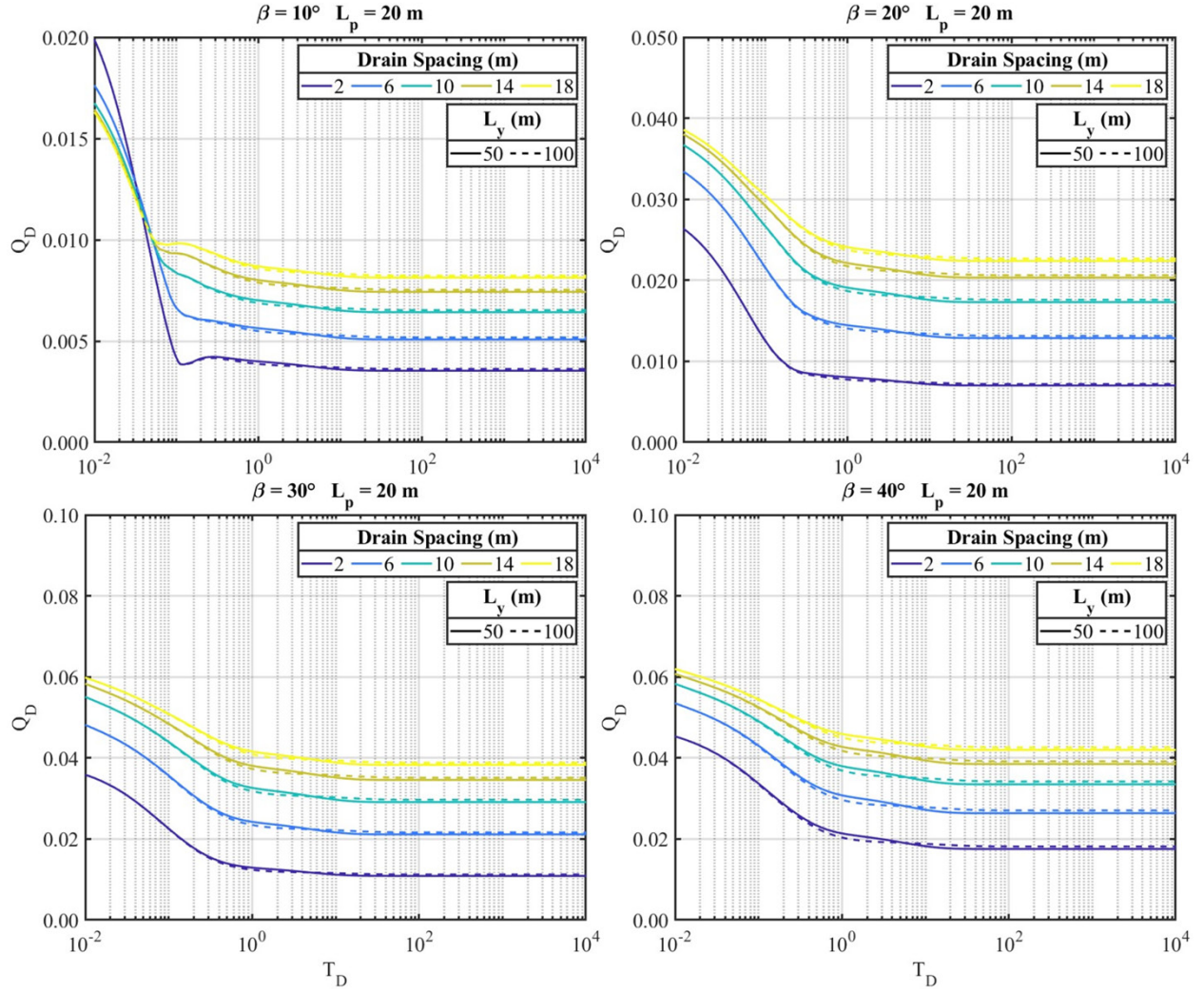


Figure 3.60. Total dimensionless outflow discharge for drain length of $L_p = 20$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

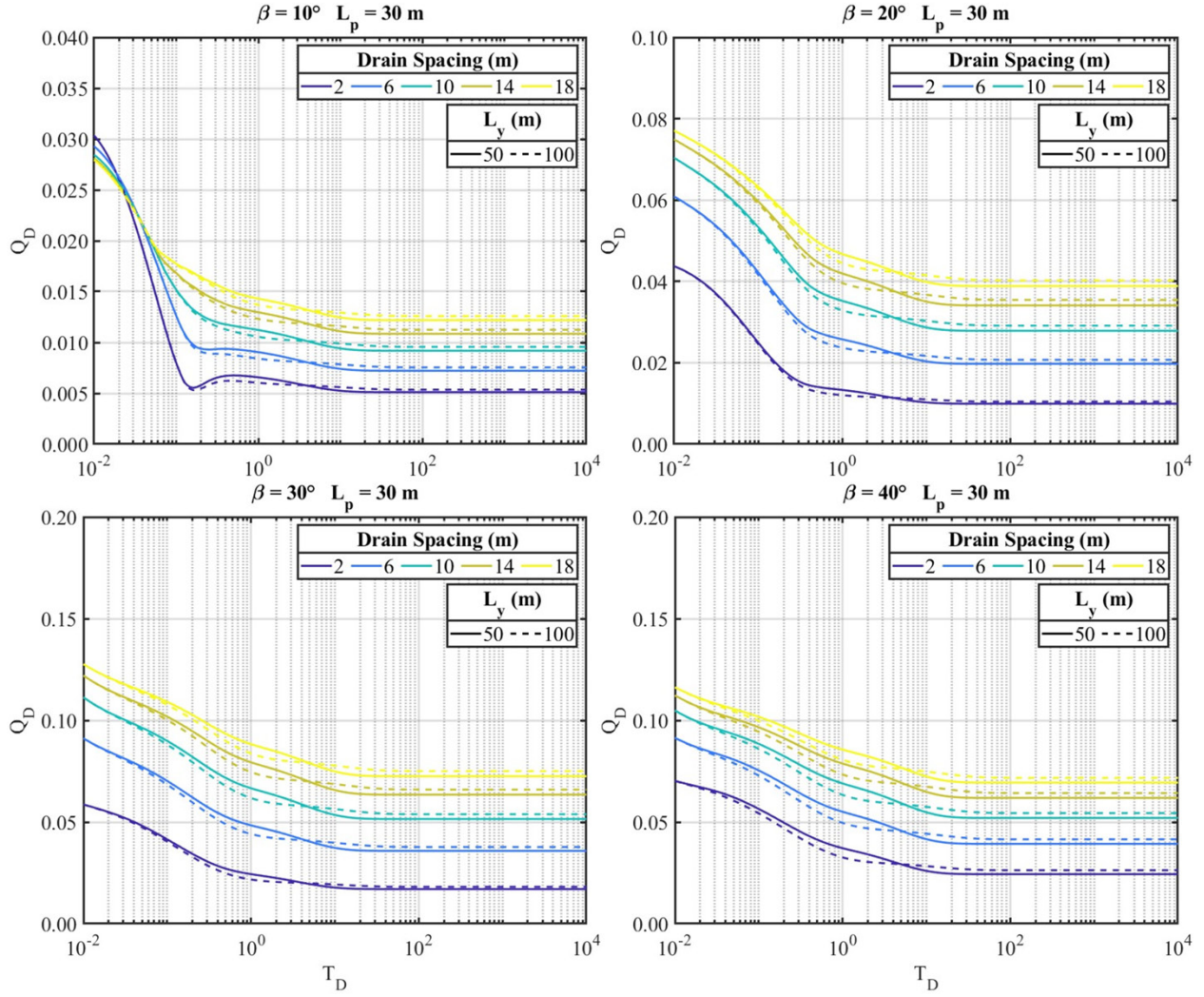


Figure 3.61. Total dimensionless outflow discharge for drain length of $L_p = 30$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

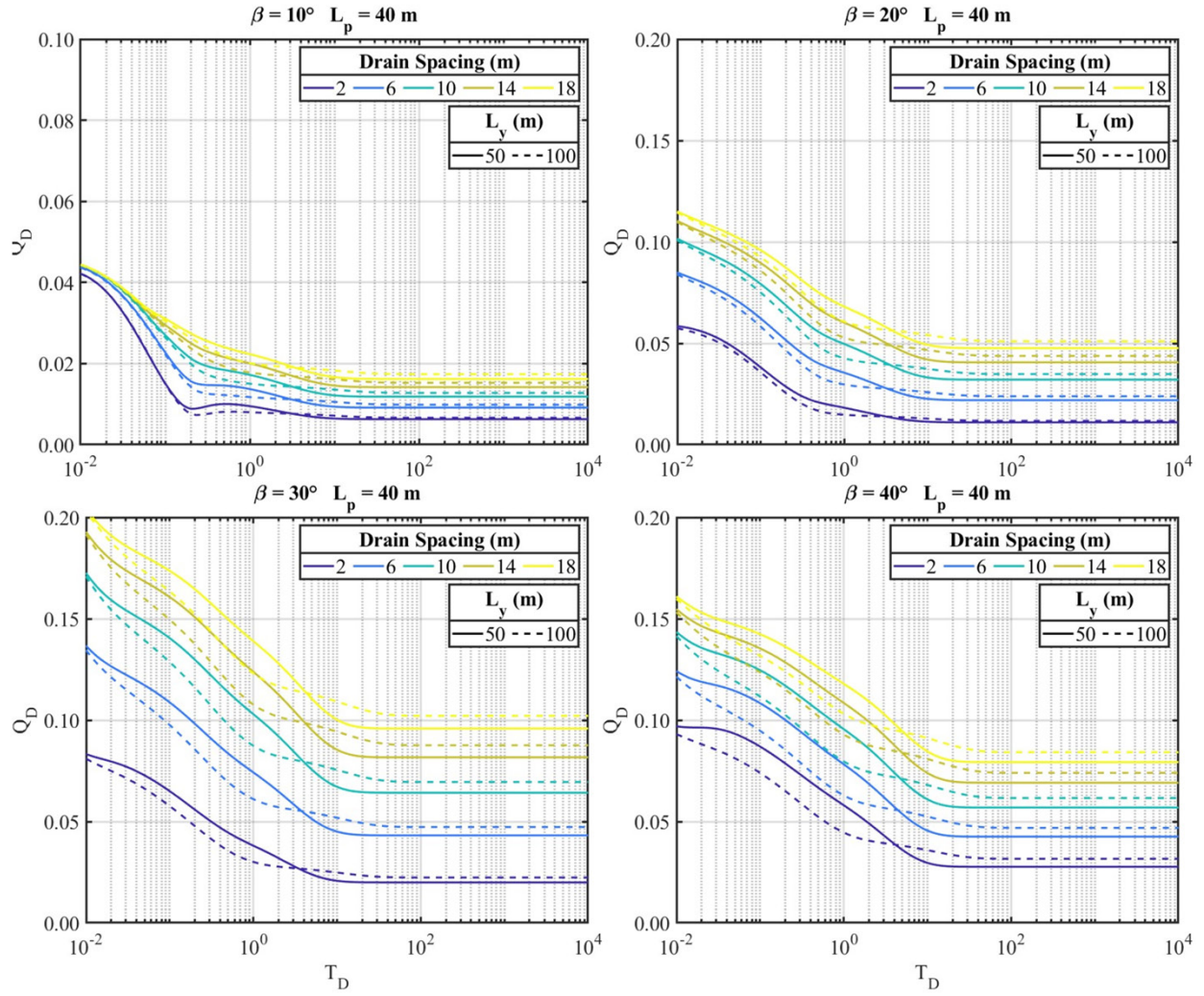


Figure 3.62. Total dimensionless outflow discharge for drain length of $L_p = 40$ m on the failure surface of $L_z = 100$ m depth for different drain spacings (L_y), aquifer length (L_x), and slope angle (β)

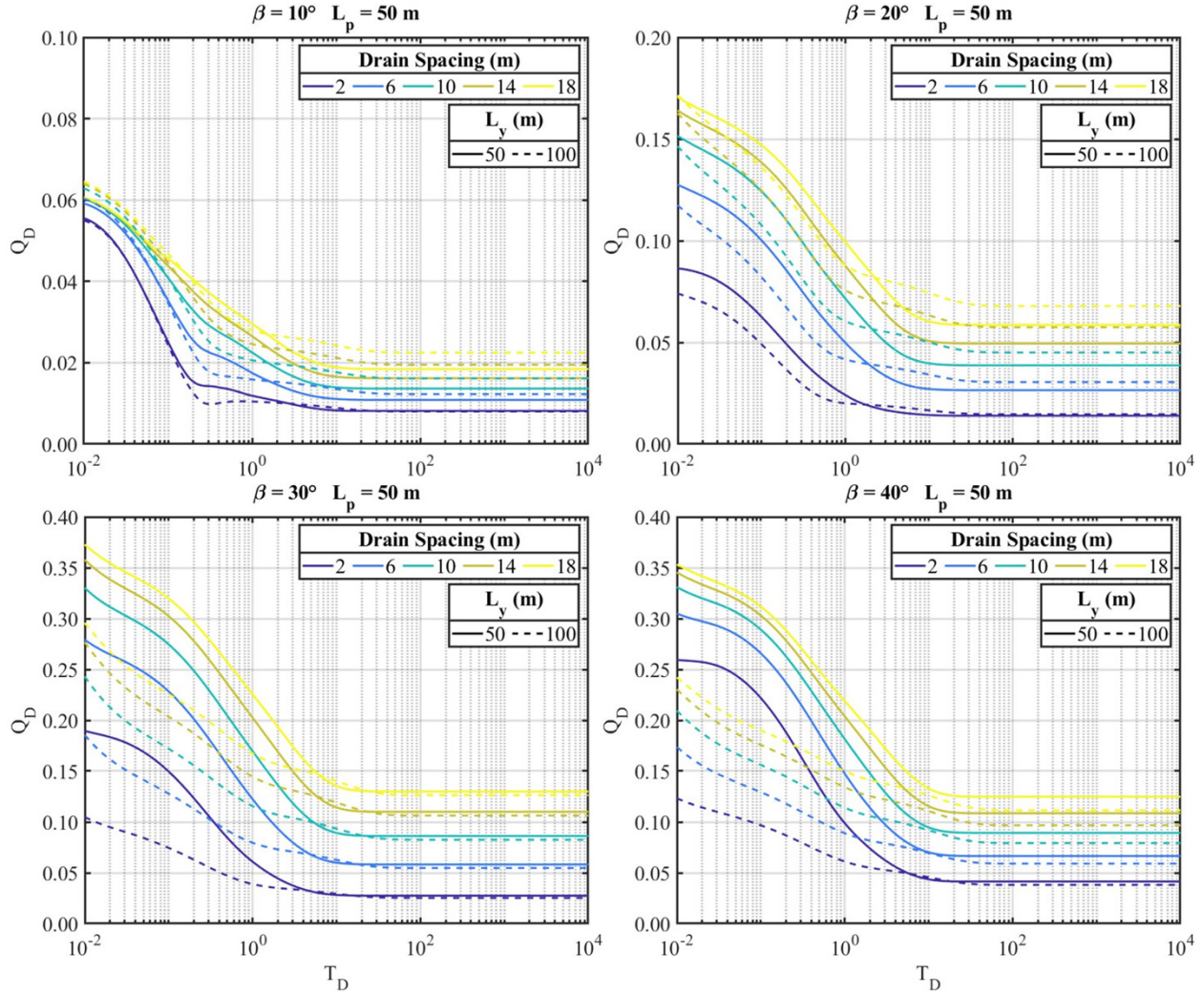


Figure 3.63. Total dimensionless outflow discharge for drain length of $L_p = 50\text{m}$ on the failure surface of $L_z = 100\text{m}$ depth for different drain spacings (L_x), aquifer length (L_y), and slope angle (β)

3.2 PREDICTIVE MACHINE LEARNING MODEL AND TOOLBOX: RESULTS & IMPLEMENTATION

3.2.1 Comparison of the models

An Artificial Neural Network (ANN) function is developed as a machine learning technique to estimate transient drawdown using various design input parameters, including aquifer thickness, hillslope angle, drain spacing, drain length, and hydraulic conductivity. An ANN function is a simple type of machine learning model that uses training data – for example the inputs and outputs of the numerical solutions for drawdown shown in the previous section – to estimate complex answers beyond the capability of typical, simplistic regressions. These outputs could include a time series of drawdown, such as those proposed by the aforementioned numerical solutions. We provide a simple ANN model trained on the numerical solutions proposed herein

for simple and quick estimation of transient drawdown from horizontal drain systems. This tool is implemented through functional GIS toolboxes, the raw script of which is provided in Appendix B. More technical details are provided in Abed et al. (2024).

A comparison of the average groundwater drawdown along the aquifer base (assumed to be the failure surface), as simulated using the proposed numerical method and the predicted values generated by the ANN model (Abed et al., 2024). This comparison is conducted over different aquifer and drainage conditions, randomly selected during transient phases. The mean drawdown is assessed through a root mean square error value of 0.037 and a correlation coefficient of 0.98, underscoring the accuracy of the ANN model in predicting drawdown across a spectrum of conditions. However, there is a slight bias towards overestimating drawdown, especially early after drain installation; consequently, some margin of safety should be used for estimates at early drawdown stages in particular. The use of ANN for predicting drawdown provides a simplified method for utilizing available tools in making practical planning-level drawdown predictions.

3.2.2 Implementation in ArcGIS

The predictive model is prepared as an add-on toolbox of ArcGIS Pro to approximate groundwater drawdown for any slope and drain conditions. To successfully implement the toolbox and predict drawdown the following steps are required to be completed:

Since the default Python environment does not have machine learning library:

1. First, the default python environment is cloned, and saved in the preferred name and destination (<https://pro.arcgis.com/en/pro-app/latest/arcpy/get-started/clone-an-environment.htm>).
2. Once the environment is cloned and activated, TensorFlow (keras TensorFlow) library needs to be installed.
3. ArcGIS Pro needs to be restarted for modifications to be effective.
4. A digital elevation model and a polygon for prediction should be prepared. Make sure that the polygon (area/slope of interest) is projected on UTM or State Plane coordinate system.
5. The rest of the parameters should be given in the unit of the projection system (i.e., UTM uses meter as linear unit, so the pipe input properties also need to be entered in meters).
6. The model is ready to run. It should be noted that the ML model, `ann_logx1_relu_sigmoid_hn_4_bs_23.h5`, must be saved in the folder where the DEM model is located.
7. The results will be saved in the form of three files, which are a drawdown figure, `parameters.csv` and `timed.csv` in the folder where the toolbox is located.

The results are presented in dimensional format and the x-axis presents time in days and y-axis drawdown in meters. The files associated with this simple GIS-based toolbox are provided in a digital appendix.

3.2.3 Step-by-Step Guide to Drawdown Toolbox

A step-by-step guide is provided for running the GIS drawdown toolbox for a simple example.

1. The files required to run the toolbox are found in the digital appendix of this report (available upon request from ODOT Research Project Manager in archived SPR834 folder) and include:
 - The drawdown toolbox - [Drawdown.atbx](#)
 - A trained machine learning model - [ann_log_r_relu_sigmoid_hn_5_bs_10.h5](#)
 - The DEM and *slopeofinterest* folders have an example digital elevation model and a polygon shapefile (See Figure 3.64)

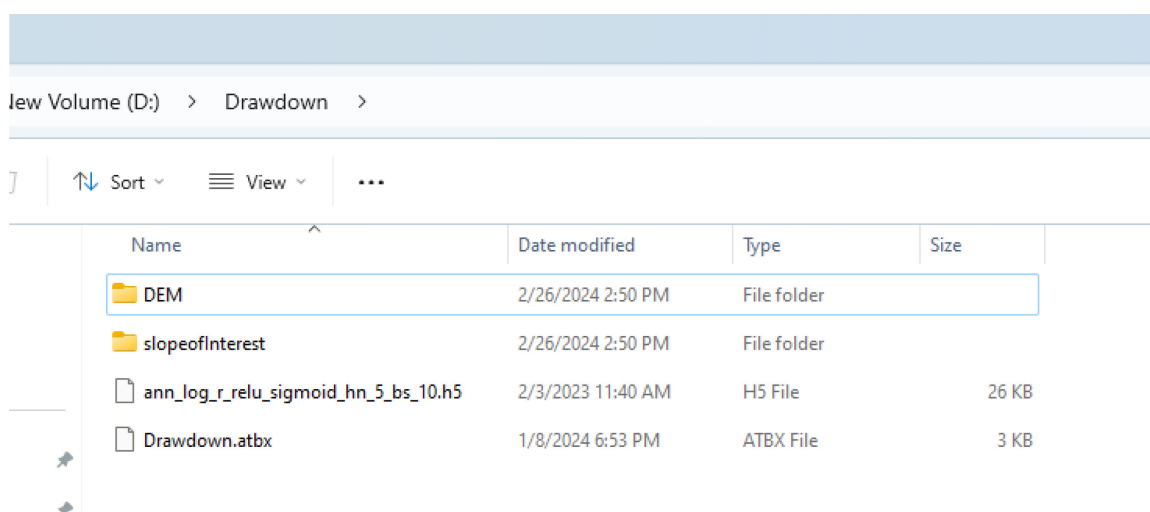


Figure 3.64 *slopeofinterest* folders

2. To execute the toolbox, you may keep the [Drawdown.atbx](#) & [ann_log_r_relu_sigmoid_hn_5_bs_10.h5](#) files together in a folder.
3. If your ArcGIS package does not have machine learning libraries, the required machine learning libraries can be installed by running the Deep Learning library installer downloadable from - <https://github.com/Esri/deep-learning-frameworks> (See Figure 3.65)

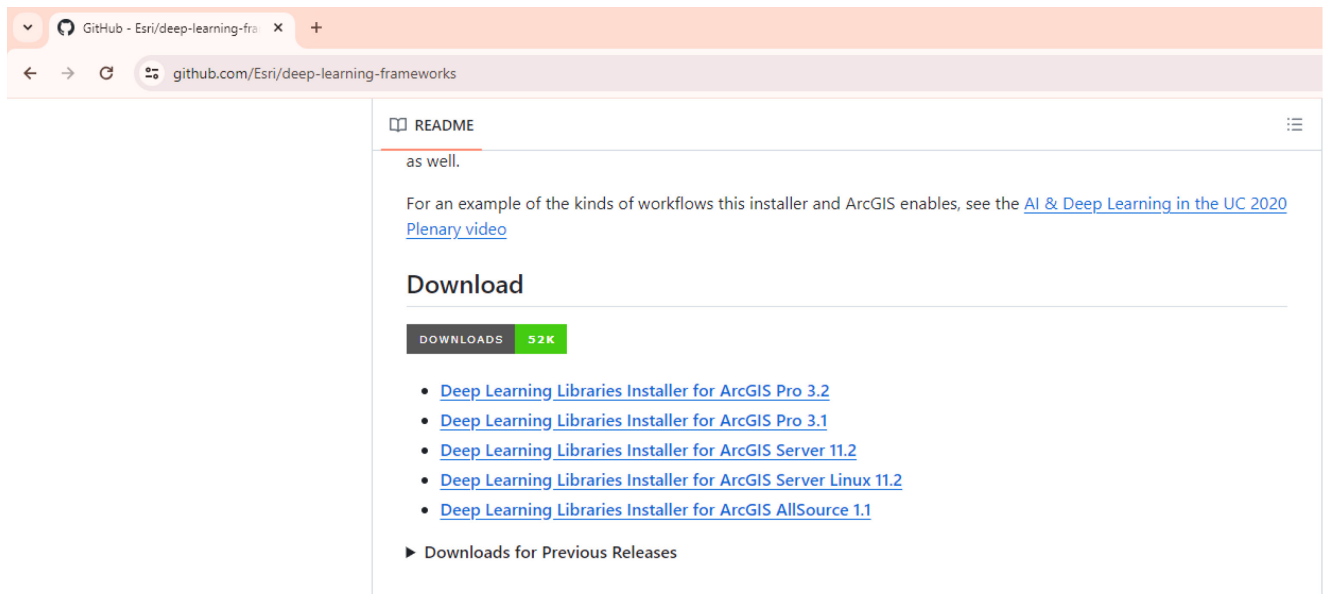


Figure 3.65 Deep Learning library installer download

4. Add the [Drawdown.atbx](#) to ArcGIS Pro window.
 - Go to Catalog pane > Toolboxes > navigate to the downloaded [Drawdown.atbx](#) (See Figure 3.66)

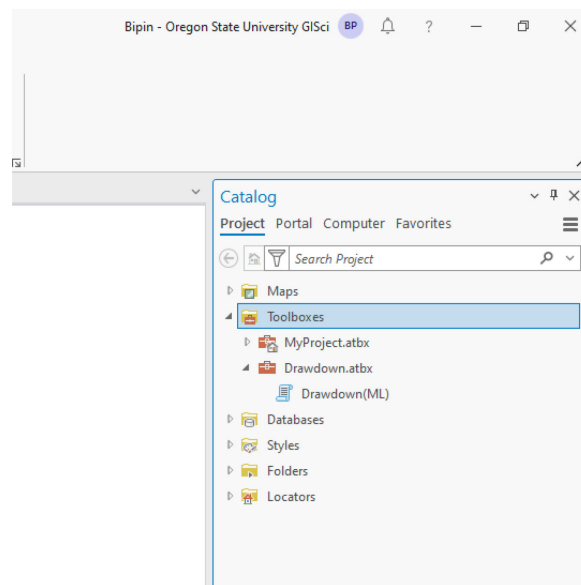


Figure 3.66 4. Add the Drawdown.atbx to ArcGIS Pro

5. Double click on the Drawdown (ML) script to open the toolbox's interface. (See Figure 3.67)

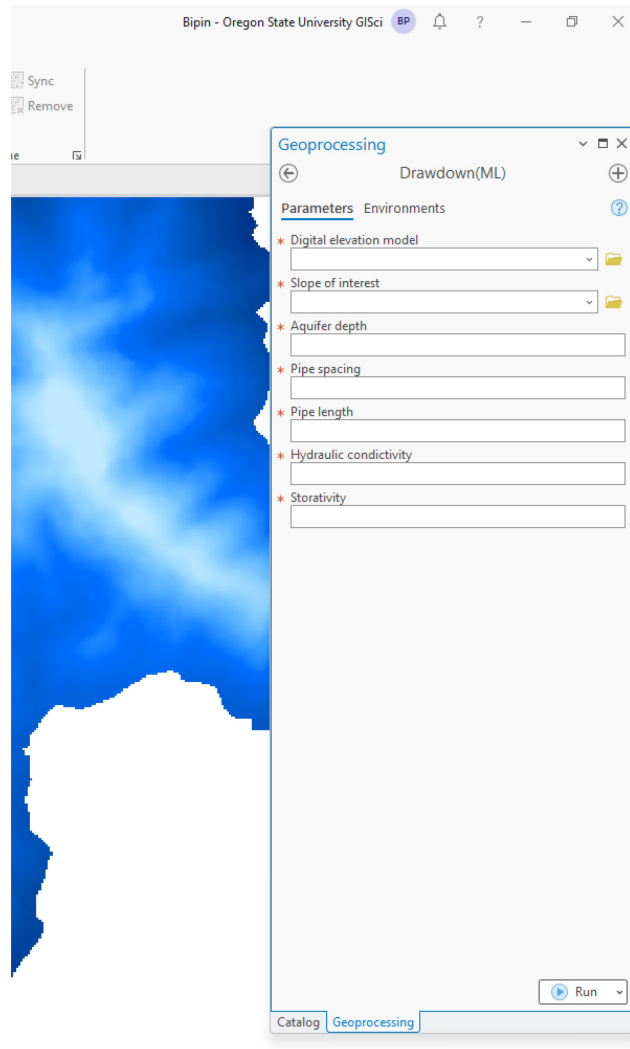


Figure 3.67 toolbox's interface

6. The required inputs for the toolbox are;
 - Digital elevation model (DEM)
 - Slope of interest polygon
 - Aquifer depth
 - Pipe spacing
 - Pipe length
 - Hydraulic conductivity
 - Storativity
7. Add the DEM & Slope of interest polygon to the ArcGIS window. (See Figure 3.68)

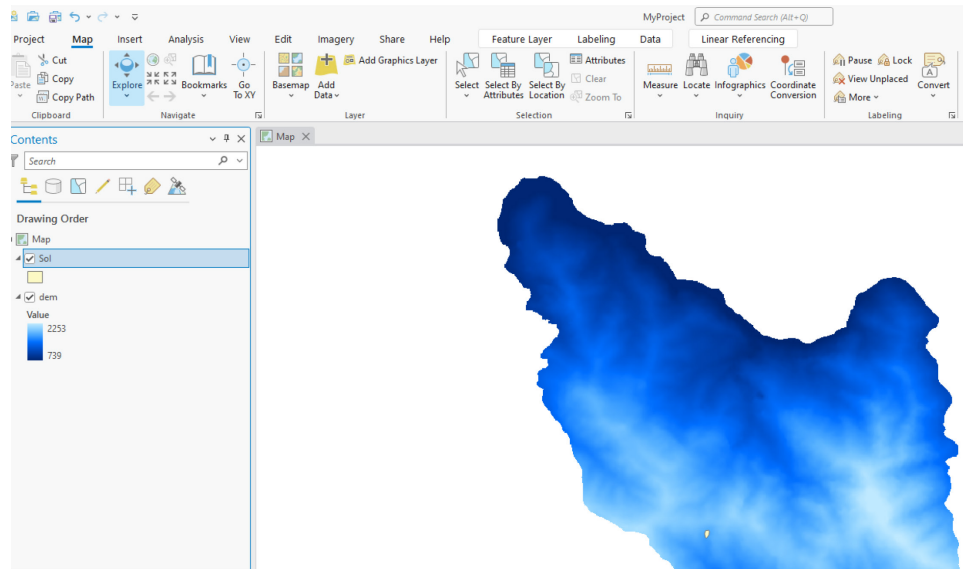


Figure 3.68 Example DEM & Slope of interest polygon

8. If the DEM and slope of interest polygon are projected on UTM, please enter the rest of the inputs in meters. If the projection's linear unit is feet, you may enter the rest of the inputs in feet.
9. The current DEM & Slope of interest polygon are projected on UTM, so the entered values are in meters. (See Figure 3.69)

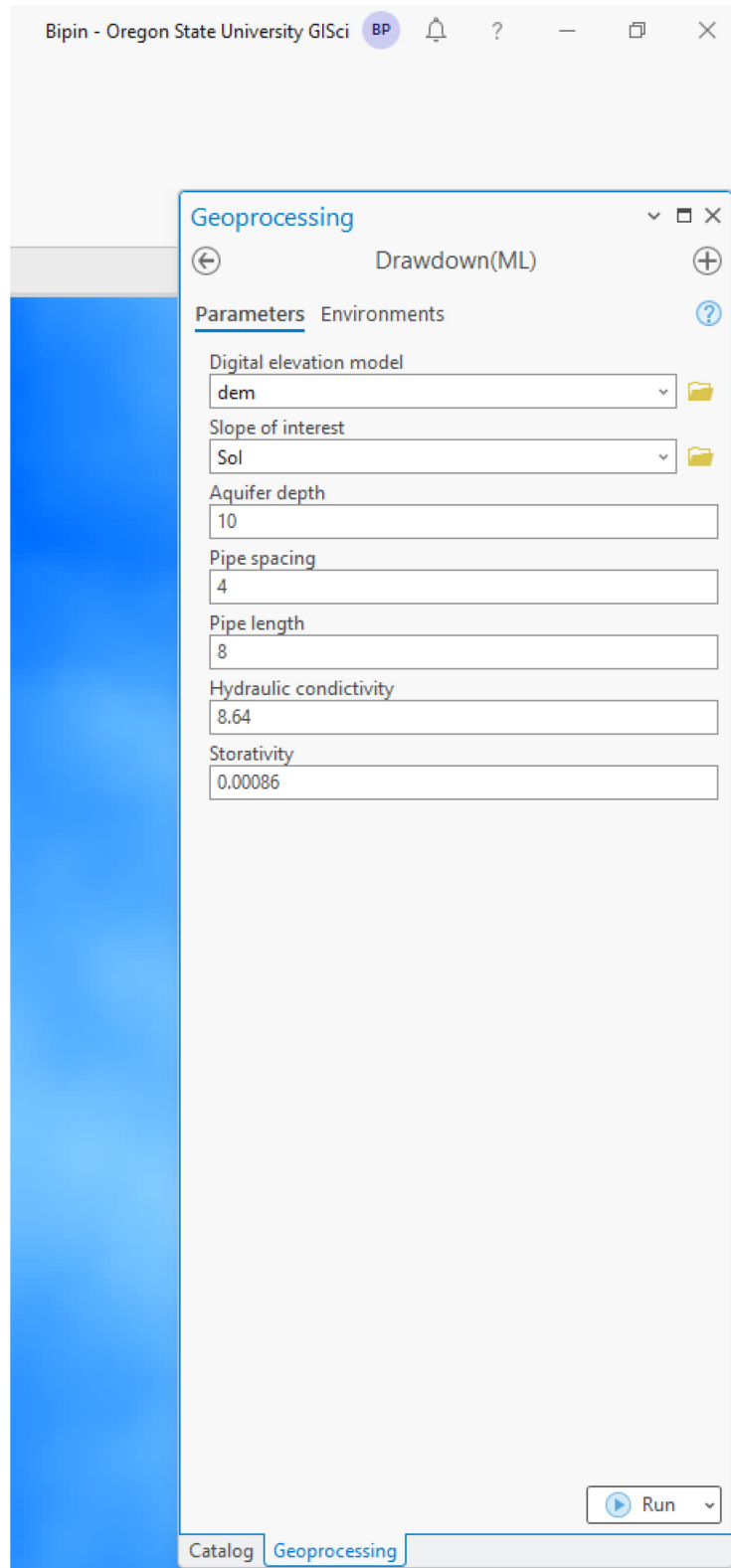


Figure 3.69 Example Parameters

10. The Run button will then process and output the prediction (the tool will calculate the slope gradient and slope length from the DEM and slope of interest polygon, respectively).
11. The created outputs (See Figure 3.70) will be:
 - parameters.csv – stored metadata of the input parameters (including slope gradient and slope length)
 - Drawdown.png – figure that gives drawdown vs. time
 - ddttime.csv – an excel sheet that gives drawdown vs. time

Note: The unit of time will be the as same as the unit of hydraulic conductivity (in this case, the entered hydraulic conductivity was in m/day) (Figure 3.71).

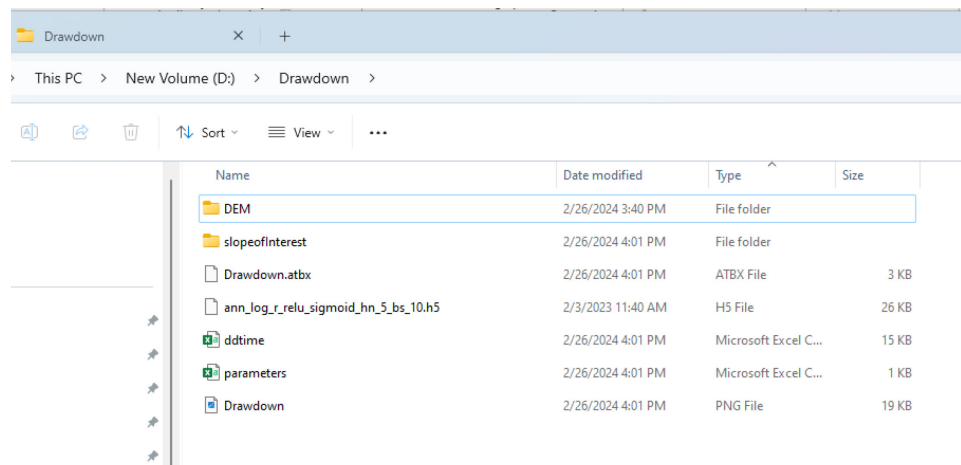


Figure 3.70 created outputs

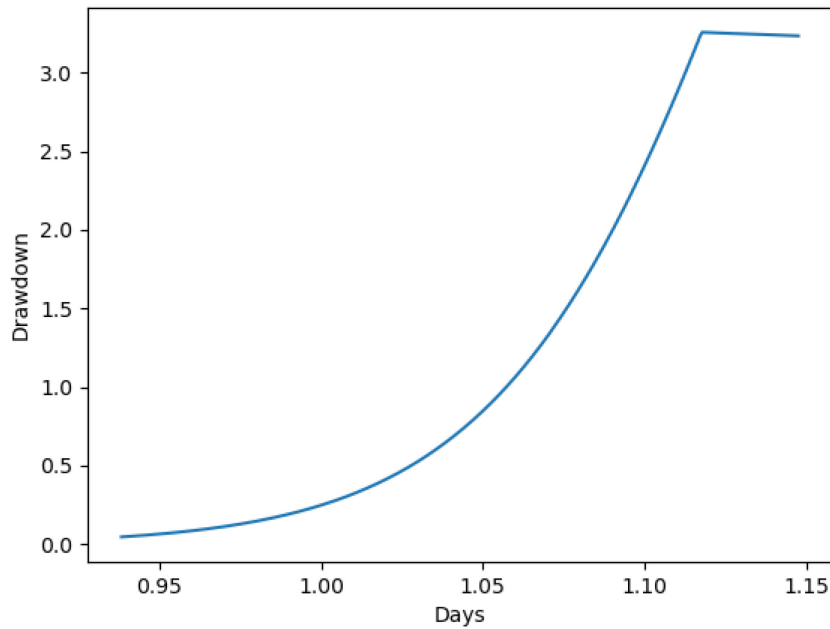


Figure 3.71 Drawdown vs. time output.

12. If you want to re-run the toolbox, please delete or move the created output files from the folder.

3.3 SILTATION AND DRAIN DESIGN LIFE

The longevity of horizontal drains is affected by various factors, including the flow rate variability inside the drain, the location and size of perforations allowing suspended soil particles from the surrounding soil to enter the pipe, the settling velocity of particles, and the particles' diffusivity. The dispersivity or diffusivity of the particles is determined by flow characteristics, channel size, and particle size. For this study, a constant value of $D_f = 10^{-6} \text{ m}^2/\text{s}$ is used for the diffusivity coefficient, owing to highly variable flow rates and particle sizes within the pipe. Soil particles entering the pipe are filtered by the width of perforations, and assuming the perforation width is $8.5 \times 10^{-4} \text{ m}$, it allows only soil particles equal or smaller than very fine sand ($d_{50} = 10^{-5} \text{ m}$) to enter the pipe.

The head above the pipe controls the discharge rate from the aquifer into the pipe, therefore, flow rate varies along the length of the pipe, where lower flow rates are present at the embedded pipe section, and higher flow rates occur at the outlet of the pipe as the result of accumulation of flow. As the amount of sediment entering the pipe depends on the flow rate of inflowing water (Eq. 3.3), each section of the pipe receives a commensurate volume of sediment. Hence, one of the critical factors controlling the settlement of material inside the pipe and the time to clog the pipe is the flow rate and how it varies along pipe length. It should be noted that there are three different particles sizes assumed to enter the pipe in this study which are very fine sand ($d_{50} =$

10^{-5} m), silt ($d_{50} = 5 \times 10^{-6} \text{ m}$), and clay ($d_{50} = 10^{-6} \text{ m}$) – all selected to represent constituent materials that can enter pipe perforations and deposit within these pipe systems.

We suggest a straightforward set of guidelines for establishing pipe serviceability criteria, defined as the overall loss of cross-sectional area, based on the inflow concentration and total discharge flow rates for specific design lives. Figures 3.72 to Figure 3.81 provide the concentration of particles at the outflow discharge that can result in 10%, 25% and 50% loss of pipe cross sectional area over the period of 10, 20, 50, and 100 years, considering three possible suspended soil particles of fine sand, silt, and clay, for the pipe lengths of 10m to 100m. It should be noted that the transport and entrainment of settled material is not considered in this analysis, and the particles do not move after settling, which suggests that the results presented here may be underestimated. However, these analyses are conservative and offer a method for determining design life using measurable discharge data, including concentration and flow rate. The results demonstrate that, regardless of pipe length and suspended material, higher flow rates inside the drain necessitate lower concentrations to produce specific losses in cross-sectional areas. However, this behavior hinges on the assumption that sediment concentration is directly proportional to flow rate; it is conceivable that sediment yield may depend on other factors, such as the time since installation, changes in flow rate over time, or filter material outside the pipe. These figures also indicate that by keeping the concentrations of materials entering the horizontal drain at lower levels, longer life cycles can be achieved for all suspended particle sizes, pipe lengths, and flow rates. This underscores the importance of being careful during drain maintenance to avoid increasing sediment entry, for example, during hydraulic jetting for cleaning, and other related activities.

Based on site measurable factors such as the outflow rate (Q), material concentration, sediment type and pipe length, Figures 3.72 to Figure 3.81 can be used for analysis of present state of the pipe. As an example, a pipe with 80m length with outflow rate of $10^{-3} \text{ m}^3/\text{s}$ carrying a material concentration of $3.4 \times 10^{-7} \text{ m}^3/\text{m}^3$ of fine sand material, may experience a reduction in cross-sectional area by 25% within a period of 20 years. The same flow condition carrying silt, however, over the same time frame would only lose 10% of its cross-sectional area with even slightly higher concentration ($4.5 \times 10^{-7} \text{ m}^3/\text{m}^3$). On the other hand, clay particles require lower concentration of $1.5 \times 10^{-7} \text{ m}^3/\text{m}^3$ to block 50% of the pipe within 20 years.

Another means of using these charts with measurable data is using the flow rate of sediment (Q_{s-out}) and flow rate of water measured (Q_{w-out}) at a pipe outflow. Specifically, Q_{s-out} can be approximated from the existing design charts as:

$$Q_{s-out} \cong C_0 Q_{w-out} \quad (3-1)$$

or

$$V_{s-out} \cong C_0 Q_{w-out} t = C_0 V_{w-out} \quad (3-2)$$

In such an instance, the terms can be rearranged to approximate C_0 as:

$$C_0 = \frac{Q_{s-out}}{Q_{w-out}} = \frac{V_{s-out}}{V_{w-out}} \quad (3-3)$$

Thus, if sediment flow rates measured at a pipe outflow are less than the values determined from the design charts (i.e. below the design life isoline), then the pipe has not yet reached its design life and is within a reasonable operable range. These conditions assume reasonable pipe yields with demonstrated prior good performance. For the prior example of 25% blockage with fine sand within 20 years, a sediment trap would show approximately 11 liters of captured sediment (possibly larger volumes for slowly-deposited loose materials) over a year timeframe. One potential means of monitoring drains further would be using such sediment traps on sampled or selected drains. During weir maintenance, the stored sediment and knowledge of the contributory drain system could also be aggregated into such a calculation.

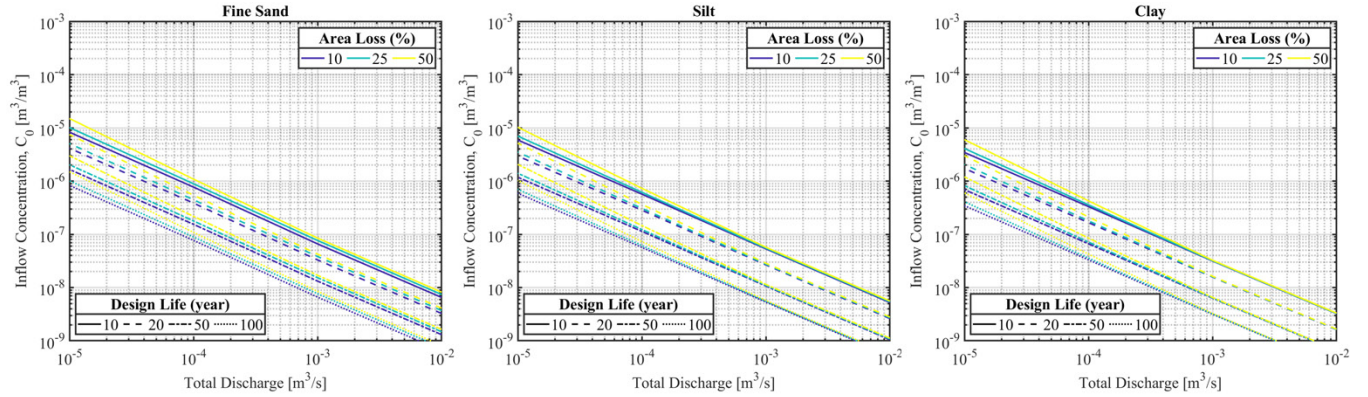


Figure 3.72. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 10m for different sizes of suspended particles

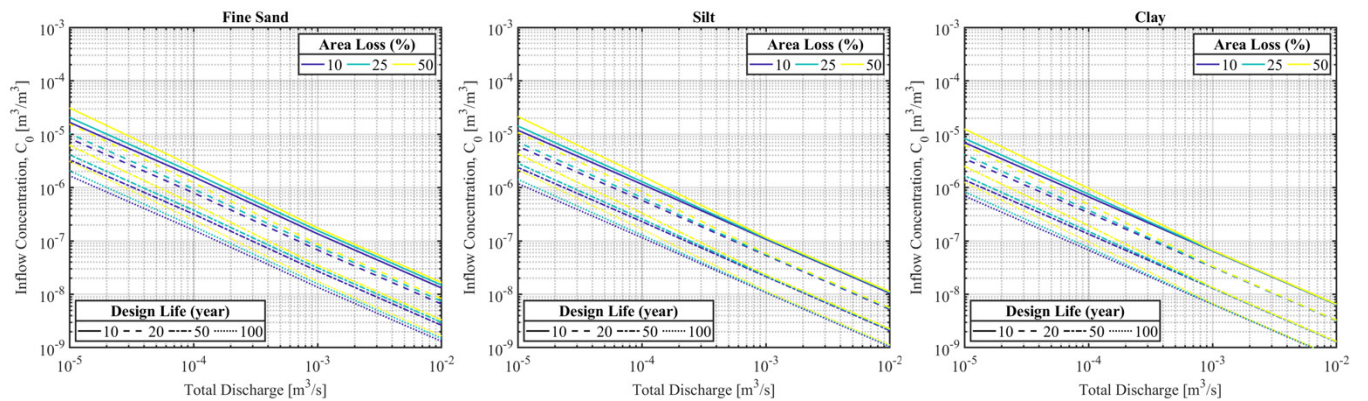


Figure 3.73. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 20m for different sizes of suspended particles

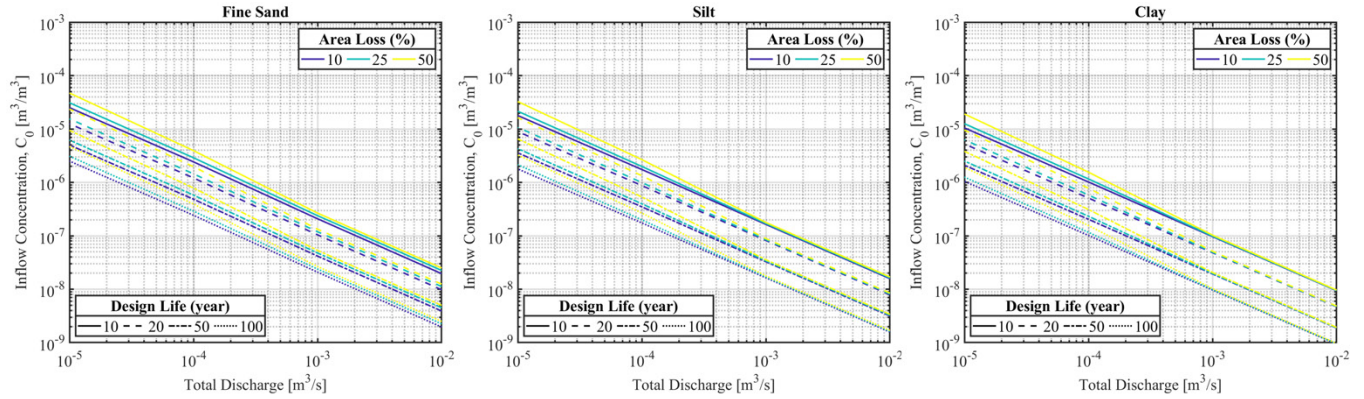


Figure 3.74. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 30m for different sizes of suspended particles

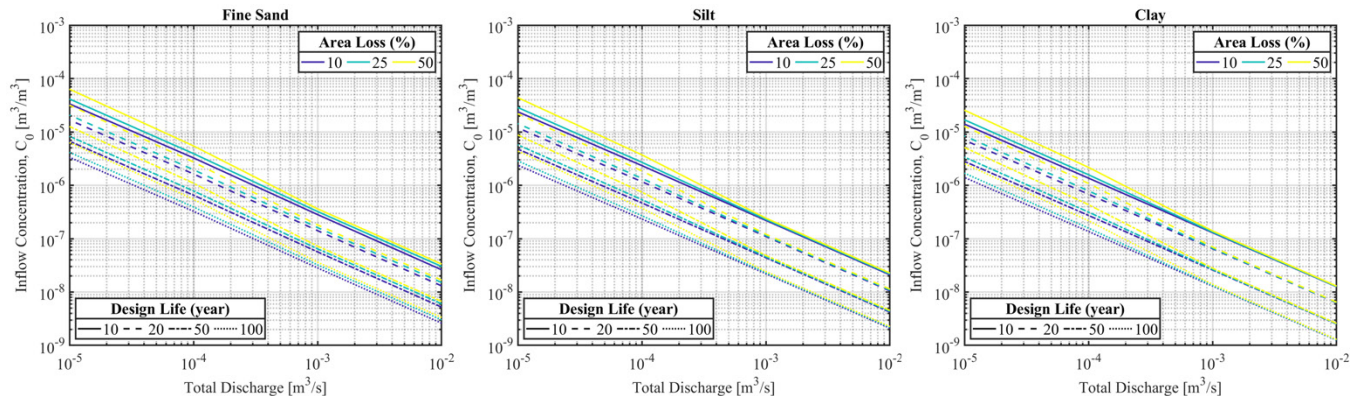


Figure 3.75. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 40m for different sizes of suspended particles

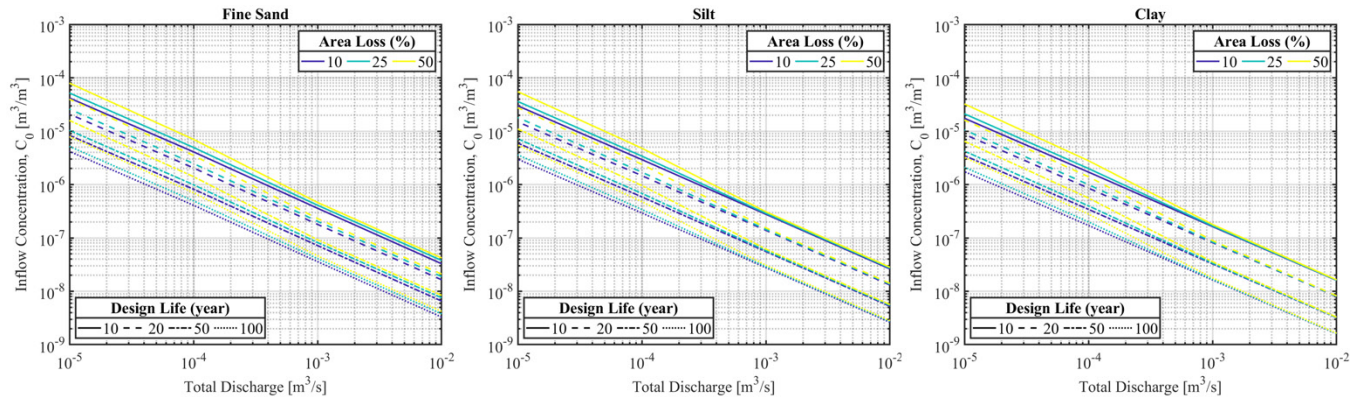


Figure 3.76. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 50m for different sizes of suspended particles

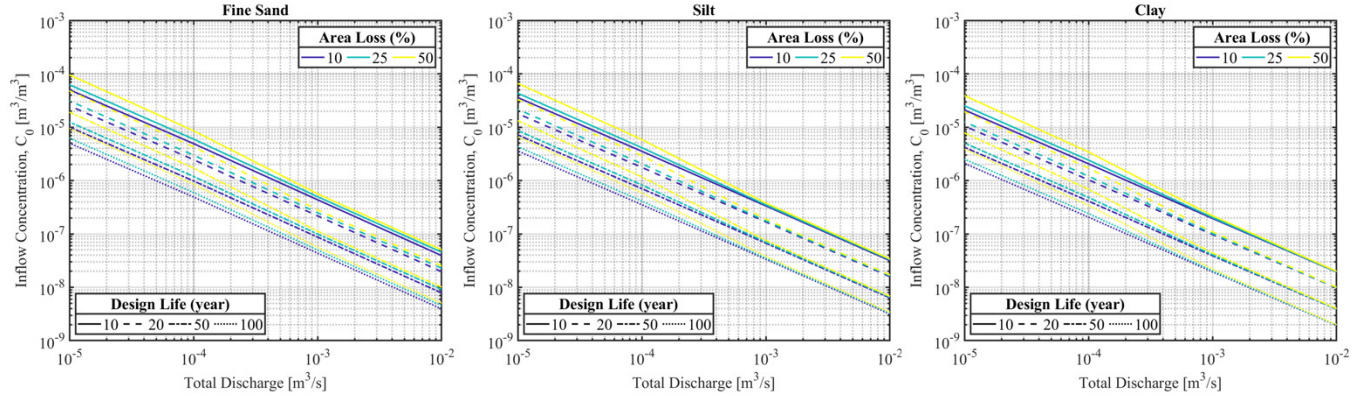


Figure 3.77. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 60m for different sizes of suspended particles

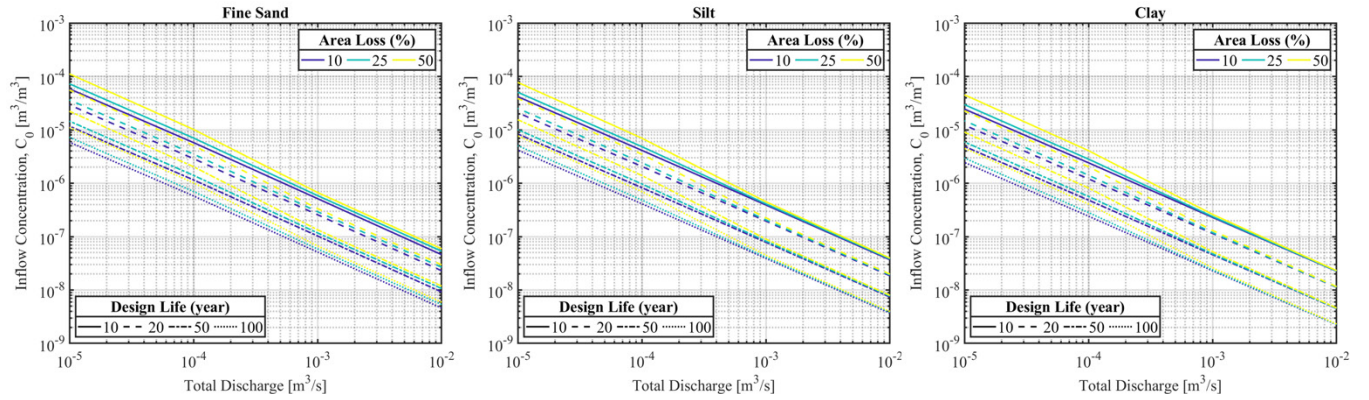


Figure 3.78. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 70m for different sizes of suspended particles

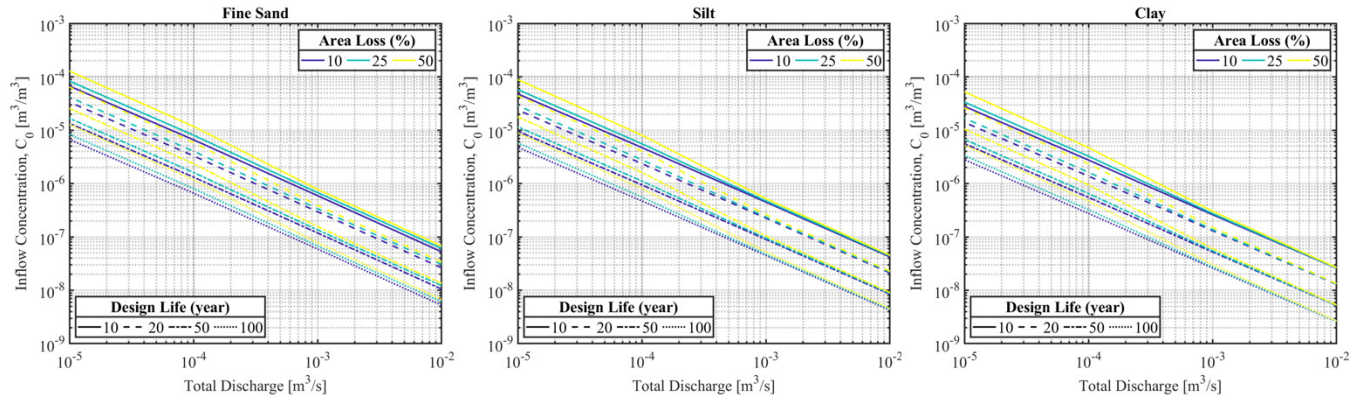


Figure 3.79. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 80m for different sizes of suspended particles

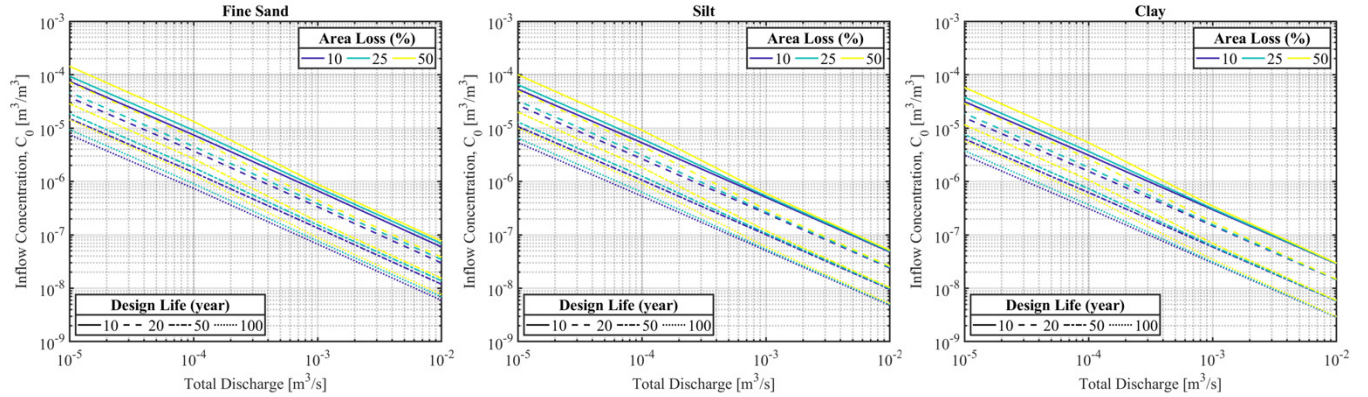


Figure 3.80. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 90m for different sizes of suspended particles

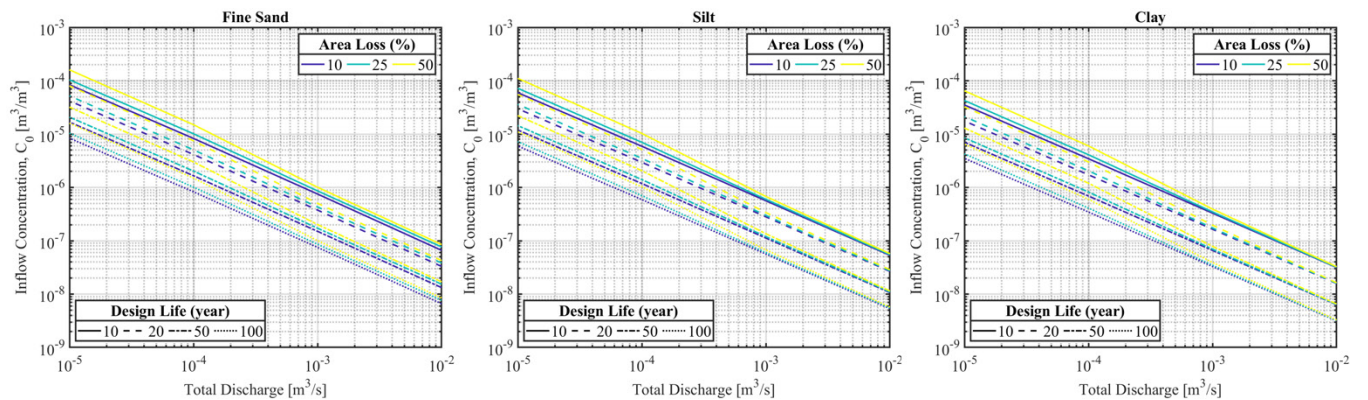


Figure 3.81. Concentration of flowing suspended material vs total outflow discharge to predict area loss percentage at a specific design life for pipe length (L_p) of 100m for different sizes of suspended particles

3.4 SYSTEM LEVEL DESIGN CRITERIA

An observation-based hazard matrix is proposed as a means of evaluating overall, systems-level performance of horizontal drain systems, largely based off observations from the HWY20 Pioneer Mountain-Eddyville (PME) Realignment. Conceptually, the proposed approach requires capture of direct or indirect measures of horizontal drain performance (e.g. short- and long-term piezometric data, drain discharge, landslide movement) in comparison to forcing conditions (antecedent groundwater, precipitation). The data used for the approach proposed herein is explained in detail in Jones et al. (2023).

3.4.1 Expected Piezometric Response after Drain Installation

Following the completion of the drain installation at PME, a prompt decrease in groundwater levels was observed at many of the sites, where piezometers located both within the drain arrays and throughout the landslide area displayed varying degrees of lowered groundwater. The readings from piezometers within the drain arrays typically exhibited a seasonal decline in head

levels after the installation of the drains. Additionally, the amplitude of the piezometric level rise during wet months was also attenuated. This suggests that appropriate horizontal drain function decreases steady-state groundwater conditions stemming from recharge (Jones et al., 2023) but also enables more rapid removal of excess groundwater upon infiltration. As an example, prior to drain installation, piezometer EBIN10-4 experienced a rise of up to seven meters during wet months, whereas after drain installation, the seasonal rise was limited to less than one meter. It is important to note that the drain installation process itself may contribute to the observed pulses of increased groundwater, as high-pressure water injection methods were employed. However, these pulses are transient and localized while often followed by a rapid decrease in head levels.

The response of piezometers to drain installation varies depending on factors such as the geological profile and distance to drain arrays, as well as other site conditions, and the steady-state or antecedent moisture that exists prior to infiltration of precipitation. For example, at PME there are observable trends in groundwater levels apparent at each landslide site following the installation of horizontal drain arrays. Notably, piezometric levels during both wet and dry seasons (June-September and October-May, respectively) are significantly lower, and the immediate groundwater response to storm events is attenuated. To further investigate the response to storm events, a groundwater surface is created through kriging and superimposed on a digital elevation model (Jones et al., 2023). Groundwater change is assessed relative to the start of the wet season (September 1), a time when groundwater levels are typically at their minimum. Comparing two similar storms from 2012 (before drain installation) and 2016 (after drain installation) in the Cougar Creek landslide area provides insight towards reducing both antecedent, steady-state groundwater as well as the “flashy” hydrologic response from heavy precipitation. Although direct comparison of storms is challenging due to their varying intensities, both storms occurred during the peak of the wet season (April) and had similar cumulative rainfalls (2.2 and 3.1 cm for 2012 and 2016, respectively), preceded by limited rain. This example demonstrates the appropriate function of horizontal drain systems, including:

1. Reduced long-term, steady-state groundwater levels through removal of groundwater from recharge;
2. Reduced groundwater rise stemming from infiltration during storm events, facilitated through enhanced removal capacity of the drain systems;
3. Diminished storage capacity of the aquifers, driven by removal of perched or unconfined groundwater above the drainage arrays.

Alongside measurements of forcing (e.g. precipitation, snowmelt, antecedent groundwater), these conditions serve as quantitative, but observational metrics by which the performance of horizontal drain systems can be evaluated over time. That is, a comparison of disturbance (e.g. a storm event with a defined intensity and/or duration) and the evolution of the response over time (e.g. groundwater rise both short and long term) provide a qualitative and quantitative metric about the performance of horizontal drain systems over time. These metrics are used in the form of a hazard matrix to evaluate performance of horizontal drain systems over time.

3.4.2 Evaluation of Horizontal Drain Systems using Systems-Level Approach

Methods for planning monitoring and maintenance for horizontal drain systems are proposed. Suggested criteria are rooted in the Observational Method, indicating the necessity for ongoing

monitoring of both site stability and hydrological conditions. The time history of groundwater elevation from a single piezometer could suffice for such analyses, but the use of multiple piezometers could provide better evaluation of uncertainty and overall system function.

To effectively apply these proposed criteria, it is recommended to conduct a comparative analysis over a reference period (e.g., water years before drain installation or the initial system response after drain installation) and compare the results against behavior observed over the service life. It is essential to account for climatic variability, especially in the context of long-term droughts or intense rainfall events, as they can significantly influence the hydrological response of the site irrespective of the drain systems in place. This evaluation can guide decisions on whether adjustments are needed in (1) the frequency of monitoring or (2) the strategic planning of inspections and maintenance. Failure to meet one or more of these criteria should prompt a reevaluation of the monitoring frequency and refinement of site-specific inspections before making decisions related to maintenance or risk. Subsequently, decisions about maintenance should involve a more detailed inspection of drain systems and site instrumentation, considering the potential risks associated with maintenance activities. Example criteria for comparing drain performance is provided, but other data can be used as available with the frequency and consistency required for long-term assessment. More advanced and refined criteria and expanded hazard matrices with examples from the Pioneer Mountain-Eddyville Realignment are presented in Jones et al. (2023).

Two simple criteria are proposed for evaluating the serviceability, monitoring frequency, and maintenance needs of horizontal drain systems. These criteria include comparison of short-term groundwater response to reference storm events (e.g. the “spikes” in groundwater in Figure 3.82), and the long-term, steady-state groundwater levels outside or in-between storm events (the baseline groundwater levels in Figure 3.82). Herein, we focus on simple monitoring criteria and hazard matrices (Figures 3.83 and 3.84) along with a conceptual example (Figure 3.82). Utilizing a time series of piezometric data from any number of piezometers on a site, both before and after the installation of horizontal drains, allows for the evaluation of the groundwater level (individual piezometric data, median head, mean head, etc.) within a defined landslide area.

3.4.2.1 *Comparison to Pre-Drain Installation Conditions*

Successful implementation of horizontal drains for the purpose of dewatering landslides at a systems level should manifest as a reduction in steady-state groundwater in comparison to pre-drain conditions (Figure 3.82A, outcome A3), whereas the pre-drain conditions are considered during a reference water year where sufficient data on groundwater response is available (see Jones et al., 2023). Further, it should result in diminished transient groundwater spikes from storm events. That is, for a given storm intensity that occurs both pre- and post-drain installation, effective and serviceable drain systems will attenuate the amplitude of groundwater spikes through removing groundwater before it can build up significantly. If the system is not successful or functioning as expected, it will result in similar groundwater response in comparison to pre-drain conditions (Figure 3.82A, outcome A1), suggesting that the drains have not altered the groundwater response. The outcomes A1 to A3 presented in Figure 3.82A are mapped to a representative hazard matrix (Figure 3.83) that provides pathways of action for different observations. Namely, increasingly effective drain function (A3) will result

in less frequent monitoring and no need for repair, retrofitting or alternative landslide mitigation, while ineffective drain systems require planning of retrofitting and continued monitoring (A1).

3.4.2.2 *Comparison to Initial Post-Drain Installation Conditions*

Sustained implementation of horizontal drains for the purpose of dewatering landslides at a systems level should manifest as a continued, lowered steady-state groundwater level in comparison to post-drain installation conditions (Figure 3.82B, outcome B3), whereas the post-drain conditions are considered during a reference water year (e.g. the first winter after installation) where sufficient data on groundwater response is available (see Jones et al., 2023). Further, it should result in sustained, minimal transient groundwater spikes from storm events. That is, for a given storm intensity that occurs following drain installation, effective drain systems will continue to attenuate the amplitude of groundwater spikes through removing groundwater before it can build up significantly. If the system is not successful or functioning as expected, it will result in an amplified groundwater response in comparison to reference conditions (Figure 3.82B, outcome B1), suggesting that the drains are losing capacity and stormwater infiltration for a comparable storm intensity is resulting in heightened groundwater transients. The outcomes B1 to B3 presented in Figure 3.82B are mapped to a representative hazard matrix (Figure 3.84) that provides pathways of action for different observations. Stable drain function (B2) manifests as similar steady-state groundwater conditions in comparison to previous water years and similar transient groundwater response for comparable storms. Horizontal drain systems can improve over time as hydrological pathways manifest surrounding a drain system. In such an instance, one would observe increasingly effective drain function (B3), which would require less frequent monitoring and no need for maintenance, retrofitting or alternative landslide mitigation, while ineffective drain systems require planning of maintenance and continued monitoring (B1).

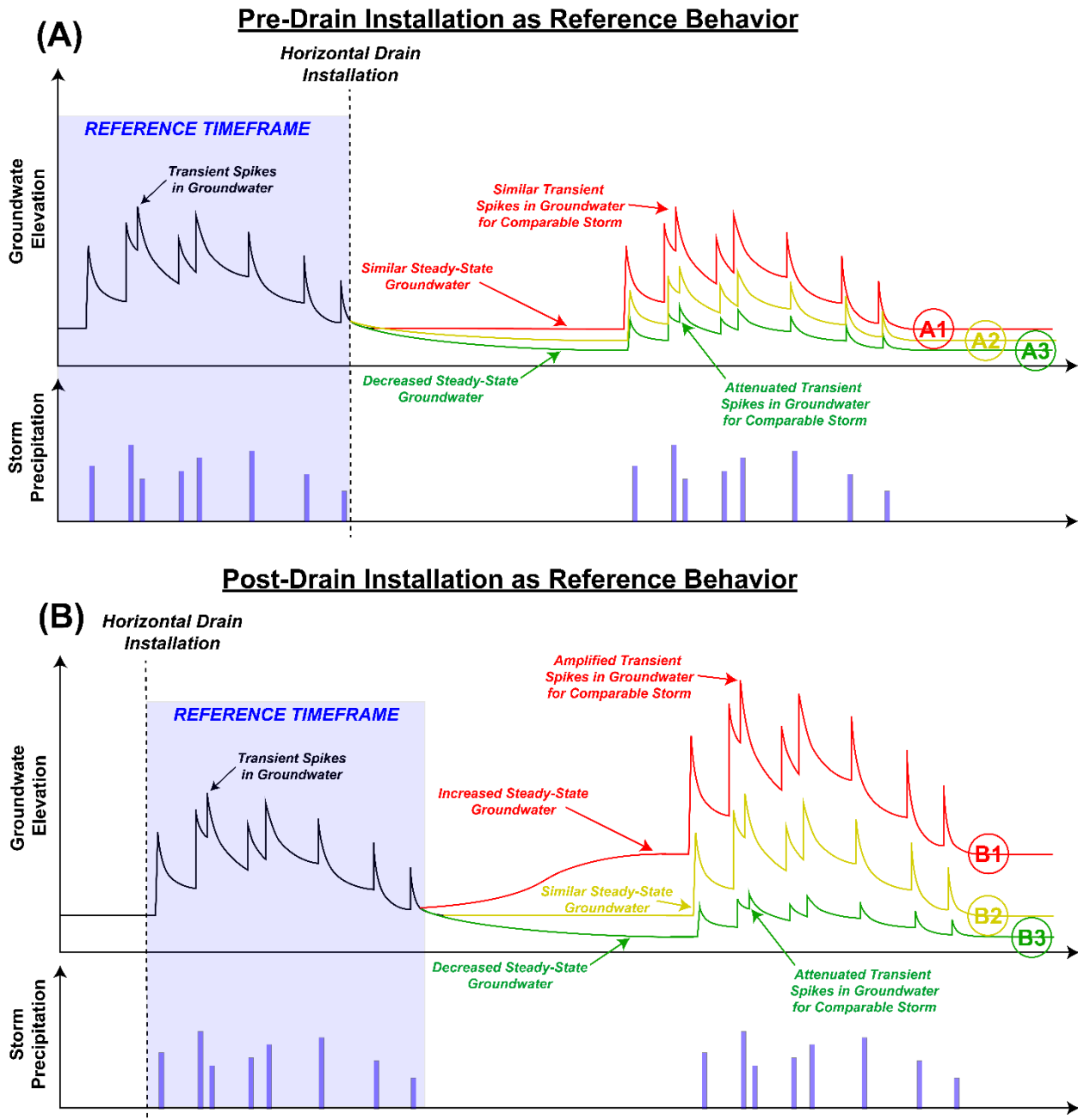


Figure 3.82 Idealized time series of horizontal drain behavior and efficiency (A) when using pre-drain installation conditions as a reference. A1-A3 are reflected in the following hazard matrices as examples of evaluating horizontal drain behavior at a systems level. The upper plot represents groundwater time history while the corresponding storm events and associated precipitation are shown in the lower plot. (B) when using post-drain installation conditions as a reference. B1-B3 are reflected in the following hazard matrices as examples of evaluating horizontal drain behavior at a systems level. The upper plot represents groundwater time history while the corresponding storm events and associated precipitation are shown in the lower plot.

Example Hazard Matrix for Drain Performance: Change in Groundwater Levels Compared to Pre-Drain Conditions

		<i>Significantly Decreased Groundwater Levels</i>	<i>Decreased Groundwater Levels</i>	<i>Similar Groundwater Levels</i>
Storm Intensity Compared to Pre-Drain Conditions	<i>Higher Intensity</i>	A3: Significant increase in drain efficacy (Less frequent monitoring, no repair or added mitigation required)	A3: Increasing drain efficacy (Less frequent monitoring, no repair or added mitigation required)	A2: Stable drain function (Yearly monitoring, no repair or added mitigation required)
	<i>Similar Intensity</i>	A3: Increasing drain efficacy (Less frequent monitoring, no repair or added mitigation required)	A2: Stable drain function (Yearly monitoring, no repair or added mitigation required)	A1: Decreasing drain efficacy (More frequent monitoring, consider repair or added mitigation)
	<i>Lower Intensity</i>	A2: Stable drain function (Yearly monitoring, no repair or added mitigation required)	A1: Decreasing drain efficacy (More frequent monitoring, consider repair or added mitigation)	A1: Severe decrease in drain efficacy. (Monitor continuously, repair or added mitigation required)

Legend

A3: significant increase
 A3: increasing
 A2: stable
 A1: decreasing
 A1: severe decrease

Cell text gives the monitoring, repair, and mitigation action for each assessment.

Figure 3.83 Example hazard matrix for evaluating drain performance and associated actions mapped to the example conceptual behavior in Figure 3.82A, which uses pre-drain installation conditions as a reference.

Example Hazard Matrix for Drain Performance: Change in Groundwater Levels Compared to Initial Post-Drain Conditions

		Decreased Groundwater Levels	Similar Groundwater Levels	Increased Groundwater Levels
Storm Intensity Compared to Initial Post-Drain Conditions	Higher Intensity	B3: Significant increase in drain efficacy (Less frequent monitoring, no maintenance required)	B3: Increasing drain efficacy (Less frequent monitoring, no maintenance required)	B2: Stable drain function (Yearly monitoring, no maintenance required)
	Similar Intensity	B3: Increasing drain efficacy (Less frequent monitoring, no maintenance required)	B2: Stable drain function (Yearly monitoring, no maintenance)	B1: Decreasing drain efficacy (More frequent monitoring, consider maintenance)
	Lower Intensity	B2: Stable drain function (Yearly monitoring, no maintenance required)	B1: Decreasing drain efficacy (More frequent monitoring, consider maintenance)	B1: Severe decrease in drain efficacy. (Monitor)

Legend

B3: significant increase
 B3: increasing
 B2: stable
 B1: decreasing
 B1: severe decrease

Cell text gives the monitoring, repair, and mitigation action for each assessment.

Figure 3.84 Example hazard matrix for evaluating drain performance and associated actions mapped to the example conceptual behavior in Figure 3.82B, which uses post-drain installation conditions as a reference.

3.4.2.3 Alternative Criteria for Evaluating Horizontal Drain Performance

The proposed criteria to evaluate long-term drain performance are not exhaustive. As these proposed criteria are designed primarily at a systems level, they offer guidance for more strategic and refined monitoring or inspection approaches. Decisions related to the maintenance of horizontal drains should be based on a combination of criteria, typically incorporating more specific and conventional indices. Traditional slope monitoring often involves the installation of standard piezometers and inclinometer systems. In landslides influenced by groundwater changes, proper drain function with dewatering should arrest observed movements detected by inclinometers. The attenuation of groundwater rise can be assessed using robust geostatistical techniques, such as kriging analysis, or through the use of "canary piezometers," strategically placed near the inferred landslide rupture surface and to measure lowered pore pressures stemming from drain installation (Machan and Black, 2012). When extensive piezometric monitoring is lacking, strategic placement of piezometers can inform the three proposed criteria. Finally, using inferred groundwater conditions at different periods with conventional slope stability analyses is valuable for evaluating the relative influence of horizontal drain function, both before and during drain performance. Slope stability analysis provides insights into the relative stabilizing effect of horizontal drains and the overall stability of an ongoing or potential slope failure during drain function.

The proposed monitoring criteria function as observation-based principles to assess horizontal drain performance in dewatering large, active landslides, as highlighted in detail in Jones et al. (2023). In line with the Observational Method, all monitoring criteria should be utilized as guidance along with sound judgment and conventional stability analyses to determine a threshold requiring action. A relative threshold on stability on a slide-by-slide basis is sensible for determining when further action is necessary, such as drain maintenance. The application of the proposed criteria demands judgment, considering that each landslide, even within a short geographical distance, may exhibit different hydrogeologic conditions and consequently requires distinct mitigation practices. Judgment becomes crucial, especially considering the variability associated with climate and antecedent groundwater conditions at different times. Careful attention should be given to the use of a reference behavior; for instance, considering a dryer-than-average winter as a comparison to a subsequent wet year may raise concerns about drain performance while the variability of climate is the major control on groundwater in such an instance. However, the conceptual approach proposed in this case study is best applied over a period where climatic and hydrogeologic variability can be systematically observed, and engineers' intuition developed. Lastly, if maintenance interventions are considered, it is critical to consider potential negative outcomes associated with drain maintenance, such as jetting. While jetting drains may effectively remove sediment at screens and within the drain, it introduces transient, elevated pore pressures and may damage screens or well-formed, natural filtration surrounding drain perforations. Therefore, it is crucial for engineers to have criteria that dictate when maintenance is necessary, including those proposed in this report, in addition to traditional slope monitoring techniques (Jones et al., 2023).

3.5 DRAIN LEVEL MONITORING CRITERIA

3.5.1 Rationale

Horizontal drain systems remove groundwater from landslides, helping maintain the stability of the hillside. These drain systems may require maintenance to ensure that they function over time. Deciding when maintenance is necessary requires regular, more frequent inspections with simple criteria (described below) and more robust, less frequent criteria, such as those from interpreting data from instruments, such as that described in Section 3.4. Communication and documentation of pertinent information outlined in this section will enable strategic monitoring and decision-making regarding significant maintenance of horizontal drain systems, such as jetting or more drain installations.

3.5.2 Suggested Timeframe for Inspections

The frequency and timing of inspections should be agreed upon between Geo and Maintenance. Anecdotal evidence suggests that Horizontal Drain Systems tend to have issues between 15-25 years after installation, but no fixed lifespan is known as it depends on site conditions, climate, and other factors. The proposed approach outlined below requires simple, regular inspections from relevant parties, ideally either yearly or every two years. Inspections are best performed around the same time of year – preferably winter or spring – to ensure that groundwater conditions are comparable.

For more critical highways or sites with significant landslide activity, more frequent inspections may be necessary. Other reasons for more frequent maintenance could include notably intense rainfall, extensive snowmelt, extended freezing events, or reports of rockfall or sunken grades. For less active landslide sites or sites with sustained good performance over the first several years, less frequent inspection may be possible.

Less frequently or upon simple inspection, personnel should perform quantitative checks for drain performance, including comparison of instrumentation data in boreholes. Deterioration of individual drains is less important or concerning than signs of deterioration in numerous drains. Other concerning signs that require reporting include signs of slope movement or major disturbances (examples: wildfire, extended freezing, snowmelt).

An example collaborative inspection plan is presented below:

- Year 1: Inspect drain performance using parallel criteria, including instrumentation and the simple checklist provided in this section.
- Years 2-4: Personnel inspect using the criteria below on a yearly basis. Drain performance should be documented, especially if problems are observed.
- Year 5: Inspect drain performance using parallel criteria, including instrumentation and the simple checklist provided in this section.
- Years 6-9: Personnel inspect using the criteria below on a yearly basis if drain performance is concerning, but possibly every two years if performance is satisfactory. Drain performance should be documented, especially if problems are observed.
- Year 10: Inspect drain performance using parallel criteria, including instrumentation and the simple checklist provided in this section.
- Years 11-14: Personnel inspect using the criteria below on a yearly basis if drain performance is concerning, but possibly every two years if performance is satisfactory. Drain performance should be documented, especially if problems are observed.
- Year 15: Inspect drain performance using parallel criteria, including instrumentation and the simple checklist provided in this section.
- Years 16-20: Personnel inspect using the criteria below on a yearly basis if drain performance is concerning, but possibly every two years if performance is satisfactory. Drain performance should be documented, especially if problems are observed.
- ***Repeat as Necessary...***

3.5.3 Inspection Procedure and Action Plans

Example steps for inspecting and documenting individual drain performance are presented below. An example inspection document along with examples of good drain performance and inadequate drain performance are provided in a spreadsheet in the digital appendix of this report.

Items Required:

- Personal Protective Equipment
- Container with known volume (example: 5 gallon bucket)
- Stopwatch or timer (a smartphone timer will be suitable)
- Wrench or other tools if drains are rusted or difficult to open.

Inspection Preparations

1. If this site has been inspected before, skip to Step 3. For a given site, assign each drain a name and number (examples: Spangler-01, Spangler-02, etc.). These names and numbers will be used as a reference during maintenance inspections now and in the future, enabling consistent comparison of drain inspection observations.
2. Mark each drain outflow pipe or valve with the name and number assigned to it using a permanent label for future reference.

Drain or Collector Pipe Inspection Procedure

1. Write the date in the first column of a given drain's spreadsheet under the column "DATE". Each row in this sheet represents a date of inspection. The following steps should be completed within that row.
2. Write the name of the inspector under the column "INSPECTOR".
3. If known, write the total rainfall in the previous week under the column "PRIOR 7 DAY RAINFALL". This could be determined in the office based on available weather data from the closest National Weather Service weather station or other weather stations.
4. For each drain, check if an individual outflow valve is present. If yes, please go to Step 4a. If not, for example where all drains are attached without an outflow valve to a main collector pipe, please go to Step 4b.
 - 4a. If an outflow valve is present for an individual pipe, open the outflow valve of a given drain and observe whether there is sustained groundwater discharge. Wait 5-10 seconds before making this determination as standing water can sometimes mask whether the pipe yields groundwater. If discharge is present, mark "YES" for the "YIELDS GROUNDWATER?" option on the checklist. If there is sediment (soil) or algae/biofilm that are in the bottom of the pipe, mark "YES" under the "SEDIMENT/ALGAE?" column on the checklist. If the discharge is not running entirely clear (for example, brown or gray, translucent or opaque), please mark "YES" under the "TURBIDITY?" column on the checklist. If there is no sustained

discharge, mark “NO” for the “YIELDS GROUNDWATER?,” “SEDIMENT/ALGAE?,” and “TURBIDITY?” options on the checklist.

NOTE: Just because an individual drain does not yield groundwater does not mean it is not functional. We must compare discharge to previous inspections to understand whether a potential loss of function has occurred.

- 4b. If an outflow valve for individual pipes is unavailable, but a discharge from a collector pipe can be measured, find the outflow of the collector pipe and observe whether there is sustained groundwater discharge. Wait 5-10 seconds before making this determination as standing water can sometimes mask whether the pipe yields groundwater. If discharge is present, mark “YES” for the “YIELDS GROUNDWATER?” option on the checklist. If there is sediment (soil) or algae/biofilm that are in the bottom of the pipe, mark “YES” under the “SEDIMENT/ALGAE?” column on the checklist. If the discharge is not running entirely clear (for example, brown or gray, translucent or opaque), please mark “YES” under the “TURBIDITY?” column on the checklist. If there is no sustained discharge, mark “NO” for the “YIELDS GROUNDWATER?,” “SEDIMENT/ALGAE?,” and “TURBIDITY?” options on the checklist.
5. If the drain yields groundwater discharge, take a container of known volume (example: a five-gallon bucket) and measure how long it takes the discharge to fill the container using a stopwatch. Accuracy within a second is acceptable. Volumes less than a half-gallon are discouraged, especially for high flows.
6. Write the container volume in the “VOLUME” column on the form. Write down the time it took to fill the container in the “FILL TIME” column on the form.
7. The discharge rate is equal to the container volume divided by the time it took to fill. When complete, please calculate this discharge rate and enter it under the “DISCHARGE RATE” column.
8. In the “OTHER NOTES” column, please mark any observations that you deem important. Examples could include “wildfire occurred near the site,” “the site recently had a deep freeze,” “measurement made during unusually wet winter,” “pipe is broken and leaking,” “notable algae or biological material in pipe,” “reported observations to Geo,” among others.
9. Ensure that any modest issues, such as small fractures, leaks, rusted valves, and couplings are repaired as needed. If full clogging has occurred at the end of the pipe, remove the material to enable continued flow and make a note of these conditions.

Decisions after Inspection

10. Upon completing the inspection of a given drain or drain collector pipe, interpret the historical behavior of the pipe system to see if there are signs of deterioration in terms of the presence of sediment, turbidity, flow, and notes.

10a. Deterioration of flow would manifest by decreased “DISCHARGE RATE” over time in comparison to prior rainfall and/or the time of the year. For example, it is sensible to have no or little drain yield in summer months, especially for individual drains. Alternatively, it would be sensible to check drain yields at approximately the same time of year, especially in winter or spring seasons where there is notable presence of groundwater. Bad performance of a drain system would show a very large decrease in “DISCHARGE RATE” for comparable conditions (see “Deteriorating Pipe Example”). This could be a sign of pipe clogging or crushing. Some variability (+/- 100% versus previous inspections) is reasonable. If large and sustained decreases in “DISCHARGE RATE” are observed (for example, in comparison to the previous two inspections), make a note and report to ODOT Geo Personnel.

10b. Deterioration from sediment or algae/biofilm clogging would manifest as a sustained change in the presence of sediment or algae/biofilm in the pipe in comparison to the previous two inspections. For example, if very little sediment or algae/biofilm is observed for the first several inspections of drain function under “SEDIMENT/ALGAE?” but then is present for at least the last two inspections, then make a note and report to ODOT Geo Personnel.

10c. Deterioration from turbidity (“dirty” water) would manifest as a sustained change in turbidity in the pipe in comparison from the previous two inspections. For example, if clear water is observed for the first several inspections of drain function under “TURBIDITY?” but then is present for at least the last two inspections, then make a note and report to ODOT Geo Personnel.

NOTE RELEVANT TO INDIVIDUAL DRAIN MONITORING: if the changes in 10a, 10b, and/or 10c are observed for a single drain, reporting may not be necessary. However, if these changes are observed in numerous drain systems, it may be worth reporting to ODOT Geo Personnel.

10d. Be sure to keep track of “OTHER NOTES” as it can provide context to potential reasons that could cause outliers (example: a very wet winter, recent maintenance of the drains, observed landslide movement, etc.). This section can also capture any minor maintenance activity needed (example: minor cleaning, sealing leaks, etc.). If something is considered out of the norm for the drain system, report to ODOT Geo Personnel.

11. If no major changes are observed, report that “no major changes were observed” to Geo Personnel and provide associated record (see template excel document in Digital Appendices).

Make plans for next site visit at approved time interval. Coordinate with Geo Personnel as to maintenance needs if necessary.

4.0 FLODAR: FIELD MONITORING

The slow movement of deep-seated landslides may compromise the integrity of infrastructure; for these slope failures, the most common and economical mitigation technique is the installation of embedded pipe networks (horizontal drains), which remove groundwater through gravity-driven seepage. However, the performance of these systems and their influence on groundwater removal is only inferred through qualitative field observations. The optimal operation and maintenance of these systems is currently unknown. In collaboration with the Oregon State College of Forestry, a low-cost sensing system – FloDar – was developed by OPEnS Lab to quantify groundwater discharge with an ultrasonic flow meter. A FloDar is capable of measuring velocities up to 10 m/s of flow in pipe sizes DN15 to DN100 mm. For project implementation, we use a 1.5” schedule 40 pipe which allows flow measurements upwards of 700 L/min bidirectionally. FloDar is reliant on battery power to allow for prolonged (>50 days) deployment. The only intervention necessary is to obtain recorded data from a local microSD card and swap batteries. This system presents a low-cost means of monitoring groundwater discharge and its properties, which is of relevance to landslide mitigation drains, irrigation, and other groundwater management systems.

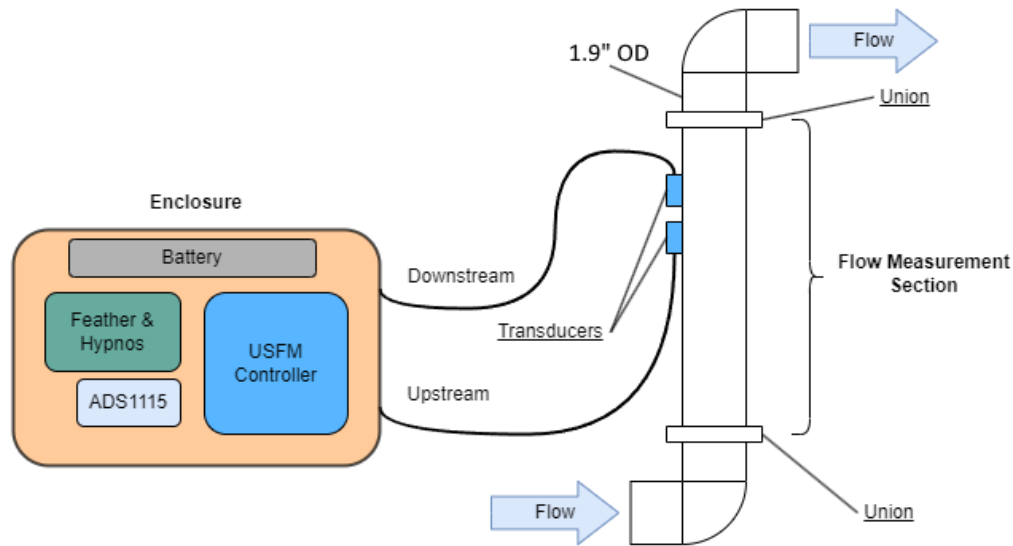


Figure 4.1. FloDar System Diagram

4.1 HARDWARE DESCRIPTION

The FloDar can be divided into several sub-parts: 1) Structure: the weatherproof pelican case and laser-cut or 3D printed plastic internal mounting; 2) Sensors: ultrasonic flow meter (USFM) with TS-2 clamp on transducers, optional thermocouple and turbidity sensor (not included here); and 3) Electronics and circuits: 12V/5V rechargeable battery, wires and cables, printed circuit boards: Adafruit Feather M0, OPEnS Lab Hypnos, Adafruit ADS1115, custom breakout board, and optional thermocouple amplifier and turbidity breakout board (not included here) (Figure 4.1, 4.2).

The FloDar System can be applied for flow measurement to many systems that include full piped flow. Programmable settings include a range of pipe sizes (DN15-100 mm), pipe materials (e.g. steel, stainless steel, cast iron, copper, PVC, aluminum, glass), liners (rubber, mortar, polypropylene, polystyrene, polyethylene, Teflon, and fluids (e.g. water, sea water, kerosene, gasoline, crude oil, propane at -45°C, butane at 0°C, diesel oil, castor oil, peanut oil, alcohol, water at 125°C) (Ultrasonic Flow Meter User Manual). Additional pipe setups are possible with custom speed of sound inputs for pipe material, liner, and fluid. Example applications beyond landslide drains include inflow for flume experiments and in building plumbing systems.

4.1.1 Structure

All electronics are enclosed in a waterproof Pelican case (1150 Protector) with four cable glands: two for transducer cables, one for the thermocouple, and one for the turbidity sensor cable (Figure 4.2). Laser-cut acrylic or a 3D printed insert is placed in the bottom of the case to mount the board stack and USFM (Figure 4.3). The battery is contained by this as well in tandem with foam placed in the lid of the Pelican case.

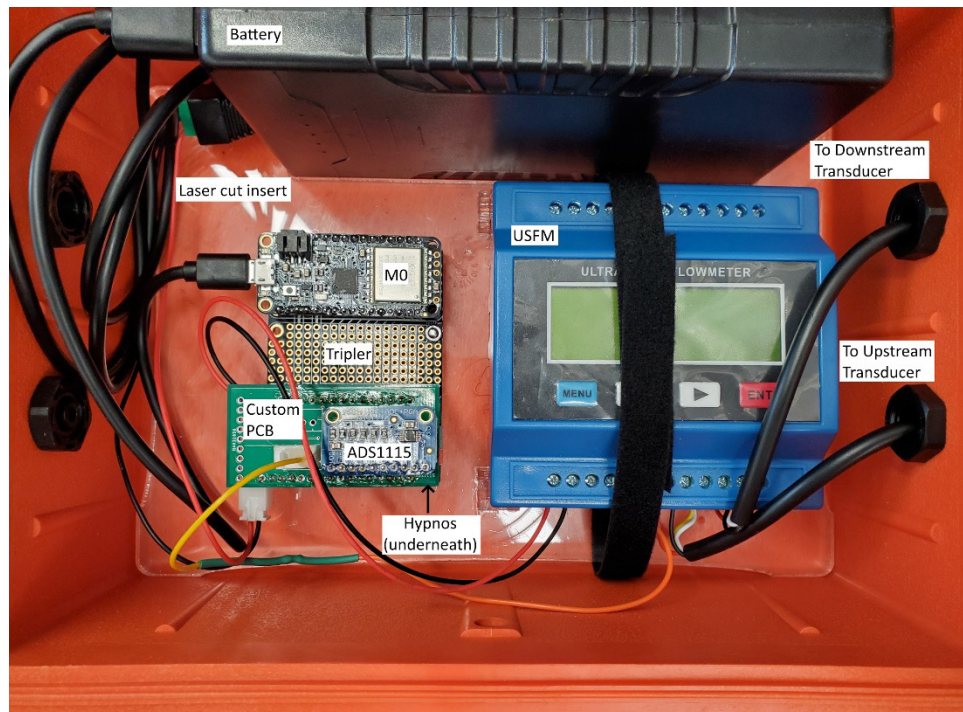


Figure 4.2. FloDar version 4 with labeled components

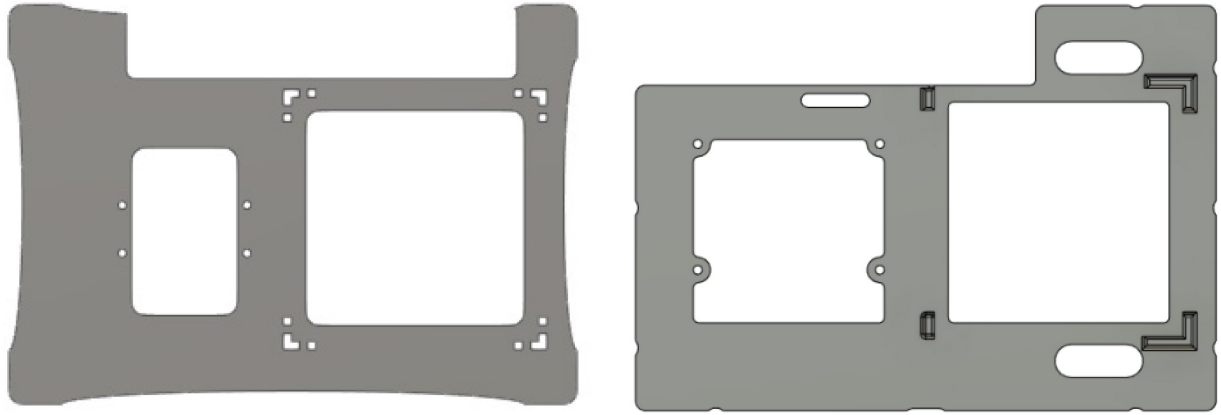


Figure 4.3. Options for structure inside Pelican case: laser cut insert (left) or 3D printed insert (right).

4.1.2 Sensors

For the FloDar implementation of the USFM setup, TS-2 clamp-on transducers are attached in the V (reflective mode) configuration using worm gear hose clamps and a 3D printed spacer to a 1.5" diameter schedule 40 PVC pipe (Figure 4.4). The transducers should have 10D (or 15.9") separation from valves and pumps on the upstream side and 5D (or 7.95") separation on the downstream side to ensure steady flow (Ultrasonic Flow Meter User Manual). Color coding on the face of the transducers and the cables is used to indicate downstream (blue) and upstream (red) (see Transducer Assembly section). Note that the USFM can read negative flows, and a reversal of these sensors is not a critical error and only results in a negative flow being observed. The transducers are connected to the USFM via a long (up to 2.5 m for each transducer) 3-wire cable provided along with the USFM. Adafruit waterproof cable connectors are used to allow safe disconnection and reconnection between the transducers and the case. The transducers have 3 terminals each; a positive, negative, and ground. The Adafruit waterproof cable connectors have 4 connections, thus the white and yellow wires are used as ground. These wires terminate at the USFM into their respective terminals (Figure 4.2).

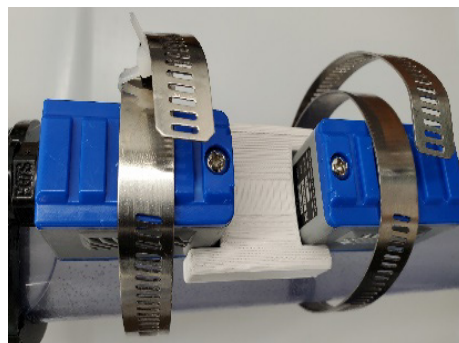


Figure 4.4. TS-2 transducers with spacer and worm gear hose clamps on 1.5" schedule 40 clear PVC pipe.

4.1.3 Circuitry

The USFM is an off-the-shelf component and is responsible for conversion of the signal from the transducers to a 0-20mA analog output signal. The USFM uses piezoelectric crystals to send and receive ultrasonic signals (Ultrasonic Flow Meter User Manual). The velocity of the fluid inside the pipe is measured from transit time: the difference between the travel time for a sound wave going from the upstream transducer to the downstream and a sound wave going from the downstream transducer to the upstream (Ultrasonic Flow Meter User Manual). The difference in travel times is directly proportional to the velocity of the fluid, and sensitive to transducer placement, bubbles, suspended solids, density, and temperature. The flow meter can be programmed to accommodate a range of fluids and pipe materials but does not compensate for temperature. The USFM uses user-given data about the pipe system to calculate the speed of sound (see 4.4 Flow Meter Setup). These settings must be set by the user and solidified. Once solidified, the USFM will remember the saved settings on startup. The USFM requires 8 to 24V power and input from the transducers to provide an analog output signal.

The analog output signal from the USFM is too large of a voltage (5V) for the ADS1115 using the recommended (250 Ohm) resistor to convert the current (maximum of 20 mA) to voltage (Ultrasonic Flow Meter User Manual). For the FloDar, a 150 Ω resistor is used to convert the 0-20mA signal to 0-3V (Figure 4.5). The ADS1115 then converts this analog reading and sends the digital value to the Hypnos/Feather stack via I2C.

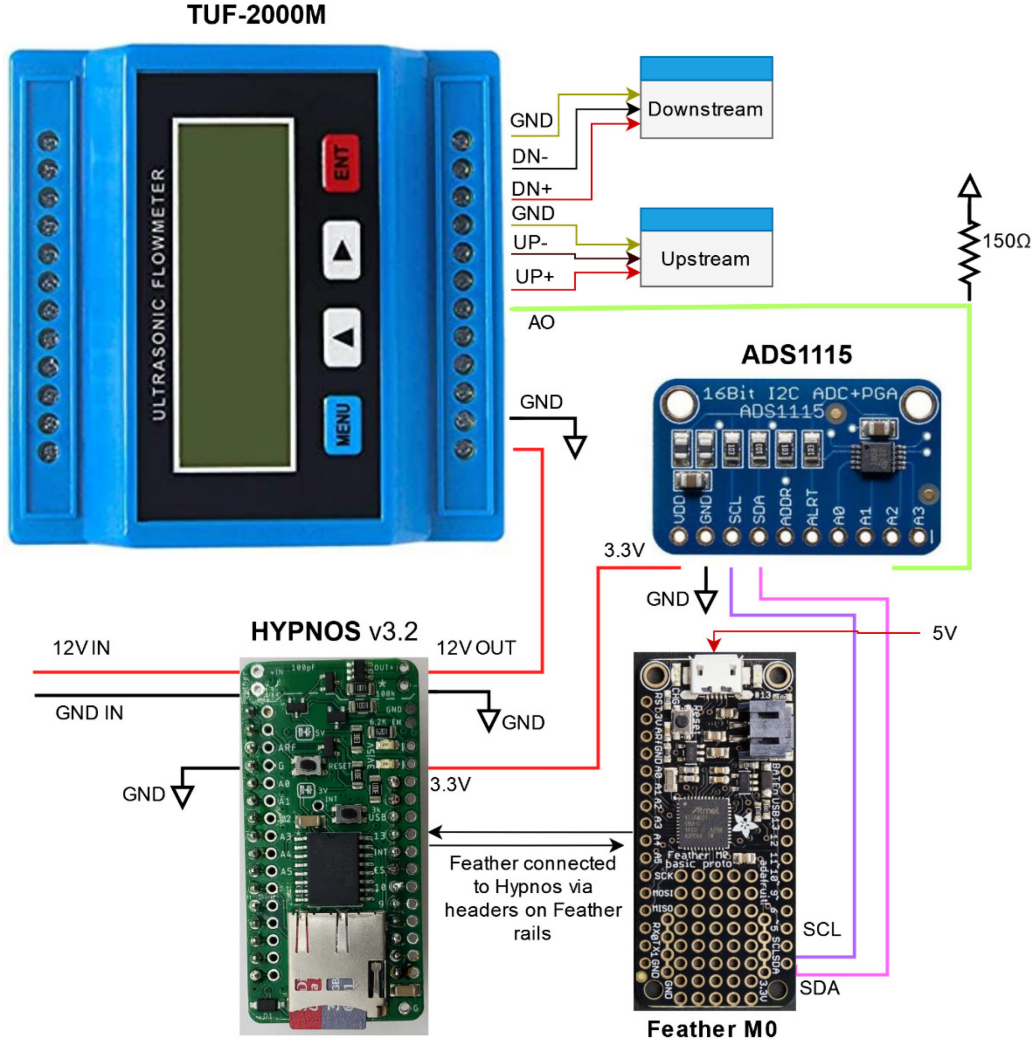


Figure 4.5. Circuit diagram of major electrical components with connections

The Hypnos and Feather M0 are responsible for several tasks. The Hypnos is responsible for logging data to an SD card, timekeeping via a real time clock (RTC), sleep functionality, and power distribution ([Hypnos wiki](#), (Nguyen et al., 2021)). The Feather M0 is the microcontroller and responsible for running the custom software (see [Loom V4](#)) that controls these various functions. The custom breakout board is a custom in-house board designed by the FloDar team to hold necessary resistors and properly connect the Hypnos/Feather stack to the ADS1115 and USFM (Figure 4.2). Lastly, the battery provides both the Feather with 5V power and 12V power to the USFM via the Hypnos (Figure 4.2).

4.1.4 Software

FloDar uses the Loom 4.1 [Arduino board profile](#) with the ADS1115, Analog, and Hypnos modules (Figure 4.6). FloDar uses custom constants MAXFLOWRATE set equal to 150 and MAXBITS set equal to 16384 (2^{14}) with the ADS1115 gain set to $\frac{2}{3}$. The duration between measurements is 15 minutes (MINUTE = 15), and the suggested pause time period after wake up

prior to taking each measurement is 10 seconds (DELAY = 10000 ms). The flow rate is calculated within the code as $(\text{ADS1115}(3)/\text{MAXBITS}) * \text{MAXFLOWRATE}$ and exported to the SD card (Figure 4.6).

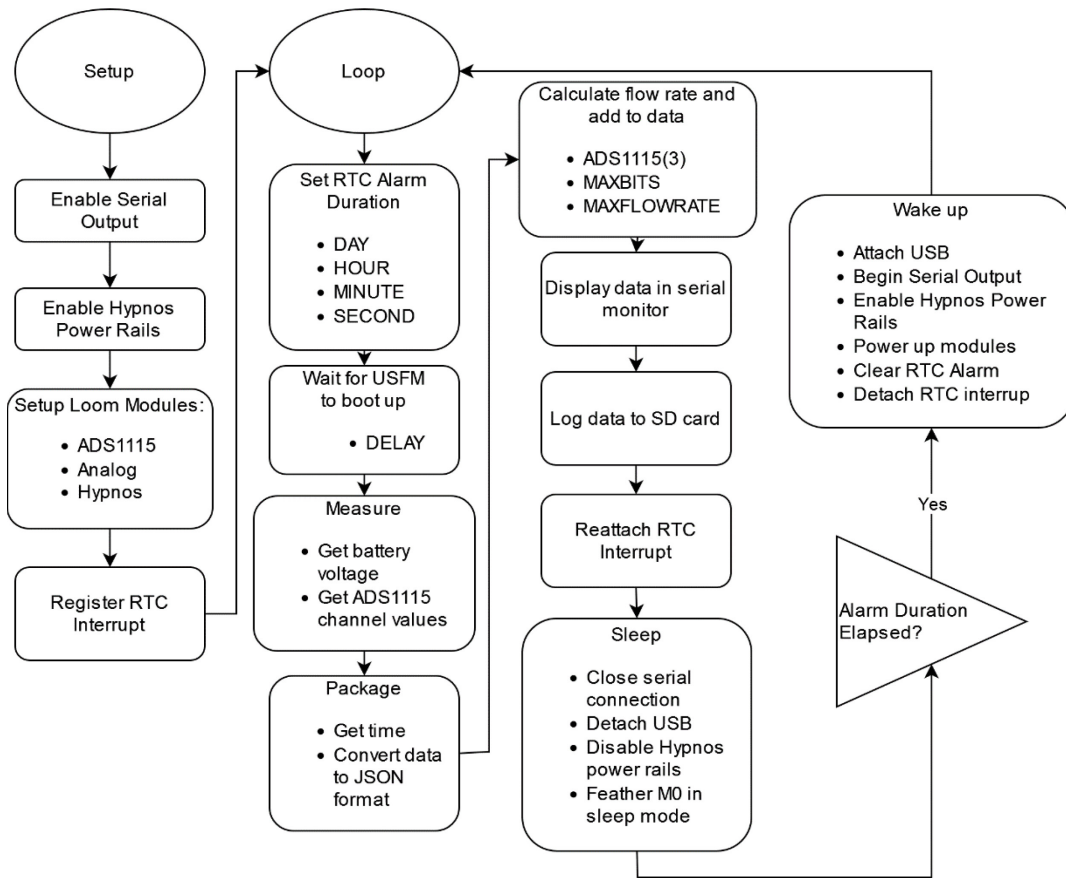


Figure 4.6. FloDar Loom 4 Software Diagram

4.2 OPERATION INSTRUCTIONS

Detailed instructions regarding the hardware specifications, material list, software, and other details are provided in Appendix A. A general overview of the build is provided herein.

4.2.1 Transducer installation

The transducers should be installed on a clean section of pipe that is free of debris or scaling on the outside and inside where there will be steady, full pipe flow with minimal bubbles and suspended sediment. See the Ultrasonic Flow Meter User Manual for more information on transducer placement in a pipe system. Apply lubricant to the oval transducer faces, set the upstream transducer face against the cleaned pipe location with the label on the downstream side, and use the clamp to fasten securely with the clamp band in the gap between raised sections on the back of the transducer. Place the spacer against the upstream transducer and slot the downstream transducer into the spacer, label touching the spacer, or measure and place the downstream transducer at the distance indicated by Menu 25 exactly in line with the upstream

transducer and use the clamp to fasten securely. The spacer can be removed or left in place. Attach the upstream waterproof connector cable from the transducer to the upstream cable attached to the flow meter, and the downstream waterproof connector cable from the transducer to the downstream cable attached to the flow meter.

4.2.2 Flow meter calibration

For the flow meter to accurately calculate fluid velocity, it must have a zero flow reference. Fill the pipe that the transducers are attached to with water, and wait until there are no bubbles or fluid movement. Turn on the flow meter and select menu 42. Select ENT to start the zero flow calibration. When calibration is complete, solidify settings in flash memory using menu 26.

4.2.3 Deployment

After the transducers are installed, place the pelican case in an adjacent location and open it. Switch on the battery and wait up to 30 seconds for the flow meter to turn on: initial setup waits for a serial monitor connection for 20 seconds, then the flow meter takes up to 10 seconds to boot up. If the flow meter does not power on, check all wire connections and battery voltage. When the flow meter powers on, check that the flow meter display shows signal quality values greater than 60 for each transducer, and then a flow value within the expected range, and “R” (normal) for the system error code in the upper right corner of the display. If not, consult the Ultrasonic Flow Meter User Manual for troubleshooting. Close and latch the pelican case, ensuring that there is no debris or wires between the gasket in the lid and the bottom lip.

4.3 VALIDATION

During the summer of 2022, FloDar units were installed on pipes at the Spangler field site (Figure 4.7). Two pipes on the same hillside (Figure 4.8) showed relatively constant to a slight decline in flow from the end of July (7 ± 2 L/m for pipe 10, 6 ± 2 L/min for pipe 14) to the beginning of October (7 ± 3 L/min for pipe 10, 4 ± 1 L/min for pipe 14). Staggered hillside response to rain events in October and November can be seen in the outflow for pipes 10 and 16 (Figure 4.9). For pipe 10, the flow data was much noisier during the response to the rain event with values ranging from 23 to 57 L/min within a 2-hour period. In contrast, pipe 16 had only 2-3 L/min variability in values over short periods before, during, and after the response to the rain event. Note that the FloDar units on each pipe were changed between the summer and fall datasets. All datasets presented, except Pipe 16 after October 13, were filtered to remove intermittent low data points likely caused by entrained air bubbles. The specifications provided herein present a simple means of monitoring these drain systems. Overall discharge at the sites of interest for this project showed good horizontal drain performance, although discharge was variable from each pipe within a drain array.



Figure 4.7 FloDar installed at Spangler field site, July 2022.

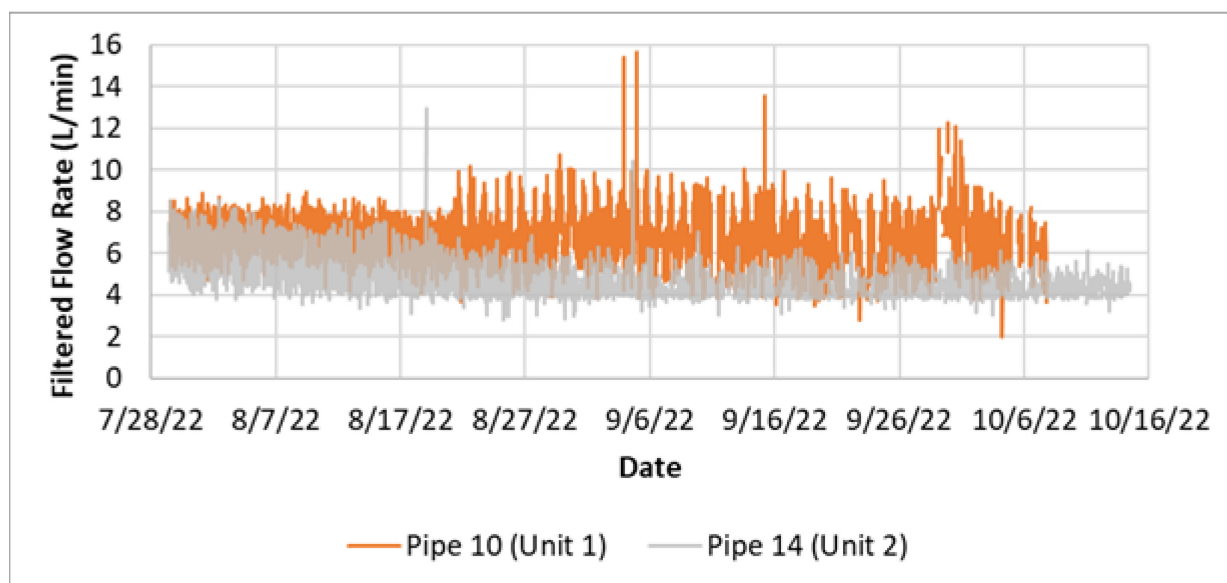


Figure 4.8 Summer 2022 flow from units 1 and 2 on pipes 10 and 14 (respectively) at Spangler

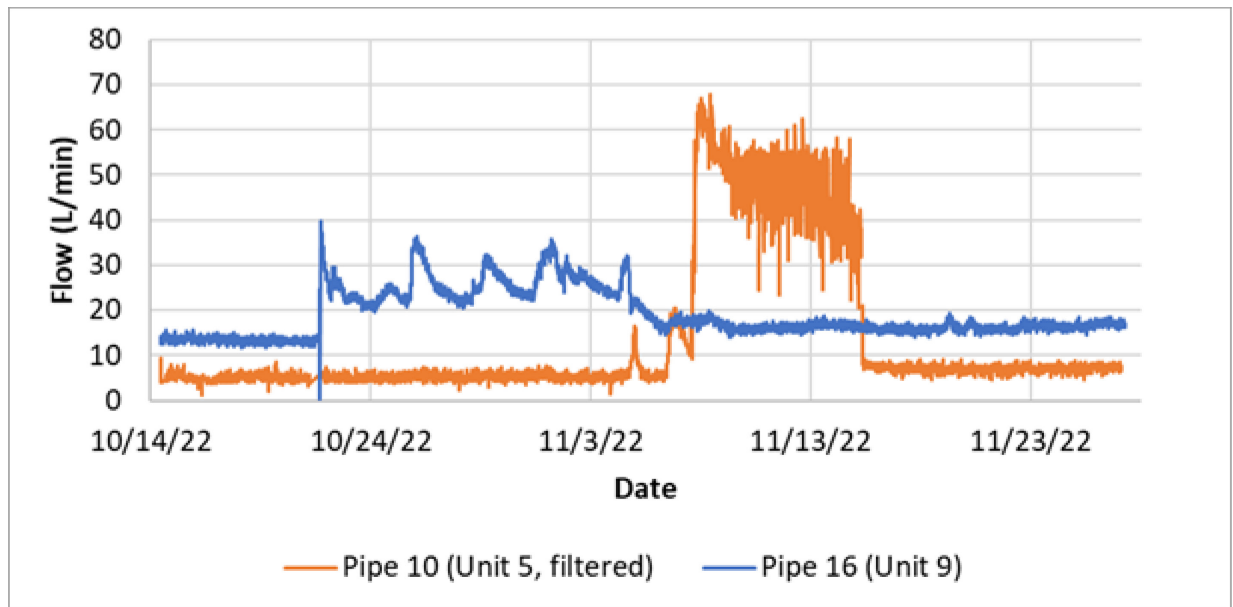


Figure 4.9 Fall 2022 flow from units 5 and 9 on pipes 10 and 16, respectively, at Spangler.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This report presents a framework to assess the effect of horizontal drains on groundwater drawdown, potential mechanisms for siltation and simple metrics for evaluating potential clogging lifecycles of these systems, and an Observational Method-based approach towards evaluating overall horizontal drain system performance based on data from the Pioneer Mountain-Eddyville Alignment. Additionally, to avoid computational expense associated with the drawdown techniques presented, both design charts and a Machine Learning predictive model are also presented to estimate drawdown based on simple site conditions. The efficiency and life span of horizontal drains can be altered due to siltation and clogging inside the pipes; therefore, a three-dimensional transient advection-diffusion in cylindrical channels was numerically solved to provide time-to-clog charts for maintenance or replacement of the drains. Further, a low-cost sensing system – FloDar – was developed in collaboration with OPEnS Lab to quantify groundwater discharge with an ultrasonic flow meter. The key points in Chapters 1-4 are as follows:

- Landslides arise from a range of factors, including seismic events, in-situ weathering of soil and rock, and most significantly, precipitation. Elevated groundwater is a primary control on slope failure; therefore, draining the water is a common solution for slope stabilization.
- Horizontal drains have proven to be an effective landslide mitigation technique in the presence of water. Implementing horizontal drains results in a lowering of the water table elevation and a concurrent decrease in pore water pressure, effectively enhancing the shear strength of the soil. This approach offers advantages due to its rapid deployment and typically lower costs compared to alternative methods.
- Unlike alternative stabilization techniques, drain systems lack a well-established design methodology and frequently suffer from either conservative design or qualitative design approaches. Furthermore, significant concern arises from the lack of data regarding the drains' long-term effectiveness, which can be compromised by the accumulation of silt and sediment, consequently diminishing their efficiency, and necessitating regular maintenance.
- The efficiency of this system is governed by various factors, including the type, location, quantity, length, and spacing of drains, alongside the crucial role of soil characteristics and slope geometry as critical governing parameters.
- A numerical approach towards three-dimensional transient groundwater drawdown in presence of horizontal drains was proposed to study the role of horizontal drains on mitigating landslides. Further, a sensitivity analysis was performed to investigate the effect of design parameters, namely drain length, drain spacing, slope angle, and aquifer length and depth. It was shown that the drain length and spacing are the most critical factors in controlling groundwater drawdown, mobilized friction angle, and

total discharge out of the drain. Based on these design factors, a robust series of design charts was proposed.

- A predictive model using Artificial Neural Network (ANN) regression technique was developed to enable simple and quick application of the transient drawdown solutions proposed. Based on the predictive model, a toolbox for ArcGIS Pro was provided to approximately measure groundwater drawdown with a few key design parameters, such as drain length and spacing, aquifer dimensions, and properties.
- Siltation may be a long-term concern for horizontal drain function. Particles from the surrounding soil of the drains are transported by the flowing water into the drainpipe, leading to a deposition of some particles on the inner pipe wall while others are washed away. A continuity equation of mass balance transport and deposition in cylindrical channels was developed to model the long term performance of the drains as siltation and sediments and results in efficiency reduction of the drains. Based on this model, time-to-clog charts of different design lives for specific total outflow discharge and grain sizes were proposed and can be used as a metric to guide inspection or maintenance of drain systems.
- The analysis of piezometric, inclinometer, and weir data from the Pioneer Mountain-Eddyville realignment (PME) offers a comprehensive evaluation of the actual site's response to the introduction of horizontal drains. Kriging interpolation is employed to create time series of piezometric data, facilitating the assessment of water balance and the behavior of multiple paleolandslides at the PME site. This method allows for a nuanced comparison of groundwater data before and after the installation of horizontal drains, enabling insightful observations regarding the effectiveness of the drainage system. Based on this data, a series of hazard matrices are proposed based on the Observational Method. These matrices provided a means of comparing reference hydrological behavior (e.g. prior to drain installation, after drain installation) to current hydrologic behavior to evaluate the trajectory and potential intervention or inspection needs of horizontal drain systems. These results were published in depth in Jones et al. (2023).
- To monitor the groundwater discharge and its properties from horizontal drains and to provide a guideline for operation and maintenance of these systems, a low-cost sensing system, FloDar, was developed in collaboration with the OPEnS Lab to quantify groundwater discharge with an ultrasonic flow meter. FloDar is reliant on battery power to allow for prolonged (>50 days) deployment. The system offers an economical approach to track groundwater discharge and its characteristics, holding significance for applications such as landslide mitigation drains, irrigation, and various groundwater management systems. The FloDar is capable of measuring velocities up to 10 m/s in pipe sizes DN15 to DN100 mm.

5.2 RECOMMENDATIONS FOR FUTURE WORK

The work described herein characterizes the transient mechanisms of groundwater drawdown from horizontal drains and provides design criteria for parameters affecting the efficiency and

overall performance of horizontal drains for landslide mitigation. Further, it provides an implementable, general process by which horizontal drain performance can be evaluated over time. To further enhance findings, scope, accuracy, and implementation, future work and potential areas for improvement include:

- One of the assumptions of the numerical solution for groundwater drawdown by horizontal drain was constant atmospheric pressure inside the drain. However, this assumption might change due to seasonal fluctuations. To have a more accurate estimation of groundwater drawdown and improvement of slope stability, the effect of pressure inside the drain can be incorporated into the model.
- Flow may often be governed by secondary flow or fracture flow, which is not easily captured using Darcian flow conditions. However, such conditions can be estimated and treated as a higher hydraulic conductivity using the proposed design charts.
- For simplicity of the siltation model, it was assumed that particles that settle are not being entrained or transported. This assumption provides a more conservative estimate of design life for long term performance of horizontal drains. Considering the effects of particle entrainment and transport would provide more accurate maintenance guidelines for horizontal drains.
- Expanded long-term monitoring of both flow and siltation would help expand the findings from this project.

6.0 REFERENCES

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APPENDIX: A

7.0 APPENDIX A: FLODAR BUILD SPECIFICATIONS

Table 7.1: Design Files

Design Filename	File Type	Description	Source
Pelican Insert Laser Cut	DXF	Acrylic insert option for holding components in place.	Github
Pelican Insert 3D Print	STL	ASA insert option for holding components in place.	Github
Transducer Spacer	STL	ASA spacer for ensuring exact transducer separation for V method installation on 1.5” schedule 40 pipe.	Github
Breakout Board	Gerber	Custom PCB for connecting electrical components.	Github
FloDar_Field_Lo om4_1	ino	Arduino code for operating system.	Github

7.1 BILL OF MATERIALS

Table 7.2: Mechanical Components

Designator	Component	Qty.	Cost per Unit	Total Cost	Source of Materials	Notes
Pelican Case	1150 Pelican Case	1	\$49.95	\$49.95	B&H Photo	
Structure	Acrylic 1/8" x 12" x 12'	1	\$4.99	\$4.99	Grainger	Each design uses 8.27" x 5.81"
Cable Gland	PG7 Plastic Waterproof Cable Gland Connectors	2	\$0.45	\$0.90	Amazon	Pack of 20
Drill bit	Multidiameter Drill Bit	1	\$21.85	\$21.85	McMaster	
12mm M3 Screw	18-8 Stainless Steel Socket Head Screw	4	\$0.06	\$0.24	McMaster	Pack of 100
M3 Jam Nut	Steel Thin Hex Nut	8	\$0.04	\$0.34	McMaster	Pack of 100
Velcro	Velcro 3/4 in x 30 ft Roll	25	\$0.01	\$0.27	Amazon	~25 cm needed for each
PVC Pipe	2.5' 1.5" schedule 40 PVC	1	\$18.43	\$18.43	McMaster	Minimum order length 10'
Marine Epoxy	Loctite Epoxy Marine, 0.85 fl oz	1	\$8.50	\$8.50	Amazon	

Table 7.3: Electrical Components

Designator	Component	Qty.	Cost per Unit	Total Cost	Source of Materials	Notes
Feather	Adafruit Feather M0 Basic Proto	1	\$19.95	\$19.95	Adafruit	
Hypnos	Hypnos V3.2 or V3.3	1	\$27.00	\$27.00	OPeNS	
2 pin JST right angle socket	2 pin JST XH right angle socket	2	\$0.19	\$0.38	Digi-key	
Male headers	28 for Hypnos	1	\$0.50	\$0.50	Adafruit	
Female headers	10 for ADS1115, 30 for Hypnos	1	\$2.95	\$2.95	Adafruit	
Breakout Board	FloDar Breakout Board	1	\$3.87	\$3.87	OPeNS	Minimum order of 3
Resistor	SAMD 150 Ohm Resistor	1	\$2.12	\$2.12	Digi-key	
Tripler	FeatherWing Tripler Mini Kit	1	\$8.50	\$8.50	Adafruit	
ADS1115	ADS1115 16-Bit ADC	1	\$14.95	\$14.95	Adafruit	
SD Card	SanDisk 32GB microSDHC Memory Card with SD Adapter	1	\$7.95	\$7.95	B&H Photo	
Coin Cell	CR1220	1	\$0.88	\$0.88	Digi-key	
Cable Connector	Waterproof Polarized 4-Wire Cable Set	2	\$2.50	\$5.00	Adafruit	
USB Cable	Micro USB Cable	1	\$1.60	\$1.60	Amazon	Pack of 5
3-pin JST plug cables and sockets	3 PIN JST XH plug 200mm 26 AWG cable, socket	1	\$0.75	\$0.75	Amazon	Pack of 20
2-pin JST cables	22 AWG 2 Pin JST XH2.54 Connector Plug	2	\$0.50	\$1.00	Amazon	Pack of 20, 10 usable
Battery	TalentCell Rechargeable 12V Lithium Ion Battery	1	\$39.99	\$39.99	Amazon	
DC Power Jack	DC Power Jack Plug Adapter	1	\$1.00	\$1.00	Amazon	Pack of 10

Table 7.4: Flow Meter

Designator	Component	Qty.	Cost per Unit	Total Cost	Source of Materials	Notes
USFM	TUF-2000M	1	\$253.00	\$253.00	Amazon	
Transducer	TS-2 Pair	1	(included)	-		
Transducer Cable	Transducer Cable	5 m	(included)	-		
Hose Clamps	Hose Clamps	2	(included)	-		
Heat Shrink	Heat Shrink	8	(included)	-		2x Red 2x Blue 4x Black small
Spades	Fork Spade U-Type Connectors	6	(included)	-		
Large black heat shrink	1/4" 3:1 adhesive lined heat shrink	5	\$0.05	\$0.25	Amazon	20 ft, each cable needs 2.5"
Solder seal connectors	Marine grade solder seal connectors 18-22 gauge	6	\$0.20	\$1.20	Amazon	Pack of 50, 1.5" long
Silicon Lubricant	Dow Corning 111 O-Ring Silicone Lubricant	1	\$7.95	\$7.95	Amazon	

7.2 BUILD INSTRUCTIONS

7.2.1 FloDar printed circuit board (PCB) assembly

Tools: soldering iron, solder, solder paste, reflow oven or heat gun, hot glue gun and glue, fan for solder fumes (optional), fume hood (optional)

7.2.1.1 *ADS1115*

Components:

- ADS1115 (with included male headers)

Procedure:

1. Solder provided male headers on to the ADS1115 with the short end of the pins sticking up through the top of the board (Figure 7.1).

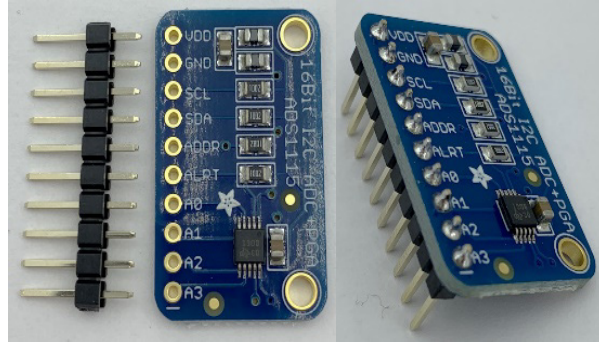


Figure 7.1 ADS1115 top with male headers separate (left), and with headers attached (right).

7.2.1.2 Custom PCB

Components (Figure 7.2):

- Custom PCB
- Female headers (10)
- Male headers (14, 16)
- Resistor
- 3 pin JST XH socket
- 3 pin JST XH plug with wires

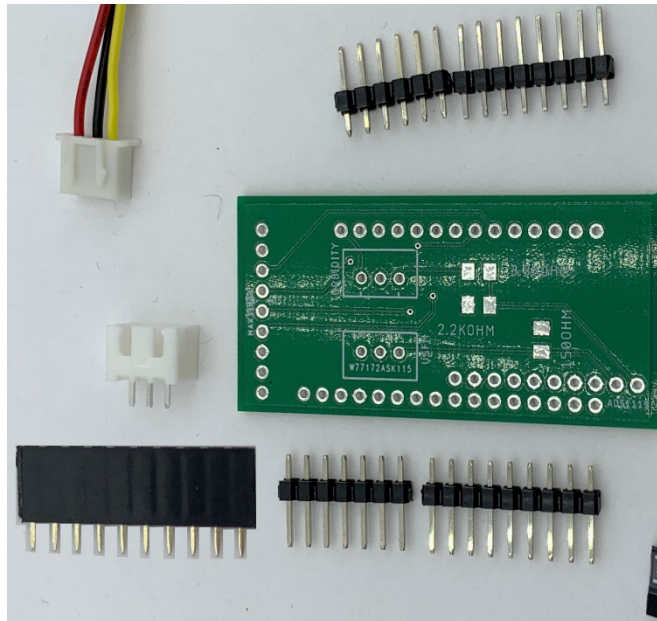


Figure 7.2 Components for breakout board assembly.

Procedure:

1. Apply solder paste to pads adjacent to 150 Ohm label (Figure 7.3, top)
2. Place the resistor across the two pads (direction does not matter).
3. Use either a reflow oven or heat gun to heat the solder paste enough to connect the resistor to the PCB (Figure 7.4).
4. Insert the short side of the 14 and 16 long male headers from the bottom of the board into the holes labeled for Hypnos Control in Figure 9 and solder them into place from the top (Figure 7.4).
5. Insert the pins for the female header into the board from the top side in the holes labeled ADS1115, flip over the board, and solder into place (Figure 7.4).
6. Insert the pins for the JST socket into the through holes labeled USFM from the top of the board, flip over the board, and solder into place (Figure 7.4). Direction does not matter.
7. For the JST plug with cable, plug into the JST socket to determine which wire will be closest to the USFM label. Remove the socket and remove with tweezers or cut flush all wires except the one that will be closest to the USFM label (Figure 7.4). Plug the connector back into the socket and hot glue into place.

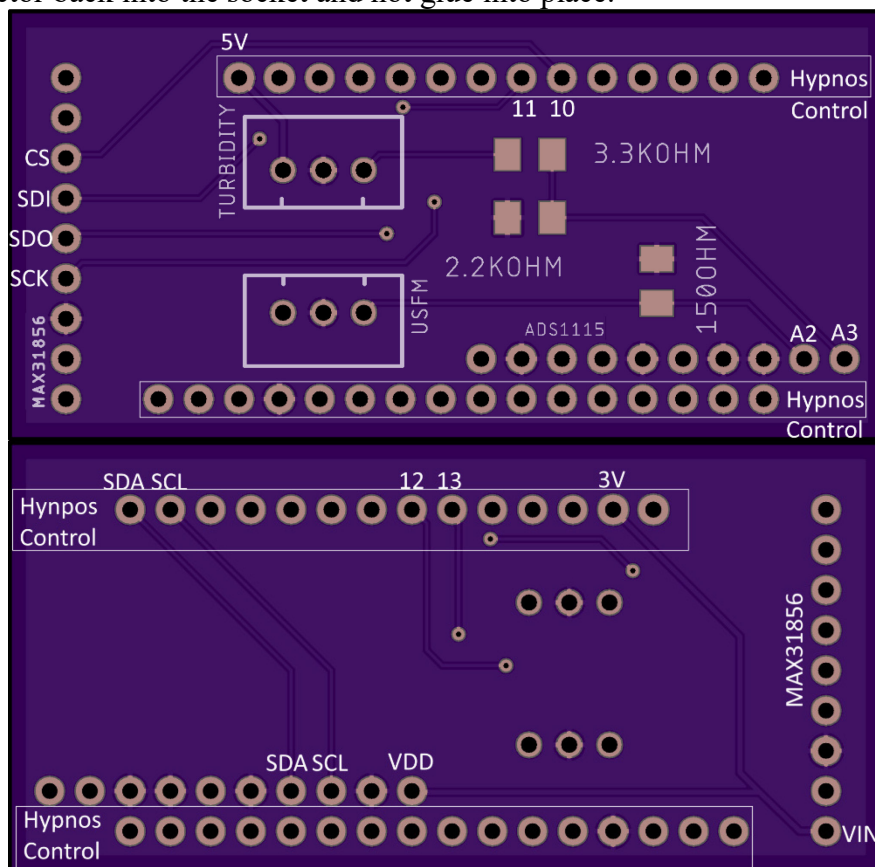


Figure 7.3 Custom PCB front (top) and back (bottom) with added labels. Note through holes labeled for MAX31856 are for implementation with a thermocouple. Through holes labeled for turbidity and 3.3 kOhm and 2.2 kOhm resistors are for implementations with a turbid sensor. Credit: OSHPark rendering of Gerber file.

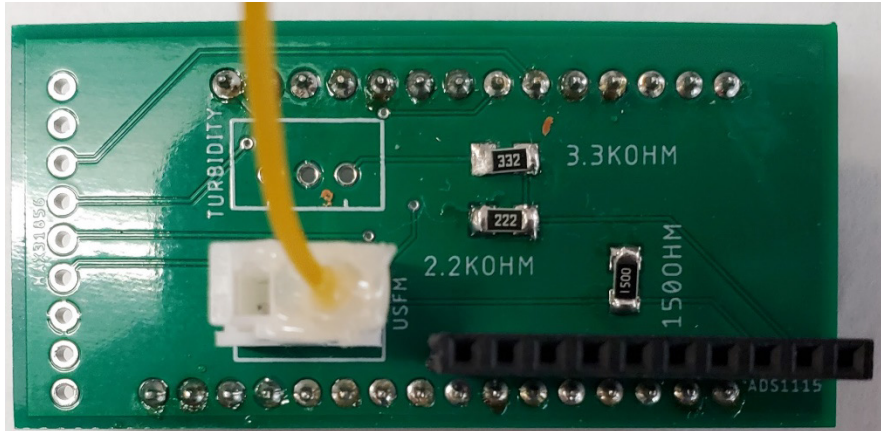


Figure 7.4 Assembled breakout board. Note 3.3 kOhm and 2.2 kOhm resistors are only used for implementations with the turbidity sensor.

7.2.1.3 *Tripler*

Components (Figure 7.5, left):

- Tripler
- Include female headers (2 x 12, 2 x 16)
- Procedure:
 1. Insert pins of female headers into outermost holes for the first and third board outlines as shown with the added red outlines in Figure 7.5 (left).
 2. Flip the board over and solder each pin into place (Figure 7.5, right).

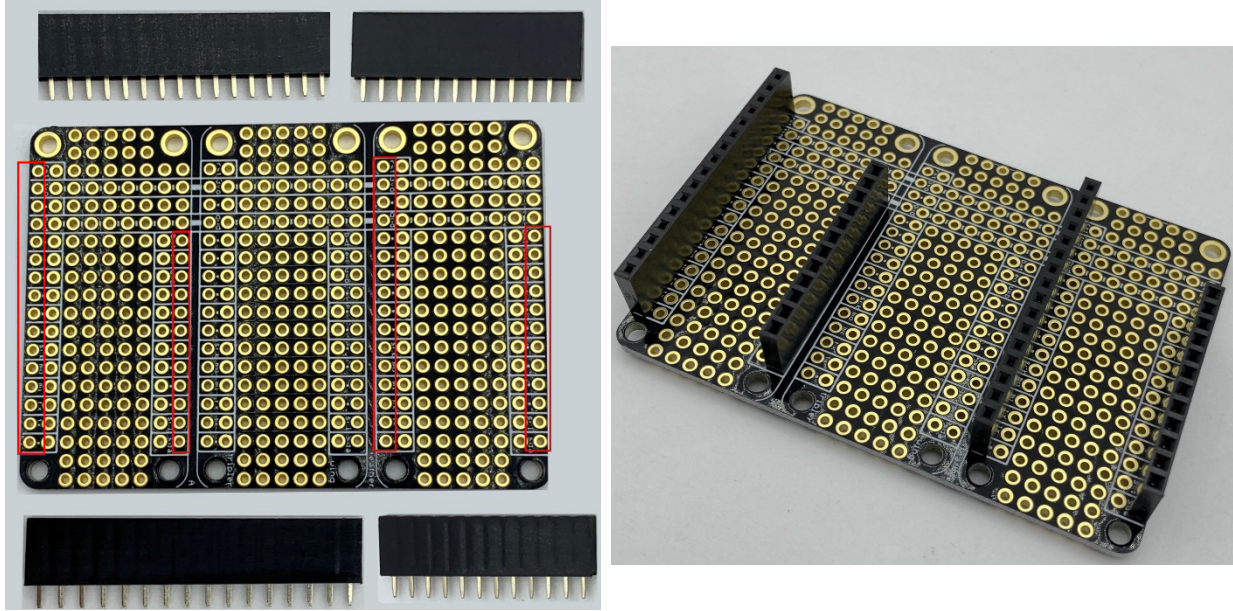


Figure 7.5 Tripler with headers separate and placement shown with red outlines (left) and assembled (right).

7.2.1.4 Hypnos

Components (Figure 7.6):

- Assembled Hypnos PCB (Nguyen et al. 2021)
- Male headers 12, 16
- Female headers 14, 16
- 2 2-pin right angle male JST sockets
- 2 2-pin female JST plugs with wires
- CR1220 coin cell
- microSD card

Procedure:

1. Insert the short side of the male headers from the back side of the board into the through holes labeled Feather starting with the holes closest to the end with the microSD socket (Figure 7.7, left). Flip over the board and solder each pin into place.

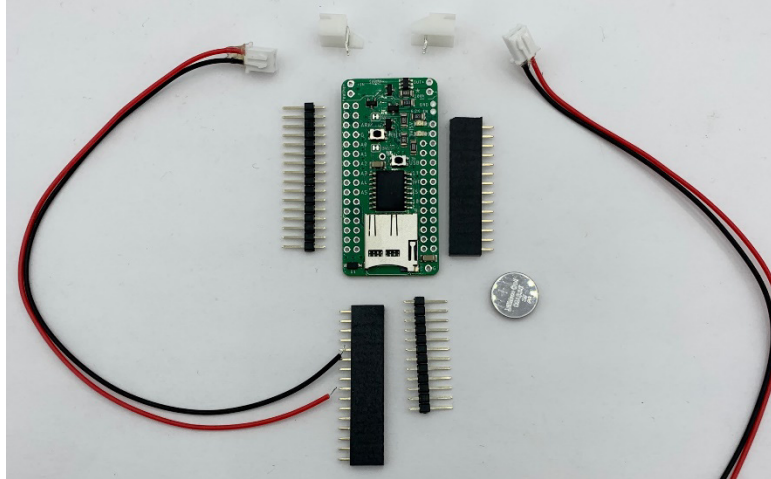


Figure 7.6 Top of assembled Hypnos PCB with components to be added. Note 2 pin JST on left has a clipped fin and microSD card is not shown.

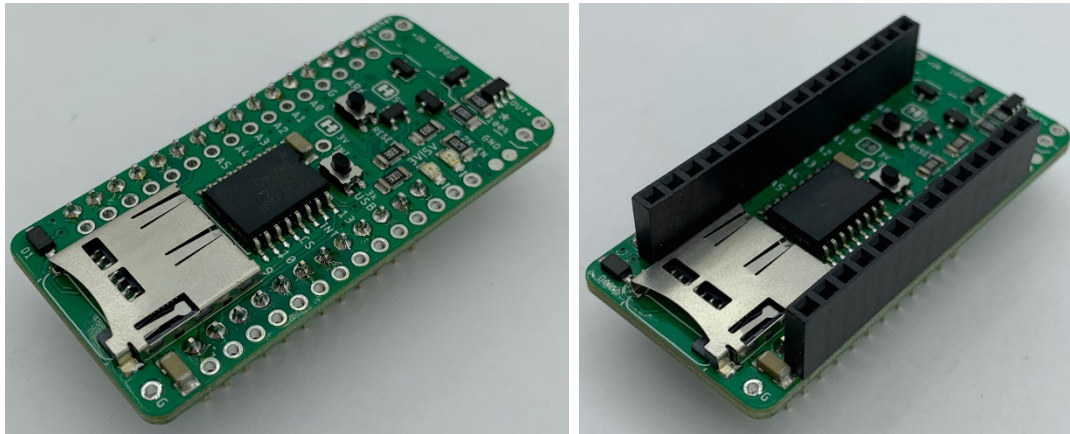


Figure 7.7 Top of assembled Hypnos PCB with male headers attached (left), and male and female headers attached (right).

2. Insert the pins of the female headers into the through holes on the PCB from the top side (Figure 7.7, right). Flip over the PCB and solder each pin into place.
3. Clip the right fin off of one of the 2 pin right angle JST sockets (Figure 7.8). Insert from the top into the top of the board in the two through holes labeled “In” so that the entry is facing out from the board. Flip over the board and solder into place.
4. Insert the other 2 pin right angle JST socket from the top into the top of the board in the two through holes labeled “Out” so that the entry is facing out from the board (Figure 7.8). Flip over the board and solder into place.

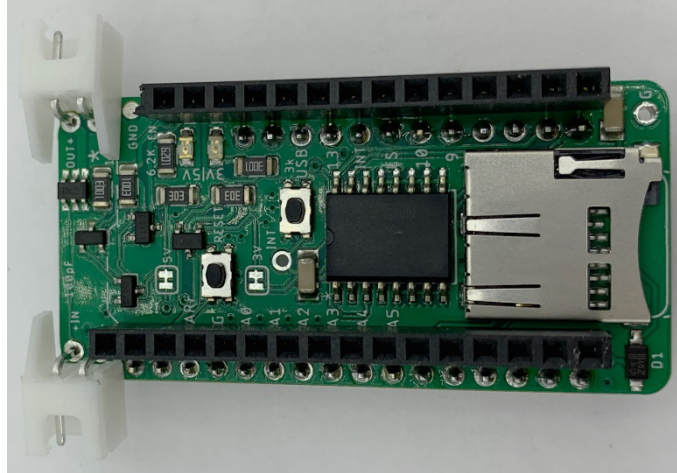


Figure 7.8 Top of assembled Hypnos PCB with headers and 2 pin right angle JST sockets.

5. Insert the JST plugs into the sockets. Verify the polarity matches the board for both: red wire at the end where the + symbols are on the board, black wire closer to the headers (Figure 7.9). If it does not match, use tweezers to gently pull up the plastic tabs holding the crimped connectors inside the case for each wire, pull out the wires, and insert on the appropriate side. Add hot glue to where the wires come out of the case to help hold in place.

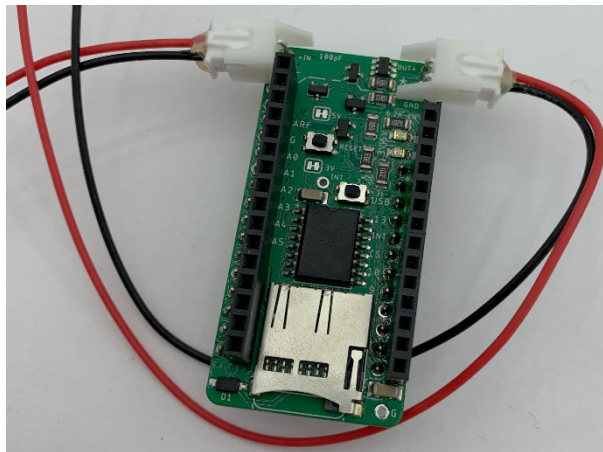


Figure 7.9 Fully assembled Hypnos showing correct wire positions.

6. Insert the coin cell into the coin cell holder on the back of the Hypnos board.
7. Insert the microSD card into the microSD socket on the front of the Hypnos board.

7.2.1.5 Feather M0

Components:

- Feather M0
 - Included male headers (12, 16)
 - Procedure:
1. Insert the short end of the male header pins into the Feather M0 board from the bottom (Figure 7.10, right).
 2. Flip the board over, and solder each pin.

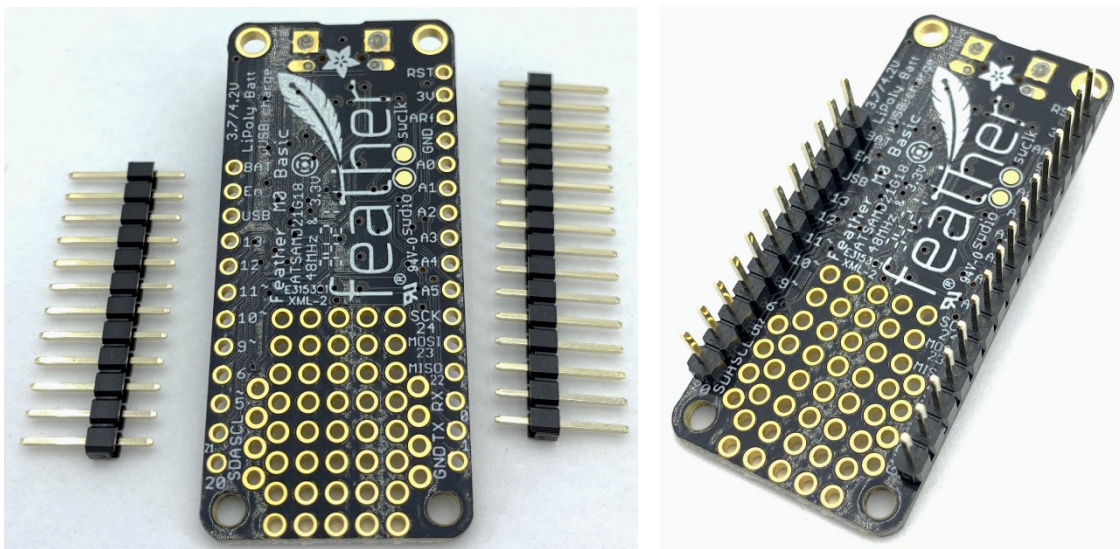


Figure 7.10 Feather M0 bottom with separate headers (left) and assembled (right).

7.2.1.6 Conformal coating

In a well-ventilated area or fume hood, coat all surfaces on all PCBs with conformal coating except 1) the unsoldered side of male header pins, 2) on and around buttons, 3) the microSD socket, and 4) the coin cell holder. Leave to dry for up to 48 hours.

7.2.2 FloDar transducer assembly

Tools: Phillips Screwdriver, Flush Cutters, Wire Strippers (22 Gauge, 10 or 12 Gauge), Soldering Iron, Heat Gun (1500 W recommended), Crimpers, Fan for Solder Fumes (Optional)

Components (Figure 7.11):

- Transducers
- 5 m Transducer Cable
- Electrical Tape
- 2x Large Heat Shrink
- 2x Large Blue and Red Heat Shrink
- 2x Waterproof Cable Connectors
- 6x Fork Spade U-Type Connectors
- 6x Solder seal connectors



Figure 7.11 Materials for assembling transducers

7.2.2.1 Transducer heads

1. Measure and cut each transducer cable in half to have two cables approximately 2.5 m in length (or less depending on location of transducers vs. pelican case).
2. Split all the components into two equal piles.

Repeat steps 3 through 21 for each transducer:

3. Strip back the outer jacket of the transducer cable at one end using the larger gauge strippers, about 3 cm (Figure 7.12). Note there is a copper wire casing - do not remove this - as well as a thread strand.



Figure 7.12 Transducer cable with outer jacket stripped back.

4. Unwind the copper, keeping it as intact as possible.
5. Isolate the thread, and cut it out using the flush cutters.
6. Twist the copper tightly to form a cleaner and more usable wire.
7. Strip the black and red cables using the smaller gauge wire strippers for about 0.5 to 1.25 cm (Figure 7.13).

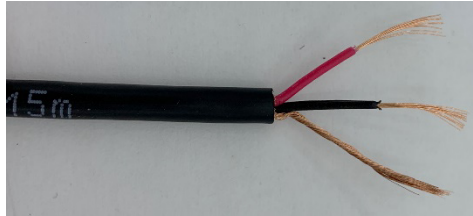


Figure 7.13 Transducer cable with outer jacket and individual wire jackets stripped back.

8. Twist the copper in the black and red wires so they are neat as well. Set aside.
9. Unscrew the screw in the lid on the transducer head and remove the lid (Figure 7.14).



Figure 7.14 Transducer head with lid removed.

10. Take off the cable gland cap on the transducer head.
11. Poke a hole in the cable gland either using the flush cutters or other sharp object.
12. Use a round blunt object such as your screwdriver to loosen the hole in the cable gland. Be careful not to rip the gland. If the gland comes out of the housing but is undamaged, it is acceptable to place the gland back in its housing.
13. Slide the cable gland cap over the transducer cable such that the side with the threads is facing the stripped end (Figure 7.15). If you do this step backwards, you are still able to take the cap off the other end of the transducer and flip it around. This will NOT always be the case.

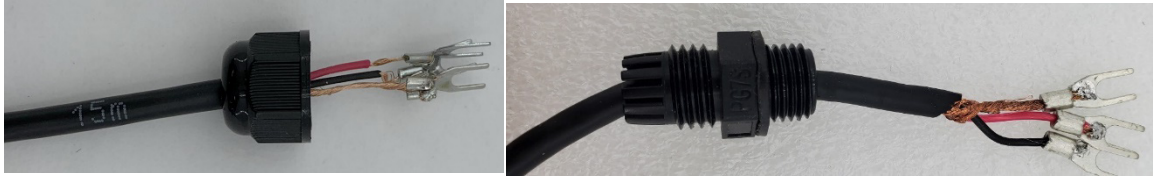


Figure 7.15 Transducer wire with cable gland nut (left) and cable gland body (right). Note that the cable gland body right side should still be screwed into the transducer head unlike as shown.

14. Feed the stripped wires into the cable gland body and pull it through such that the stripped wires are on the inside of the transducer and the outermost casing of the transducer wire is through the cable gland (Figure 7.15). It may help to fold the exposed metal back on itself.
15. Slide a fork spade onto the end of each wire.
16. Optional: Solder each wire end to the fork spade just after the crimp section. Ensure the fan is on prior to soldering.
17. Crimp each fork spade onto each wire. It may help to note the sequence that the wires are placed into the transducer and orient the fork spades so that they are facing up (Figures 7.16, 7.22). Ensure that each crimp holds tight.
 - a. Red goes to the (+)
 - b. Black goes to the (-)
 - c. The bare copper goes to the ground $\oplus$.
18. Unscrew each connection without fully taking the screw out. Place the fork spades under the screw and the square washer. It may be necessary to pull or push the transducer cable through the cable gland more to adjust where the fork spades land due to the small space.
19. Screw each of the contacts back down, ensuring that each one is tight and does not move (Figure 7.16).



Figure 7.16 Wires with fork spades attached inside transducer head. Note the cable gland nut is not shown but should already be on the cable in orientation shown in Figure 21 (top).

20. Place the transducer top back on the transducer and screw it back down. Be careful not to screw back in at an angle as you are screwing directly into the plastic. Also ensure that the top forms a tight seal against the transducer body, cracks could allow water to seep into the transducer and cause shortage.

21. Screw the cable gland cap that was already on the transducer cable tightly onto the cable gland to grip the transducer cable.
22. If this is the first transducer, repeat for the second transducer.

7.2.2.2 Transducer cable to waterproof connector cable

Repeat steps 1 to 10 for each transducer:

1. Slide a 6 cm long piece of the large black heat shrink over the untouched end of the transducer cable.
2. Strip the outer jacket of the transducer cable back about 4.5 cm: enough to fit a solder seal connector with 1.5 cm of wire exposed (similar to Figure 7.12).
3. Same as before, unwind the copper casing and isolate the thread, cutting it off. Twist the copper neatly together.
4. Strip back the jackets of the red and black wires using the smaller strippers about 1.5 cm (similar to Figure 7.13). Twist the copper strands for each wire together.
5. Slide the large black heat shrink at least 10 cm away from the end of the transducer cable.
6. Switching to the waterproof connector cable, identify whether this is the up (red) or down (blue) transducer, and place the respective color heat shrink on the wire end of the each side of the connector cable and slide to next to the threads or connector. Use a heat gun to shrink on to each cable (Figure 7.17). This is a critical step; if forgotten, you may not be able to place the heat shrink on after further steps are completed.
7. For remaining steps, use the side of the connector cable that has threads for the transducers. Set aside the side that the cap goes over. It is used for the pelican case.



Figure 7.17 Waterproof connector cable with blue heat shrink to indicate down transducer, and heat shrunk connections to transducer cable (completed in step 10).

8. Strip the jackets about 1.5 cm of all four wires on the connector cable using the smaller gauge wire strippers (Figure 7.18).

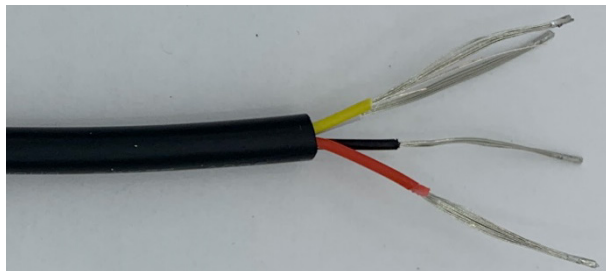


Figure 7.18 Waterproof connector cable with wire jackets stripped.

9. For each of the three transducer wires:
 - a. Slide on a solder seal connector.

- b. Twist the wire from the waterproof connector cable around the appropriate transducer cable wire:
 - Waterproof connector cable wire color Red, Transducer cable wire color Red.
 - Waterproof connector cable wire color Black, Transducer cable wire color Black.
 - Waterproof connector cable wire color White/Yellow, Transducer cable wire color Bare.
- c. Slide the solder seal connectors so that the metal ring of solder is on top of each of the combined wires (Figure 7.19).
- d. Make sure the fan is on, if using, and use a heat gun at $\sim 200^{\circ}\text{C}$ or the highest setting for a 1500 W heat gun to first melt the solder and then shrink the surrounding tube one side at a time.



Figure 7.19 Waterproof connector cable and transducer cable wires with solder seal connectors prior to heating (left) and after heating (right). Note directions indicate putting on and heating each connector individually, not all together as shown on the left.

10. Slide the large black heat shrink over all three wire connections and use the heat gun to shrink the heat shrink (Figure 7.17).
11. If this is the first transducer, repeat for the second transducer.

7.2.3 Pelican case assembly

7.2.3.1 Cable glands

Tools: drill or drill press, drill bit

Components:

- Pelican case
- 2x cable glands
- Marine epoxy

Procedure:

1. Take out the bottom foam piece in the case, and discard.
2. Use the drill and drill bit to drill two 1.25 cm diameter holes in the right side (when looking at the pressure valve) of the pelican case at 4.5 cm from the bottom and 4.4 cm from each side (Figure 7.20). Hole locations do not need to be exact.

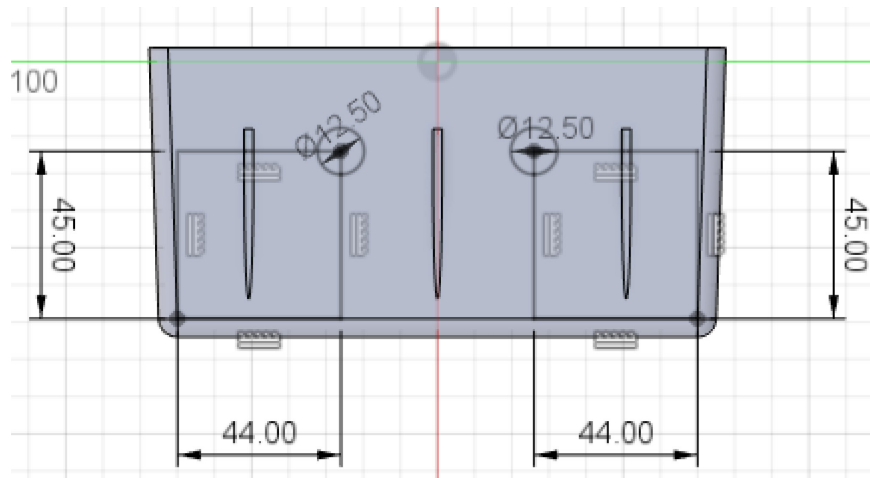


Figure 7.20 CAD rendering of the side of the pelican case showing hole placements with measurements in mm.

3. Unscrew the flat nuts and remove the rubber gasket from each cable gland. The pelican case is too thick to use the gasket, so epoxy will be used to seal the gland instead.
4. Mix the two parts of the epoxy, and apply to the base of the threads of each cable gland on the side for the flat nut. Insert cable glands into the holes in the pelican case from the outside, and fasten on the inside with the flat nut (Figure 7.21).

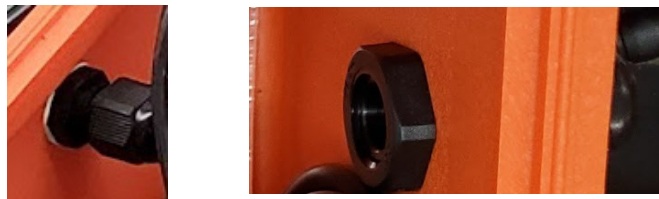


Figure 7.21 Cable gland in pelican case shown from outside (left) and inside (right).

7.2.3.2 *Insert*

Tools: 3D printer or laser cutter

Components:

- acrylic or ASA filament

Procedure:

1. 3D print or laser cut the insert. If using the acrylic insert, after cutting, glue the four flow meter tabs into place with Acrylic Plastic Cement (e.g. Weld-On 3).
2. Insert the 2-4 bolts for the tripler into the 3 mm holes in the insert from the bottom (see orientation in Figure 7.3) and fasten in place with nuts.

3. Put the insert into the case with the flow meter section on the right and the bolt threads up (Figure 7.2, 7.3).

7.2.3.3 *Final Assembly and Wiring*

Tools: Small screwdriver, scissors

Components:

- Pelican case with insert
- PCBs: ADS1115, custom breakout board, Hypnos, Feather M0, tripler
- Unattached waterproof connector cables
- USB cord
- DC power jack
- Flow meter
- Battery (fully charged)
- Velcro

Procedure:

1. PCBs
 - a. Set the tripler on the bolts in the insert and use one nut on each to fasten in place.
 - b. Stack the Hypnos board on the headers on the left side of the tripler (Figure 7.22).
 - c. Stack the custom breakout board on top of the Hypnos board (Figure 7.22).
 - d. Stack the ADS1115 board on top of the custom breakout board (Figure 7.22).
 - e. Stack the Feather M0 on the headers on the right side of the tripler (Figure 7.22).
 - f. Connect the USB cable to the USB port on the Feather M0.

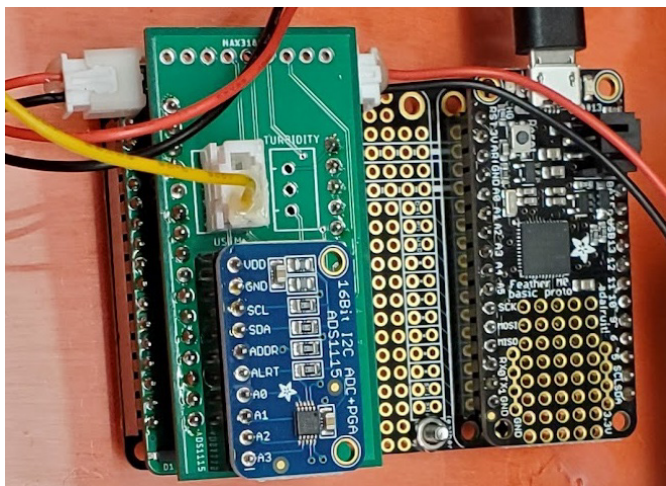


Figure 7.22 PCBs stacked with connections.

2. Battery
 - a. Put the battery upright in the case in the long slot against the back so that there is room to make the connection.
 - b. Connect the other end of the USB cable to the battery. Make sure any excess cable length will not get closed in the case seams.
 - c. Unscrew the terminals on the DC power jack, insert the ends of the wires (red to + and black to -) from the JST connector in the “In” location on the Hypnos, and screw back down.
 - d. Insert the DC power jack into the battery barrel jack socket.
3. Flow meter
 - a. Cut a ~25 cm long piece of velcro, and slide it under the insert. For the 3D printed insert, the velcro comes up in the oval holes above and below the flow meter. For the laser cut insert, the velcro comes up in the battery slot and the narrow space between the insert and case wall (Figure 7.22).
 - b. On the flow meter, unscrew the terminals for 24+, 24-, A0, UP+, UP-, GND, DN+, DN-, and GND (Figure 7.22).
 - c. For each of the waterproof connector cables, slide the nut onto the unthreaded side with the threads facing away from the bare wires (Figure 7.24).
 - d. Loosen the nuts on the outside of the cable glands in the pelican case.
 - e. Insert, bare wires first, the waterproof connector cable with the red heat shrink for the upstream transducer in the cable gland closer to the handle.
 - f. Insert, bare wires first, the waterproof connector cable with the blue heat shrink for the downstream transducer in the cable gland closer to the hinge.
 - g. For the upstream cable, insert the end of the red wire into UP+ terminal, and tighten down the screw. Insert the end of the black wire into the UP- terminal and tighten down the screw. Insert the ends of the white and yellow wires into the GND terminal between the UP- and DN+ terminals and tighten down the screw.
 - h. For the downstream cable, insert the end of the red wire into DN+ terminal, and tighten down the screw. Insert the end of the black wire into the DN- terminal and tighten down the screw. Insert the ends of the white and yellow wires into the farthest right GND terminal and tighten down the screw.

- i. Insert the end of the red wire from the “Out” JST of the Hypnos into the 24+ terminal and tighten down the screw.
- j. Insert the end of the black wire from the “Out” JST of the Hypnos into the 24- terminal and tighten down the screw.
- k. Insert the end of the wire from the 3 pin JST on the custom breakout board into the A0 terminal and tighten down the screw.
- l. Rotate the flow meter and set into place and secure with the Velcro.
- m. Tighten the outer nuts on the cable glands.



Figure 7.23 Flow meter with all wire connections. Note labels are below the ports for the wires, so in the image labels have been duplicated next to the screw terminals for clarity.



Figure 7.24 Pelican case with waterproof connector cables, battery, and flow meter.

7.2.4 Program Feather M0

1. Follow the directions on the Loom Wiki for installation of the Arduino IDE and Loom 4.1 Board profile: <https://github.com/OPEnSLab-OSU/Loom-V4#Install>
2. Download the [FloDar_Field_Loom4_1.ino](#), and place in a folder with the same name (FloDar_Field_Loom4_1).
3. Open the .ino file with the Arduino IDE.
4. Adjust constants as desired:
5. Time period between measurements: DAY, MINUTE, HOUR, SECOND on lines 21-24
6. Maximum flow rate: MAXFLOWRATE on line 31 (Must match flow rate for 20 mA set in flow meter menu 57 in Section 4.5.2).
7. Time zone: Line 36, third variable for Hypnos object creation. See [Loom_Hypnos.h](#) lines 31-53 for options.
8. Follow the directions for selecting a board profile, port and compiling code on the Loom Wiki under “[Run an example](#)”, but use the FloDar code instead of an example. See also guidance from [Adafruit](#).
9. Once the code has successfully compiled, open the serial monitor: Tools\Serial monitor or magnifying glass like icon in upper right corner.
10. Follow the prompts in the serial monitor to set the clock.

7.2.5 Flow meter setup

To obtain the correct speed of sound and output from the flow meter, many settings need to be changed from the default (see Ultrasonic Flow Meter User Manual for more information). During normal operations, the flow meter is turned on for just long enough to capture a reading. In order to keep the flow meter on for long enough to change parameters, either reprogram the Feather M0 with software to keep the whole system on (e.g. [FloDar_Lab.ino](#) which includes data logging), or directly wire the 24+ and 24- to the DC power plug for the battery. Turn on the battery. Remember to change the program or wiring after setup is complete.

There are four buttons for navigating and changing parameters on the flow meter:

- a) MENU: Allows input of a specific menu number
- b) : Increments to greater menu item, or with menu button pressed or changing a parameter cycles through 0-9, +, -, .
- c) : Decrements to a lesser menu item or moves the cursor over
- d) ENT: Finishes menu number input or enters into a sub menu

7.2.5.1 *Speed of sound related parameters*

Optional: Menu 30: Set unit system to English (all values below will be in English units)

- 1. Menu 11: Outer diameter of pipe: 1.906 in
- 2. Menu 12: Pipe wall thickness: 0.145 in
- 3. Menu 14: Pipe material: (5) PVC
- 4. Menu 16: Lining parameters: (0) none, no liner
- 5. Menu 20: Liquid type: (0) water(general)
- 6. Menu 23: Transducer type: clamp-on TS-2
- 7. Menu 24: Transducer mounting type: (0) V
- 8. Menu 25: Transducer installation distance: Set by flow meter - verify it is 1.01 in

7.2.5.2 *Output and display related parameters*

- 9. Menu 31: Flow rate unit: L/min (or other desired unit that is consistent across the flow meter and Arduino code parameters)
- 10. Menu 55: Analog output mode: 0-20 mA
- 11. Menu 56: Value corresponding to 0 mA current: 0
- 12. Menu 57: Value corresponding to 20 mA current: 150 (or value that is consistent across the flow meter and Arduino code parameters)

7.2.5.3 *Save parameters*

Press enter twice in Menu 26 to “solidify settings”: save to internal flash memory. Without this step, none of the parameter changes will remain after power is removed.

APPENDIX: B

8.0 APPENDIX B: SCRIPTS FOR DRAWDOWN PREDICTION TOOL

8.1 ARCPY SCRIPTS

```
#required libraries
#import arcpy
import numpy
import pandas as pd
from matplotlib import pyplot as plt
import tensorflow
from tensorflow import keras
from tensorflow.keras.models import load_model
import os
#setting static library
os.environ['KMP_DUPLICATE_LIB_OK'] = 'TRUE'
#overwiting existing files

#parameter optimization
zdepth          = float(20)
slope            = float(20)
slope_radians    = numpy.deg2rad(slope)
slope_length     = float(50)
pipe_spacing0    = [2,4, 8, 10,12,14, 16, 18, 20]
pipe_length      = float(40)
K                = float(8.640000000000000)
Ss               = float(0.0008640000000000000)
Kx= float(K)
Ky= float(K)
Kz= float(K)
dx=float(1)
dy=float(1)
dz=float(1)

#time processing
time=numpy.logspace(-3,4,500)          # initial time
dt_min =
1/(2*max([Kx/Ss,Ky/Ss,Kz/Ss])*(1/(dx**2)+1/(dy**2)+1/(dz**2)))
dt_log=numpy.log10(dt_min)
time=numpy.logspace(dt_log,4,500);
time_dmnl=(time*(K/Ss/zdepth/zdepth))    # time
dimensionless
```

```

time_dmn1_log10=numpy.log10(time_dmn1)           # log10 of
dimension less time
tsize = numpy.size(time_dmn1)

for pipe_spacing in pipe_spacing0:
    #parameter dimnensionless
    sl_dim1 = [float(slope_length/zdepth)]*tsize
# slope length
    ps_dim1 = [float(pipe_spacing/zdepth)]*tsize
# pipe spacing
    sg_dim1 = [float(slope_radians)]*tsize          #
slope gradient
    pl_dim1 = [float(pipe_length/zdepth)]*tsize      #
pipe length
    #data arraying
    x1=numpy.array(time_dmn1_log10)
    x2=numpy.array(sl_dim1)
    x3=numpy.array(ps_dim1)
    x4=numpy.array(sg_dim1)
    x5=numpy.array(pl_dim1)
    x1= x1.reshape(500,1)
    x2= x2.reshape(500,1)
    x3= x3.reshape(500,1)
    x4= x4.reshape(500,1)
    x5= x5.reshape(500,1)
    x = numpy.concatenate((x1,x2,x3,x4,x5), axis=1)
    #arcpy.AddMessage('Predicting drawdown')
    #arcpy.SetProgressorLabel('Predicting drawdown')
    #loading ml model & prediction
    loaded_model =
load_model('ann_log_r_relu_sigmoid_hn_5_bs_10.h5')
    dd_dim1 = loaded_model.predict(x)

    #time & dd in dimension
    time_dim=list(10**(x1/K*Ss*zdepth*zdepth))      #time
dimensional
    dd_dim = list(dd_dim1*zdepth)

    #plotting results
    # plt.figure()
    # plt.plot(time_dim, dd_dim)
    # plt.xlabel('Days')
    # plt.ylabel('Drawdown')
    # plt.savefig('Drawdown.png')
    #saving as .csv file
    #pd.DataFrame({'slope gradient':sg,'slope
length':sl,'aquifer depth':zdepth,'pipe

```

```

length':pipe_length,'pipe
spacing':pipe_spacing},index=[1]).to_csv('parameters.csv') #save
parameters,steady state and time
    # remove square brackets from time_dim and dd_dim
    #time_dim = [val[0] for val in time_dim]
    #dd_dim = [val[0] for val in dd_dim]
    time_dmn1_flat = numpy.ravel(time_dmn1)
    dd_dim1_flat = numpy.ravel(dd_dim1)
    n1='H_'+str(zdepth)
    n2='_sl_'+str(slope)
    n3='_Ly_'+str(slope_length)
    n4='_Lx_'+str(pipe_spacing)
    n5='_Lp_'+str(pipe_length)
    n6='.csv'
    name = n1+n2+n3+n4+n5+n6

pd.DataFrame({'Time':time_dmn1_flat,'Drawdown':dd_dim1_flat}).to
_csv(name, index=False, header=True)

```