Listing and Description of Animations

Fundamentals of Open Channel Flow

Glenn E. Moglen

The following are brief summaries of the content of the animations included with this book. The provided animations illustrate "movement," but this movement (with the exception of the "step_transient" animation) does not generally correspond to true transient behavior. Instead, most of these animations show the continuum of steady-state solutions to a set of similar problems in which one input is allowed to vary. This varying input is generally not something that varies with time such as channel roughness, channel slope, or the size of a sluice gate opening. Thus, a transient behavior is not being illustrated. Rather, what is being illustrated is how the behavior of the overall channel system varies along a continuum as a function of that varying input.

A note on symbology: Color is used in these animations to distinguish different segments of flow phenomenon. Where possible, flow that corresponds to a different regime (supercritical, subcritical, critical) is shown in a different color, both in its physical system depiction and on any accompanying figures (e.g. *E*-*y* diagram, *M*-*y* diagram, etc.). Similarly, different symbols: "✕", "○", "□", and "◊" are used to indicate specific locations on *E*-*y*, *M*-*y*, and occasional other curves corresponding to initial and/or current conditions in a simulation. Finally, different line styles are also used. A dashed line can indicate many things: it can represent a bounding depth (showing initial or terminal conditions), it can represent a virtual curve (such as a potential surface water profile or its conjugate curve), and it can represent the potential for multiple accessible pathways (as in the case of the step and constriction animations). When gradually varied flow profiles are shown, an even dashed line is used to indicate critical depth and a dash-dot line indicates normal depth.

<u>Energy</u>

Steady-State Evolution:

- **`step.avi`:** The animation shows an upstream subcritical flow as it encounters an upward step. The top subplot shows a side view of the channel and water surface. The lower subplot shows the *E*-*y* diagram that applies to the illustrated flow. As the animation evolves, the top plot shows a growing step height and the water surface dipping down at the step. The lower subplot shows the initial energy and the energy over the step that is reduced by the step height "dz". When the step height is great enough that the initial upstream energy is insufficient to pass the entire discharge, a choke results and the animation shows the steady-state result of the flow backing up upstream of the step and dashed lines in the water surface downstream of the step indicate that the downstream condition after the step may be either subcritical or supercritical. This is also reflected on the *E*-*y* diagram by the diamond points. Color codes are as follows: blue is subcritical, magenta is supercritical, cyan is critical. Green indicated initially specified depth (a subcritical depth).

- **Conditions modeled**: Q=100 ft^3/s, initial depth is 2.8 ft, channel width is 10 feet. Step height increases from 0 ft to 1.77 ft. The flume is frictionless and rectangular in cross-section.

- **`constriction.avi`**: The animation shows an upstream subcritical flow as it encounters a constriction in channel width. The top subplot shows a top view of the flume and the growing constriction. The middle subplot shows a side view of the channel and water surface. The bottom subplot is divided in two. The bottom-left subplot is an overall *E-y* diagram showing the initial *q* curve (q = 10 ft^2/s) as well as the *q* curve that corresponds to flow in the constriction. A dashed box in this subplot shows the enlarged area in the bottom-right subplot. The bottom-right subplot shows the *E-y* diagram focused on the dashed box in the bottom-left subplot. This is the region of the figure that is most closely engaged in the evolution being shown. When the constriction is severe enough that the initial upstream energy is insufficient to pass the entire discharge, a choke results and the animation shows the steady-state result of the flow backing up upstream of the constriction and the dashed lines in the water surface downstream of the constriction indicate that the downstream conditions after the constriction may be either subcritical or supercritical. The cyan color indicates critical conditions within the constriction with the downstream dashed blue surface being the subcritical downstream possibility and the downstream dashed magenta surface being the supercritical downstream possibility. The red diamond points on the *E-y* diagrams indicate the alternate depth pairs that are possible downstream of the critical (choke) condition.
  - **Conditions modeled**: Q=100 ft^3/s, initial depth is 2.8 ft, channel width decreases from 10 feet to 5 feet. The flume is frictionless and rectangular in cross-section.
- **`trapezoid.avi`**: The animation (upper sub-plot) shows a cross-sectional view of the channel starting from a wide trapezoidal shape and with side slopes evolving towards a rectangular shape. The initial energy held by flow in cross-section starts at 0.70 m. The discharge is fixed at 4 m^3/s. Side slopes start at m=10 and tend towards vertical (m=0) in steps of 0.1. They act similarly to a constriction in a rectangular channel flow. Flow that was initially sub-critical is driven to critical conditions. Thereafter, the flow shown is the steady-state condition resulting from the flow backup from the choke. The animation shows total energy (magenta dash-dot) and actual depth (shaded blue). Just below the animation is a text ticker indicating m (side slope) value and if choke conditions exist. Two other lower plots exist. The lower-left subplot shows the *E-y* diagram with initial (and current) energy, initial *E-y* curve for m=10 (thin, black), and current *E-y* curve (thick, blue) with current depth (location on current *E-y* curve) indicated by a blue circle. When choke engages, initial and current energy diverge and both are shown. The lower-right subplot shows energy (magenta), depth (blue), and minimum energy (red) plotted against sideslope, m. When choke engages, a vertical line is drawn showing the value of m when choke engages and the depth and energy plot with dashed blue and magenta lines, respectively. The minimum energy line shows through the magenta dashed line.

- **Conditions modeled**: Q=4 m^3/s, initial energy is 0.70 m, channel sideslope decreases from 10H:1V to 0H:1V. The flume is frictionless with varying cross-section sideslope.

Transient Evolution:

- **`step_transient.avi`**: The animation shows an upstream subcritical flow as it encounters a step. The animation shows the transient back-up of flow as the system adjusts to the step and returns to steady-state. Subplots show growth of storage behind the step over time, *Q* vs. *t*, and the *E*-*y* diagram illustrating the transient behavior.
  - **Conditions modeled**: Q=100 ft^3/s, initial depth is 2.8 ft, step of height, Δz = 2.0 feet appears at t = 5 hours. Depth-volume relationship is approximately, V=39,000y^3 (where V is in ft^3 and y is in ft). The flume is frictionless and rectangular in cross-section.

<u>Energy and Momentum</u>

- **`gatejump.avi`**: The animation shows a gate lowering on a subcritical flow in a horizontal, frictionless, rectangular flume. There are three depths of interest: upstream of the gate, immediately downstream of the gate (alternate to upstream gate depth) and downstream of hydraulic jump (if present). The top subplot shows the water surface itself and an animation of the effect of the sluice gate on the downstream depth and ultimately on the hydraulic jump that occurs downstream. The lower subplot is divided in three. The lower-left subplot shows the *E*-*y* diagram with the depths at the three locations indicated (if appropriate). The gate opening is indicated on the *E*-*y* diagram by a horizontal black line. The *E*-*y* diagram is useful for seeing: alternate depths, the effect of a choke when the gate depth decreases to less than the alternate depth to the initial upstream depth, the energy loss in a hydraulic jump. The lower-middle subplot shows the *M*-*y* diagram with the depths at the three locations indicated (if appropriate). The *M*-*y* diagram is useful for seeing: conjugate depths, the loss in momentum at the sluice gate. The lower-right subplot shows the loss of energy in the hydraulic jump as a function of the Froude number upstream of the jump.
  - **Conditions modeled**: q=20 ft^2/s, initial depth is 3 ft, gate opening evolves from 3 feet to 1 foot. The flume is frictionless and rectangular in cross-section.

<u>Normal Depth</u>

Five similar animations showing normal depth changing as width changes (steep and mild cases are presented separately), as roughness changes, as slope changes, and as discharge changes. All in this series work from a generally fixed set of parameters with only one of the quantities varying from fixed. The water surface is animated in the upper-right subplot. In the upper-left subplot, various measures (e.g. normal depth, Froude number, energy, etc.) vs. the changing quantity are presented. Critical depth is indicated in animations so mild/steep conditions can be identified and contrasted.

- **General Conditions modeled**: Q=100 ft^3/s, Manning's n=0.03, S_0 = 0.005 (generally), width = 10 ft, The flume is rectangular in cross-section.

- **`ynorm_width_mild.avi`**: Illustrates changing channel width on a mild reach and its effect on normal depth. S_0 = 0.005, width varies from 10 ft to 49.6 ft.
- **`ynorm_width_steep.avi`**: Illustrates changing channel width on a steep reach and its effect on normal depth. S_0 = 0.04, width varies from 10 ft to 49.6 ft.
- **`ynorm_n.avi`**: Illustrates effect of changing channel roughness on normal depth over a range of roughnesses that span from steep to mild flows. Manning's n varies from 0.01 to 0.04.
- **`ynorm_slope.avi`**: Illustrates the effect of changing channel slope on normal depth over a range of slopes that span from mild to steep flows. S_0 varies from 0.001 to 0.04.
- **`y norm_discharge.avi`**: Illustrates the effect of changing discharge on normal depth over a range of discharges that span from mild to steep flows. S_0 = 0.02 and Q varies from 2.5 ft^3/s to 240 ft^3/s.

<u>Energy and Normal Depth</u>

- **`Discharge_problem.avi`**: This is an illustration of Henderson's (1966) "Discharge Problem". Slope varies from steep to almost zero. The upper figure shows the system and the water surface both within the discharging lake and downstream. Both the normal (red dash-dot) and critical (red dashed) depths are indicated in the reach. The total energy in the lake is shown as a cyan dashed line above the lake. The lower-left figure shows the length of the S_2 curve downstream of the lake outlet. This curve only exists when the reach is steep. The lower-right figure shows discharge vs. slope. Critical slope is indicated in both lower figures and logically forms the lower boundary to where the S_2 curve is non-zero in length and forms the lower boundary to where discharge is no longer a function of channel slope.
  - **Conditions modeled:** Q=100 ft^3/s (when reach is steep) down to as little as 18.8 ft^3/s (when reach slope is near zero), S_0 varies from steep (0.0244) to near zero (0.000175), Manning's n=0.03, channel width=10 feet, channel length=40 feet. The flume is rectangular in cross-section.

<u>Gradually Varied Flow</u>

- **`m3m2animation.avi`**: The animation shows a gate lowering on a mild reach producing an M_3 curve immediately downstream which then undergoes a hydraulic jump to an M_2 curve that is propagating upstream from a free overfall at the downstream end. The animation also shows in red dashes the conjugate curve corresponding to the M_3 curve. The location of the intersection of the conjugate curve with the M_2 curve becomes the location for an idealized vertical hydraulic jump. Upstream of the gate, the initial upstream portion of an M_2 curve evolves to an M_1 curve over the course of the animation. Three subplots are provided showing the lengths of the M_1, and M_2 profiles (upstream of the gate) and the M_2 and M_3 profiles (downstream of the gate) as a function of the gate opening. An *E-y* diagram is also provided and shaded to correspond to the different flow profiles as the animation progresses.

  - **Conditions modeled:** Q=100 ft^3/s, S_0=0.001, Manning's *n*=0.03, channel width=10 feet, channel length=100 feet. Gate opening evolves from 1.4 feet down to 0.15 feet. The flume is rectangular in cross-section

- **`chanlength.avi`**: The animation shows a mild reach downstream of a fixed sluice gate which has a varying total channel length. Initially, the channel length is 1000 meters. Over the course of the animation this length diminishes to 5 meters. The animation illustrates how the location of the jump travels downstream as the intersection of the M_2 curve with the M_3's conjugate curve travels downstream with diminishing total channel length.
  - **Conditions modeled:** Q=4 m^3/s, S_0=0.001, Manning's *n*=0.03, channel width=3 meters, channel length evolves from 1000 to 5 meters. Gate opening set to 0.11 meters. The flume is rectangular in cross-section.
- **`mild_vary.avi`**: The animation shows an upstream mild reach and a downstream reach that varies from two times milder than upstream to steep. Upstream and downstream boundary conditions are normal depth at all times. Surface water profiles evolve on one or both reaches as the downstream reach slope varies accordingly. The lower-right subplot shows an *E-y* diagram with normal depths indicated by plotted squares. The colored regions of the *E-y* diagram indicate where surface water profiles engage (blue is M_1 curve, magenta is M_2 curve, green is S_2 curve). A water surface colored in cyan is at normal depth. The lower-left subplot shows the length of the M_1, M_2, and S_2, curves as they evolve with changing downstream reach slope. The vertical dashed lines on this subplot show the upstream slope and the critical slope. These form boundaries on the evolution of the different surface water curves, as would be expected.
  - **Conditions modeled:** Q=100 ft^3/s, $S_{0,1}$=0.005, $S_{0,2}$ varies from 0.0025 to 0.0515. Manning's *n*=0.03, channel width=10 feet. The flume is rectangular in cross-section.
- **`steep_vary.avi`**: The animation shows an upstream steep reach and a downstream reach that varies from mild to steeper than upstream. The range of downstream reach steepness varies so that the hydraulic jump migrates from the upstream to the downstream reach. The downstream reach continues to get steeper passing through critical slope and resulting in first S_3 curves, then S_2 curves appearing on this reach. The upstream and downstream boundary conditions are normal depth at all times. The lower-right subplot shows an *E-y* diagram with normal depths indicated by plotted squares. The colored regions of the *E-y* diagram indicate where surface water profiles engage (blue is S_1 curve, magenta is M_3 curve, green is S_3 curve, and yellow is S_2 curve). A water surface colored in cyan is at normal depth. The lower-left subplot shows the length of the S_1, M_3, S_3 and S_2, curves as they evolve with changing

downstream reach slope. The vertical dashed lines on this subplot show the conjugate slope (slope of downstream reach is such that normal depth on upstream reach is exactly the conjugate depth to the normal depth on the downstream reach), upstream slope and the critical slope. These form boundaries on the evolution of the different surface water curves, as would be expected.

  - **Conditions modeled:** Q=100 ft^3/s, $S_{0,1}$=0.04, $S_{0,2}$ varies from 0.0017 to 0.079. Manning's n=0.03, channel width=10 feet. The flume is rectangular in cross-section.

- **`drown_step.avi`**: The animation shows the "drowning" of surface water features (an M_1 curve upstream of the step and a hydraulic jump that migrates up the downstream side of the step until it disappears when the step no longer represents a choke). The main concept being conveyed is that a channel feature that has a profound effect on surface water profiles at low flows is "drowned" to the point of insignificance when the flow becomes large. Secondary concepts that can be observed are energy buildup (M_1) in front of an obstruction and energy dissipation (hydraulic jump) downstream of an obstruction. The migration of the jump and the evolution of the profile in the vicinity of the obstruction are unique features that are illustrated as only possible in an animation. Three graphs appear below the figure. The lower-left graph shows the prescribed change in discharge from 2.5 ft^3/s to 300 ft^3/s. It is this increasing discharge that drives the drowning of the water surface profiles near the step. The lower-middle graph shows the excess energy $[E_0 - (E_c + \Delta z)]$. A curve is traced in red as the excess energy is negative (i.e. choke conditions exist). The curve shifts in color to black when the excess energy is positive and the choke conditions no longer exist. The lower-right graph shows the trace of two depths as they occur on the middle of the step. In dashed red is the critical flow depth. In solid blue is the actual flow depth. When choke conditions exist, these two traced curves coincide. When the excess energy is positive then the actual flow depth is greater than critical depth.
  - **Conditions modeled:** Q=2.5 to 300 ft^3/s, S_0=0.003 (mild for all discharges), Manning's n=0.03, step height Δz=0.5 feet, channel width=10 feet, channel length=1000 feet. The flume is rectangular in cross-section.