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The 1889 Johnstown, Pennsylvania Flood - A physics-based Simulation

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1. Introduction

1.1 Thumbnail review of the 1889 flood.

In 1889 Johnstown Pennsylvania was an industrial workingman's town, sited on a flat triangle of ground at the confluence of the Little Conemaugh and Stoney Creek Rivers (*Figure 1*). Johnstown and its neighbors in the valley—Cambria, Woodvale and E. Conemaugh—housed 30,000 residents. Years of industrialization narrowed and channelized the valley's three rivers to a fraction of their natural widths (*Figure 2*). As a consequence, nearly every spring Johnstown flooded. Even so, the water was little more than aggravation to town folk who simply relocated carpets and furniture to upper floors to wait out the water's retreat.

On May 30 and 31, 1889 the upper reaches of the Little Conemaugh and Stoney Creek basins experienced the strongest rains in anyone's memory. The Conemaugh River at Johnstown rose from 1 foot to 23 feet in just over 24 hours. By mid-day on the 31st, water crept over most of the lower town reaching to Central Park. Although everyone agreed that this flood was worse than usual, residents nonchalant about the affair, yet again moved carpets and furniture upstairs.

Like floods of the past, the 1889 one would have faded from history if not for South Fork Lake, 24 km up the Little Conemaugh River and 140 meters higher than Johnstown (*Figure 1*). Also swollen by the strong rains, South Fork Lake rose steadily throughout May 31 and water began running out its spillways at mid-day. Had it been rebuilt to its original 1853 specifications, South Fork Dam may have withstood even this torrent. However, blunders in the dam's 1886 reconstruction and later management led to its overtopping and failure around 2:45 PM. Collapse of the 22 m high dam released 16 million cubic meters of water into the Little Conemaugh River targeting Johnstown and neighboring boroughs. When the surge arrived eighty minutes later, it found no match for the wood frame construction in the valley. Hundreds of families waiting out high water in upper floors were carried away -- house and all. Until the terrorist attacks on September 11, 2001, the 2200 casualties in the 1889 Johnstown Flood amounted to the largest single-day disaster in United States history.

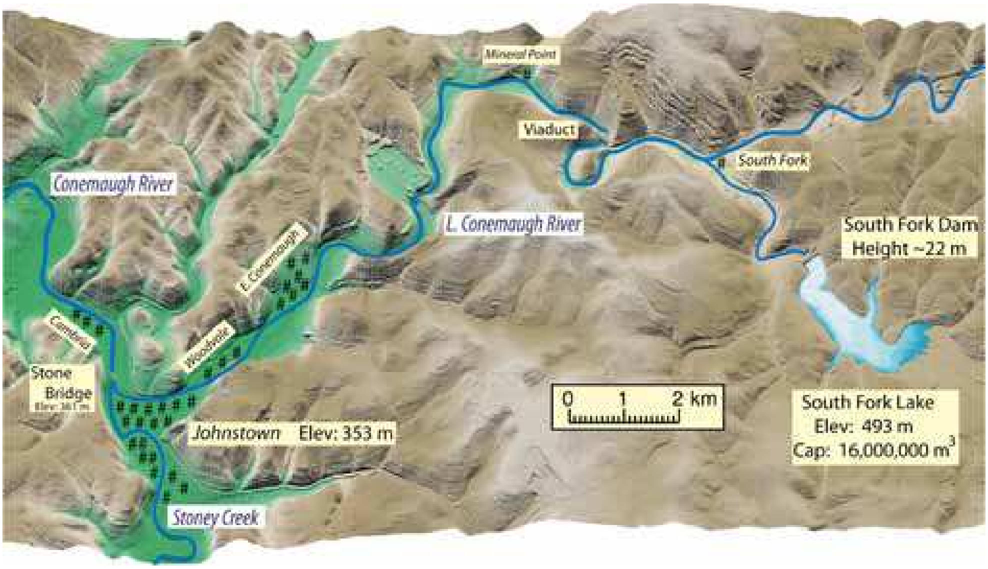

Fig. 1. Map of the Johnstown region showing the principal locations and players in the events of May 31, 1889.

1.2 Physics-based simulation versus hollywood animation:

Dozens of published accounts, memoirs, summaries *(e.g. Johnson, 1889; Beale, 1890; McCullough, 1968.)* and Hollywood films chronicle the Johnstown Flood. This article breaks from storytelling; instead, it constructs a physics-based simulation of the dam break and flood. In contrast to artistic depictions, physics-based simulations take care to discern anecdotal reports from quantitative information. Times, locations, elevations, volumes, velocities, flow rates, depth and flood extent comprise particularly valuable constraints. Unfortunately, the majority of information that one finds in researching the Flood is sketchy. Pinning even the basics, like the time sequence of events can be challenging. In that era, few people owned, much less carried, watches. “Somewheres around 4 PM” is a typical reckoning. Accounts of flood size too make for good reading—“It looked like a 40 foot high wall of water”—but scantly find application in physical modeling. Even tantalizing specifics —“Afterwards I measured water marks eight feet high on my rail car”— are not much help if they lack critical details; in this case, the location of the car and the level of grade where it stood.

In the face of hit-or-miss data, physics-based simulations hold special worth in that they can accept input from a wide range of observations. Too physics-based simulations can output quantitative predictions on aspects that were not, or could not, be measured. Truth to say, physics-based simulations also have limitations. In the 121 years since the Flood, things have changed —rivers have been channelized, flow controls constructed, various fills and excavations have forever changed the lay of the land. Spot elevations today may not reflect 1889 elevations, indeed “the spot” may no longer exist. It may not be possible to re-create events with the desired level of detail even with a numerical approach. Still, some quantitative information exists and not every version of the flood story is physically likely within those constraints. Sorting historical inconsistencies through the screen of physical laws, partly justifies computer simulation. Too, by wearing physics-based eyeglasses, new insights and connections may appear in the Johnstown Flood story that had been invisible before.

Fig. 2. Johnstown before the flood. View looks down Stoney Creek River toward the Stone Bridge. Note the infilling at the river banks and the construction virtually in the river bed. You can imagine that it would not take much of a flood to float these wood frame structures from their foundation can carry them off.

2. Tsunami Ball approach.

This article closely follows *Ward* and *Day* (2010a, 2010b) who simulated wave runup and inundation from the 1958 Lituya Bay Alaska and the 1963 Viaont, Italy landslide disasters. Simply put, tsunami balls are pencil-like columns of water gravitationally accelerated over a 3-D surface. The volume density of tsunami balls at any point equals the thickness of the water column there. Tsunami balls care little if they find themselves on parts of the surface originally under water or on parts originally dry. Such indifference is made-to-order for flood-like inundations.

2.1 Tsunami Ball flow chart.

The tsunami ball method distills to six flow chart steps.

A. Distribute N tsunami balls over initially wet areas at initial positions $\mathbf{r}_j$ with regular spacing $\Delta x \Delta y$.

B. Assign each ball a zero initial velocity and a volume $V_j = \Delta x \Delta y H(\mathbf{r}_j)$ based on the initial water thickness at the site $H(\mathbf{r}_j)$.

C. Evaluate the water surface $\zeta(\mathbf{r}_g, t)$ at time t on a fixed set of grid points $\mathbf{r}_g$ (*Figure 3*)

$$\begin{aligned}\zeta(\mathbf{r}_g, t) &= \sum_{j=1}^{N} V_j\, A(\mathbf{r}_g,\ \mathbf{r}_j(t)) + \mathrm{h}(\mathbf{r}_g) \\ &= H(\mathbf{r}_g, t) + \mathrm{h}(\mathbf{r}_g)\end{aligned} \tag{1}$$

In (1), V_j is the fixed water volume of the j-th ball, $\mathbf{r}_j(t)$ is the ball's location at time t, $h(\mathbf{r}_g)$ is topographic elevation and $A(\mathbf{r}_g,\mathbf{r}_j(t))$ is an averaging function with m^{-2} units such that when integrated over all (x,y) space

$$\int A(\mathbf{r},\mathbf{r}')\mathbf{dr}' = 1 \tag{2}$$

Operation (1) smoothes tsunami ball volume at arbitrary positions $\mathbf{r}_j(t)$ to grid positions $\mathbf{r}_g$.

D. Accelerate each tsunami ball for a short duration Δt using

$$\frac{\partial \mathbf{v}_j(t)}{\partial t} = -g\nabla_h \zeta_{smooth}(\mathbf{r}_g,t) - C_d \mathbf{v}_j(t)\left|\mathbf{v}_j(t)\right| \tag{3}$$

The $\mathbf{r}_g$ here is the grid point closest to the ball's position, ∇_h is the horizontal gradient and $\zeta_{smooth}(\mathbf{r}_g,t)$ is a version of (1) smoothed over time and space.

E. Update the ball position,

$$\mathbf{r}_j(t+\Delta t)=\mathbf{r}_j(t)+\mathbf{v}_j(t)\Delta t+\frac{\Delta t^2}{2}\frac{\partial \mathbf{v}_j(t)}{\partial t} \tag{4}$$

ball velocity,

$$\mathbf{v}_j(t+\Delta t)=\mathbf{v}_j(t)+\Delta t\frac{\partial \mathbf{v}_j(t)}{\partial t} \tag{5}$$

and time t=t+Δt.

F. Here you might return to Step (**D**) several times keeping the surface fixed at its most recent evaluation (inner loop); or, return to Step (**C**) to compute a fresh surface (outer loop). Regardless if the tsunami ball is in water or has been tossed onto land, steps (**C**) to (**F**) hold. Note that acceleration (3) includes a dynamic drag friction to control balls that might encounter unreasonably steep surface gradients and run away. I specify C_d in Section 4.

What in the flow chart makes the flood? Floods and waves get stirred if the underlying topography $h(\mathbf{r})$ in (1) becomes a function of time

$$h(\mathbf{r}) \Rightarrow h_0(\mathbf{r})+\Delta h(\mathbf{r},t) \tag{6}$$

where $h_o(\mathbf{r})$ is the original value in flow chart step (**B**) and $\Delta h(\mathbf{r},t)$ is the bottom uplift or subsidence due to a earthquake, landslide or in this case, failure of the South Fork dam.

2.2 Stabilization.

Numerical stability is the primary concern in any approach that employs granular material, particularly with respect to evaluating the gradient operator in (3) that drives the balls. Fluid simulations especially, because they have both flow-like and wave-like behaviors, can run amok rapidly. No single recipe guarantees stability, but I find that combinations of the three methods below usually can generate simulations that "look right".

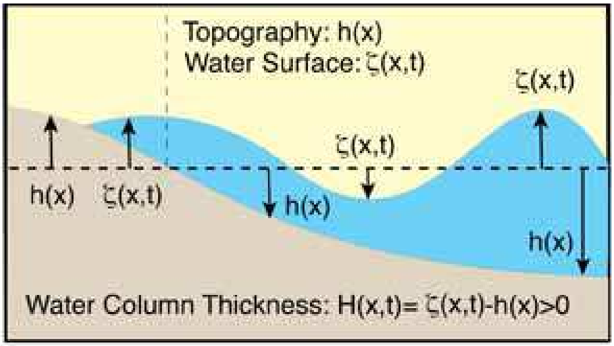

Fig. 3. Geometry for tsunami ball calculations. Topography h(**r**) and water surface ζ(**r**,t) are measured positive upward from some arbitrary level.

(a) Spatial Smoothing. Water surface $\zeta(\mathbf{r}_g, t)$ = H($\mathbf{r}_g$,t) + h($\mathbf{r}_g$) at grid points $\mathbf{r}_g$ is the sum of water thickness and topographic elevation. Both functions need to be spatially smoothed. The fastest means for this is rectangular smoothing, first applied to all grid rows and then to all grid columns. The q-th smoothed value in a grid row or column might be

$$\bar{G}_q = \frac{\Sigma_q}{Norm}; \quad \Sigma_q = \sum_{r=q-w}^{q+w} G_r \tag{7}$$

where G_r are raw values in the row or column, W is the half width of smoothing and Norm is some normalization. The q+1-th smoothed value is

$$\bar{G}_{q+1} = \frac{\Sigma_{q+1}}{Norm}; \quad \Sigma_{q+1} = \Sigma_q + G_{q+w+1} - G_{q-w} \tag{8}$$

You can see that each value (8) derives from the previous value (7) by only one addition, one subtraction and one division. The number of numerical operations in rectangular smoothing is proportional to the number of grid points only, and independent of both the number of balls and the smoothing half width. It takes experimentation to select an appropriate smoothing width. Smoothing width for the topography may not be the same as that for the water thickness. The goal is to stabilize the calculation, not to lose interesting aspects nor add many artifacts. I run the simulation on the smoothed topography, but display it on unsmoothed topography.

(b) Temporal Smoothing. Water thickness H(**r**,t) is also function of time, so temporal smoothing helps to damp waves versus flows. Smoothing any time series *F*(t) usually means storing many past values of the function and then averaging. If *F*(t) is also a function of space, storage may be overwhelming. One way to smooth in time without storing long-past values evaluates

$$F_{smooth}(t) = qF(t) + (1-q)F_{smooth}(t - \Delta t) \tag{9}$$

where q is less than one. For $t=N\Delta t$, it is easy to see that

$$F_{smooth}(N\Delta t) = \sum_{n=0}^{N} q(1-q)^n F([N-n]\Delta t) \quad (10)$$

and that the sum of the weights

$$\sum_{n=0}^{n\to\infty} q(1-q)^n = 1 \quad (11)$$

Evaluating (10) needs all past values of *F,* whereas (9) needs just the one current value. You choose q in (9) to give the desired half-life $t_{1/2}$ to the smoothing

$$q = 1-(1/2)^{\Delta t/t_{1/2}} \quad (12)$$

I employ both spatial and temporal smoothing to generate the water surface $\zeta_{smooth}(\mathbf{r}_g, t)$ for use in (3) and for display in the figures to follow.

(c) One Way Gravity. "One-way" gravity is yet another means to keeps accelerations (3) under control. One way gravity picks the value of g in equation (3) at each location and time based on the current velocity $\mathbf{v}_j(t)$ of the tsunami ball being accelerated and the gradient of the surface slope $\zeta_{smooth}(\mathbf{r}_g, t)$ at the nearest grid location

$$\begin{aligned} &-\nabla_h \zeta_{smooth}(\mathbf{r}_g, t) \bullet \mathbf{v}_j(t) < 0; \text{ then } g = 9.8\text{ m/s} \\ &-\nabla_h \zeta_{smooth}(\mathbf{r}_g, t) \bullet \mathbf{v}_j(t) > 0; \text{ then } g = \varepsilon \times 9.8\text{ m/s} \end{aligned} \quad (13a,b)$$

In words, if acceleration $-g\nabla_h \zeta_{smooth}(\mathbf{r}_g, t)$ opposes ball velocity $\mathbf{v}_j(t)$, then gravity acts in full force. If acceleration $-g\nabla_h \zeta_{smooth}(\mathbf{r}_g, t)$ reinforces velocity $\mathbf{v}_j(t)$, then fractional gravity ε x g, acts. If (13b) is persistently met over several time steps, the tsunami ball accelerates to terminal velocity soon enough, whereas reaction to short lived stimulus is less. Herein lies the temporal smoothing.

3. 1889 flood simulation: input information

As mentioned earlier, delving into the Johnstown Flood reveals lots of information -- much of it mistaken, dramatized, conflicting, or just not quantitative. I found certain post-event investigations and records of the Pennsylvania Railroad inquiry to be most helpful. Railroad engineers, conductors, station agents, yard masters, signal tower and telegraph operators were competent people accustomed to detailed observation and living according to schedules. In the course of their jobs, many had access to accurately set clocks.

South Fork Dam. While the center half of the South Fork Dam vanished in 1889, its two ends exist to this day largely unaltered from their original configuration. Engineering diagrams from a 1891 investigation fix the elevation of the eastern end of the original 1853 dam at 1613.34 (491.9 m). It is generally agreed that the center of the 1887 dam was rebuilt lower than the original one by several feet to accommodate two-way carriage traffic. (This decision reduced spillway capacity and largely contributed to the 1889 overtopping.) The 1891 engineering diagram places the center of the rebuilt dam at 1610.76 feet (491.1 m). Hours before failure, workers hastily ran a two foot high dirt bank across the top of the dam attempting to stem the overflow. At failure, water ran one or two feet over that bank. I put

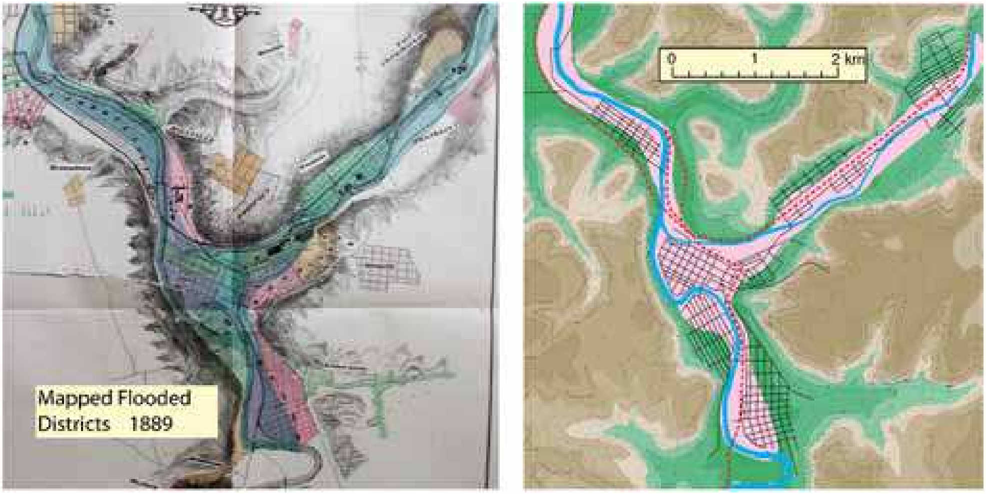

Fig. 4. (*Left*) Plate from Cadwell's 1890 Atlas of Cambria County. Bluish-green tint covers the "flooded districts" of the Conemaugh Valley. (*Right*) My translation of Cadwell's flood zone over today's topography and a 1900 street map. Ideally, the simulated flood will cover the pink area. Dashed red lines are railroads.

the final lake level at 1614 feet (492 m). Reportedly, the lake was rising about 1 foot per hour at the time of failure. Supposing that it takes the lake one and one-half or two hours to drain, inflows would add an equivalent 1-2 feet to lake level. For purposes here, I fix "Effective Lake Level" at 493 m. Adding a virtual dam to a modern Digital Elevation Map and refilling the basin to 493 m, reconstructs South Fork Lake containing 16 million cubic meters of water (*Figure 5*).

Timing- South Fork Arrival. Testimony by Emma Erhefield, telegraph operator at South Fork, specifically times the flood. It first reached the junction of South Fork Creek and the Little Conemaugh River (*Figure 5*) at "At 3 O'clock, probably a minute or two after". C. P. Dougherty, Railroad Agent at South Fork confirms this timing. He testified that he found the South Fork station clock reading 3:08, stopped when the flood knocked the place off its foundation a few minutes after first arrival.

Timing- Dam Failure. Timings of the dam failure vary, but both E. J. Unger and W. T. Sherman Showers testified that major water began to flow over the breast at 2:45 PM and that it was only minutes until the gap reached full size. My simulations require about 10 minutes for water to run the 3.6 km from the Dam to South Fork Junction. Given the firm 3 PM arrival time at South Fork, I place dam failure at 2:50 PM.—roughly 20 minutes earlier than often reported.

Timing- East Conemaugh Arrival. Telegraph operator Charles V. Haak was specific about the flood's arrival at East Conemaugh Railway Yard (*Figure 7a*). Watching the clock for a 4 PM shift change he says, "It came at exactly ten minutes of four." Going outside, he states that water jumped bank onto the railroad tracks a minute or two later. This timing is supported by Engineer V. Wierman who was walking the tracks about 2 km upstream of the Yard toward "AO" signal tower. He met the tower operator walking downstream on the track. Mr. Wierman recalls that the operator carried the AO station clock—stopped at 3:40 PM. The operator said that he had removed the clock just as flood took the tower into the river.

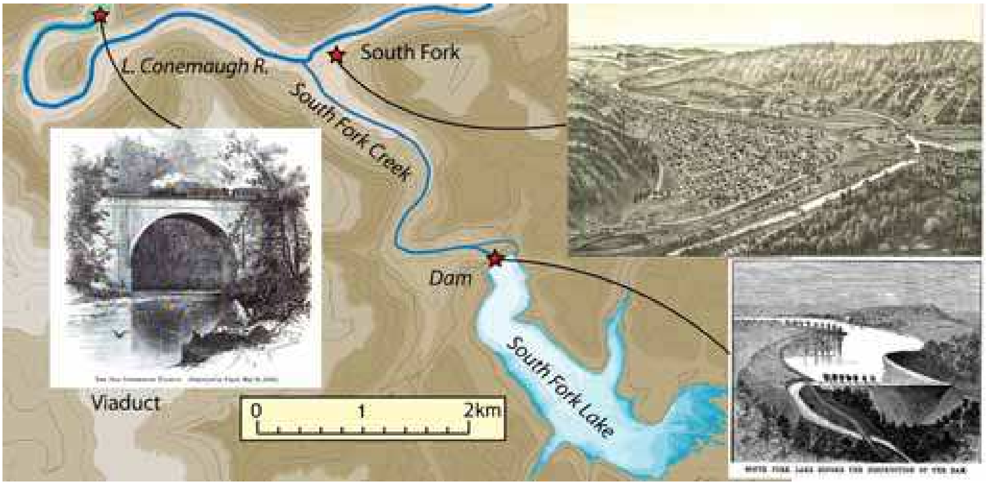

Fig. 5. Overview of the Little Conemaugh River near South Fork. The three historical prints show the Viaduct Arch, The South Fork Dam and Lake, and A panorama of South Fork Town Site looking up South Fork Creek toward the Lake. The star at South Fork marks the railroad station.

Timing- Johnstown and Stone Bridge Arrival. T. H. Watt, Johnstown ticket agent described conditions at his house which stood "a great deal lower than the main Johnstown station and directly opposite. The flood struck us at 4:07." Corroboration comes from District Supervisor W. M. Hays who was on a railroad work party at the Stone Bridge attempting to clear the arches—already beginning to clog with debris. (Booms at the lumber storage yard in Stoney Creek River above Kernville had broken earlier that day piling hundreds of logs under the Bridge.) "About 4:10 our attention was attracted by people shouting, and I saw this bank of water and drift coming down the Conemaugh, almost like a wall. About 4:10, it crossed the town before it reached our bridge."

Timing and Size of Causeway Breach. Period photographs show the causeway breach at the east end of the Stone Bridge repaired with temporary trestle. I measure the width of the breach to be well less than one-half the 170 m length of the bridge. Time of the causeway breach is indefinite, but "Somewhere past 5 PM". For this simulation, the Stone Bridge and Causeway act like dam until I introduce a 70 m wide causeway gap at 5:10 PM.

Timing- Lake Drainage and Flood Durations. Durations are elusive because while the flood initiated rapidly, it decayed away slowly. Rarely do accounts specify what defines the beginning and end of the interval. W. Y. Boyer, present at the dam, testified that it took "about an hour and ten minutes- for the lake to drain to creek bottom, but that others have different opinions." W. T. Sherman Showers states "about 2:45 the wearing away of the dam became more rapid, so that it was cut out quite fast and the water began to go through in great and still increasing quantities, so that by about four o'clock the main body of water had gone out." Placing full breakage at 2:50 PM, 4 o'clock equates to one hour and ten minutes for the Lake to drain, the same as Boyer's estimate. Because the tsunami balls follow longer and shorter paths in transit, certainly the duration of flood downstream must exceed the one hour ten minutes it took to pass the dam. Accounts that give a shorter flood duration must be suspect.

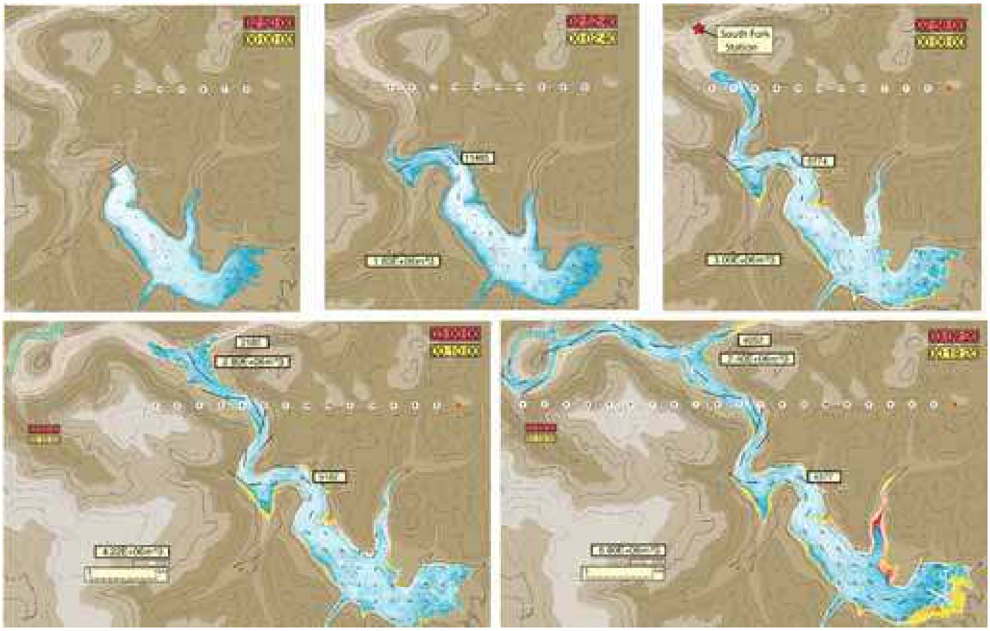

Fig. 6. Snapshots of the early phase of the flood simulation. The yellow backed clock gives elapsed time T= 00:00, 02:40, 06:00, 10:00 and 00:19:20. The red backed clock gives clock time T= 2:50, 2:52, 2:56, 3:00 and 3:19 PM. Note up-river counter flow at the junction of the South Fork and Little Conemaugh Rivers (Panel D) and the floodwater cutting across the oxbow in front of the Viaduct (Panel E). (Movie at http:/ / es.ucsc.edu/ ~ward/ jtown-lake-close-s.mov).

Existing conditions water in channel. It is agreed that the lower sections of Johnstown stood awash waist high and more before the flood's arrival. Elsewhere, witnesses described the rivers as "bank full". In the simulation, the Stone Bridge and Causeway act like a dam early on, so trapping additional tsunami balls (1.8 x 10^6 m^3) in river channels nearby submerges lower Johnstown under a meter or so of water. It is tougher to simulate bank full conditions in the upper reaches of the Little Conemaugh. Water placed there will simply run to Johnstown ahead and with the flood. While it is possible to start the simulation with tsunami balls in the upper channel, this simulation assumes it to be dry.

Inundation Zone. *A. A. Cadwell* (1890) was in the final stages of assembling his "Atlas of Cambria Country, Pennsylvania" when the Flood struck. He quickly commissioned several existing Atlas' plates to be revised with hand coloring covering flooded districts of the Conemaugh Valley (*Figure 4, left*). Figure 4 (*right*) shows my interpretation of the flooded zone overlain on today's topography and a street map of 1900 vintage. *Cadwell* likely mapped the flood damage zone rather than the inundation zone. Too, I find that some edges of his zone cut oddly across topographic contours. Still, *Cadwell's* plates represent the best information available to bound flood extent.

4. 1889 flood simulation:

4.1 DEM and dam failure conditions.

I started this exercise by extracting a 1/9 arcsec (~3 m spacing) DEM from the USGS National Elevation Dataset and then down sampling to every third point (~10 m spacing). For the 1889 flood simulation, 1 million tsunami balls filled a reconstructed South Fork Lake. Behind a virtual dam of 493 m elevation sat 16 x10^6 m^3 of water. By all accounts, the dam failed within minutes after first breach. A few test runs suggest that whether dam failure happened instantly or over a few minutes does not alter significantly the flood history down stream. For my purposes, there is no need for additional model assumptions regarding timing of failure. There is also no need for additional model assumptions regarding the geometry of the breach because the immediate landscape has not been altered significantly since 1889. The simulations assume that the virtual dam instantly reverts to remnant dam's current shape. After releasing the tsunami balls, I follow the flow chart in Section 2, and update their acceleration, position and velocity every Δt=0.1s (inner loop), reform a new surface every 4s (outer loop) and generate a movie frame at 40s intervals.

4.2 Dynamic drag

The only remaining physical element to be fixed is the dynamic drag C_d coefficient. C_d imparts a terminal velocity to overland flow of

$$\mathrm{v}_{term}(\mathbf{r}) = \sqrt{\frac{g\left|\nabla_{\mathrm{h}}\zeta_{smooth}(\mathbf{r})\right|}{\mathrm{C_d}}} \tag{14}$$

so the flood timings established in Section 3 heavily influence its selection. With C_d too small, the flood arrives early. With C_d too big, the flood arrives late.

Another flow related aspect, is that by all accounts the flood onset rapidly in step-like pulses or waves. With water's natural tendency to spread out, how could it maintain a steep onset after an hour or more of travel? People speculated almost immediately that the flow dammed and re-dammed itself several times with transported debris and fallen obstacles (like Bridge #6, ~500 m east of AO tower). Each short-lived blockage, presumably trapped water behind and sent forward a pulse when it broke. While such things are possible, it is hard to say if multiple dams could survive long enough to have much effect or how much volume the blockages could retain to release as pulses.

Another means to maintain steep onsets without multiple blockages lets C_d depend upon the flow thickness H($\mathbf{r}$,t). If C_d increases with H($\mathbf{r}$,t), thin flows that outrace the main body suffer more drag and lower terminal velocity (14). Thin vanguards will be forced to slow and wait for the main body. Thickness-dependent friction keeps the flow together and its onset steep. After several trial and error runs, the following form of C_d($\mathbf{r}$,t) seemed to match all the information:

$$\begin{aligned} &C_d(\mathbf{r},t)=0.0045/\mathrm{m} \text{ if } H(\mathbf{r},t)<2\mathrm{m},\\ &C_d(\mathbf{r},t)=0.0022/\mathrm{m} \text{ if } 2\mathrm{m}<H(\mathbf{r},t)<3\mathrm{m}, \quad (15)\\ &C_d(\mathbf{r},t)=0.0011/\mathrm{m} \text{ if } 3\mathrm{m}<H(\mathbf{r},t)<4\mathrm{m} \text{ and}\\ &C_d(\mathbf{r},t)=0.0001/\mathrm{m} \text{ if } H(\mathbf{r},t)>4\ \mathrm{m}. \end{aligned}$$

To get a feeling for these values, let's compute representative terminal velocities. From South Fork Lake to Johnstown, floodwater dropped 140 m over a 24 km run, so $\left|\nabla_{\mathrm{h}}\zeta_{smooth}(\mathbf{r})\right| \sim 0.00583$ and average terminal velocities (14) would be

v_{term}= 3.6 m/s if H($\mathbf{r}$,t)<2m,
v_{term} =5.1 m/s if 2m<H($\mathbf{r}$,t)<3m, (16)
v_{term} =7.2 m/s if 3m<H($\mathbf{r}$,t)<4m and
v_{term} =23.9 m/s if H($\mathbf{r}$,t)>4 m.

Naturally v_{term} would be higher than (16) on the steeper parts of the water course near the Dam, and less than (16) on the flatter sections near Johnstown. Be aware that the velocity of flood advance v_{flood} generally lags v_{term}. Rarely does $\nabla_h \zeta_{smooth}(\mathbf{r})$ point directly down river. Too, in a contorted channel, the tsunami balls bounce back and forth between the walls slowing the advance of the flood. Lower v_{term} can actually increase v_{flood} because slower speeds reduce the bouncing and make for a shorter flow path.

4.3 Output products.

Figure 6 shows the initial phases of the 1889 flood in 2D map view at T= 00:00:00, 00:04:00 00:12:00, and 00:19:20. (Quicktime movie animations accompany all of the simulations presented in this article. See Appendix A. View the movie of Figure 6 at http://es.ucsc.edu/~ward/jtown-lake-close-s.mov). In Figure 6 and those that follow, the circled numbers measure peak flow depth to that time in meters anywhere along a vertical line passing through the circle. The small numbers in the thin white boxes list peak flow depth to that time at that position. The numbers in the thin yellow boxes list two-minute average flow rates past that location. Thin lines in the flow give time averaged ($t_{1/2}$=80s) speed and direction.

⇒*T: 0:00-3:00 (2:50–2:53PM)* (*Figure 6: Frames A & B*): Two minute average flow through the dam gap quickly increases to a peak of about 12,000 m^3/s. Multiple bends in the channel hold the flood advance to 5-6 m/s.

⇒*T: 3:00-6:00 (2:53-2:56PM)* (*Figure 6: Frame C*): Flow rates through the breach decrease to 7000 m^3/s. $3x10^6$ m^3 has already passed the dam. Peak flow depth at the second bend below the dam hits 9.2 m. Water has now traversed two-thirds the distance to South Fork. Flow speeds increase to about 7 m/s.

⇒*T: 6:00–12:00 (2:56-3:02PM)* (*Figure 6: Frame D*): After eight minutes, water reaches South Fork Junction 3.6 km below the dam, hits the hill on the north bank and splits into east and west streams. The westward one continues down river toward the Viaduct. The counter flow pushes eastward up the Little Conemaugh River toward South Fork Station. Mean velocity of flood advance to now is 3590m/(8*60s)= 7.5 m/s. By T=12:00, two minute average flow rates through the breach slacken to 5000 m^3/s. More than ¼ of the lake has drained.

⇒T: *12:00-30:00 (3:02-3:20PM)* (*Figure 6: Frame E*): The counter flow reaches its maximum up stream extent (900 m east of the river junction) putting 6.4 m of water in the channel behind South Fork Station, 400 m east of the junction. Nineteen minutes after the breach, part of the flow cuts the oxbow narrows and fills the pool in front of the Viaduct. (It is said that such a division of flow did occur.) The majority of the flood runs around oxbow and reaches the Viaduct in 20-22 minutes. Mean velocity of flood advance from the Dam to the Viaduct is 8390m/(22*60s)= 6.4 m/s. In the simulation, the Viaduct acts like a barrier until T=30:00 when it fails completely (see next section). Of the $16.0x10^6$ m^3 of water originally in South Fork Lake, $7.0x10^6$ m^3 and $9.2x10^6$ m^3 have escaped by 20 and 30 minutes respectively.

Figure 7 maps the flood as it passes "AO" Tower, E. Conemaugh and Woodale.

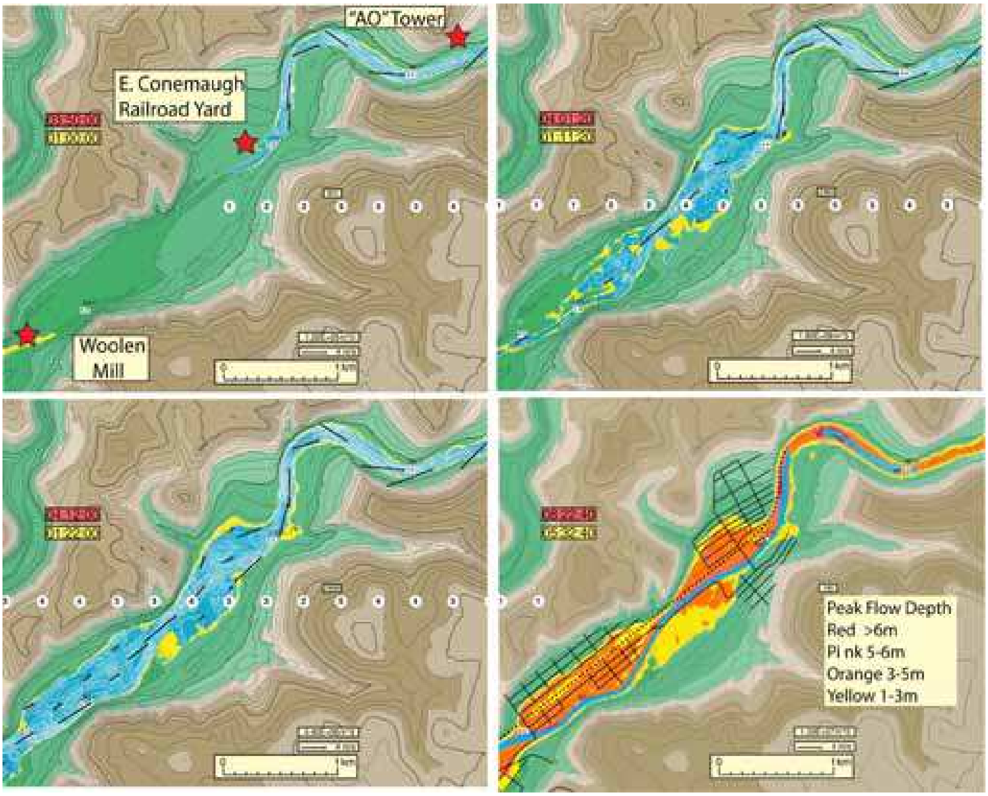

Fig. 7. Snapshots of the flood simulation through E. Conemaugh and Woodvale at T= 1:00:00, 1:11:20, 1:22:00 and 5:32:40 (3:50, 4:01, 4:12 and 8:22PM). Panel A locates "AO" signal tower, the E. Conemaugh Rail Yard and the Woolen Mill at the south end of Woodvale. Panel D shows the final extent and depth of flooding and a 1900 vintage street map. Note that the flood expands to cover the full width of the valley. Compare Panel D with Figure 4, right. (Movie at http://es.ucsc.edu/~ward/conemaugh-close-s.mov).

⇒*T: 50:00-60:00 (3:40–3:50PM)* (*Figure 7: Frame A*): The flood passes AO tower and arrives at E. Conemaugh rail yard. The simulation gives 5.5 m and 4.7 m of peak flow in the channel at the two locations.

⇒*T: 1:00:00-1:10:00 (3:50–4:00PM)* (*Figure 7: Frame B*): Upon rounding the bend above the rail yard, the flow jumps the north and south banks into the streets of E. Conemaugh and Franklin respectively. From there southward, water fills the whole 500 m width of the valley. Two minute average flow rates passing the rail yard exceed 3000 m^3/s. To put this flow into perspective, consider information from the U.S. National Weather Service who has operated a river gauge close to the E. Conemaugh rail yard since the 1930's. Their web site (http://www.erh.noaa.gov/ctp/hydro) calculates that the Little Conemaugh River suffers major double bank flooding here when flow hits 950 m^3/s. Only once during the gauge's existence did the river run this high, in 1936, during the Valley's worst flood of the 20-th century. According to the simulation, flow rate passing the rail yard in 1889 exceeded by three times that experienced in 1936. By 4:00 PM, one hour and ten minutes after the breach, 85% of the reservoir has drained. I take this stage to be "down to creek bottom" as described by W. Y. Boyer.

⇒*T: 1:10:00-1:20:00 (4:00 – 4:10PM)* (*Figure 7: Frame C*): The valley-wide flow tears through Woodvale, wiping most of the town clean. Only the brick Woolen Mill at the south end of town survived. The simulation puts 5.5 m of water in the channel there and 4.4 m at the building site. Because the lower Valley slopes just slightly compared to its upper reaches, velocity of flood advance slows to 3.6 m/ s.

⇒*T: 1:30:00-past 5:00:00 (4:20-7:50PM)* (*Figure 7: Frame D*): About 2 hours after it arrived, the flood fully passed Woodvale and moved down stream. Sometime during that interval, the whole valley had been covered with 3-5 meters of water (orange color, Panel D, Figure 7). In the simulation, water reached to the third street of E. Conemaugh and it took out all but the two highest streets in Woodvale. In Panel D you can clearly the see the raised railroad bed (yellow stripe) running up from Johnstown. Flooding on rail beds was 2-3 m less than on spots adjacent. Raised rail beds helped save a few parked trains. Still, virtually all of the track and rolling stock from the Railway Yard to Johnstown Station washed away—many passengers included.

Figure 8 pictures the flood as it rolls into Johnstown and then Cambia.

⇒T: *1:00:00-1:15:00 (3:50-4:05PM)* (*Figure 8: Frame A*): The flood passes below the Main Station and into Johnstown, already under 1- 2 m of water. Although the mean velocity of flood advance from the Dam to the Woolen Mill is 5.3 m/ s (22.2km/ 70*60s), water entered town more slowly, 2 to 3 m/ s. I imagine that structural damage and causalities would have been worse still had the water maintained its previous 5 or 7 m/ s speeds.

⇒T: *1:15:00-1:30:00 (4:05-4:20PM)* (*Figure 8: Frame B*): The flow splits again, one stays in the channel running below the Main Station toward the Stone Bridge. The other cuts directly across town and down Clinton Street toward Stoney Creek. Upper Clinton Street tracks a reclaimed section of the old portage railroad canal basin. The street occupies a slight linear depression and offered an attractive path for the flood.

⇒T: *1:30:00–2:00:00 (4:20-4:50PM)* (*Figure 8: Frame C*): Trapped behind the Stone Bridge now acting like a dam, floodwater forms "Lake Johnstown". Eventually the lake submerges everything at elevation less than 361 meters – a bit higher than the level of the bridge rails. Velocity arrows in Frame C show the "counter flow" as water backs up Stoney Creek River. This counter flow heavily damaged Kernville on the west bank; however, it saved many floating houses (and fortunate occupants) by directing them upstream away from sure destruction at the Stone Bridge. Many of the buildings swept down the valley came to rest in Kernville and were later relocated back to their original locations. Some eloped houses are still in use today.

⇒T: *2:00:00–4:00:00 (4:50-6:50PM)* (*Figure 8: Frame D*): At T=2:20:00 (5:10 PM) the simulation extracts a 70 m wide piece from the causeway at the east end of the Stone Bridge. Lake Johnstown drains, but progress is slow because considerable volume (>1000 m^3/s) continues to arrive down the Little Conemaugh. The town remained several meters submerged when the simulation stopped at 8:20 PM. Many hours more pass before water vacates the streets. The 70 m wide causeway break dumped far more water into the downstream channel than it could hold. The excess discharged through the large buildings of Cambria Iron Works on the east bank and the homes of Cambria town on the west bank.

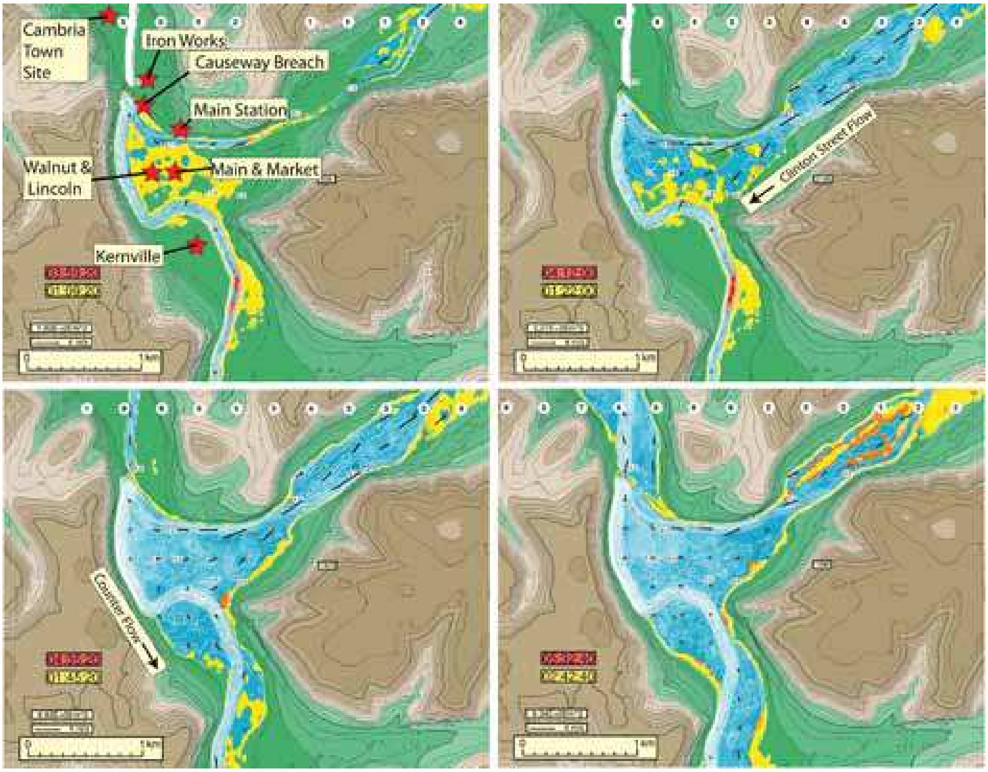

Fig. 8. 2D view of the flood at Johnstown at T= 1:09:20 (3:50 PM), 1:22:00 (4:12 PM), 1:48:00 (4:38 PM) and 2:36:40 (5:26 PM). Note the back current in Panel C pushing water up Stoney Creek and washing Kernville on its west bank. After the causeway failure at 5:10 PM, water rushing through the breach floods the Iron Works and Cambria town site (Panel D). (Movie at http:/ / es.ucsc.edu/ ~ward/ jtown-close-s.mov).

5. Assessment of the 1889 flood simulation:

Having run the 1889 flood simulation, one asks -- How well did it do? Did it match observations?

Duration of Lake Drainage. The red line in the bottom panel of Figure 9 graphs volume past the dam versus time. About 50% of the lake volume evacuated in 25 minutes and 85% in 70 minutes. Earlier I recounted firm testimony that the lake drained "to creek bottom" in 1 hour-ten minutes. Simulation and observation coincide here.

Timing and Flood Heights at South Fork. The simulated flood arrives at South Fork at 2:58PM (*Figure 6, Frame C*) and fully pushes upstream behind the South Fork Station by 3:09 PM (*Figure 6, Frame D*). These times coincide with the telegraph operator's statement and the 3:08 time of the flood-stopped station clock.

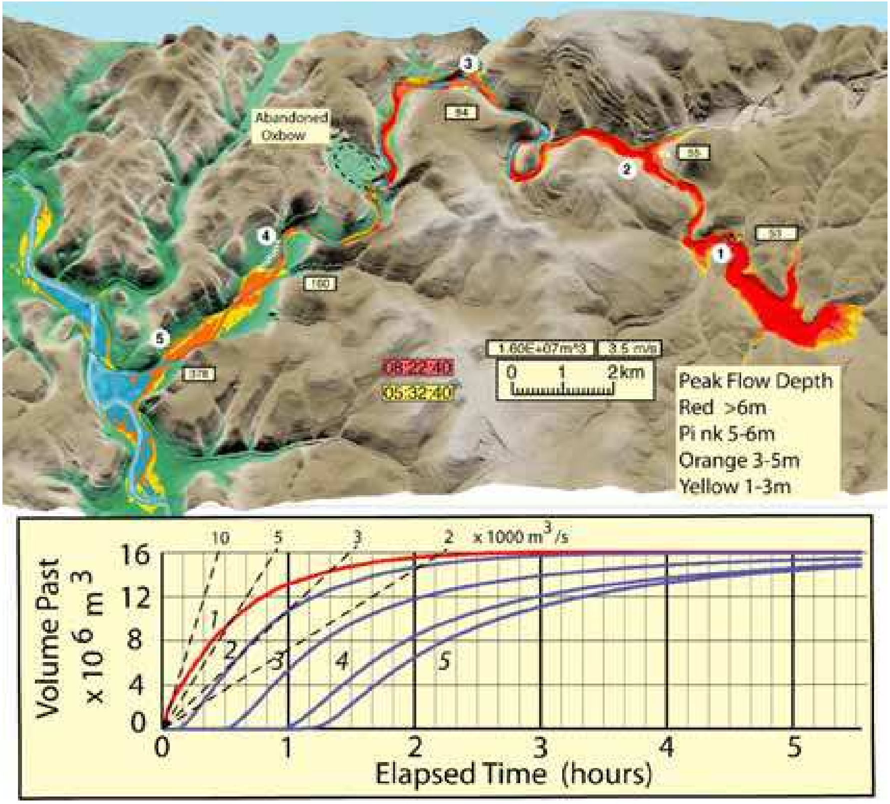

Fig. 9. (*top*) 3D-like view of the flood at 8:22 PM. The Lake had long drained by now and the Little Conemaugh River returned to pre-flood conditions. Water still covers much of Johnstown and will do so for several more hours. (*bottom*) Total water volume versus time past five locations in the valley marked with white circles: 1. The dam, 2. South Fork, 3. Mineral Point, 4. E. Conemaugh, 5. E- Johnstown. Slopes of these curves reflect average flow rate. Dashed lines mark 10,000, 5,000, 3,000 and 2,000 m^3/s. Nominal flow over Niagara Falls is 2,800 m^3/s. The 1936 flood rate was 950 m^3/s at E. Conemaugh. Note the now-abandoned oxbow between Mineral Point and E. Conemaugh. The river currently runs through a large cut, parallel to the railroad cut extant in 1889.

C. P. Dougherty further testifies that the counter flow at South Fork went ½ mile (800 m) up stream from the junction and that engineers later measured a 23 foot (7 m) increase in water level due to the dam break alone — high water already in the river being accounted for. No conflict here. In the model, peak flow depth reached 6.4 m in the riverbed behind the station and the counter flow stretched 900 m up stream from the junction.

Timing and Flood Heights at the Viaduct. One of the stories dealing with the 1889 flood concerns the Stone Viaduct located at the oxbow below South Fork. The Viaduct was a massive stone structure built in 1853 as part of the portage railroad (*Figure 5*). It stood 22 meters above river bed atop a single 80 foot diameter arch. All that we know for certain is that the Viaduct vanished during the flood. Some say that the arch clogged with debris when the flood cut across the oxbow (*Figure 6, Panel E*). Water then dammed behind, flowed over top by several feet, and eventually knocked down or undermined the structure. I have not discovered any definitive accounts to support or quantify the Viaduct story. Others suggest that, like the Stone Bridge, the Viaduct was far too massive to succumb to flood alone. Dynamite, they say, packed in a railroad boxcar washed down from South Fork struck and blew up the structure.

To interpret the Viaduct story from a physics-based perspective, first consider water volume and timing. From the modern Digital Elevation Map, I find that damming the river at the Viaduct to the 444 m elevation of the railroad bed would impound 4.4 million cubic meters of water. Raising a temporary lake several feet over the tracks (to 446 m elevation) requires 5.6 million cubic meters. South Fork Lake held considerably more water than this, so if the Viaduct arch really could have dammed tight, and if the structure held in place long enough, the flood could have overtopped it. Timings remain an issue however, "Can sufficient water reach the Viaduct rapidly enough so that the well documented arrivals of the flood downstream can still be met?" Figure 9 (*bottom*) says that $4x10^6$ m^3 of water passed South Fork in 25 minutes and $6x10^6$ m^3 million in 34 minutes. Flood travel time from there, around the oxbow to the Viaduct is about 12 minutes. So, four million cubic meters could back up behind the Viaduct in 37 minutes or (3:27 PM) and 6 million by 46 minutes (3:36 PM). These volumes would be achieved a bit sooner if I added water already in the river channel to that of South Fork Lake. Recall that the flood must reach E. Conemaugh Rail Yard by 3:50 PM. In the simulation it takes about 25 minutes for the flood to travel from the Viaduct to the Rail Yard. Although the flood has a very tight schedule, conceivably water could have overtopped the Viaduct by 3:25-3:30 PM and still met the timing requirements down stream.

Whether water really overtopped the Viaduct and whether flood or dynamite caused its demise, will take further forensic investigation. In any case, the simulation breaks the Viaduct at T=30:00 (3:20PM) after $5.06x10^6$ m^3 have passed South Fork on the way to the short-lived lake.

Timing and Flood Extent at E. Conemaugh and Woodvale. The simulated flood reached "AO" tower and the Rail Yard at 3:40 and 3:50 PM as the accounts state. Granted, I adjusted the dynamic drag coefficient C_d and Viaduct failure time to generally meet these constraints.

It might be noted that in 1889, the Little Conemaugh River circled a large oxbow between Mineral Point and the Rail Yard (*Figure 9*). The oxbow is abandoned now and the river course lost to mining operations. The modern river runs through a man made cut just west of the railroad cut extant in 1889. Eyewitnesses state that 1889 flood flowed many feet deep through the railroad cut and helped knock out Bridge #6 on the west side. It seems that much of the 1889 water bypassed the oxbow and followed a path not too different from the current one. Although the oxbow path is not included in the simulation, I do not believe that this substantially alters flood circumstances down stream. Still, a reconstruction of the old oxbow might be worth considering.

The simulation puts 3 to 5 m of water over the Rail Yard (*Figure 7, Panel D*). I have not discovered any definitive measurements of flood heights there for comparison. References to water marks on surviving locomotives do exist but, railroad beds stand a few to several meters higher than surroundings. The Yard's multiple parallel sidings of various elevations further complicate the interpretation of locomotive watermarks. Yard managers in fact did everything possible to park delayed trains as far up and away from the river as possible. Adjacent trains, even adjacent cars, fared better or worse depending on location.

Although the depth of flooding here was uncertain, the extent was well indicated. Both *Cadwell's* Atlas and Railroad Testimony agree that flooding reached the third street in Conemaugh. The simulation (*Figure 7, Panel D*) finds no disparity.

Timing and Flood Extent at Johnstown. The simulated flood passes the Main Station at 4:08 PM and reaches the Stone Bridge at 4:11 PM, in accord with the accounts.

The models puts 3-7 m water over the town, nearly replicating the pattern of depths expected in a static "Lake Johnstown" filled to 361 m (*Figure 10*). Few quantitative observations of water depth in the city exist. Most of the structures upon which one might measure it were destroyed. City Hall at Main and Market provides one definitive datum - a plaque marking high water, 6.4 m above grade. Nearby at Walnut and Lincoln, photographs show a clear high water mark on a surviving house. Judging from the size of a person standing in the photo, I fix flood height there at 6.7 m. The simulation predicts 6.1 m and 6.5 m at these two places – close enough. Further investigation should uncover other quantitative flood heights in the city and better test the "Lake Johnstown" hypotheses.

I see no glaring mismatch between the predicted inundation zone in the city (*Figure 10*) and the flooded areas mapped in *Cadwell's* Atlas (*Figure 4*). In Kernville and South Johnstown the simulated flood does extend a few streets beyond the mapped zone. I note that *Cadwell's* inundation limit at these places runs oblique to, rather than parallel with topographic contours. Inundation need not parallel topography in high-speed flows, but flooding oblique to topography is difficult to reconcile in this situation where water moves very slowly. Possibly, the artists painting the Atlas' plates were a little interpretative. Also as I mentioned, *Cadwell's* mapping likely speaks to the damage zone rather than inundation zone, the latter being more extensive. At the edges of a flood, water stands in the streets but inflicts no damage.

Timing and Flood Extent at Cambria. The timing of causeway failure dictates the onset of the simulated flood at Cambria Iron Works and Cambria Town. Time of causeway failure (5:10 PM) is a kinematic input parameter. I do not have any independent timings of the flood in Cambria, but there may be quantitative information from witnesses further down river that could be brought to bear.

Comparing inundation zones in Figure 10 with Figure 4, I see that the simulation puts a considerably wider flood track over the Iron Works than did *Cadwell*. Compared with other locations in the Valley, the Iron Works was rather featureless (few roads) and its steel construction distinct from and perhaps stronger than the wood frame construction elsewhere. I do not know how well the Atlas mapped inundation in the industrial zone. In Cambria Town, the residential area across the river, the simulated flood extent agrees with the Atlas within a street or two.

Overall Assessment. In my opinion, the Johnstown Flood simulation successfully reproduces the bulk of credible historical information to the extent that that information is quantified. Additional facts affirming or contradicting its predictions will certainly come to light, and the model may need modification. Regardless, the exercise demonstrates that realistic physics-based simulations of long-run river floods are achievable with modest laptop-computer resources. When applied in an historical context, physics-based models add new dimensions and flavors to "storytelling" accounts and they help contemporary folk better understand and appreciate the drama of that day.

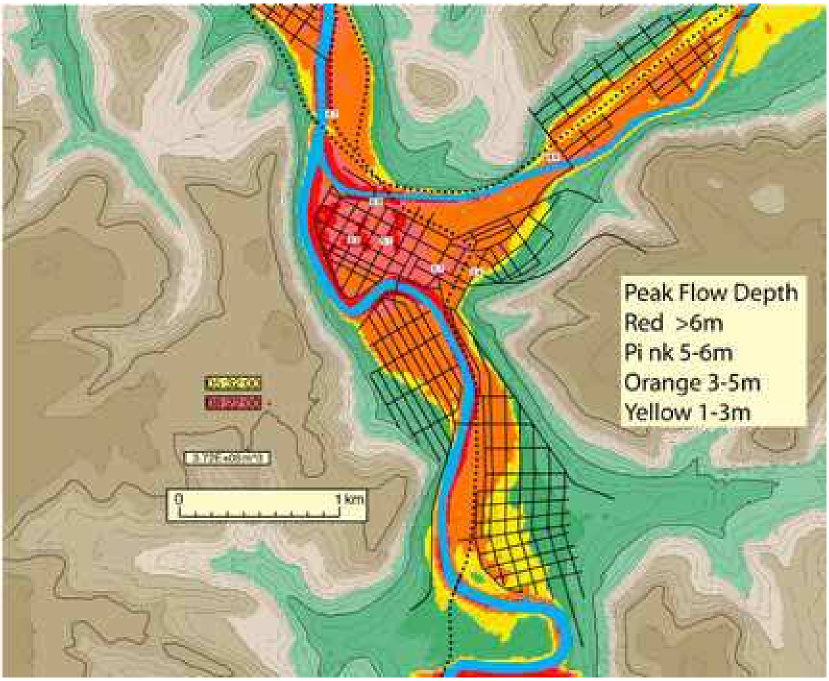

Fig. 10. Map of inundation zone and peak flow depth flood extent at T=5:32:00 (8:22PM). Compare with the observed inundation extent in Figure 4 (*left*).

6. Conclusions

The May 31, 1889 Johnstown Flood was a tragic engineering and societal failure. I approach the story for the first time from a science-based perspective. By combining text and photographic information to constrain dynamic and kinematic parameters, the simulations successfully capture in time and space the full sequence of events including: the breaking of and initial high flow rate through the dam, the down draw of the lake, the counter flow flooding at South Fork, the overtopping of the Viaduct, the valley-filling expansion of the flood at E. Conemaugh, the creation of "Lake Johnstown" behind the Stone Bridge, the back flow up Stoney Creek River, the failure of the causeway, the flooding of Cambria and the eventual passage of the flood.

Being more than artist's conceptions, physics-based simulations can accept input from a wide range of observational information and they can output quantitative predictions on many aspects that could not be measured. For instance, the simulation estimates that the

peak flow past East Conemaugh in 1889 surpassed by three times, that of the 1936 flood, the greatest of the 20-century. As by-products, physics-based simulations build support for, or cast shadows over, anecdotal accounts such as the overtopping of the Viaduct.
Given the speed, flexibility and modest computational requirements of the tsunami ball approach, the method should continue to find application in dam break and flood situations. Perhaps the technique might help to mitigate losses in future Johnstown style disasters.

7. Acknowledgement

Much of the historical information quoted in this article came from websites hosted by *The National Park Service Johnstown Flood National Memorial*:
http://www.nps.gov/archive/jofl/home.htm
and the *Johnstown Flood Museum*
http://www.jaha.org/FloodMuseum/oklahoma.html

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Appendix A.

Quicktime movie links to the simulations presented in this article.

Composite with Text and Photos (Figure 1)
http://www.youtube.com/watch?v=tMc9kP9q-d8

Lake View Close (Figure 6):
http://es.ucsc.edu/~ward/jtown-lake-close-s.mov

East Conemaugh View Close (Figure 7):
http://es.ucsc.edu/~ward/conemaugh-close-s.mov

Johnstown View Close (Figure 8):
http://es.ucsc.edu/~ward/jtown-close-s.mov

Flood in Map View (Figure 9-10):
http://es.ucsc.edu/~ward/jtown-map-s.mov

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Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.