REVISITING THE TIMING AND EVENTS LEADING TO AND CAUSING THE JOHNSTOWN FLOOD OF 1889

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The Johnstown Flood of May 31, 1889, was responsible for more recorded deaths than any other disaster in the United States until the Galveston hurricane of 1900.[1] An important difference between the two is that the Johnstown flood was not a natural disaster. Although the Johnstown region was in the midst of a particularly wet spring and the former boroughs that now form the city of Johnstown were already experiencing low-level flooding on May 31, the ultimate reason for the high death toll was the catastrophic failure of the South Fork Dam, located fourteen miles upstream from the outskirts of Johnstown on the South Fork of the Little Conemaugh River (see fig. 1). The millions of tons of water released by the failure of the dam caused devastation along the Little Conemaugh River drainage. As the water moved downstream it was temporarily impounded by debris dams behind two Pennsylvania Railroad bridges (Viaduct and Bridge no. 6), which caused "reformation of the lake" at these points. When Bridge no. 6 failed, the rejuvenated flood wave sped toward Johnstown. Most structures

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were no match for the violent floodwaters, which carried debris from the dam itself, trees, houses, bridges, railroad cars, barbed wire; even livestock and people were caught in the torrent. By the time the flood wave reached the Stone Bridge in Johnstown, it had traveled about sixteen miles. At this point most of its energy was spent and a huge debris jam formed at the bridge. The debris jam subsequently caught fire, claiming additional victims who had been trapped among the debris. In the end, over 2,200 people lost their lives.

Despite the infamy of the Johnstown Flood of 1889 (or perhaps because of it), there is much conflicting, and sometimes inaccurate, information surrounding the factors contributing to the flood and the flood itself. This article reviews the events leading up to the flood and provides new insights as to the cause of the dam's failure, with respect to the fill material used in its reconstruction, the rainfall amounts and intensity, the rate of floodwater runoff into Lake Conemaugh (previously known as the South Fork Reservoir), and the travel time of the flood wave to Johnstown. Special attention is given to resolving the conflicting accounts as to the time of failure for the South Fork Dam, the volume of Lake Conemaugh at the time of the dam failure, the length of the dam's embankment, and the time it took to drain the lake. Finally, we hope to show that the often-presented idea that the designed

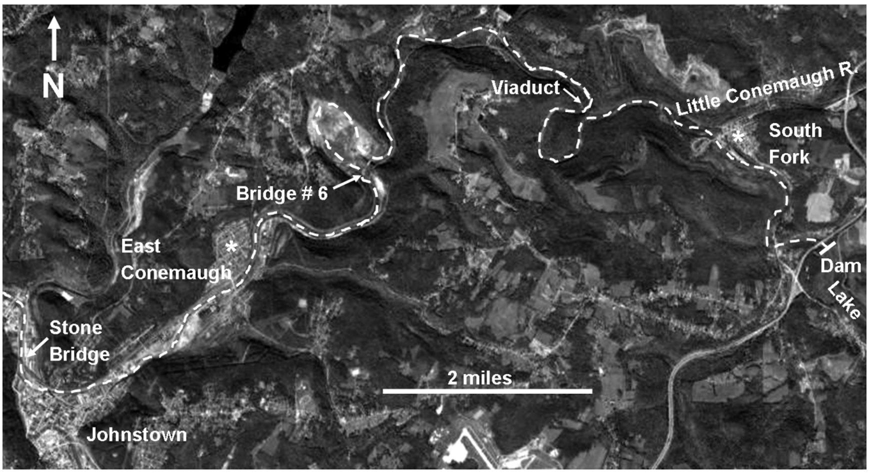

FIGURE 1: Path of the flood from the South Fork Dam through present-day Johnstown, shown by the dashed white line. Note that the meander bend upstream of Bridge no. 6 no longer exists. It has been filled in, primarily with steel-mill slag, and the river now flows through a rock cut in the neck of the meander bend. Base map source. Google Earth image. Software available at: http://www.google.com/earth/index.html.

spillway for the original dam was inadequate is without merit and that indeed the culpability for this tragedy rests in large part with the actions/ inactions of the South Fork Hunting and Fishing Club.

Original South Fork Dam

The South Fork Dam was designed to hold back water that could be used as a dry-season water supply for the Pennsylvania Main Line Canal, with released water traveling down the Little Conemaugh River to the Johnstown terminus of the canal. William E. Morris, one of the state engineers of the Western Division of the Pennsylvania Canal, prepared the dam's original design in 1839.[2] Authorization for dam construction contracts and iron work occurred in January 1840 and work began in April of that year.[3] Due to Pennsylvania's financial difficulties, funding for the project ran out in 1842 and Morris, along with the other engineers, lost their employment with the Canal Commission. Nevertheless, Morris prepared a modified design in 1846 that would reduce some of the costs when construction resumed. The partially built dam slowly deteriorated during the 1842–51 construction hiatus, and in 1847 a partial break in the dam resulted in minor downstream flooding. Although not completed until the spring of 1853, the dam provided water to the canal as early as the summer of 1852.[4]

Morris estimated that the completed dam, at a water height of 62 feet, would hold about 480 million cubic feet of water, while during dry spells (with water two feet below the lip of the spillway due to evaporation) 450 million cubic feet would be available for the canal.[5] We performed a Geographic Information Systems (GIS) analysis of newly available Light Detection and Ranging (LiDAR) data to obtain a new estimate of the lake volume and acreage. LiDAR is an optical remote sensing technique for measuring distances, and is used for very detailed mapping. The LiDAR data uses high-quality, remotely sensed point data in x, y, and z values to indicate each point's location and elevation.[6] It is processed to remove tree canopies, buildings, and other unwanted features to produce a "bare Earth" relief map that can be used to create a digital elevation model.

Our analysis reveals that Morris's estimate was on the high side and the dam would only store 388 million cubic feet of water below an elevation contour of 1,609 feet. This elevation is slightly above the spillway lip elevation but we consider it a close approximation of the "normal pool" at high lake level in 1857. Figure 2 shows features in the vicinity of the dam and lake, and the surface extents of the lake in 1857 and at the time of the 1889 flood. Note that these modern (2008) LiDAR elevations are 5.4 to 6.0 feet higher than the elevations given in the 1891 report by James B. Francis and others.[7] Our analysis using GIS software (ArcGIS 10) shows that at the moment the dam breached in 1889, the impoundment held about 495 million cubic feet of water (or about 15.5 million tons) below a contour elevation of 1,615 feet, which we find approximates the modern elevation of the impounded lake water at failure. The calculated tonnage is almost 5 million tons less than the usually cited figure of 20 million tons. Our work with modern LiDAR data (1-meter resolution) updates previous results by the National Park Service, which used an older digital elevation model (10-meter resolution), to estimate a lake volume of 449 million cubic feet of water when the dam failed.[8] The older 10-meter digital elevation model used lower-quality data that was primarily derived by digitizing contours from U.S. Geological Survey 7.5-minute topographic quadrangle maps.

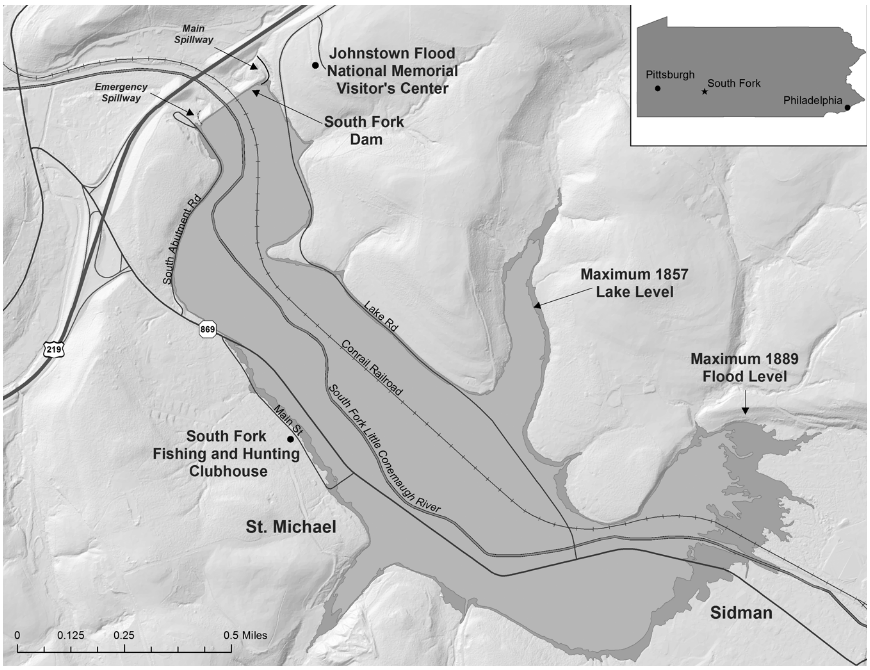

FIGURE 2: Overhead view of the former Lake Conemaugh, superimposed on a relief map with present-day features that include a railway through the dam breach, Highway 219, and the park visitors' center. The areal extent of the lake is shown for two different times: normal pool level of 1,609 feet in 1857, when the dam was acquired by the Pennsylvania Railroad, and later, at maximum flood level (1,615 feet) when the dam breached in 1889. Image prepared by authors for this article. Google Earth image. Software available at http://www.google.com/earth/index.html.

The modern lake volumes represent upper limits because lake-bottom sediments were present at the time of the 1889 flood (see fig. 3). The flood washed out some of these sediments and rain over the ensuing years eroded away additional lake-bottom sediments. Our LiDAR-based volumes represent the present basin, but some adjustments, such as for the modern double-track railroad bed, and dam slope have been taken into account so that the basin would be more similar to what existed in 1889. The present study also gives a new acreage value for the lake at spillway lip level (1,609 feet) of 374 acres, and defines the drop in elevation from the base of the dam (1,543 feet) to the Stone Bridge in Johnstown as 380 feet.

A key specification of the original plans was that the aggregate width of spillway channels be at least 150 feet, which could be accomplished by a single large spillway on one side of the dam, or a spillway on each side of the dam. A single curving spillway, 98 feet wide at the bridge over the spillway (narrowing to about 69 feet wide downstream) and 10 feet deep, was cut into bedrock on the northeast side of the dam and is still

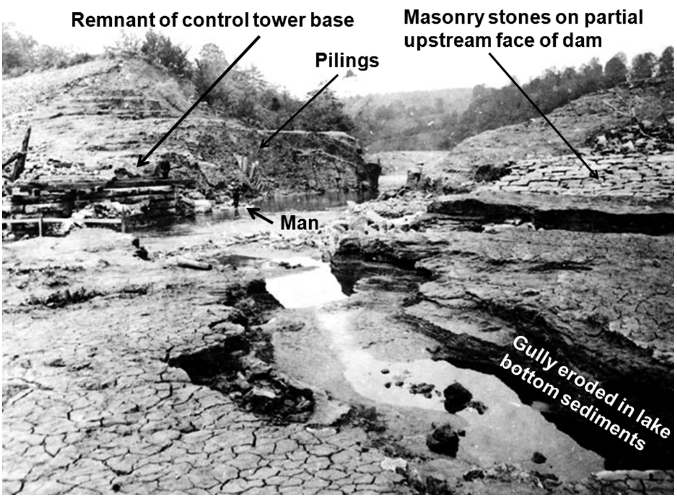

FIGURE 3: View of the former lake bed upstream of the dam. An erosional gully is carved in the lake-bottom sediments. The structure at left center includes remnant of the former control tower and stone culvert. Remains of hemlock pilings used to block the culvert are also visible in the middle of the breach on the left side, near a man standing beside the stream. Masonry covering part of the upstream side of the dam can be seen on the right. Figure courtesy of the Johnstown Area Heritage Association.

evident today. However, Walter S. Frank, in discussing the causes of the flood, makes a strong argument that a second, much shallower spillway was originally excavated on the opposite (southwest) side of the dam. He points out that "it is inconceivable that any engineer would approve the completion of a dam with a waste-way [spillway] width of 69 feet at its narrowest point, when specifications called for 150 feet."[9] This secondary spillway would have been about 3 feet deep (down to bedrock) and approximately 70 feet wide. The present study confirms the probable existence of an auxiliary spillway. Such a spillway would have begun to accommodate flow if the lake rose to within about three feet of overtopping the original dam and would therefore substantially increase the safety margin for the dam at high flows.

The original dam also had a series of cast-iron sluice pipes at the base. Five sluices, consisting of seven-foot-long sections of two-foot inside-diameter cast-iron pipes, ran for a total of 77 feet under the dam and fed water to an arched stone culvert, which then discharged at the base of the downstream breast. Sluice gates, controlled from a tower built above the culvert entry, regulated flow into the pipes, which would then eventually feed the Main Line Canal in Johnstown, thus making the canal navigable for most of the dry summer season. Sluice pipes are also important for two other reasons. They allow the water level to be lowered, making it possible to carry out repair work on the upstream dam breast and provide the means to control water level during flood events in order to reduce the possibility of the dam being overtopped. Morris specified an all-masonry control tower in the original 1839 plans, although the control tower ended up as a wooden structure on a stone foundation as a cost-saving measure.[10]

The 1839 dam specifications called for a rubble masonry wall laid in a full bed of cement that was to have been built within the shale core of the embankment. The masonry wall was to have been sunk into the bedrock and was to have been 25 feet high, 6 feet thick at the bottom, and 2 feet thick on top. Omission of this "heart wall" in the 1846 plan saved the Commonwealth of Pennsylvania approximately $40,000 in construction costs. Only the shale core remained. Additionally, a 15-inch-thick dry masonry covering for the upstream slope of the dam was only partly built. Less than one-fourth of the northeast embankment slope was covered this way in 1889 (see fig 3). The original design also called for an 18-inch-thick paving of dry masonry on top of the dam crest. It seems probable that this was not done as maintenance operations for the dam in 1856 included "gravelling of its surface." All these omissions reduced to some extent the overall integrity of the dam and its ability to withstand flood conditions. In particular, the lack of a heart wall was critical in subsequent events.[11]

Upon its completion, the 72-foot-high South Fork Dam was the largest earthen dam in the world, creating the largest artificial reservoir in the United States, and was widely considered an engineering marvel. Morris, in his original plans, estimated that the length of the embankment would be 850 feet, while a number of secondary sources, such as McCullough, Degen and Degen, and O'Connor, give a dam breast length of 931 feet. The first mention of this last number is in an *Engineering Record* article that probably included some of the natural topography (abutment) on either side of the dam embankment.[12] Frank, using survey data from Francis's ASCE paper, gives the length of the dam's embankment as 918 feet, but this also includes some of the abutment. Our GIS study using LiDAR data gives a length along the crest of the dam embankment (excluding abutments) of about 860 feet, which matches more closely Morris's original plan and clarifies the confusion as to the true length of the reconstructed dam structure.

During the 10-year period of service to the Pennsylvania Canal, the South Fork Dam experienced several problems. Workers discovered and immediately repaired two small leaks in 1854, although no information is known about the location or nature of these breaks.[13] Rapid snowmelt in March 1856 caused concern of a possible dam break, especially in light of a leak in the dam and elevated water level in the reservoir; however, the dam held.[14] In 1857 the entire Main Line Canal system, including the South Fork Dam, was sold to the Pennsylvania Railroad.[15]

During the time of Pennsylvania Railroad ownership the dam was not inspected or maintained on a regular basis. Weakening of the mortar joints in the culvert roof led to a partial collapse of the culvert arch on July 18, 1862, but no flooding ensued and the Pennsylvania Railroad seems to have ignored the problem. However, a significant breach occurred on July 26, 1862, when the upstream section of the stone culvert underwent further collapse and a 200-foot section of the dam washed out to a depth of approximately 50 feet.[16] At the time there was less than 50 feet of water behind the dam and water level in the river was low. The railroad watchman at the dam, observing muddy water flowing from the culvert, opened the sluice pipes. Little downstream flooding occurred because the breach formed gradually and the lake drained over a period of 11 hours, causing the nearly dry bed of the Little Conemaugh River to only rise between one and three feet. It should also be noted that had the heart wall been present the dam would probably not have washed out to that depth. By 1864 the Pennsylvania Railroad essentially abandoned the Western Division of the Pennsylvania Main Line Canal and left the South Fork dam site in complete neglect.[17] The wooden control tower burned down sometime between 1864 and 1875. In 1875 the Pennsylvania Railroad sold the land parcel encompassing the dam and former lake to John Reilly, a former congressman from Altoona, who recouped some of his investment through the salvage and sale of the remaining iron pipes and valves.[18]

Rebuilding the Dam

After the 1862 breach, the dam was left in disrepair until 1879, when Benjamin F. Ruff became involved with the nascent South Fork Hunting and Fishing Club (SFHFC) of Pittsburgh, which had been incorporated in May of that year and chartered in November. Ruff seems to have begun repairs to the dam in late 1879 even though the club did not have title to the land until March 1880. The SFHFC started with fifteen prominent members from Pittsburgh. Eventually membership grew to nearly seventy members and included, among others, Andrew Carnegie, Andrew W. Mellon, Henry C. Frick, Robert Pitcairn, Philander C. Knox, Marvin F. Scaife, Durbin Horne, and Benjamin Ruff (the promoter and first president of the club). F. J. Unger was the last president/manager of the SFHFC. The SFHFC commissioned repairs on the dam to re-establish the lake. The first stage of reconstruction involved filling the breach and culvert with any available material, including brush, tree stumps, hay, and manure; however, heavy rains in December 1879 washed away the repairs. When repairs resumed in 1880, hemlock pilings replaced debris as a means to close off the culvert remnants, with earth and rocks used to fill the void left by the breach (see fig. 3 above).[19] Later inspection by engineers concluded that the hemlock pilings were not only improperly emplaced but were also the incorrect material to accomplish proper closure.[20] This resulted in continuous leakage at the base of the dam.

Ruff stated that 22,000 cubic yards of fill were emplaced during the reconstruction, but it is doubtful that all this fill came from local borrow pits. Accounts stated that the fill included dirt, clay, shale, old bricks, and, once again, brush, hay, and straw. It is probable that at least part of the fill came from cheap and easily attainable coal- and clay-mining wastes. The Lower Kittanning coal crops out in the South Fork area and was extensively mined at this time.[21] A plastic clay is associated with the Lower Kittanning seam and this clay would have been in the waste rock from mining operations. One of the club members, Pitcairn, had a friendship with the superintendent of the Argyl coal company, which operated three mines in the Lower Kittanning.[22] The presence of coal waste in the dam is supported by observers who noticed "sulfur water" seeps from the dam breast.[23] Although Ruff tried to dismiss these as natural springs, there is no doubt that this was, in fact, lake water in contact with mine waste in the dam fill seeping through the dam breast. Natural springs would not flow from the abutments to the central portions of the dam, nor is there any evidence of such seeps from the embankment remains today.

The reference to old bricks relates to waste from fire brickyards near South Fork.[24] Along with the old bricks, this waste contained a certain amount of plastic clay, which was used to manufacture bricks. When wetted, plastic clay has very low shear strength and was probably a major factor in the resultant catastrophic failure.[25] In addition, brick as fill material results in incomplete compaction, especially when there was no attempt to fully compact the fill. An important omission in the repaired dam was the puddled clay in the core of the dam that had originally been used to reduce the permeability of the upstream section of the dam. The absence of low-permeability puddled clay material meant that water saturation could extend further through the core of the dam, making it susceptible to piping and liquefaction. Furthermore, the downstream face of the dam was compromised by the failure to replace the very large rip-rap that originally armored it. Instead, the downstream face of the repaired section was covered by undersized rock (see fig. 4).

Of even greater concern was the fact that, since the new fill in the reconstructed dam was not properly compacted, there was a sag in the central portion of the embankment so that the freeboard (the height to which water could rise without overtopping the dam) above the spillway floor was further reduced. Estimates vary as to the amount of sag, but as measured by Davis it was at least two feet relative to the ends of the embankment two weeks after the flood.[26] As a result, water overtopped the dam in the center, which is the worst possible case for an earthen dam.

Upon inspection of the dam in 1880, geologist and engineer John Fulton wrote, "It did not appear to me that this work was being done in a careful and substantial manner, or with the care demanded in a large structure of this kind." Another engineer, P. F. Brendlinger, also visited the site in 1880 and expressed similar concerns regarding the construction method, comparing it to the construction of a railroad embankment, and noting a series of leaks near the base of the dam.[27] Qualified engineers did not supervise any of the dam repairs.

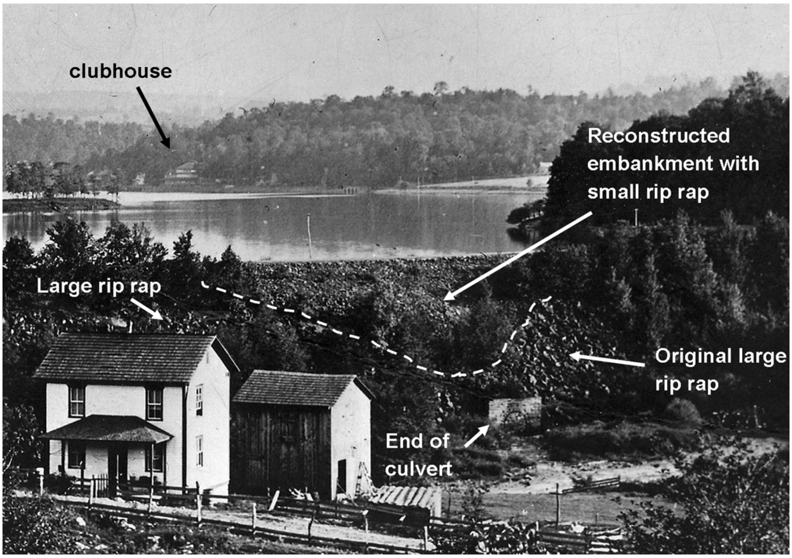

FIGURE 4: Pre-flood view looking upstream at the dam, as repaired by the SFHFC. Note the much smaller rip-rap of the repaired section. Figure courtesy of the Johnstown Area Heritage Association.

Additional modifications to the dam included building a bridge over the spillway and lowering the height of the dam crest by at least two feet, ostensibly to widen the carriage road, but we believe this was also a cheap expedient way to provide additional fill material for dam reconstruction. This lowering of the crest of the dam, in combination with the previously mentioned sag, then reduced the total original freeboard from 10 feet to an effective freeboard of less than 6 feet in the central portion of the dam. Investigations by Davis shortly after the flood found high-water marks in the spillway 6.7 feet above its base, which corroborates witness statements that the maximum overflow depth in the center was about a foot.[28] In addition, the lowering of the dam crest essentially negated the auxiliary spillway on the southwestern end. Therefore, the single spillway on the northeastern abutment of the dam now served as the sole discharge point for water in the lake and therefore the"normal" lake level was now at, or slightly above, the base of the spillway (a water depth of at least 62 feet). As a result, water was usually flowing through the spillway and the SFHFC found this satisfactory since club members could picnic by the small waterfall at the outlet of the spillway (see fig. 5).

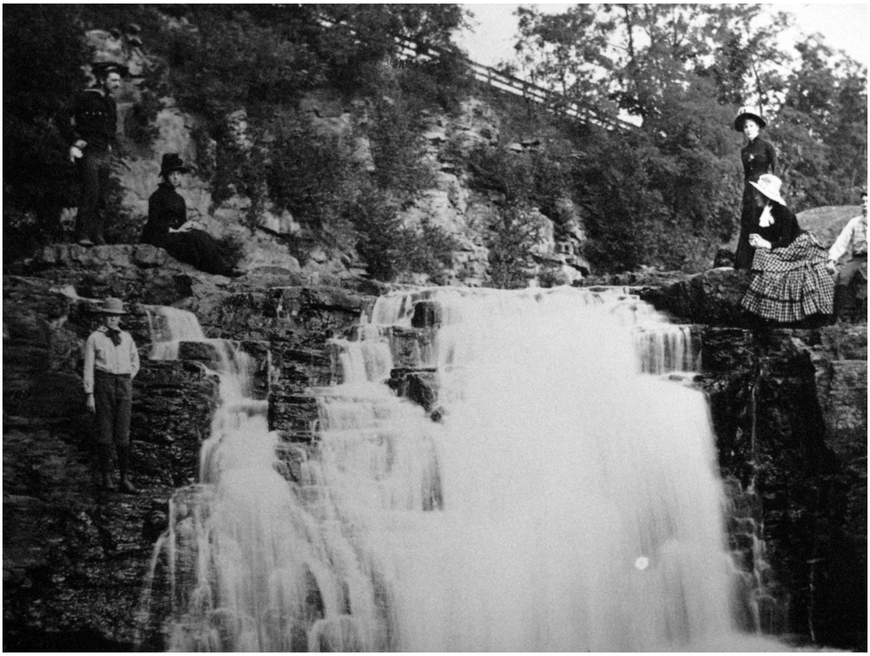

FIGURE 5: Small waterfall at outlet of main spillway on northeastern side of dam. This feature has not been preserved in its original form. Figure courtesy of the Johnstown Area Heritage Association.

Once the water level had risen sufficiently in the reservoir, the SFHFC stocked the lake with imported game fish. Fish screens on the spillway bridge supports prevented the downstream escape of stocked fish. The height of the initial screen was about two feet, including the sill at the base of the bridge, for the average water level in the spillway, which by marks on the screen seems to have been 9–12 inches above the base of the spillway.[29] However, club members soon realized that spillway water depth at times exceeded the height of the fish screens and therefore constructed a floating V-shaped log boom to extend into the lake from the bridge. This boom had three-quarter-inch wire mesh attached to 8-inch by 8-inch timbers to a height of 43 inches. As the timber was mostly submerged, iron spikes projected 4 inches from the top of the wood to keep the fish in the lake.[30] The total height of this device, including nails, was about 4.5 feet. There is no doubt that the fish screens and log boom, along with the associated trapped debris, increased the water level behind the dam by reducing the outflow at the entrance to the spillway.

Regional Rainfall and Runoff during Late May 1889

The rainfall event preceding the failure of the South Fork Dam is usually described as "torrential" and, ultimately, the cause of the failure. However, this simplistic statement requires further scrutiny. Investigation of the available records of this multiday rainfall event, although indicating sustained moderate to heavy precipitation, do not support a continuous torrential storm as is often assumed. On May 28, 1889, a large regional storm system developed over Kansas and Nebraska and proceeded eastward, and by the late afternoon to early evening of May 30 the storm had reached the Johnstown area, with the heaviest rainfall occurring during the night of May 30–31.[31]

Total rainfall amounts increased west to east across the Allegheny Mountains. At Indiana, Pennsylvania, the May 30 rainfall was 2 inches, while it was only 1 inch the next day and the bulk of that was probably during the early morning hours. Therefore, the weather to the west and northwest of Johnstown would have been clearing by the morning of May 31. By daylight on May 31, the rain had briefly ceased in the Johnstown area and a heavy mist was hanging over Lake Conemaugh.[32] It then rained intermittently in moderate amounts through the rest of the morning and into the afternoon. The recorded rainfall in Johnstown on May 31 was 2.4 inches by 11:00 a.m. Unfortunately, the station observer was lost in the flood and no further data was recorded. Most of this recorded precipitation fell during the night. The Pennsylvania State Weather Service estimated that the total rainfall for Johnstown on May 31 was about 3.0–3.5 inches. For the full 26-hour storm, Franklin Institute rainfall contour maps estimate the rainfall for the Johnstown area at 5–6 inches.[33]

Greater rainfall amounts were recorded along the Allegheny Front to the north and east of Johnstown. The South Fork drainage basin received slightly more rainfall than Johnstown itself (an average of 6–7 inches) during the storm.[34] At Blue Knob, outside of, and about 12 miles east of the center of the South Fork drainage basin, the U.S. Signal Service recorded 7.9 inches of rain.[35] Further east of the Allegheny Mountains, record flooding occurred in the Juniata River basin, although it was Johnstown that gained international attention for flooding as a result of the failure of the South Fork Dam.

L. Blodget, in his analysis of the Pennsylvania floods of May 31–June 1, 1889, does state that this was the "the greatest rainfall of the century in Pennsylvania," but weather data are not very complete for the nineteenth century, which makes this claim difficult to evaluate.[36] Regardless, 6–7 inches of rainfall on a watershed is a heavy rain, but one must remember that since the dam failed about 17 hours into the storm, the actual rainfall leading to the disaster was somewhat less. An even better perspective may be gained when considering the 12 inches of rain that the same watershed received in the 1977 flood, making that the "storm of the century," at least for the twentieth century.[37]

In terms of surface runoff, of even greater importance than the total rainfall is the rainfall intensity.[38] As already noted, the most intense rain fell during the night hours of May 30–31. This would have resulted in extreme surface runoff in the early morning hours within the South Fork drainage basin. But it is also important to realize that this extreme runoff would not have continued into the afternoon.

In addition to rainfall intensity, soil moisture conditions also play an important part in surface runoff amounts. With respect to the 1889 flood, it should also be noted that various accounts state that the Allegheny Mountain region received considerable precipitation during the weeks preceding the storm. There had been eight to nine days of precipitation in the two weeks prior to the flood in the areas to the north and south of Johnstown.[39] Therefore, the pore spaces in local soils were largely saturated and could not have accepted much more water through infiltration. The steep topography of the area would also increase total runoff from precipitation since there are relatively few low-lying or flat areas in which water can accumulate and slowly enter the soil through infiltration. This low-infiltration capacity due to saturated soil conditions, combined with the relatively steep topography and the storm intensity, was the primary factor in the high surface-runoff rates that occurred during the early morning hours of May 31, 1889.

Rising Water Levels

Based upon eyewitness accounts of observers along the North and South forks of the Little Conemaugh River, water levels ceased to rise between 12:00 p.m. and 1:00 p.m. on May 31, and may even have started to drop. The following information comes from the collection of statements taken by Special Agent Houghton of the Pennsylvania Railroad after the flood.

Flood stage in the headwaters of the North Fork of the Little Conemaugh began sometime before dawn, probably around 4:30 a.m., on May 31.[40] About 10:00 a.m., maximum flood stage was reached in the Lilly area, approximately 10 miles from the South Fork Dam.[41] Further downstream in Portage, Wilmore, and Summerhill, high stage was reached between late morning and noon and began to fall in the early afternoon.[42] There is one report of high stage on the North Fork around 9:00 a.m., but this was probably the result of several small mill dams being washed away and not part of the general rise in stage.[43] At the village of South Fork, the North Fork began to rise rapidly sometime before 9:00 a.m. and seems to have reached maximum flood stage between 12:00 p.m. and 1:00 p.m.[44] The river never rose above bank-full stage until the flood wave hit.[45] Shortly before the dam failed, the river water level was observed to be "on a stand still."[46]

Tributaries within the South Fork of the Little Conemaugh drainage basin (upstream of the reservoir) experienced high stage around 11:00 a.m.[47] In the town of South Fork, at the confluence of the North and South forks of the Little Conemaugh, water in the South Fork began to rise rapidly at about 10:00 a.m. and maximum stage was reached between "shortly before noon" to perhaps 1:00 p.m., before falling slightly after 1:00 p.m., but there was overbank flooding.[48] Therefore, for perhaps two hours prior to the failure of the dam, the runoff into the reservoir was about constant, or at times even decreasing somewhat. Downstream on the Little Conemaugh River at Conemaugh Borough (now East Conemaugh), the water level was also observed to rise until about noon and then came to a standstill, or perhaps fell slightly, in the early afternoon.[49] Although some track was washed out east of Bridge no. 6, in general, the river remained at about bank-full conditions in the early afternoon until the arrival of the flood wave, indicating that the runoff from the combined watersheds was also about constant during the early afternoon of May 31.[50]

Dam Failure

Much of the commonly cited information about conditions at the dam on May 31, 1889, are drawn from the account of John Parke, a recent engineering graduate of the University of Pennsylvania, employed to work on a drainage sewer project at the SFHC.[51] However, there were many other observers at the dam on May 31 whose reports on conditions have been preserved.[52] This has led to many apparent historical inconsistencies. It is natural, however, that catastrophic events are viewed and remembered differently by those witnessing the event. We have collected and organized a number of these recorded observations (see the appendix) that were made about water levels, overtopping conditions, failure times, and time to drain the lake. It should be noted that some statements may have been adjusted after the flood when observers compared their experiences or read written accounts of the flood.

At about 10:30 a.m., when the water level was about one foot below the central portion of the dam crest, Unger, overall manager of the club, had laborers attempt to cut a ditch through rock on the southwestern abutment of the dam to reduce the chance of the dam being overtopped. But according to Parke's testimony for the ASCE investigation, they initially only managed to cut a channel 14 inches deep and two feet wide. Other statements (including also Parke) say that the original channel or ditch was somewhat wider and deeper.[53] Frank suggested that the ditch was within the area of the intended auxiliary spillway from the original plans of Morris.[54] This is supported by the statement of Boyer, Superintendent of Lake and Grounds, that at about 11:00 a.m., when the water was perhaps 6–12 inches from the crest, water was already going over the southwest abutment. Parke also noted that water rushed into the cut channel and made it a "swift stream" about 25 feet wide; this water width is greater than any estimates for the width of the cut channel.[55] It is therefore important to note that the water started going over the southwest abutment prior to overtopping the embankment itself. This is prima facie evidence that the original southwest abutment had an auxiliary spillway, for no one would build a dam where the abutment was lower than the dam embankment itself unless it was intended to serve as a spillway.

Even with the additional outflow through the cut channel, water was flowing over the top of the dam in several places by 11:30 a.m. After a five-mile round-trip horseback ride to the village of South Fork, Parke noticed water eroding the outer face of the dam and cutting small gullies between the rip-rap on the downstream side. At about 12:30 the water level seems to have stabilized and Parke and the workers went to lunch. By the time Parke returned to the dam after his lunch, the water had washed away some of the rip-rap stones on the downstream face of the dam and a 10-foot (width) by 4-foot (depth) hole had been cut into the face.[56] According to Parke's testimony, the water

> went on widening and deepening this hole until it was worn so near to the body of the water in the lake that the pressure of the water broke through, and then the water rushed through this trough, and cut its way rapidly into the dam at each side and bottom; and this continued until the lake was drained.[57]

This statement is somewhat misleading because our investigation of the breach does not support the hypothesis that the dam was breached by being down-cut from the top, but rather that the upper portion of the breach was due to catastrophic failure of the embankment.

A catastrophic failure is supported by the eyewitness account of U. Ed Schwartzentruver, retold in an interview many years later.[58] According to Schwartzentruver, who at the time was on the spillway side of the dam, rocks three to four feet square (rip-rap) flew through the air and an air blast blew down trees ahead of the flood wave. The claim of blown-down trees is plausible because rock falls have been known to generate air blasts capable of knocking down trees, such as one that occurred at Yosemite National Park in 1996 and was responsible for breaking about 1,000 trees.[59] Schwartzentruver remembered that the central section of the dam, instead of being cut down from the top, suddenly gave way with "a terrible roar." This lends credence to the idea that the shear strength of the repaired section of the dam was severely compromised by the addition of plastic clay from mine wastes.

Time of the General Failure of the South Fork Dam

There has always been some disagreement regarding the timing of the general failure of the South Fork Dam and subsequent draining of Lake Conemaugh. Eyewitnesses, such as John Parke, stated that the failure occurred close to 3 p.m., while Unger, who oversaw efforts to save the dam, states that is was 2:45 p.m.[60] Eyewitness statements can be flawed, and even if observers noted the time on their watch at that exact moment, there was no simple way to calibrate timepieces at remote locations at that time. The situation is further muddied by later investigators and writers who do not clearly identify the basis for their stated time of failure: Shank believes that the failure occurred a few minutes after 3:00 p.m., McCullough and O'Connor give the time of failure as 3:10 p.m., while Degen and Degen state that it was 3:15 p.m.[61]

Only one timing source of the dam failure has real credibility: the clock at the Pennsylvania Railroad stationhouse at South Fork, about 1,000 feet up the North Fork of the Little Conemaugh River from the confluence of the North and South forks of the Little Conemaugh River.[62] C. P. Dougherty, the station agent, stated that the stationhouse was knocked off its foundation when the flood wave hit the town of South Fork and at that moment (3:08 p.m.) the clock stopped because it was thrown out of plumb.[63] The South Fork station was a passenger station and care would have been taken to ensure that the clock showed the correct time. Dougherty's statement is supported by that of Emma Ehrenfeld, who was the telegraph operator at South Fork. She stated that the flood wave hit South Fork a few minutes after 3:00 p.m.[64] Telegraph lines and stations typically paralleled the railroads and enabled central calibration of clocks to maintain reasonably accurate train schedules. Since the station clock stopped at 3:08 p.m., the question becomes: "How long did it take the flood wave to travel the distance from the dam to the South Fork station?"

Dougherty also stated that the flood wave seemed to be traveling at about 15 miles per hour. At that rate, the wave would have taken about nine minutes to travel the 2.3 miles from the dam site, meaning that the dam broke at 2:59 p.m. In this study, using an estimated maximum discharge from the dam of 318,000 cubic feet per second and converting to a velocity of 13.6 miles per hour, the travel time comes out to be about 10 minutes.[65] But this only considers the maximum discharge and maximum velocity that occurred at the dam site at the time of failure; average discharge and velocity would be less. The velocity would have been reduced by friction against the streambed, substantial bends in the river, and the resistance encountered when the initial flood wave ran 50 feet up the hillside just below the dam, evidence of which was noted by Davis.[66] While we do not know the exact average velocity of the flood wave as it traveled down the South Fork, Dougherty's estimate seems to be a bit on the high side. Using a more conservative average velocity of 10 miles per hour would put the time of dam failure between 2:53 and 2:54 p.m. We believe this is a best estimate for the time of the main dam breach.

Time to Drain the Lake

Our ongoing research has also attempted to resolve the question of how long it took the lake to drain. When asked that question, Parke stated, "I do not know the actual time . . . but it was fully forty-five minutes."[67] Many modern compilations of dam breaches cite the 45-minute drain time as factual, but do not accurately report it as a minimum estimate by Parke. Boyer claimed it was one hour ten minutes, Sherman said the lake emptied in about one hour fifteen minutes, while Unger thought the lake emptied in less than an hour. Our preliminary hydraulic calculations indicate the lake took at least an hour to drain, which is more in line with the statements made by Boyer and Showers. Just as with the timing of the dam failure, most of these eyewitnesses were likely not referencing an accurate timepiece at the exact time of failure and the end of draining.

In his statement to the ASCE, Parke stated that after the lake had drained, "there still remained in the bed of it a violent mountain stream four or five feet deep, with a swift current. . . . This stream in the bed of the lake showed no signs of diminishing in volume until late in the following day, and was impassable with a boat for several days."[68] This shows that even after the lake was "drained," there remained a considerable amount of water in the lakebed. Our calculations for time to drain the lake did not take the lake volume to zero; rather it allows for approximately five feet of water remaining.

Travel Time and Velocity of the Flood Wave to Johnstown

Using the previously determined time of failure (2:50–2:55 p.m.) the total travel time of the flood wave can be calculated. Downstream times of flood-wave arrival remain unchanged: 3:40 p.m. at the AO tower near Bridge no. 6 and 3:50 p.m. at East Conemaugh. About 4:07–4:10 p.m. the flood wave hit downtown Johnstown.[69] This means that the flood wave took longer (a total of 75–80 minutes) to travel the distance between Lake Conemaugh and Johnstown than commonly reported. Temporary impoundments by debris dams behind the railroad viaduct upstream of Mineral Point and, to a lesser extent, Bridge no. 6 (between East Conemaugh and Mineral Point) increased the travel time of the floodwaters. However, there is no information as to how long these impoundments held back the flood wave. Ignoring these impoundments, we estimate that the maximum average flood-wave velocity was approximately 12 miles per hour, which approximates the speed of the famous train that, with whistle blowing, raced ahead of the flood wave, at 10–12 miles per hour, to warn Conemaugh.[70] Note that the Little Conemaugh River meander bend near Bridge no. 6 no longer exists—it has been filled in with steel-mill slag (see fig. 1 above) and therefore is not shown as a riverbed on modern maps. Our calculations of flood travel time have included travel through that meander bend. A recent published simulation of the flood did not include this part of the travel path and assumed that most flow bypassed the meander and traveled through the railroad cut.[71] However, the cut represented a considerable bottleneck that forced a significant fraction of the flow around the meander bend, and indeed water did back up in the meander bend, almost to the height of the rails on the bridge, before it was washed away.[72]

Conclusions

This re-evaluation of issues related to the Johnstown Flood of 1889 clarifies some common misconceptions about the events surrounding the flood. Of significance is the actual timing of the dam failure, 2:50–2:55 p.m.—a full 15 minutes prior to the commonly cited time of 3:10 p.m. This investigation also concluded that the actual length of the dam's embankment is about 860 feet, and at normal level (spillway lip) the lake covered 374 acres. The volume of water behind the dam prior to failure was 495 million cubic feet (or about 15.5 million tons), and that it took at least an hour for Lake Conemaugh to substantially drain. All of these determinations differ to some extent from commonly available sources.

Rainfall and stream conditions at the dam and immediately downstream have also been clarified in this article. The late May storm of 1889 produced between 6 and 7 inches of rain in the South Fork watershed for the duration of the storm (26 hours), but the total rainfall leading to the dam failure would have been somewhat less since the dam failed about 17 hours into the storm. In spite of the high runoff rates upstream of Johnstown, the Little Conemaugh River drainage had minimal overbank flooding and it was for the most part at bank-full conditions. Although rain did fall in the South Fork watershed most of May 31, maximum runoff into the lake occurred in the early to mid-morning on that day. Therefore, we find that at the time of failure, runoff from the watershed was not increasing, as is often assumed. Instead it remained relatively constant for at least the two hours preceding the failure, and the water level in Lake Conemaugh also remained about level (and perhaps even dropped somewhat) in the hours before the dam failed. This is supported by the fact that Parke and the laborers stopped for lunch between noon and 1 p.m. since it is hard to imagine them doing this if the water level was rising higher and higher. That the depth of the water overflowing the dam was relatively low is also corroborated by Schwartzentruver's account of his friend crossing the breast on foot just before failure.[73] Such a feat would have been extremely difficult if the water had even been one foot deep. This statement also invalidates the concept that the dam was being cut down from the top.

Modifications to the original design specifications for the South Fork Dam and inadequate repairs after an earlier failure contributed to the catastrophic failure of the dam in 1889. Deviations from the original design that were minor contributing factors include the failure to completely armor the upstream side and crest of the dam with fitted stone. A major factor was the omission of the rubble masonry wall, or heart wall, in the core of the embankment, and to instead rely entirely on puddled clay.

The club's repairs of 1879–81 did not even try to meet the original design specifications and the rebuilding was accomplished in a shoddy and unprofessional manner. In the repaired dam the previous break was filled with substandard material and no puddled clay was emplaced. Nor was there any attempt to replace the sluice pipes or rebuild the control tower, which would have enabled the water level to be controlled. Rip-rap on the repaired section of the downstream face of the dam was of insufficient size. In addition, improper closure of the remnant of the stone arch culvert resulted in continuous leakage at the dam base. At the time of the failure, only one effective spillway remained, as the auxiliary spillway on the western abutment had been rendered useless by lowering of the dam crest two feet, and the remaining spillway was partly obstructed by a sizable fish screen. Not only had the dam crest been lowered, but insufficient compaction of materials used in the repair of the central portion of the dam caused, at minimum, an additional two-foot sag in the center of the dam. The structural integrity of the dam was further compromised by including plastic clay from local mines which reduced the shear strength of the repaired section of the dam, leading to the catastrophic failure of the upper part of the breach. It is hard to imagine what else the SFHFC could have done to invite the forthcoming disaster.

The common excuse given for the club is that the existing spillway was underdesigned. This is based on the Francis report, which states, "the failure was due to the flow of water over the top of the earthen embankment caused by the insufficiency of the waste-way [spillway] to discharge the flood water."[74] It is hard to fathom how the original existence of the auxiliary spillway could have been missed since it clearly shows up in the surveying data contained in the report. By not taking into account the auxiliary spillway, and also by incorrectly assuming that the runoff into Lake Conemaugh continued to increase up to the time of failure, the Francis report erroneously concluded that the original spillway design was inadequate and that failure was inevitable. Unfortunately, the existence of the former auxiliary spillway is not obvious today because that area of the southwestern abutment has been turned into a parking lot.

The SFHFC always kept its internal affairs secret and even today no club documents have ever been found. Therefore it is impossible to review the exact actions or inactions that were authorized by the club. Nevertheless, in the light of modern analysis, it is quite clear that the club had overwhelming culpability for the tragedy. Yet, at the time, neither the club nor its members were ever assessed any legal liability for this disaster. The members simply abandoned their properties and never returned to Lake Conemaugh.

APPENDIX. Conditions at the South Fork Dam on May 30–31, 1889

Time	Conditions	Eyewitness	Comments
May 30—evening	Water was about 7 feet from top of dam.	Parke,[a] Boyer[b]	
May 31—6 a.m.	Water was 4–5 feet from top of dam.	Unger[b]	
6:30 a.m.	Water rose 2 feet overnight and was about 5 feet from top.	Parke[c]	
"During breakfast" (6:30–7:30 a.m.)	Water rose 4–5 inches on stakes at Clubhouse.	Parke[c]	
8 a.m.	Water was about 4 feet from top of dam.	Boyer[b]	
8:30 a.m.	Water was about 4 feet from top of dam.	Bidwell[b]	
~ 10 a.m.	Water was about 1 foot from top of dam. Workers began to throw up furrow (temporary embankment) on dam crest with a plow.	Boyer[b]	
10–11 a.m.	Water rose 9 inches per hour.	Parke[c]	
~ 10:30 a.m.	Unger ordered workers to dig ditch. Cut was "about fourteen inches deep and about two feet wide."	Showers[b], Parke[c]	The cut, or ditch, was on the west abutment; or as Parke puts it, on "the original ground." In other words, the ditch was beyond the end of the dam itself, in the area of the probable auxiliary spillway. This shallow depth (14 inches) must refer to the soil depth, not the total depth of the ditch.

(*Continued*)

APPENDIX. Conditions at the South Fork Dam on May 30–31, 1889 (*continued*)

Time	Conditions	Eyewitness	Comments
	"cut through about four feet of shale rock."	Parke[a]	Parke was quoted by Johnson as saying that the ditch was much deeper (4 feet). The final depth of the cut, as measured by the ASCE investigators after the flood, was between 3 and 4 feet deep.
~ 10:30–11:00 a.m.	Water started to run over west end (abutment) of dam.	Boyer[b]	At this time the water level was above 1,610 feet relative to the ASCE survey (uncorrected to modern elevations) and was running over the west abutment but not over the crest of the dam.
	Width of water was 6–8 feet.	Unger[b]	
~ 11 a.m.	Water was within 6–12 inches of crest of dam.	Boyer[b]	
	Water level at head of lake "lowered somewhat."	Webber[a]	
~ 11:30 a.m.	Water began running over the dam.	Bidwell[b]	
	Water went over the dam in numerous places for a "distance of 300 feet."	Parke[c]	Water was breaking through the temporary embankment that had been thrown up by a plow.
	Stream in ditch "fully twenty feet wide and three feet deep."	Parke[a]	
~ 12:15 p.m.	Water in ditch "about twenty inches deep" and "twenty-five feet wide." Water depth on dam about 6 inches.	Parke[c]	Parke rode a horse over the dam.

Time	Conditions	Eyewitness	Comments
~ 12:30 p.m.	"Water at the time was almost at a stand."	Parke[c]	Parke went to dinner at this time. He must have believed that the danger had passed.
~ 12:45 p.m.	Water was about 2 feet from top of new central embankment.	Showers[b]	Workers broke for dinner. Since the plowed-up temporary embankment was only about 2 feet high in the center of the dam, this means that the water level must have dropped noticeably and would explain why the workers were released to go to dinner.
~ 12:45–1:00 p.m.	Central water sheet over dam was 50–60 feet wide.	Siebert[b]	No one was at work on the dam. The width of water going over the dam was now only about 60 feet, further confirming that water level behind the dam had dropped.
~ 1 p.m.	Water was running over dam, but no channel cut into crest.	Boyer[b]	
	Water depth on dam "about three inches"	Parke[a]	Parke walked across dam. According to Parke's previous statements the water depth over the dam seemed to have dropped about 3 inches since noon.
~ 1:15 p.m.	Spillway and ditch were full.	Unger[b]	
~ 2 p.m.	Water was running "over" new 2-foot embankment, but only in the center.	Showers[b]	Workers returned from dinner. It is more likely that instead of "running over" the temporary embankment, the water had cut through.

(*Continued*)

APPENDIX. Conditions at the South Fork Dam on May 30–31, 1889 (*continued*)

Time	Conditions	Eyewitness	Comments
~ 2 p.m.	Water was running over crest and came out of a hole in the breast of the dam about 12 feet down from crest.	Wilson[b]	
~ 2 p.m.	Water had cut a notch 10 feet wide and 4 feet deep on outer face of dam.	Parke[c]	Parke returned to dam from dinner.
~ 2:15 p.m.	Notch cut in center of dam.	Baker[d]	The cut mentioned here probably refers to erosion on the dam's downstream face, not across the crest.
2:30–2:40 p.m.	Dam broke.	Boyer[b]	Timing is probably not correct.
2:45 p.m.	"Stones in center of dam sink because of undermining, within eight minutes a twenty foot gap in lower half of dam face."	Webber[a]	
~ 2:45 p.m.	Dam broke.	Unger,[b] Showers,[b] Schwartzentruver[e]	
2:45–2:50 p.m.	Dam broke.	Dougherty[b]	
~ 2:50 p.m.	Water was over the top of the dam by about 1 foot and dam broke "a few minutes later."	Rev. Brown[f]	
2:50–2:55 p.m.	Dam broke.		Based upon calculation of travel time from dam to South Fork Railroad station.
"Nearly 3 p.m."	Dam broke.	Parke[c]	
	"Big break took place at just three o'clock."	Parke[a]	

Time	Conditions	Eyewitness	Comments
3:10 p.m.	Dam broke.	McCullough[d]	Although no source is given for the stated time, this is the most often quoted time for dam failure.
3:15 p.m.	Dam broke.	Degen and Degen[g]	Probably from a quote attributed to Unger in a Pittsburgh *Press* article.

[a]W. F. Johnson, *History of the Johnstown Flood* (Philadelphia: Edgewood Publishing, 1889).

[b]National Park Service, "Stories," U.S. Department of the Interior, http://www.nps.gov/jofl/historyculture/stories.htm.

[c]James B. Francis et al., "Report of the Committee on the Cause of the Failure of the South Fork Dam," *Transactions of the American Society of Civil Engineers* 24 (1891): 431–69.

[d]David McCullough, *The Johnstown Flood* (New York: Simon and Schuster, 1968).

[e]T. H. Russell, "All at Once, the Dam was Gone!," *Johnstown Tribune-Democrat*, May 29, 1964.

[f] David J. Beale, *Through the Johnstown Flood by a Survivor* (Philadelphia: Hubbard Bros., 1890; reprint, Fort Washington, PA: Eastern National, 2009).

[g]Paula Degen and Carl Degen, *The Johnstown Flood of 1889* (Durham, NC: Eastern Acorn Press, 1984).

NOTES

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1. Most of the victims of the 1900 Galveston hurricane were white. Scarcely remembered are two hurricanes that struck southern U.S. coasts in 1893, causing an estimated death toll of 3,000–4,000, and possibly many more. Most of these victims were African American workers of low income, and a detailed accounting of those who perished is lacking. See Ted Steinberg's *Acts of God: The Unnatural History of Natural Disaster in America* (New York: Oxford University Press, 2006), where he points out that "race has had a filtering effect on the collective memory of disaster" (70).
2. William E. Morris, "Report of William E. Morris, Engineer," *Pennsylvania House Journal*, appendix to vol. 2 (1840): 45–56, 401–5; Harlan D. Unrau, "Historic Structure Report: The South Fork Dam Historical Data, Johnstown Flood National Memorial, Pennsylvania," package no. 124, U.S. Department of the Interior, National Park Service (1980). The Unrau is an extremely comprehensive and well-documented report.

3. James B. Francis et al., "Report of the Committee on the Cause of the Failure of the South Fork Dam," *Transactions of the American Society of Civil Engineers* 24 (1891): 431–69. Francis and Worthen had also previously served on an ASCE committee investigating the Mill River flood. See Elizabeth Sharpe, *In the Shadow of the Dam: The Aftermath of the Mill River Flood of 1874* (New York: Free Press, 2004).
4. Unrau, "Historic Structure Report"; David J. Beale, *Through the Johnstown Flood by a Survivor* (Philadelphia: Hubbard Bros., 1890; reprint, Fort Washington, PA: Eastern National, 2009). Beale's is one of the better early narratives of the flood. Unrau, "Historic Structure Report"; Nathan D. Shappee, "A History of Johnstown and the Great Flood of 1889: A Study of Disaster and Rehabilitation" (Ph.D. diss., University of Pittsburgh, 1940).
5. Francis et al., "Report of the Committee."
6. Paul Longley, Michael F. Goodchild, David Maguire, and David Rhind, *Geographic Information Systems and Science*, 3rd ed. (New York: John Wiley and Sons, 2011).
7. Francis et al., "Report of the Committee."
8. K. Penrod, A. Ellsworth, and J. Farrell, "Application of GIS to Estimate the Volume of the Great Johnstown Flood," *Park Science* 24, no. 1 (2006): 7.
9. Francis et al., "Report of the Committee." See also Walter Smoter Frank, "The Cause of the Johnstown Flood: A New Look at the Historic Johnstown Flood of 1889," http://smoter.com/flooddam/johnstow.htm. Frank was the first to suggest that an auxiliary spillway was part of the original construction.
10. Unrau, "Historic Structure Report"; Francis et al., "Report of the Committee."
11. Francis et al., "Report of the Committee"; Unrau, "Historic Structure Report," 51.
12. Morris, "Report of William E. Morris"; David McCullough, *The Johnstown Flood* (New York: Simon and Schuster, 1968); Paula Degen and Carl Degen, *The Johnstown Flood of 1889* (Durham, NC: Eastern Acorn Press, 1984); Richard O'Connor, *Johnstown, the Day the Dam Broke* (Philadelphia: J. B. Lippincott, 1957); *Engineering Record* 20 (1889): 211. McCullough's account is the best of the popular histories of the flood.
13. Francis et al., "Report of the Committee."
14. Unrau, "Historic Structure Report."
15. John Bach McMaster, "The Johnstown Flood, I," *Pennsylvania Magazine of History and Biography* 62 (1933): 209–43.
16. Shappee, "A History of Johnstown and the Great Flood of 1889."
17. Unrau, "Historic Structure Report"; N. B. Henry (Pennsylvania Railroad engineer), interview by John H. Hampton, July 1889, Pennsylvania Railroad, Pittsburgh, PA, http://www.nps.gov/jofl/historyculture/henry.htm; John A. Harper, "The History and Geology of the Allegheny Portage Railroad, Blair and Cambria Counties, Pennsylvania," in *From the Shield to the Sun: Geological Field Trips from the 2011 Joint Meeting of the Geological Society of America Northeastern and North-Central Sections, Field Guide* 20 (Boulder, CO: Geological Society of America, 2011), 111–41.
18. Robert Pitcairn (superintendent of the Western Division of the Pennsylvania Railroad), interview by John H. Hampton, July 1889, Pennsylvania Railroad, Pittsburgh, PA, http://www.nps.gov/jofl/historyculture/pitcairn.htm (hereafter Pitcairn interview).
19. Unrau, "Historic Structure Report"; Frank, "The Cause of the Johnstown Flood."

20. A. M. Wellington and F. B. Burt, "The South Fork Dam and Johnstown Disaster," *Engineering News and Railway Journal* 21 (1889): 540–45.
21. W. C. Phalen, "Johnstown Folio, Pennsylvania," in *Geologic Atlas of the United States Folio 174, Field Edition* (Washington, DC: U.S. Geological Survey, 1911).
22. Pitcairn interview.
23. Fred Ehrenfeld (track laborer), interview by John H. Hampton, July 1889, Pennsylvania Railroad, Pittsburgh, Pennsylvania, http://www.nps.gov/jofl/historyculture/emma.htm.
24. H. Leighton, "Clay and Shale Resources of Pennsylvania," Pennsylvania Topographic and Geologic Survey Bulletin M23 (1941).
25. A similar situation (using mine waste) seems to have occurred in the Buffalo Creek disaster. See Kai Erikson, Everything in Its Path: Destruction of Community in the Buffalo Creek Flood (New York: Simon and Schuster, 1976), 25–28.
26. C. Davis, "The South Fork Dam," Proceedings of Engineers' Society of Western Pennsylvania (1889): 89–99.
27. Unrau, "Historic Structure Report," 68. See also William R. Brice, "John Fulton, Surveyor, Geologist, and Friend of the Second Pennsylvania Geological Survey," *Southeastern Geology* 38 (1999): 203–14.
28. Davis, "The South Fork Dam."
29. Wellington and Burt, "The South Fork Dam and Johnstown Disaster."
30. McMaster, "The Johnstown Flood."
31. L. Blodget, "The Floods in Pennsylvania, May 31 and June 1," in *Annual Report of the Secretary of Internal Affairs of the Commonwealth of Pennsylvania*, pt. 1 (Harrisburg: Commonwealth of Pennsylvania, 1890), A143–A149. From May 30 to June 1, this regional storm caused flooding throughout northern Virginia, Maryland, a large portion of Pennsylvania, and the southern tier of upstate New York.
32. Francis et al., "Report of the Committee."
33. T. F. Townsend, "Monthly Weather Review for May, 1889," in *Annual Report of the Secretary of Internal Affairs of the Commonwealth of Pennsylvania*, pt. 1, A76–A85.
34. Blodget, "Floods in Pennsylvania." Forty-five miles to the north, near Anderson Creek in Clearfield County, 8.6 inches of rain were recorded over a thirty-two-hour period for May 30–31.
35. Francis et al., "Report of the Committee."
36. Blodget, "Floods in Pennsylvania," A143.
37. Uldis Kaktins and Harold C. Fry, "The Floods of Johnstown," in *Geology of the Laurel Highlands of Southwestern Pennsylvania, 54th Annual Field Conference of Pennsylvania Geologists* (Harrisburg: Field Conference of Pennsylvania Geologists, 1989), 139–49.
38. Townsend, "Monthly Weather Review for May." For example, in the Anderson Creek area (Clearfield Co.), six inches of rain fell in seven hours.
39. Ibid.
40. Mary Edwards of Lilly, statement obtained by Special Agent John H. Hampton of the Pennsylvania Railroad, 1889, http://www.nps.gov/archive/jofl/morestat.htm.
41. Charles Studt (division foreman), interview by John H. Hampton, Pennsylvania Railroad, Pittsburgh, July 1889, http://www.nps.gov/jofl/historyculture/studt.htm.

42. Jacob S. Keel, J. G. Piper, and Daniel Sipe, interviews by David J. Beale, 1889, http://www.nps.gov/jofl/historyculture/collections.htm.
43. Wallace Sherbine and H. W. Plotner, interviews by David J. Beale, 1889, http://www.nps.gov/jofl/historyculture/collections.htm.
44. Interviews of Pennsylvania Railroad workers by John H. Hampton, Pennsylvania Railroad, Pittsburgh, July 1889: John Hoy (engineman), http://www.nps.gov/jofl/historyculture/hoy.htm; George E. Vance (conductor), http://www.nps.gov/jofl/historyculture/vance.htm; S. H. Allshouse (flagman), http://www.nps.gov/jofl/historyculture/allshouse.htm. J. C. Luke, interview by David J. Beale, 1889, http://www.nps.gov/jofl/historyculture/collections.htm (hereafter Luke interview).
45. Interviews of Pennsylvania Railroad workers by John H. Hampton, Pennsylvania Railroad, Pittsburgh, July 1889: J. S. Gettemy (engineer), http://www.nps.gov/jofl/historyculture/gettemy.htm; Fred Brantlinger (freight conductor), http://www.nps.gov/jofl/historyculture/brantlinger.htm.
46. Joseph Reynolds, interview by David J. Beale, 1889, http://www.nps.gov/jofl/historyculture/collections.htm.
47. C. P. Dougherty (agent in South Fork), interviewed by John H. Hampton, Pittsburgh, July 1889, http://www.nps.gov/jofl/historyculture/dougherty.htm (hereafter Dougherty interview).
48. Luke interview. Interviews of Pennsylvania Railroad workers by John H. Hampton, Pittsburgh, July 1889: A. H. Butler (engineer), http://www.nps.gov/jofl/historyculture/butler.htm; A. H. Lytle (division foreman), http://www.nps.gov/jofl/historyculture/lytle.htm; Jerry Stormer (conductor), http://www.nps.gov/jofl/historyculture/jerry-stormer.htm; J. C. Walkinshaw (East Conemaugh yard master), http://www.nps.gov/jofl/historyculture/walkinshaw.htm; D. H. Hare (flagman), http://www.nps.gov/jofl/historyculture/hare.htm (hereafter Hare interview).
49. Interviews of Pennsylvania Railroad workers by John H. Hampton, Pittsburgh, July 1889: Samuel S. Miller (brakeman), http://www.nps.gov/jofl/historyculture/smiller.htm; William Adams (engineer), http://www.nps.gov/jofl/historyculture/william-adams.htm; S. E. Bell (conductor), http://www.nps.gov/jofl/historyculture/bell.htm; P. N. Pickerell (tower worker), http://www.nps.gov/jofl/historyculture/pickerell.htm.
50. Interviews of Pennsylvania Railroad workers by John H. Hampton, Pittsburgh, July 1889: P. Doran (engineer), http://www.nps.gov/jofl/historyculture/doran.htm; M. Trump (assistant superintendent of the Pittsburgh Division), http://www.nps.gov/jofl/historyculture/trump.htm (hereafter Trump interview); Levi P. Easton (conductor), http://www.nps.gov/jofl/historyculture/easton.htm; J. G. Miller (brakeman), http://www.nps.gov/jofl/historyculture/jgmiller.htm; Isaac Miller (fireman), http://www.nps.gov/jofl/historyculture/imiller.htm; C. A. Warthen (conductor), http://www.nps.gov/jofl/historyculture/warthen.htm.
51. Francis et al., "Report of the Committee."
52. National Park Service, "Stories," U.S. Department of the Interior, http://www.nps.gov/jofl/historyculture/stories.htm.
53. W. F. Johnson, *History of the Johnstown Flood* (Philadelphia: Edgewood Publishing, 1889). This was one of the earliest narratives, full of purple prose and pushing the outer limits of literary license, that was rushed to press before the end of 1889.
54. Frank, "The Cause of the Johnstown Flood."

55. W. Y. Boyer, "Statement of W. Y. Boyer," http://www.nps.gov/archive/jofl/boyer.htm; Francis et al., "Report of the Committee," 449.
56. Beale, *Through the Johnstown Flood.*
57. Francis et al., "Report of the Committee," 451.
58. T. H. Russell, "All at Once, the Dam was Gone!," Johnstown (Pennsylvania) *Tribune-Democrat*, May 29, 1964.
59. Gerald F. Wieczorek et al., "The Unusual Air Blast and Dense Sandy Cloud Triggered by the July 10, 1996, Rock Fall at Happy Isles, Yosemite National Park, California," *Geological Society of America Bulletin* 112 (2000): 75–85.
60. Although Unger is usually given the title of "Colonel," we have found no evidence that he ever served in the military at that rank.
61. William H. Shank, *Great Floods of Pennsylvania* (York, PA: American Canal and Transportation Center, 1972); McCullough, *The Johnstown Flood*; O'Connor, *Johnstown the Day the Dam Broke*; Degen and Degen, *The Johnstown Flood of 1889.*
62. Trump interview.
63. Dougherty interview.
64. Emma Ehrenfeld (South Fork telegraph operator), interview by John H. Hampton, July 1889, Pennsylvania Railroad, Pittsburgh, http://www.nps.gov/jofl/historyculture/emma.htm.
65. Carrie Davis Todd, et al., "A Determination of Peak Discharge Rate and Water Volume from the 1889 Johnstown Flood," *Geological Society of America Abstracts with Programs* 41 (2009): 216.
66. Davis, "The South Fork Dam."
67. Francis et al., "Report of the Committee," 451
68. Ibid.
69. Interviews of Pennsylvania Railroad workers by John H. Hampton, Pittsburgh, July 1889: Charles V. Haak (Conemaugh telegraph operator, http://www.nps.gov/jofl/historyculture/haak.htm; Hare interview; W. M. Hayes (division supervisor), http://www.nps.gov/jofl/historyculture/hayes.htm; Miller interview; J. B. Plummer (fireman), http://www.nps.gov/jofl/historyculture/plummer.htm (hereafter Plummer interview); Victor Wierman (assistant engineer), http://www.nps.gov/jofl/historyculture/wierman.htm (hereafter Wierman interview).
70. Plummer interview.
71. S. N. Ward, "The 1889 Johnstown, Pennsylvania Flood--A Physics-Based Simulation," in *The Tsunami Threat: Research and Technology*, ed. Nils-Axel Mörner (New York: InTech, 2011), 447–66.
72. Wierman interview.
73. Russell, "All at Once, the Dam Was Gone!"
74. Francis et al., "Report of the Committee," 454.