# How to dig a canal

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## *Preface*

In my neighborhood there is a canal dug in 1830–34, the Delaware and Raritan Canal. Originally from New Brunswick, NJ, to Bordentown, NJ, (the main canal), it provided cheap transport for the coal from Pennsylvania across New Jersey to New York City. It is still fully watered, although not for transportation; it is a water company and a state park. To fill its summit there is a feeder canal from Raven Rock, NJ to Trenton, NJ. That, too, is fully watered, and is part of the state park.

Two portions of the main canal are gone. Of the original 44 miles, 33 remain. The feeder canal is still complete except about 100 yards at its Trenton end. At one time the feeder canal had a T intersection into the main canal near downtown Trenton. Today the feeder flows alongside Feeder Street through a quite nice little park, makes a sharp turn, and disappears into an underground culvert. It still connects to the main canal, but that connection is underground. The main canal reappears about a mile or so downstream.

The park consists of a hiking trail almost the full length of the watered sections of both the main and the feeder canal. It is a truly serene place to visit.

I have both biked and hiked the main canal's full length, and portions of the feeder canal, not in one trip, but in several short trips. I am a retired engineer, so naturally my eye drifted towards construction details. The locks are the most noticeable; there are five still in existence on the main canal, and two and parts of a third on the feeder. But with subsequent visits the eye notices smaller or more hidden items: culverts, water bypass sluices and valves, viaducts, purge valves, overflow areas in the berm, and more. There is lots of detail of interest to an engineer.

I have also read books and magazine articles and brochures on this and other 18th and 19th century canals. (See the bibliography at the end.) Generally I am looking for the surveying and construction techniques. Most readings on this subject emphasize canal politics, economics, and sociology. There is some engineering, notably in "Erie Waters West", but it only whets my appetite for more.

What I would love to find, but have not, is an engineering manual describing these features, with correct terminology, and with other engineering data: surveying and marking, and construction techniques, etc. Just how do you dig a canal, what was the technology almost 200 years ago? What was the technical language used?

The goal of canals have always been economic. Given natural water deep enough for cargo boats, no canals are needed. Canals supplement natural water. As such, they typically connect two natural waters: rivers, bays, lakes, ocean. They were designed to carry bulk cargo like coal, gravel, lime, and lumber. Even a small canal boat of 200 years ago could carry 20 or 30 tons of cargo, and the larger ones 100 years ago could carry 80 or 100. Compared to the alternative, horse drawn wagons which could carry two or three tons, this was significant enough to justify the investment for canal construction.

Canals are rather elaborate designs. They must be planned. The plans must be communicated to the builders, typically contractors. And the resulting construction must be tested. Engineering supervision is needed for all these steps. My emphasis in this paper will be the engineering details I have observed on this particular canal, plus a few others I have visited more briefly.

A word about terminology. Any technology generates a language used by its practitioners. And so it was with these 19th century engineers. Some engineering terms are used in the literature I have read: berm, lock, gate, sluice, and purge and other kinds of valves to give a brief sample. But I have found myself inventing my own terminology to describe certain things for which there is no word in the literature I have studied. For example, I refer to directions as "down canal" and "up canal," and their orthogonal directions as "high side" and "low side." "Orthogonal slope" is my term for the slope of the ground across the canal from the high side to the low side. I need words for these concepts.

My invented terminology is almost certainly not authentic. I would guess the 18th century engineer had terminology for these concepts. Someday I hope to know their choice of words. So in a sense this paper exposes my ignorance. In fact a whole section entitled "Thought Experiments" exposes it further. In a way that is the purpose of this paper. By exposing my ignorance I invite others to enter the fray, teach me what they know, and even perhaps expose their own ignorance a bit. For ignorance is really just open questions, and these lead to answers, and further knowledge.

At the end of the paper is a bibliography of my readings, with a brief review of what the book or article has of engineering interest.

### *Acknowledgment*

Thanks to Joe McGinity for helping me research the feeder canal, which is in his neighborhood. And to Bruce Puerling for an editorial pass over the text.

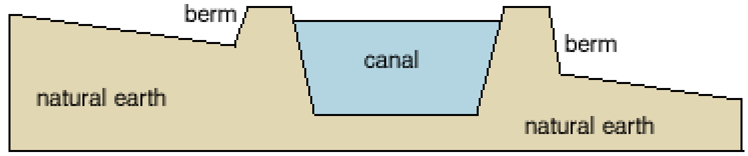
## Overview of a canal's elements

### *Profile*

A canal was designed for a specific size boat, and that size was published. The size was usually four dimensions: length, draft, breadth and height above waterline. The first three dimensions made sure the boat would fit into the locks. The latter was to be sure it would fit under fixed bridges. For the D&R there were no fixed bridges; every bridge rotated totally out of the way of boats. So there was no restriction on height. Therefore sailboats (whose other three dimensions were OK) could go through with their masts up.

The depth and breadth of boats established the canal's dimensions. The canal depth was at least two feet deeper than the allowed boat maximum draft. If the boat bottom was close to the canal bottom strange wave action starts to happen and pulling the boat at even the slow canal speeds became quite difficult. The breadth was sufficient so two boats going opposite directions could pass easily, just like a modern highway.

The dirt excavated for the canal is piled on one or both sides as needed to create two berms. Typically the ground is not level, but rises on one side of the canal and falls away on the other. I call these side directions "high side," and "low side." The low side is frequently the flood plain of a stream or river.

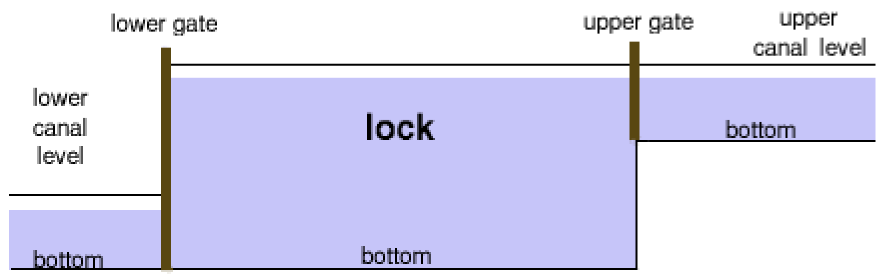



Natural ground slopes gently downwards from left to right. The excavation exposes the canal bottom. The dirt is piled into berms on each side. The water is contained between the berms. One berm is also used as the tow path

## Lock

The purpose of a lock is to either raise or lower boats between canal sections. It does this entirely by gravity. Even raising boats is done with water flowing down.

A lock is a box with a gate at each end. It is barely larger than the largest boats of the canal. In 19th century technology the box was made with masonry, and the gates with wood. The lock has an upper and lower end. The canal comes up to the lower end at one level and goes out the upper end at a higher elevation, as much as 10 feet higher in the 19th century. The purpose of the lock was to lift or lower boats between these two levels. It was done entirely by gravity, no engines, pumps, or other complexity.




Boat enters floating on water from left. Water in the lock is lowered to be equal to the water in the lower canal. Lower gate is opened. Boat enters lock. Lower gate is closed. Water is entered into the lock until its level is equal to water in upper canal. Upper gate is opened. Boat proceeds out floating on canal water at upper level.

Notice that the lower gate must be tall enough to go from the bottom of the lower canal to the top of the lock. But the upper gate can be shorter, as it goes only from the bottom of the upper canal to the top of the lock.

The ***lift*** of a lock is the difference in levels between the upper and lower canal. 19th century masonry/wood locks would typically have lifts of less than 10 feet. The D&R lifts were about 8 feet each.

The gates, when closed, sealed off the flow of water from the upper canal into the lock, and from the lock into the lower canal. Two sets of valves which could be independently opened or closed allowed water to flow into or out of the lock box. Typically they were just small openings in the gate itself with wooden covers that could be slid up or down by levers on top of the gates. The valve in the lower gate I call the "lowering valve", and the valve in the upper gate the "raising valve."

This is how it works to raise a boat. We start with a boat in the lower canal, waiting. Close both gates and all sluice valves. Open the lowering valve. That allows water to flow from the lock into the lower canal, and away down-canal. After a minute or two the water in the lock is lowered to a level equal to that of the lower canal. Close the valve, and open the gate. It opens easily because the waters inside and outside are at equal levels. The waiting boat now proceeds through the gate into the lock. Once completely inside, the lower gate is closed. If you are on the boat you are now surrounded by lock walls and gates. The fill valve is now opened. Water flows from the upper canal into the lock. Slowly the boat rises. After a minute or two the boat is at the level of the upper canal. The fill valve is closed, the upper gate opened. The boat now leaves the lock and enters the upper canal level. At this time if another boat is waiting to be lowered, it can enter the lock for that purpose. The upper gate is closed, the lower valve opened, and we are back where we were at the beginning of this paragraph.

In the engineering section of this article I give more details about locks and their gates.

### Natural water and Guard lock

Enough water but not too much is the situation in the canal. But at each end is natural water: a river, lake, bay, or the ocean. Nature is variable. The natural water almost always has variable height. It may be tidal, floodable, or just have high and low water due to season. Rivers, bays, oceans, lakes all have highs and lows. So the lock at each end must be designed to accommodate this uncontrolled water height. There is nothing special, it has gates at each end just like the other locks, but its dimensions must be set so it is operable with high and low natural water. This lock is called a "guard lock" because of its special role. It usually must lift or lower boats from whatever the natural water level is at the time to the first canal level.

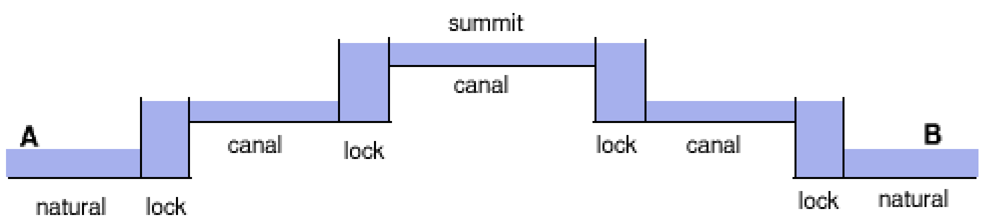
An excellent example guard lock is lock 14 in New Brunswick, NJ, recently restored. It is the only lock on this canal showing gates, controls, etc. as they were 100 years ago. This guard lifts boats from the Raritan River to the canal level.

A second example is the guard lock at Ravens Rock, NJ, also called Bull's Island. This one is a bit unusual, and is described in detail later.

### A Cruise

From the natural body of water you enter via a guard lock, continue with occasional lifts (usually locks) until you reach the canal's highest level. That level is called its summit. After traversing the summit you typically have more locks to lower your boat until you reach the canal's last lock, probably a guard, and exit into another natural body of water. Such is the D&R, the Morris, the Delaware, and many others. That's the end of our cruise, but although brief it has a few lessons.

The pattern is: natural navigable water (point A), enter, lift usually multiple times, traverse the summit, lower usually multiple times, exit into natural navigable water (point B).

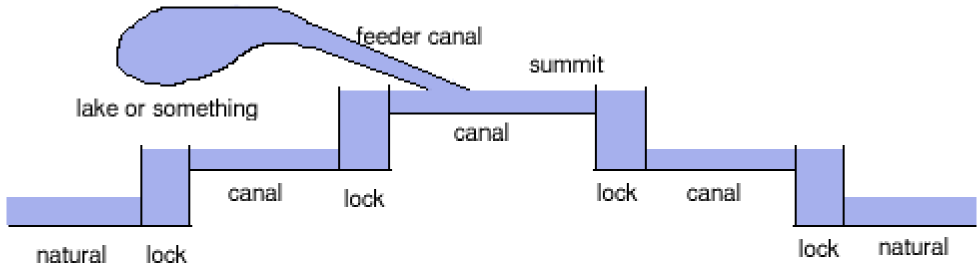



## Engineering details

### Water supply

"Use gravity" is the fundamental rule for all a canal's water. Pumps are not used; they are just too expensive to build and to operate. The amount of energy available from gravity is enormous, and free.

Our picture in the section "A Cruise" above is incomplete; it needs water for the summit and for the lower sections as well. The natural water at each end cannot be used in the canal itself, it cannot flow by gravity into higher sections. If we can get water into the summit then water can flow downhill both ways to fill the other sections of the canal. If that is enough water for the entire canal our water problem is solved. Ultimately that summit water flows out into both natural bodies. So a more adequate picture is:




Now we can fill the top level and by gravity it can flow into the other levels also. The water supply may be a nearby lake, or river. Notice that it flows by gravity from the supply. It must therefore be at a higher elevation than the summit. A significant construction may be needed just to get this water to the canal. The feeder for the D&R for example is 22 miles long.

Water comes into the summit at some feeder point, and flows along the summit to fill other sections of the canal. The canal is therefore not absolutely level. Instead, from the feeder point, the canal slopes very gently downwards, one foot per mile, towards the other sections. One engineering challenge is to survey the canal, marking the depth to dig at each point, and getting that as accurate as one foot per mile.

Water is lost three ways: evaporation, seepage (leaks), and operations.

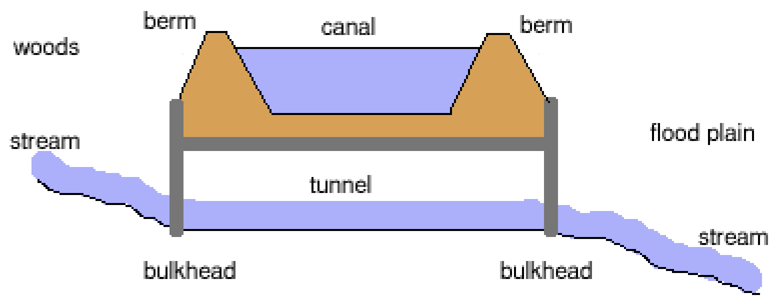
The total water losses may be more than can be accommodated from the summit level. In that case the canal may have additional water supplies such as lakes or streams which feed the intermediate levels. Perhaps Lake Carnegie was such an intermediate supply to the D&R canal just below Lock #8 at Kingston.

So when you plan a canal you need to think not only about its route, and the locks (or other lifts, more on this later), but you need to think about the quantity and sources of water to supply it, and how to get that water from where it is to where it is needed.

### *Culverts*

Foreign water is ground water outside the canal that is not wanted in the canal. For example water flowing in a stream from the high side towards the canal that needs to get to the low side. Picture this: on the high side of the canal is a gently rising wooded hill. Nice dry ground. On the low side is the flood plain of a river, and beyond the flood plain the river itself. The canal is following a contour up above the flood plain. But along the way the wooded hillside has a deep gulch with a stream flowing into the flood plain cutting right across the path of the canal. The canal will cross this stream. The canal berm, if built across the stream bed, becomes a dam. The stream will back up and eventually, having nowhere to go, will overflow the berm into the canal. After all our careful design to control water level in the canal we do not want this invasion of "foreign" water. The solution is a culvert. A culvert is a tunnel under the canal from one side (the woods) to the other (the flood plain) so the stream can get through unhindered.

On my first canal bike rides I noticed culverts, and even got off my bike and studied them. Walk off the berm (actually the tow path) down into the stream bed and you can see the culvert is masonry built. There is a bulkhead of stone. You can see the tunnel (or tunnels, sometimes as many as three) coming out of the bulkhead. You cannot really see the construction of the tunnel itself, but it too is most likely stone mortared into an arch that penetrates all the way to the other side of the canal, where it comes out of a bulkhead on that side. These arched tunnels were about four or five feet wide and three or four feet high. The entire culvert was then covered with dirt from bulkhead to bulkhead, and the canal built on top of this covering dirt, berms and all. There is no passage connecting the canal water to the stream water, they are separate.



Bulkheads have arched opening (not shown) for stream to pass through

stream has a large enough watershed to provide a reliable supply of water, and if water was needed at this place in the canal design, then you might also dam the stream somewhere up the hill to the left. But even dams need overflow for excess water, so the culvert shown above is still needed. The dam of course would need a path for the water to flow into the canal (not shown) and valves to control the flow. This variation is one way water would be supplied at an intermediate level of the canal. I have read somewhere that the Lake Carnegie was used as an intermediate supply for the D&R. But other readings suggest it was always just a boating lake for Princeton University.

### *Viaduct*

If the gulch is deep and wide it may be uneconomical to build culverts and fill dirt over the culverts. As the dimensions of a fill increase, the amount of dirt required increases by a cube law. So a gulch twice as deep and twice as wide needs 8 times the dirt, and probably 4 times the masonry. If it is 4 times deeper and wider, it needs 64 times the dirt and 16 times the masonry. At some point it is better to built a classical Roman-arch viaduct up to the floor level of the canal, and carry the canal on the top. The Erie canal had 16 viaducts. The Delaware & Raritan has a couple of viaducts carrying the feeder over large streams. One of these is in Trenton at Cadwalader Park, and goes over what is now Parkside Ave. But in 1830 I'll bet Parkside Ave was a significant stream.

### *Controls*

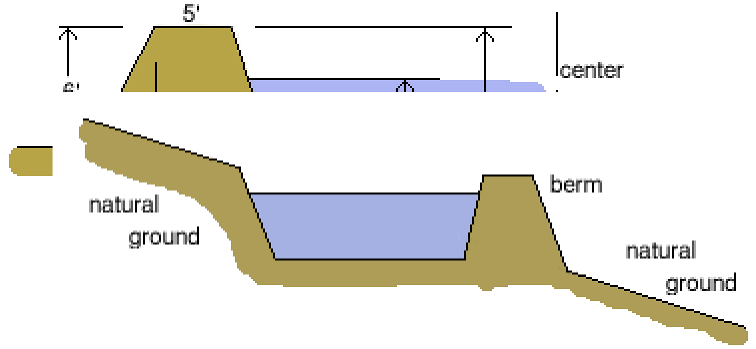
Canal water levels are carefully controlled. I have seen the D&R in wet and dry times, and the level never varies by more than a foot. Too much water causes damage. Too little means boats hit bottom. Excess water is purged by opening purge valves built in for that purpose, and in extreme cases excess water flows over the canal berm in a low rock-paved place designed just for that purpose. That overflow water needs a place to go, and typically it flows into the flood plane of an adjacent river, or directly into the river. Typically an intentional overflow point is built just up-canal from each of its locks. Locks are particularly level sensitive. Water too high at a lock would overflow the lock gate and make operation pretty impossible. So the intentional overflow protects the lock.

### *More on the profile (fun with geometry)*

I calculated the amount of digging for a 70 foot wide (at the water level), 7 foot deep canal, assuming the slopes of the berm walls are 2 to 1. You would dig only 4 feet deep, piling the excavated dirt equally on both sides to create two berms 6 feet high. That makes the canal's vertical dimension 10 feet. Fill this with 7 feet of water and you have a 3 foot bank from the water to the top of the berm. One consequence is the water itself is 3 feet above the natural ground. Instead of a ditch, the profile is mostly above natural ground.

These calculations assume a level ground, side to side. That is rarely the case. Usually there is a slope, and therefore a well defined high side and low side. If the slope is extreme enough, there is no berm on the high side, and all the excavation goes into a pretty tall low side berm.

And there are places with no berms at all. Where the D&R transitions from the upper Stony Brook watershed, south of Princeton, to the upper Assunpink Creek watershed, north of Trenton the level of the canal is entirely below natural ground level. The canal is entirely within the excavation. The excavated material is there, and is technically a berm, but it does not contain the canal waters. Instead it seems to be a flood wall, protecting the canal from Stony Brook floods.




The excavation is deep enough on the high side that no berm is needed there. The low side berm may be quite tall, 10 feet on its inside face and 15 or more feet on its outer face.

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is 102 square feet, (0.5x(29+5)x6). One half of the excavated dirt goes into this berm, and that excavation area is 100 square feet, (21x4 + .5x8x4).

Profiles vary with the situation.

## *Lock details*

When a lock is operated through its cycle it can lift one boat and lower another. Water moves from the upper canal level into the lock chamber, and then from the lock chamber to the lower canal level. The net effect is water is moved from the upper level to the lower level. Canal water is typically precious, and a design goal is to minimize the loss of water. To do that locks are made as small as possible, often only inches larger that the maximum boat size. The water that flows through the lock due to its operation is "operating water loss", but that loss is only relative to the upper level. At the lower level it is a gain.

The construction of a lock starts by excavating a foot or two deeper than the lock floor. Wood pilings are then pounded into the bottom to make a firm foundation. Upon these a wooden floor is built with at least two or three layers. The masonry walls go on top of this flooring. Valves and gates are fitted, and the masonry backfilled with dirt. A fairly large flat work area is needed all around the lock. Several wood or concrete posts (bollards) along each side are used to tie the boat and hold it steady during the locking process. Boat crew are required to adjust these lines as the boat raises or lowers.

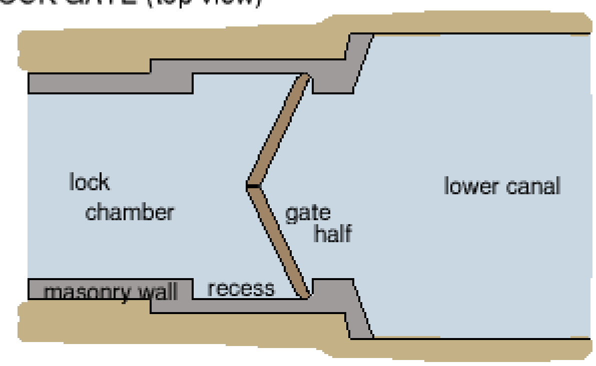
The valves (raise and lower) are typically just openings in the gate doors themselves, covered with a sliding wooden flap. Levers on the gate's top are used to open or close the flap. These were cheap and easily maintained, but probably slow, taking 2 or 3 minutes to raise of lower the lock water. Better (faster) valves were used, but were more expensive to build. They were built into the lock masonry, had large water passageways also built into the masonry, and had multiple iron rotating flaps controlled by levers and chains to open/shut the valve. The D&R originally used the simple kind, and later the more elaborate. The museum at Blackwells Mills shows drawings of the elaborate variety.

## *Lock Gates*

A gate is usually a pair of vertically hinged "doors" about a foot thick. When the gate is opened, each gate–half goes into a recess designed into the lock's masonry.

Another type of gate is a drop gate. This was a single thick wooden "flap" hinged horizontally at the bottom, down under the water. They were weighted to a slightly negative buoyancy, and raised and lowered by chains. When lowered it lays flat on the canal bottom and the boat entered the lock by passing over it. When the boat was in the lock the gate was raised, coming up to seal the end of the lock chamber. These when used were always at the upper end of the lock. The sluice valve mechanism could not be part of the gate and so was built into the masonry walls and/or canal bottom.

A LOCK GATE (top view)




Only the lower end of the lock is shown. The gate halves, when opened go into the recesses in the masonry lock walls. When closed they come together as shown into a V. This withstands the water pressure and also helps seal the gate by forcing the gate halves together, and forcing each half into its hinge socket in the corner of the recess.

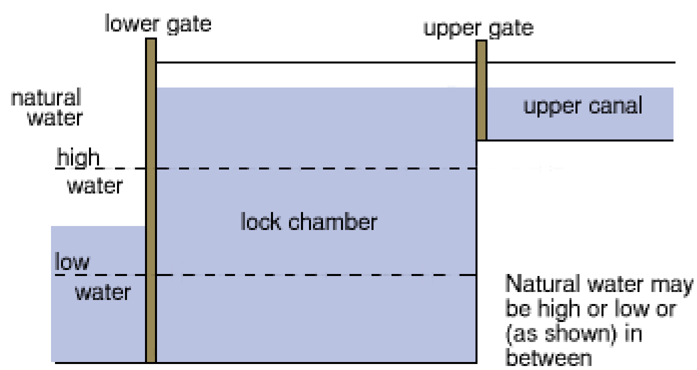
Because of the pressure, the gate cannot be opened unless the water on each side is equal height. In that case the net pressure is zero and the gate opens easily.

Opening and closing is done by a variety of mechanisms. The simplest is just a long wooden horizontal handle set in the top of the gate half and extending over the work area. Just push the handle around to open, or pull it to close. It acts as a lever. More elaborate mechanisms include cranks, gears, and push/pull iron rods or straps. Lock 12 at Lumberville has such a mechanism still in place.

The D&R originally used classical "door" gates at both the upper and lower ends of its locks. Later it converted the upper gates to drop gates.

### Guard lock details

The only thing special about guard locks is they need to accommodate high and low water out in the uncontrolled water area, nature's water. That just requires a taller lower gate. Here is a picture which assumes the canal level is higher than the natural water:




Somebody must study the natural water and determine its highest and lowest levels for engineering purposes. Notice how tall the gate must be to accommodate low water. Recall the 10 foot lift limit for masonry locks, and look at the picture: the lift limit will apply when the water is low. That puts a constraint on this lock that is more severe than the simple lift locks not performing the guard function.

The D&R had four guard locks, two on the main canal at New Brunswick and Bordentown, and two more on the feeder at Ravens Rock and Lambertville. I have visited two of these and describe them later. The Ravens Rock guard has natural water higher than canal water, and boats are lowered into the canal.

### Other lift technologies

There were other means to lift and lower boats, an inclined plane, for example. The lower canal ends, but rising up an incline is a railroad. The tracks go down into the water. On these tracks and down beneath the water is a large flat car. It has posts along each side with cleats for tying. These posts are all that is above the water. You guide your canal boat between the posts and tie up to them. Then a large motor starts pulling a cable tied to the flat car, and it starts moving out of the end of the canal and up the incline. Your boat is tied to its posts, so your boat moves also. As the car rises it literally picks your boat up and lifts it bodily out of the water and up the incline. The lift may be 100 feet. At the crest the tracks level out and then start going downhill into the upper canal until your boat, still tied to those posts, is afloat in the upper canal. You untie and float off the car into the upper canal. These inclined planes were used in many of the Pennsylvania canals, and also the Morris Canal in northern New Jersey. The "motors" were impulse water wheels, a 19th century technology that works on the same principle as a jet engine.

This technology is to me amazing. I am sure I will have more to write on it once I have visited the Morris Canal Museum.

### *Canal complexity*

The "lift" of a lock is how far it lifts boats from the low section to the high section. For 19th century masonry locks (stone and mortar) ten feet is about the limit of lift. One measure of the complexity of a canal is the sum of all its lifts. The D&R for example has 14 locks with an average lift of 8 feet. Its total lift is 112 feet. You add up all the lifts as positive numbers even though some of the locks are used to lower in a particular direction. If you add up the lift as positives for lifting, and negative for lowering you get the net lift. The D&R net lift is probably a small number like three or four feet. Net lift does not measure the complexity of the locking system, but rather just the net difference in levels between points A and B in the above pictures.

A design goal is minimum lockage, just because it is expensive to build, maintain, and operate each lock. If you are lucky, you can build a canal with no locks, e.g. a sea level canal like the Cape Cod Canal, or the Chesapeake and Delaware. But the more general situation is to plan a route that is not too indirect but follows river valleys, flood plains, and other reasonably flat land features. When in the hills, follow the contours.

### *Canal Boats*

A canal boat's requirements are simple: maximum cargo, fit within a canal's specifications, inexpensive to build and maintain, and easy to handle by a small crew. They could not sail, or (in the early days) motor. Their motive power was mule–power. The resulting design is truly simple: flat bottom, vertical wall sides, very blunt but slightly rounded ends. They were not fragile as they took a beating bouncing off lock walls, berms, and probably each other. So they were stoutly built. The photographs in the reference materials say much more than I can on this subject, and I leave it to them to tell the rest of the boat story.

### *A review*

We now have all the basics:

- guard locks/lift locks
- water supply
- water control: valves, overflows
- culverts
- total lift
- boats

# A tour of my neighborhood canal

The Delaware and Raritan (D&R) canal is about an hour's drive from my home. It is not operational as a canal today, except for recreational canoes. It is operational as a water supply for many communities in middle New Jersey. The feeder canal is fully watered, and the main canal 3/4 watered. For the last 20 years or so it has also been a state park, specifically the tow path along one of the two berms.

## *Main canal*

The main canal started in the Delaware River near Bordentown behind Duck Island. The Delaware is navigable at this point, and like any river has its high water and low water moments. So there was lock #1, a guard. About 5 miles and a total of seven locks later the canal climbed the bluffs above the Delaware River into Trenton, NJ. This whole section is today unwatered, and may or may not have access points for hikers. I have not yet done this section. The lift in these 5 or so miles was about 50 feet, and it reaches the summit. Most of the summit level is now watered and parkland. It continues at this level ten miles, and comes to Lock #8, the first to step down from the summit at Kingston, just a bit north of Princeton. The Princeton–Kingston stretch is without a doubt the most popular walking/biking stretch of the park.

The dam forming Lake Carnegie is just south of Kingston, and there may have been a sluice from the dam around the lock for water to flow from this lake into the canal section just below the lock. All the controls now are modern water–company controls. Traces of an old sluice are there, but you have to look closely to see them. An historical layout drawing of this lock shows this sluice connecting the upper canal level to the lower, but does not indicate a connection from the lake. My guess is there was a connection and it is not shown on this drawing. The drawing is displayed (along with others) in a tiny museum in the lock tenders house at this lock [KM]. Whether or not Lake Carnegie was an intermediate water supply for the D&R is one of my open questions.

The canal continues north with locks every few miles, following the Millstone River valley. In fact it hugs the gentle hills on the east side of the valley. There is a culvert for a stream about every mile. When biking I noticed only the most prominent of these, but when walking I was quite amazed by their frequency. Most were tiny one–tunnel jobs, but the most prominent had three tunnels. The park system (or maybe the water company) is rebuilding these. They are using masonry for at least the bulkheads, the visible portions. And in a few of these are bronze plaques with the dates of the original (about 1834) and the reconstruction (1980's/1990's). This masonry reconstruction HAS to be more expensive than poured reinforced concrete, and knowing nothing of the plans or funding or whatever, I would say it is to the park department's credit they are honoring the history of the canal by using masonry.

After about 30 miles the main canal leaves the Millstone valley and enters the Raritan valley. It is well up on the bank of this river, and there it starts its swing eastward, and eventually southeastward. There are 6 locks still accessible, locks 8 (Kingston) through 12, all lifts, plus lock 14, the guard into the Rariton river.

Not all the above is park, nor is all watered or even visible today. The canal was operating for boats as late as 1931, but then the owners (the Pennsylvania Railroad at that time) simply did not open it for navigation the next season. Abandoned, it soon became a water company, and that is what probably saved it. From the summit to the Delaware at Bordentown it was de–watered, perhaps five or six miles. I have not visited this section, but it had seven of the fourteen locks. Through Trenton three miles were "paved over" in 1933 for Route 1. In fact the canal simply disappears, fully watered, beneath a kind of steel I–

beam platform and the highway is on top of that.

At the other end, New Brunswick, the park trail ends at a concrete overflow (recent construction, I'm sure) which is not passable. On the far end you can see a modern sluice control and then there is a highway on–ramp. Highway 18 for 1–1/2 mile is built over the old canal and lock #13. I found about two miles further down the Raritan River a city park (Boyd Park) with access to the last half mile of the canal, and there was guard lock #14, with its entry into to the Raritan. In 1997, the gate doors were off. The end of the lock was protected by a coffer dam. It was full of stagnant water. I read a magazine article (about 15 years old) saying a group was planning to rebuild this lock and the last half mile of canal. Indeed it has happened; the lock is now rebuilt and very accessible. See the section below on Lock #14.

The 5 accessible lift locks (#'s 8 through 12) show the original masonry. They were doubled in size when the canal was about 10 or so years old, and the doubling was done with concrete. So you often see a lock whose upstream end is masonry, and downstream is concrete. The gates and wooden linings are gone. But the lower gate recesses (see locks, below) are still there, as are recesses to receive timbers for the lining. The upper gate recesses are used to anchor modern valve controls used by the water company to control flow. The water roars through these, and is turbulent through the lock's chamber. With no gate at the outlet the water just flows out and within a few feet becomes a quiet gentle flow.

The berm with the hiking trail is on the towpath side, mainly. For the Millstone River stretch (about 15 miles of a total of 33 hikable miles) this is beside the river's flood plain. Across the canal is the high side berm where needed, and beyond that dry ground which slopes gently upwards most places, but rises quite steeply in the area of Rock Hill, and a couple of other places. There is a culvert about every mile. I was struck by the way the canal hugged the edge of the flood plain of the Millstone, often a bit up the bluff bordering this plain.

In only one place did I find evidence of a lock's bypass sluice, and that was at "10 mile lock" (park departments name) which I believe is lock #10 (same number is a coincidence). There I found a ditch, some masonry, and even the remains of the control gate, iron and wood, crank, gear, rack and pinion to convert rotary to linear motion. The vertical was wood, but there was nothing left of the gate itself, almost certainly one inch wood planks. I hope the park department preserves this last vestige of a control.

I was looking for the sluice that admitted water from Lake Carnegie into the canal below the Kingston Lock, and found just a little. Parts of a secondary berm are there, and the concrete portion of a valve. An historical drawing shows this bypass, but shows it connected only to the upper canal. I believe it also connected to an outlet from the lake.

The lake has modern control valves on the canal end of the dam. There is probably a modern underground pipe from these to the canal, somewhere. It is a water company, now, and this is water.

So out of the 44 miles of the original main canal, the current watered hikable distance is 33 miles from northeast Trenton to an overflow in New Brunswick. Where does this water come from? The answer is a second canal, called the "feeder canal," fully watered for its 22 mile length from Raven Rock to Trenton. Only the last 100 yards are gone. That is our next story.

## *Feeder canal*

Recall our theory section above: we need WATER for the summit. Trenton–to–Kingston is the summit of the main canal. The water must come from some higher elevation. The supply for that is the Delaware River itself. But Trenton is built upon a bluff 50 feet above the Delaware. How to you get water to flow uphill? The answer is you don't. Instead you go up the Delaware River 22 miles. By that time its elevation is well above the Trenton bluff. Tap into the Delaware and let the water flow gently downhill all the way to the summit level in Trenton.

The feeder canal was made navigable, too. It tapped into the Delaware River for both water and boat traffic. It had a guard lock at Ravens Rock about 1/2 mile below the entrance from the Delaware, another in Lambertville, and two locks to lower boats during its route. But it flows downhill all the way. Unfortunately we cannot see the junction of the feeder and main canals today. About 100 yards before its end the water is now diverted into an underground passage, and it emerges a mile or two down the main canal. Where the feeder and main canal did meet is now US Highway 1.

The feeder canal, too, is state park all the way from Ravens Rock (the headwaters of the whole canal system) down to within a block of the junction.

So this canal does follow the complete model as laid out in the "Water" section above. The water supply is the Delaware River, 22 miles upstream from Trenton.

## *Lock 14*

New Brunswick has recently renovated a city park, Boyd Park, for about half a mile along the river front. Part of that renovation is the reconstruction of Lock 14, including gates, and wooden lining. This is really two guard locks, side by side. Access is excellent, there are five pedestrian bridges over the locks and canal, and you can walk the berm that separates the canal from the river.

## *The Raven Rock guard lock*

This guard is underneath the Bull's Island Park entrance road. As you enter this park it feels like you are driving over a bridge, and you can see canal to the left and right. In fact it is not a bridge, but a road built on top of the guard. The best access is from the highway side of this "bridge" down into a canoe launch area. There you can see what looks like a stone masonry dam. That is the control. There are remains of two culverts under the dam on its far end. They are blocked off and not currently used, but you can see the tops of their masonry arches. Being the headwaters of the whole system, a great deal of water needed to be admitted here. That was the role of the two quite large, and now silent culverts.

Where water roars through a modern control was an old guard lock that lowered boats from the Delaware into the canal. Evidence is in the stonework at water;s edge, and also in the "dam" itself. At water's edge is one wall of the lock, including the recess for its lower gate. The other lock wall is removed, but you can see evidence in the dam where they once joined. Thus are the headwaters of this entire canal system.

It is worth walking on the park side northwest along the canal from the guard to the Delaware about a half a mile above the guard. This little section is canal, i.e. it is dug, not natural. But its waters are natural, sometimes high, sometimes low. One of my "thought experiments" below has to do with the excavation of this half mile.

### *Lock 12, Lumberville, Pennsylvania, and the low dam*

Walk across Bull's Island and you will find a pedestrian bridge across the Delaware, a pleasant side trip. As you walk across, look up the river and notice a very low dam across the Delaware. At high water the river flows over its full breadth. At low water it flows only through a plume in the center. Its purpose is to form a pool of reliably deeper water at the canal's entry. We discuss this in one of our thought experiments later.

Across this bridge is the Delaware Canal, part of Pennsylvania's canal system. You can visit lock 12 of this canal just a bit up the road. It, too, is a park. The lock is quite small, as this canal is designed for small canal boats. The lock gates are still hung, and iron controls to open and close them. The raise and lower valves are in the gates. The bypass is still there, and its control. A bridge gives access to the river side of the lock, so you can study it all around. A very nice, kind of miniature, of all of a lock's elements.

### *The Prallsville Mill overflow*

Three miles below Raven Rock is Prallsville Mill. This mill pre-dates the canal, and today is an historical site maintained by Prallsville Mill Historical Society. The first major overflow is there. It is quite large and is of modern concrete construction. Just below the overflow is a lift lock. The role of the overflow is to protect this lock, and in fact the entire feeder canal downstream from excess water.

## Thought experiments

This section is not history. It is really an engineer's questions, "How did they do this?" and possible answers. But I mix in a bit of evidence I picked up either from books or from my own observation.

### *Instructing Illiterate Workers*

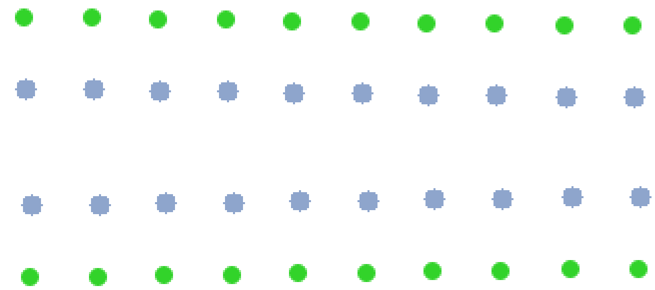
Hire 20 or 200 workers, give them shovels, and say "dig here" and you will get chaos. What do you really tell these workers?

From [EWW], I learned that the State of NY did not hire workers to dig the Erie Canal. They hired the engineering staff. The engineers wrote specifications for each canal-contract-section. These sections were quite tiny, some as small as one quarter mile. They specified not how to dig/construct, but rather what the final result was to be. It was up to each contractor to make it happen.

But contracts were only one "language" of communication. The other was the survey stakes. According to [EWW], when the contractor went to the site, there were four lines of stakes: the outer two lines were for clearing of vegetation: trees, etc. That was "grubbing" and was one contract you could bid on. It had to be done first. Another two lines of stakes inside were the breadth of the canal itself.

The grubbing process would probably have been pretty destructive. You had to chop down trees, pull stumps, and pull or burn all vegetation. My guess is most of the 'c' stakes would be gone, and many of the 'g' stakes, too, when grubbing was complete. If the grubbing workers just hammered in a toppled over 'c' stake, vital information would have been compromised. Maybe it was done that way, but I have my doubts.

Here is my thought experiment on the subject of surveying, and we will get back to instruction illiterate workers.



According to [EWW]: The greens are grubbing stakes. The blues are canal digging stakes. The grubbing must be done first.

## Surveys and Construction Interleaved, and the Message of the Stakes

It would seem there must have been lots of surveys, each for a different purpose, and these interleaved with the actual construction.

The first survey would have been exploratory, probably done on horseback, and without instruments. The goal was to find a feasible route, document it, and estimate the project's difficulty. No stakes would be put down, but a notebook would reference natural landmarks and contain other vital data.

Once funded, the first "real" survey would be done with instruments and stakes. The result was a single row of stakes, probably down the middle of the canals path. Levels would be taken and noted in a notebook for each stake. So to correspond the notebook entries with the stakes themselves required numbering the stakes.

A surveyor's chain is 66 feet long. 80 chains is a mile. My guess is a stake's number was a mile and a chain number, i.e. 8–25 would be mile 8, 25th chain. In the field notebook would be at least a depth to dig at that stake. The field notebook would note the needed auxiliary structures: culverts, purge valves, locks, the whole design including important dimensions. And the orthogonal slope of the ground, or other profile data was noted. In other words, the combination of the one row of enumerated stakes plus the field notebook was the detailed design of the entire construction.

It was not necessary to document every stake; probably every 10th to 20th would suffice, i.e. every 1/8 to 1/4 mile. Most of the stakes could be somewhat flimsy, but these documented ones would be stout, hammered into the earth a bit deeper, made noticeable by some means (paint or ribbons), and have their identity marked on them in a nondestructive manner. I will call these stakes the Design stakes. [EWW] calls them "rows of red stakes."

Now a crew of surveyors came with only a chain and supply of stakes, measured from every Design stake and every 2nd or 3rd stake in between a fixed distance to each side, marking that for grubbing. These could be stakes, or they could be just little ribbons tied to vegetation. These are the 'g' stakes in the above picture. Then the grubbing contract let, and done. The grubbers were told to honor the Design stakes, i.e. don't disturb them. But if a few of the g stakes were knocked down, that was not serious. One could tell by eye from its neighbors that the grubbing was done wide enough.

Later when the most destructive grubbing was complete, a picked crew of the more careful workers could grub around the Design stakes, taking care to not disturb them. If by chance one was knocked down anyway, there was another not too far away, and the engineer would bring out the instruments and reset the disturbed one fairly quickly.

The surveyors returned yet again, and marked off the width of the canal excavation itself, the c stakes. The excavation/berm construction contract was let, and digging began. Now things got interesting. What exactly did those c stakes mark? Did they mark the waterline width? The canal floor's width? Or the width to some point on the berm? Each seems reasonable, and each has problems.

These c stakes defined the canal profile. The contractor must look at two stakes, one to the left and one to the right, and read their message, the width to excavate, and where to dump dirt for the berm. From the Design stake's documentation he would know the depth to dig.

Suppose the c stakes marked the waterline width. That would make them easy to put down, just measure 35 feet to each side of the design stakes. And the message to the contractor is a bit complex, they must dig from a point somewhat inside the line of c stakes, and pile dirt for the berm both inside and outside the stakes. During construction the stakes would be buried. Look at the profile a few pages back. You can see they would end up underneath 3 feet of berm. Nonetheless, the stakes would define the desired final result.

Alternatively, they could define the borderline between digging and piling dirt. The stakes define the constuction to be done rather than the final result. That makes the message to the contractor easy, but the exact placement of the stakes requires a stake–by–stake calculation.

My guess #1 is the c stakes did indeed measure the waterline width. That put the stakes into the line of the berm to be constructed, and they would be buried. So the digging would simply bypass the stake area, and get the canal's profile correct a bit up canal and a bit down canal. Then, just like the grubbers coming back later, the digging crew would send one or two men back with shovels and a wheelbarrow to do the c stake area. By then the profile was pretty determined, and burying the c stake was harmless. This guess has the advantage that the c stakes are a constant width apart no matter the profile. The disadvantage is that the contractor must dig a bit inside the stakes, and fill both inside and outside the stakes. The division between digging and filling was not specified by the engineer, but by eyeball by the contractor. This method would be practical only if this disadvantage is in fact not a problem. If eyeballing the dig–dump border is impractical, that leads me to...

My guess #2 is that the c stakes were placed at the borderline of the berm and the excavation. Thus they were never buried. This guess has the advantage that after construction goes by the stake, the stake itself shows the construction adhered to the design. It has the disadvantage that every c stake needs some calculation to get its distance from the centerline. But it's an easy calculation that can be done in your head. If the breadth at the water line is 75 feet, then the breadth from the center line is half that, or 37.5 feet. Multiply the slope of the inner berm wall (2 in the chapter way back) times the height of water above the ground (3 way back) and subtract that from the half–breadth. The stakes would be put 31.5 feet from the center line, assuming these data and no orthogonal slope. But this calculation gets more complicated in the presence of orthogonal slope. Although very tempting because of the easy message to the contractor, I doubt this technique was used.

There are other possibilities. But bear in mind, the contractor needed to know exactly what was the meaning of these c stakes. Their meaning was part of the message to him. I think a simple message is better than an abstract difficulty that in practice is not a difficulty. I would bet on my guess #1. But what did they really do???

In any case, like the grubbing contractor, the excavation contractor was probably instructed to stay well away from the Design stakes, and to call the engineer if one was disturbed. So the design stakes were left on little hills of unexcavated dirt. Only when the engineer accepted the excavation as dimensionally correct would they come down, and the little hills be removed.

But I am an engineer. I know that engineers do not want any part of their design record destroyed. Those Design stakes are part of the record. So I now conjecture that they were physically but not conceptually removed. I'll bet after construction bypassed a Design stake, the engineer would offset from it to another place, perhaps on top of the completed berm, and put down a new Design stake, making a record of the offset. Then the contractor can remove the old Design stake and level its little hill.

### *Back to instructing illiterate workers*

Literacy, the ability to read and cypher, was not uncommon in 1819, but it was not nearly as pervasive as it is today. The contractors themselves if they could not read needed access to someone who could read and explain the details to them, and to prepare a bid. Perhaps the engineering staff did this for them.

The contractor was the key. The engineers communicated the desired results through contract words and stakes. The contractor translated this for the workers, and probably fairly quickly the workers understood the profile, the stakes, etc.

When the Erie Canal construction began there were not sufficient contractors available to bid on the work. The canal commission knew this, and very wisely came up with a bootstrap scheme to solve the problem. The book [EWW] describes this quite well. One could bid on a very tiny construction, as small as 1/4 mile. So an entreprenourally inclined farmer could enter into a contract with minimal risk. But these folks didn't have capital to buy equipment, or pay wages during construction. The commission advanced funds to the winning contractors to do that, and paid cash on work completed, keeping careful books on it all. Consequently a farmer could make a profit and come out of a small contract with experience, equipment, and hopefully a zest to enter into a larger contract the next time. It was the contractor's job to hire and instruct the help.

### *digging a canal so it doesn't flood during construction*

I just won a contract to dig 3 miles from marker 17-26 to 20-19. Before bidding I inspected this section. The Design markers made it easy to find. The grubbing was under way. The orthogonal slope was modest. There were 3 streams crossing the right of way, and one of the 3 culverts was already under construction. That was last fall. As soon as the snows melt I will start digging, hopefully early March. Of course that's the rainy season. But on non-rainy days I will dig.

Fine, but the first rain after I've dug a bunch, do I have a swimming pool, or a construction site?

My guess is the three streams crossing were crucial to a non-wet construction plan. Start at a stream and dig up-canal. Any rain water that enters your completed work flows down-canal into the stream bed and away down the stream. No swimming pool. That is not to say you don't have a muddy mess the day after the rain. But at least you do not have feet or even inches of solid water.

### *amount of masonry, construction prerequisites*

I am struck by the amount of masonry for the D&R canal. Not just the locks, the most noticeable construction, but the culverts, and all the little things: purge valves, bypass valves, etc. They got rock where they needed it by horse drawn wagon. They needed to get lime and other mortar ingredients to each site. A canal is not just digging. A huge effort went into constructing the masonry. Where did they get the masons?

Much of the masonry would have to be in place before the excavation and berm construction. Clearly a culvert's masonry must be completed and cured to some degree of strength before it is filled over. A purge valve must have masonry completed before iron can be bolted onto it, and iron before the wooden gate. And the masonry must be done before the berm can be closed around it. And all done before the first fill.

The engineers knew all these prerequisite conditions, and got it to happen in an orderly and timely fashion. Their terminology did not include 'critical path,' but they certainly knew the concept and worked the problem.

### *The last half- mile*

Raven Rock motivates this thought experiment. How do you dig the last half upstream mile? Let me set the stage.

Bull's Island is a modern name. It was not an island but was attached to the mainland before the canal was built. Today it is a one–mile long island connected to the mainland by a road built on top of the canal's headwaters control structure. It is a state park. As you enter the park the last half mile is on your right, the controlled canal your left.

What was the topology before the canal? There were no topographic maps back then. But clues exist just by looking at the lay of the land, and the streams, and judging what is natural and what is human manipulated.

Go to the canoe unloading parking lot to the left off the park's entrance, but before crossing the canal. At the southeast end of the parking lot you will see a stream bed that emerges from a concrete culvert under the old railroad. During rain, this stream dumps water into the canal. This stream comes from inland. Across the canal is Bull's Island, and the rise of the ground suggests it is natural and was always there. So, pre–canal, this stream came down from high ground about where the culvert is, made a left turn, flowed down a perhaps rocky stream bed where the canal now is for a half mile, then turned right and flowed into the Delaware.

Now go into the park and walk along the canal from the control structure to the Delaware. My opinion is that the channel is both widened and deepened the entire length, about a half mile. My evidence is just the lay of the land both where you are walking and across the channel. It looks carved.

You will notice little streams coming down the hillside on the other side of the channel. These are flowing for a period after rains, and dry other times. None are large. That water flowed either directly towards the Delaware (ahead of us) or back towards the control structure and into the larger stream we already know about. Somewhere was the high land, a stream water divide along our walking path that separated northwest flowing stream water from southeast flowing stream water. Both flowed to the Delaware. They used different paths to get there. And those paths ultimately defined Bull Island.

My guess is the divide was either at the control structure, or a bit to the northwest, perhaps 1/4 mile. The guess is more a hunch than a substantiable estimate. My story does not rely too much on the exact place, however.

Our goal is to dig the canal up the large stream's bed, build a control structure, and keep digging until we tap into the Delaware at the islands northwest tip. And to do that in an orderly way, that is to say without having to dig at your feet while standing waist deep in water, or even ankle deep. How do you do it?

Step one, I believe, would be to divert the stream so it does not flow through the canal's intended path. Build a purge valve at the streams outlet. Then dig from that outlet up–canal behind what is now Bull's Island until the control structure site is reached, and maybe just a bit further. Now excavate for the control structure and build that. So far nothing unusual; we have followed the principal of construction without flooding.

We now have to excavate the 1/2 mile from the control structure to the Delaware River inlet. But the floor of the canal at that point is four feet below the Delaware's low water level. If the workers dug until they tapped the river, then at some point a shovelful would cause water to flow into their work. But this channel must be wide and deep enough to admit boats. The unexcavated river–bank prevents that, but would by then be mostly under water. How would that excavated? That is the crux of this thought experiment.

There are three methods available, (1) dredging,(2) prior construction of an easy to remove coffer dam, and (3) raise the river. The choice was economic. Dredging is very expensive relative to excavation per unit of removed material. If you can build a coffer dam a bit off the Delaware's bank then drain the pool it encloses, do your digging, then remove the coffer dam, and if you can do all that cheaper than dredging, then the coffer dam wins. But a low dam across the entire Delaware River may be still cheaper.

Dredging is done by dropping a scoop with an attached line into the water, and pulling the line. Whatever gets scooped up is dumped aside. The problem is you get very little material removed per scoop. It takes a lot of motion to move the filled scoop over the dump area, and than back over the water to the next drop point. And you cannot really see what you are doing. If the scoop hits rocks, you need to somehow deal with that, and if the rocks are too large you cannot dredge at all. Today dredging is done with powered machinery. I don't know how it was done in 1830, but probably the scoops were small, and the lines attached to them pulled by hand. A lot of effort would be required to move even a small amount of material.

An alternative is to construct a coffer dam. It shuts the river out of the area to be excavated. It is placed far enough from the river bank to enclose the shallow portion of the river bottom that must be deepened. The coffer dam itself is built from easily dredged material. The enclosed pool is drained down the already dug canal, through the open gates of the control structure, down the already dug second half mile of canal, to the open purge gate at the southeast end of Bull's Island, and out into the Delaware. That is why all that construction had to be done first. After all excavation is done, the control gates are closed and the coffer dam breached thus refilling the just completed canal section between the river and the control structure. But that breaching leaves most of the coffer dam still there, so it must be removed. That requires dredging, and that is why it was built from easily dredged material.

But there is a third possibility. Design the last half mile so its floor is barely *above* the river at low water. Dig as before until there is just a bit left to go to break through to the river. No coffer dam is needed. Just wait for low water and then finish digging. Those last twenty or so feet are a dry dig because the river is low. Then raise the river by building a very low dam across the Delaware from Bull's Island to the Pennsylvania side. You only need to raise the river a few feet, until there is a couple of feet depth flowing into the canal.

My guess is they used the second method, or maybe the third. Several observations support this guess. I visited at low water (last August) and you could see the bottom of the channel from the control structure to the headwaters entrance. I cannot be sure how deep it was, but 2 or 3 feet maybe? The pool formed behind the modern dam was essential to getting the water into the canal at all. When I visited at high water the purpose of the dam was less evident. My question is this: Was the dam a part of the original 1830 design, or was it added later, an improvement to increase the availability of water during drought. If original 1830 then they used method 3 (or a 2–3 combination). If it was added later they used method 2. I doubt method 1 mainly because it is more expensive than method 2. But then I know little about 1830's dredging technology. If it was advanced enough, method 1 might just be the economic choice.

### *The first fill*

My experience as an engineer is –– test small things; test bigger things only if all the small things work. I now know this is a very very old idea.

The test for a newly constructed section of canal would be to simply fill it and see what happens. This was done in tiny sections at a time. The first fill of the Erie Canal was a mere 3/4 mile [EWW]. It was such an auspicious occasion that a boat was launched, and the local dignitaries cruised up and down that little stretch.

It is simple and quick to throw up an earth temporary dam across the canal at each end to be tested. The hard part is to find water. Therefore testing almost certainly was done from water sources outwards in both directions. What this tells me is that the construction was generally from the feeder to a small summit section, and from there outwards in both directions.

There is a plaque somewhere in Kingston proclaiming that the digging of the canal began there. That is probably true. We know the D&R opened for business from Bordentown to Kingston before the rest was completed. But I would venture the largest part of the construction crew on 1831 (the first construction year) was working on the feeder canal. Any work on the main canal was just a head start, or a politically visible effort, or something. You cannot water the main canal from any source I know of except the feeder. So testing actually dictates construction priorities.

# Bibliography


## Museums

National Canal Museum brochure, National Canal Museum, 30 Centre Square, Easton, PA 18042-7743, www.canals.org. There is a bookstore here with most of the material in this bibliography.

Hugh Moore Park, Lehigh Drive, Easton, PA. A short drive southwest from the museum. There is a bookstore here, too, with the same selections.

[KM] Kingston, NJ, the lock tender's house has a small one room museum.

Griggstown, NJ, the mule tender's bunkhouse had a quite nice museum until it was damaged in the flood of 1999. It is currently being renovated. Some of its displays are now in Kingston [KM].

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Engineering in History, Kirby, et al, Dover Publications, 1990. Not specifically canals, but what is covered open's ones mind as to the skills of engineers even 2000 years ago. Descriptions of heavy lifting engines, for example. There is a chapter on roads, canals, and bridges. Lots of illustrations.

[EWW] Erie Water West, Ronald E. Shaw, The University of Kentucky Press, 1966. A chapter called "Forty feet wide and four feet deep" gives a lot of engineering details that I have not repeated here: stump pullers, underwater cement, clay lining material to minimize water loss, and more. The entire book is excellent covering politics, finances, the contract system, life on and around the canal, and more.

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