Hydrology and Environmental Aspects of Erie Canal (1817–99)

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2038

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By W. B. LANGBEIN

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METRIC EQUIVALENTS

English units are used throughout this historical account. However, units have been simplified to those now in customary use. For example, lengths are given in inches, feet, yards, or miles as appropriate and not in rods or chains. The following provides for ready conversion into metric (SI) units.

Multiply	*By*	*To obtain*
inches	25.4	millimetres
feet	.3048	metres
yards	.9144	metres
miles	1.609	kilometres
cubic feet	28.32	cubic metres
cubic yards	.7646	cubic metres
tons (short)	.9072	tonnes

GLOSSARY AND EXPLANATION OF HYDRAULIC TERMS

Aqueduct. A structure built to convey the canal across a stream. The canal in the aqueduct crossing was reduced in width as in a lock to that required for the passage of a single boat.

Berm (Berme) bank. That embankment of the canal opposite the towpath embankment. In the original Erie Canal, the berm bank was 5 feet wide at the crest, the towpath bank 10 feet wide. (U.S. usage.)

Bypass weirs. The water discharged down a canal in lockages, together with gate leakage, was not enough to furnish adequate water for canal losses. Hence, each lock was equipped with a weir whose crest was at the water level of the upper pound and which led to a channel around the lock to the lower pound. The bypass weir, usually on the berm bank side, kept the canal from overflowing the locks.

Combined locks. A staircase of lock chambers without intervening pounds. The upper gate of one chamber is the lower gate of the chamber next above, and so on.

Culvert (see also "paddle"). A structure built to convey a stream under a canal embankment.

Locks in the original canal are shown in plan on figure 7, and listed in the section on "Feeders, locks, and stream crossings." Lock chambers needed to be of about the same volume, in order that water discharged from the higher into the lower pound would equal that needed to fill the lower lock and so on.

Paddle. Movable shutter for admitting or draining water from the locks. On the original Erie Canal, the paddles were slide valves on each leaf of the miter gates, a type called gate paddles. Valves installed in pipes passing around the gates, a feature of later built canals, are called culvert paddles.

Pound. The "level" or reach between locks. The term "pound" conveys the idea that the canal reach contains water impounded by the lock gates. The pound reaches were therefore important in storing and conserving water. If pounds were too short, then emptying or filling lock chambers resulted in considerable variations in water level and required either release of water from upstream to maintain navigation depth or resulted in spill over the waste weirs to discharge excess water.

According to the Commissioners (Report dated 27 Feb. 1822, p. 11), the design sought was to space locks so that pound reaches were at least 40 rods (660 feet) long, not only to save water but so as to "prevent injurious delays in the passage of boats." In this case, the volume of water in a single locking would not result in a change in water level of more than 6 inches.

Nevertheless, short pounds existed in the long tier of locks in the reach between Albany and Schenectady (see fig. 3); Jervis (1877, p. 52) refers to his efforts to correct the lock spacing there during the enlargements begun in 1836.

Side cut. A lateral canal connecting a canal with some adjacent river, stream, or canal.

Waste weirs were installed along the course of the canal, where it crossed a natural drainage course, at a level somewhat above the operating level of the canal. These weirs, usually 20–50 feet long, were installed to discharge flood waters that might enter the canal from the many small runnels that led into it, and from hillside drainage. They would also come into operation whenever the inflow into the canal from the feeders was in excess of the capacity of the canal and the bypass weirs at the locks.

Widewater; wind. A widened stretch of canal to permit barges to pass, turn about, or lay by. Basins were widewaters constructed with docks to serve as harbors.

HYDROLOGY AND ENVIRONMENTAL ASPECTS OF ERIE CANAL (1817-99)

By W. B. Langbein

ABSTRACT

As the first major water project in the United States, the old Erie Canal provides an example of the hydrological and environmental consequences of water development. The available record shows that the project aroused environmental fears that the canal might be impaired by the adverse hydrologic effects of land development induced by the canal. Water requirements proved greater than anticipated, and problems of floods and hydraulic inefficiencies beset navigation throughout its history. The Erie Canal proved the practicality of major hydraulic works to the extent that operations and maintenance could cope with the burdens of deficiencies in design.

The weight of prior experience that upland streams, such as the Potomac and Mohawk Rivers, had proved unsatisfactory for dependable navigation, led to a decision to build an independent canal which freed the location from the constraints of river channels and made possible a cross-country water route directly to Lake Erie.

The decision on dimensioning the canal prism—chiefly width and depth—involved balance between a fear of building too small and thus not achieving the economic potentials, and a fear of building too expensively. The constraints proved effective, and for the first part of its history the revenues collected were sufficient to repay all costs. So great was the economic advantage of the canal that the rising trend in traffic soon induced an enlargement of the canal cross section, based upon a new but riskier objective—build as large as the projected trend in toll revenues would finance. The increased revenues did not materialize.

Water supplies were a primary concern for both the planners and the operators of the canal. Water required for lockage, although the most obvious to the planners, proved to be a relatively minor item compared with the amounts of water that were required to compensate for leakage through the bed and banks of the canal. Leakage amounted to about 8 inches of depth per day. The total quantities of water taken into the canal made it the largest hydraulic undertaking of the 19th century in the United States. The diversion of water to factories that were attracted to the canal as a source of hydraulic power added to the water requirements. Although new feeders and reservoirs to extend the supply were built throughout the canal's history, these efforts to cope with water shortages were never fully successful. The

primary cause of the persistent deficiencies in supply was the method used to estimate the available flow of the streams during extended dry spells. *Ad hoc,* spot measurements of streamflow consistently led to overestimation of the dependable supply.

There was a persistent hydraulic problem as well. The cross section of the canal, especially when obstructed by many barges, was inadequate to convey the large volumes of water needed to maintain navigable depths over the long distances between feeders.

The major flood problem was caused by cross-drainage—the small creeks that crossed under the canal in culverts. Washout of culverts was a never-ending source of sporadic disruption of traffic of 1 or 2 weeks duration. Repairs and replacements could not cope with the problem created by deficiency in information about the flood potentials of the small streams.

A fortunate occurrence of severe floods in 1817 at the start of canal construction provided such clear and persuasive evidence of the flood potentials of the Mohawk River, which the canal followed for about 110 miles, so as to compel putting the canal at a high level in difficult terrain.

Environmental anxieties, broached early in the planning of the canal, centered on the potentially adverse effects of land development and deforestation on floods, water supply, and erosion. The flow of rivers did not decrease as originally feared. Land use did not increase the intensity of flooding and so endanger the canal. Viewed first as a conveyor of pure water from Lake Erie to the State, water in the canal became polluted by the wastes from the persons and animals involved in operations. The extent of pollution, however, was within the oxygen assimilation capacity of the water and the canal did not become septic. The canal contained fish life, but its role in the migration of the troublesome sea lamprey and alewife to the Great Lakes remains unclear.

Among the large set of effects of the canal upon the water environment that took place but that had not been considered in the planning or design were those on river flows, landforms, ground water, vegetation, and fish migration. The overriding fact that the initial anxieties of the planners proved unwarranted and that environmental conditions did not become intolerable by the standards of that time probably led to neglect of consideration of environmental risks in subsequent public works practice during the 19th century.

INTRODUCTION

A review of the hydrologic consequences of water projects can be useful in forming public policy. Through such reviews one may determine whether performance matched expectations, whether the influences upon and by the environment were within acceptable limits, and whether maintenance and repair were increased because of inadequate information for design. The growing concern about what is happening and what might happen as a result of water development inspires increasing interest in a hydrologic post-audit of earlier water projects. As the first major water project in the United States, the old Erie Canal offers opportunity for such a post auditing. Sufficiently removed in time, the hydrologic-environmental gains and losses now may be examined without evoking current economic or political contentions.

The hydrologic issues involved in the planning, design, and operation of the project remain relevant. The proposal to build the canal aroused environmental fears lest it become a victim of the adverse hydrologic effects of the expected development of land that the building of a canal would induce. The project design failed to anticipate the problems of water supply, floods, hydraulic inefficiencies, and sedimentation that beset navigation throughout its history. None proved fatal for the Erie, and its endurance demonstrated the feasibility of major hydraulic works in this country.

A bold undertaking, the Erie Canal fit terrain and technology to the needs of trade. Despite unending hydrological difficulties the canal fulfilled the primary purpose of inland canal service. Bulky products of farm and forest moved down the canal to tidewater; returning barges carried manufactured goods for the growing farms and cities of the Midwest, together with immigrants to swell the east-west cycle of trade.

Figure 1 shows that only in New York is there a westward-leading saddle that is below 500 feet in elevation. Few facts about the topography of New York were as well and early known as the potentials of the New York pass. The Surveyors-General of the Province of New York and of the State of New York referred to it on several occasions. In 1768, Governor Sir Henry Moore sent to the legislature his recommendations for the improvement of "commerce with the interior part of the country" by making the Mohawk River navigable. The Western Lock Navigation Company, chartered in 1792 for this purpose, built locks and sluices around the Little Falls and at German Flats on the Mohawk River and built a canal across the short saddle at Rome (Fort Stanwix) to connect the east-flowing Mohawk with the west-flowing Wood Creek. (See fig. 2.)

These works were not successful. Attempts to remove riffles and other river bars were fruitless. Frequently disrupted by uncertain river behavior and by floods, droughts, and other vagaries of the river regimen, transportation fell far short of the opportunities for trade.

Yet the demands became urgent, as the geographical possibilities made New York sensitive to the potential diversion of the trade of the Great Lakes region to the port of Montreal. This anxiety was shared with equal intensity by the colonial governor,

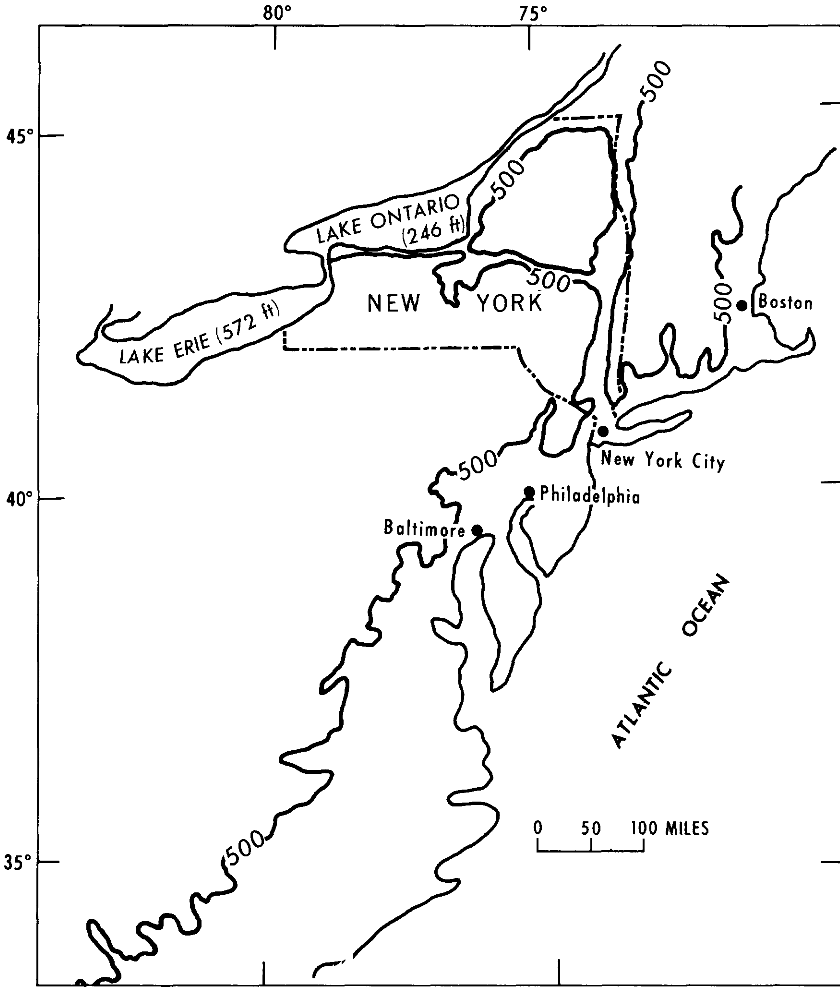

FIGURE 1.—Map of eastern seaboard showing 500-foot contour configuration. Datum is mean sea level.

Sir Henry Moore, and by the revolutionary patriot Gouverneur Morris[1] who, among others, early in the 19th century, began to promote the concept of an independent canal—one free of natural watercourses—from tidewater up to Lake Erie at an elevation of 572 feet above mean sea level and above the falls at Niagara. This scheme would open up the vast Great Lakes region to the port of New York and offer that city a trading region greater than that tributary to any other American port.

[1] Spelling in the report published in 1811 is "Governeur" Morris.

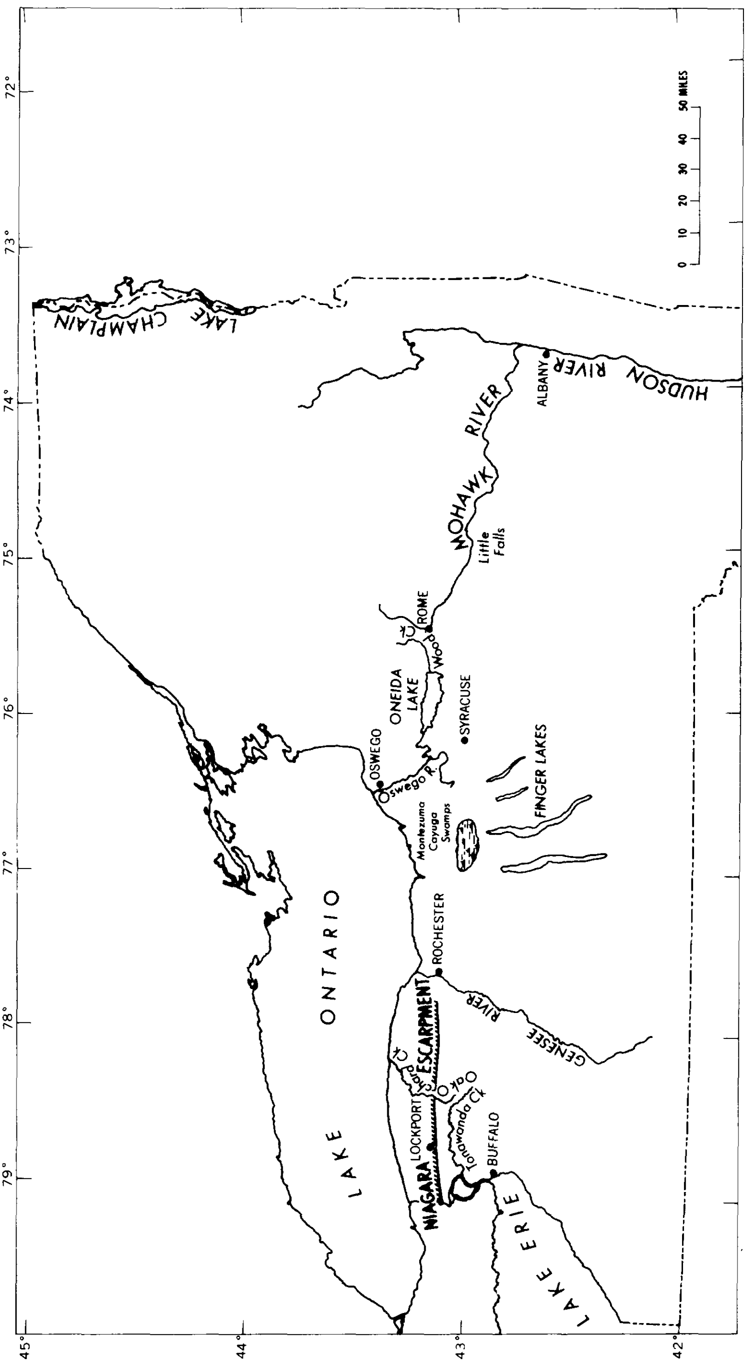

FIGURE 2.—Map of New York State showing principal geographical features referred to in this report.

Even so, the seemingly obvious facts of geography contributed to the many uncertainties and controversies about the scheme at this promotional stage. Why go west overland all the way to Lake Erie? Would it not be simpler and less costly to adopt a shorter route down the valley of the Oswego River to Lake Ontario? Such a route was indeed described in 1808 by Albert Gallatin, Secretary of the Treasury. His report also described a canal around Niagara Falls that would provide navigation between Lake Ontario and Lake Erie. In addition, there were the environmental fears already mentioned, and uneasiness about the economics of the proposal. Finally, and most important as events proved, was the prospect of a railway described as early as 1812 by John Stevens with a warning of early technological obsolescence of a canal.

Again, the clear and present advantages of a canal continued to stimulate action. There was evidence of the effect of canals on the economy and technology in Great Britain where the canal age was reaching its fulfillment in lowering drastically the cost of coal, iron, and limestone, the raw materials of the emerging iron and steam age.

Moreover, the horse-drawn canal barge represented a proven performance that was an order of magnitude greater than that of road haulage. A team of four horses on a common road could haul 1 ton 12 miles in a day, or 1½ tons on a "turnpike" with a 5-degree ruling grade. As an example, a five-horse team hauled 3 tons in 3 days over the 75-mile turnpike from Columbia, Pa., to Philadelphia (Ringwalt, 1888, p. 33). By contrast, one horse could draw a 30-ton barge on a slackwater canal at a steady rate of 2 miles per hour. Most of the lift required to raise goods "uphill" was provided hydraulically.

These prospects for improved transport seemed sufficient in 1808 for the State legislature to authorize surveys for routes between the Hudson River and Lake Erie, to Lake Ontario, and northward from Albany to the St. Lawrence River by way of Lake Champlain. Thus began the serious processes of information gathering and report making.

The information gathering naturally enough began with reconnaissance of topography (lines and levels), but more detailed information had to be obtained. Water would be needed to fill and maintain a canal; information would be needed about the earth and rock materials to be encountered or avoided in its construction, and about potential threats from floods and erosion.

There were two basic reports. The first was that of the Commissioners of 1811, appointed by the State legislature in March

1810 "to explore the route of an inland navigation from Hudson's River to Lake Ontario and Lake Erie." The seven Commissioners were headed by Gouverneur Morris, who had been one of those who participated in the Constitutional Convention of 1787. Their report issued in 1811,[2] of which Morris was the putative author, was based on some surveys made in 1808–9, and on a trip made by the Commissioners by batteau, stage, and foot over the entire 360-mile length. The second report was prepared by the Commissioners of 1816, "to provide communication by canals and locks between the Hudson and Lake Erie, and Lake Champlain," De Witt Clinton, chairman. Clinton, who had been one of those who served on the Commission, headed by Morris who died in 1816, became the force in promoting the canal project.

In the space of 38 pages, the Commissioners of 1811 described the geography, the economics, and the competitive situation *vis-a-vis* Canada. They concluded that a canal should be independent of rivers, and that conclusion made feasible the recommendation of a route directly to Lake Erie. Their report included estimates of the cost. What today would be called a planning report, it set loose a great deal of argument. Some of its dramatic "ahead-of-the-times" proposals became subjects for ridicule and proponents of the canal feared such ideas might endanger the canal proposal. Although it omitted mention of a railway alternative to a canal, then already in prospect, it raised other technological issues that surfaced from time to time over the years long after the canal was built. For example, the report identified the water-supply potentials of a diversion of water from Lake Erie to the Hudson River. It recognized the potentials of a ship canal across the State, and voiced environmental questions in clear language. But chiefly it represented in inchoate form the kind of preliminary "think-tank" report that is now often considered a desirable part of water planning.

The second report (1816–17 Assembly Jour., 40th sess., p. 313 et seq),[2] that of the Commissioners of 1816, under De Witt Clinton as chairman, completed in the light of the arguments and published debate induced by the first report, accepted its main recommendations for an independent canal to Lake Erie. This report presented the final choices for the project. Incorporating the results of the additional topographic and soil surveys, the report also set out the yardages of excavation and fill, and estimated

[2] Commissioner's and engineer's reports were published in the journals of the Senate or the Assembly until 1829 and thereafter as legislative documents. Many were also published as separate monographs. A compilation of early reports and statutes was published by the State in 1825.

costs, reach by reach. The Commissioners of 1816 and their engineers took advantage of experience on the Middlesex Canal, 27 miles long with 20 locks, that had been built in 1803 to join the Charles River at Boston with the Merrimack River. Today this report would constitute what is called "project formulation and design." Unknowns would have to be resolved during construction and later during operations.

The project was authorized and begun in 1817. When completed in 1825, the canal had a length of 363 miles, and 81 lift locks. As shown on figure 3, the canal, 40 feet wide and 4 feet deep, ran from tidewater at Hudson River near Albany, through a staircase of 20 locks, to the Mohawk River at a point above Cohoes Falls (elev 160 ft), thence following the valley plain of the Mohawk until it reached the saddle between the Mohawk drainage and the Great Lakes drainage at about 420 feet elevation near the present city of Rome. From the Rome saddle, the canal went directly westward, now crossing rather than paralleling the natural drainage. The formidable 65-foot Niagara escarpment of limestone (then called the mountain ridge) was crossed by a set of double, combined locks at a place to be called, descriptively enough, Lockport. Turning south, the canal entered Lake Erie at Buffalo, elevation 572 feet, and so earned its name from its Lake Erie destination, as

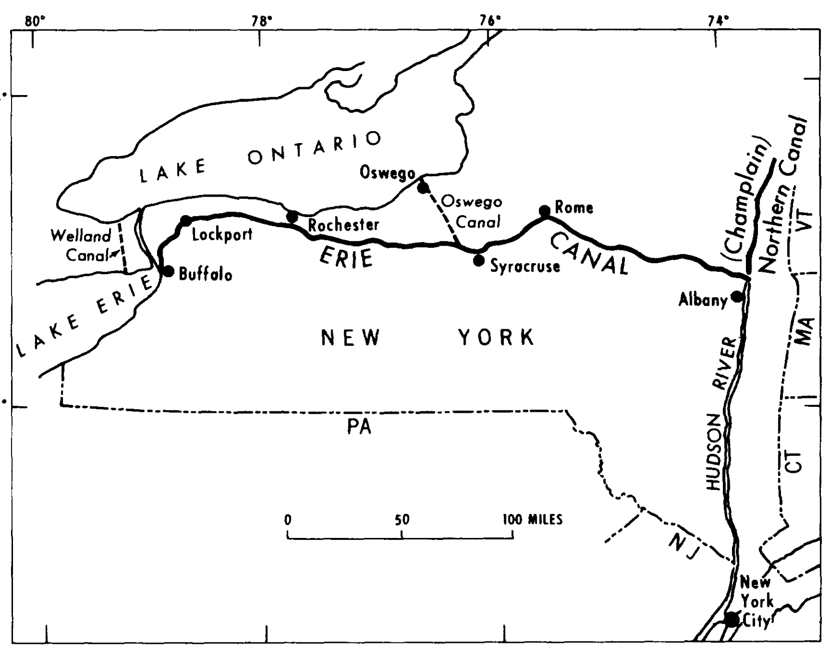

FIGURE 3.—Route of the Erie and Northern (Champlain) canals.

was the custom of the times in naming roads. As constructed, the canal permitted the passage of boats 78 feet long, 14 feet wide, and of 3 feet 6 inches draft, but boats at first were only 70 feet long and 7 feet wide with a capacity or burden of 30 tons, the same as those customary on the British canals. By standards of the time, the Erie was a "broad" canal. With steadily increasing traffic, the canal was widened and deepened over the years 1832–65 in virtually its original location and levels to permit the transport of barges of 240 tons. Transport tonnage reached its peak in the 1880's. In 1899, George W. Rafter expressed the following conclusion in a report of the U.S. Geological Survey (Water-Supply Paper 24, p. 13):

> Erie Canal has not only passed its day of usefulness, but, to some extent, stands in the way of future development, the chief cause for this being a too pronounced regard for the canal's former greatness.

Nevertheless, early in the 1900's in an effort to revive its former role in the economy of the State, the canal was again enlarged. This time, the Mohawk River was canalized for lock and dam navigation by self-propelled barges or barge tows. Called the State Barge Canal, it has little resemblance hydrologically to the former Erie Canal. The old and the new have chiefly in common that they carry about the same tonnage.

The basic record of design and performance is to be found in the annual reports of the Canal Commissioners to the legislature. A summary of the political and administrative history of the Erie Canal, as well as biographical material, is well documented by Whitford (1906) and its economic influences were more recently analyzed by Goodrich and others (1961). There are many other histories of a popular sort. None are analytical of its intrinsic hydraulic and hydrologic character.

This account looks at the water use and the water problems of its operations. The first section analyzes the primary decisions that centered on such fundamentals as the route—to Lake Ontario or to Lake Erie; the profile—a graded, inclined plane or one that follows the terrain; and the size—balancing between the faults of being too small or too expensive. The main sections of this report review the hydrological and environmental consequences of the design and operations.

The Erie Canal is usually considered to be a successful engineering project. And so it was, but only to the extent that operations and maintenance could cope with the burdens of its deficiencies of design, and to the degree that it became neither an environmental victim nor a source of environmental disaster. As to matters of current concern, the hydrological history of the Erie Canal provides insight on:

1. The operational problems that resulted from undertaking a major water project without proper hydrologic data.

2. The outcome of unfavorable environmental projections made at the start and the probable subsequent effect of this outcome on environmental assessments of water development in the United States.

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PRIMARY DECISIONS

The facts of geography were strong influences upon the building of the canal, but not so strong as to resolve all issues. As in most publicly sponsored water projects, there were divergent regional views; for example, the downstate-upstate debate (Goodrich and others, 1961). Farmers in the southern part of the State, anticipating that cheap agricultural produce from the western part of the State would depress prices, preferred a low cost canal to Lake Ontario or none.

Less in the public view but, as things turned out, of greater import was an argument of a technological nature. The now classic argument between the merits of inland seasonal navigation and those of railroads began even before rail lines existed. The controversy emerged with a published letter from John Stevens (1812), the Hoboken inventor, to Gouverneur Morris, Chairman of the Commissioners of 1811, advising that a relatively small research investment in a steam railroad would forestall the early obsolescence of the canal. Stevens explained the principles involved—for example, that the square law of resistance does not apply to motion on rails as it does to motion through water, and that a rail line is more flexible in location of route and is usable all year. The proposal was not taken seriously because canals, towpaths, and horses were known from long British experience to be a proven technology, whereas rails were still only an untested concept. Anticipation of technological change to this time is not a part of water planning in the United States (White, 1969).

The clear and present advantages of building a canal seemed to be greater than the political and technologic uncertainties of the future, so the project moved toward approval. The Commissioners of 1816 appointed to design a canal, needed only to address those engineering matters that were necessary to give physical bounds to their proposal—to adapt the project to the terrain. Thus they proceeded to resolve such fundamentals of water engineering as choosing between an Ontario canal or an Erie canal and between a ship or barge canal; selecting the profile and the route location; and, finally, the cross section—deciding on the width and depth of the canal.

AN ONTARIO CANAL OR AN ERIE CANAL

Far from determining the form the project eventually took, the geography actually seemed to dictate an entirely different and seemingly easier and less expensive alternative (Goodrich and others, 1961). From the earliest times, inland navigation meant the use of navigable rivers and lakes. And so it has generally been in this country where rivers, especially the great continental streams and the Great Lakes, were main avenues of settlement and commerce. It was therefore natural enough to view the geography of New York State in that way—the immediate object being the transport of goods from tidewater in the Hudson River at Albany, across the topographic saddle at Rome, to the Great Lakes region. However, navigation on the upland streams, such as the Mohawk River, encountered many difficulties in passing from pool to riffle, and as the river levels varied between flood to drought. Altering such rivers to improve navigability nearly always involved the construction of lift (double gate) locks to avoid natural falls, riffles, or other obstructions to navigation. River water above the falls was diverted into a canal or sluice, and thence through a set of lift locks leading to a sluice that returned to the river below the falls. Such improvements had been made in the 1790's to permit boats to avoid Little Falls on the Mohawk River and Great Falls on the Potomac River near Washington, D.C. (Civil Engineering, 1972).

A look at a map of New York State (see fig. 2) would therefore suggest a low-cost scheme that would use the natural watercourses —the rivers and lakes. One would put sluices and locks around local obstructions to navigation along the Mohawk River, across the Rome summit, thence by way of Wood Creek, Oneida Lake, and

Oswego River to Lake Ontario. Sluices and locks would also be built around Niagara River and Falls between Lakes Erie and Ontario. But the prospects of substantial savings in cost were lessened by the very considerable changes in elevation required, 150 feet down from the Rome summit to Lake Ontario, and then 326 feet up from Lake Ontario to Lake Erie, in addition to the 420 feet up the Mohawk River to the Rome summit.

Moreover, experience in Great Britain and on the Mohawk and Potomac Rivers in the United States in the 1790's proved that river improvements were thoroughly unsuccessful. The navigability of a river in its natural state between sluices is highly variable, being subject to disruption by flood, drought, and sedimentation. This experience in Great Britain had led to the adoption of independent off-river canals. Their success was proven by the Bridgewater canal, built in the 1760's for the transport of coal to the factories of Manchester. The advantages of independent canals were conveyed in a letter from Benjamin Franklin, written from London on August 22, 1772, to the mayor of Philadelphia (Ringwalt, 1888).

They look on the constant Practicality of a Navigation allowing Boats to pass and repass at all Times and Seasons, without Hindrance, to be a point of the greatest Importance, and, therefore, they seldom or ever use a River where it can be avoided * * * Rivers are ungovernable things, especially in Hilly Countries. Canals are quiet and very manageable. Therefore they are often carried on here by the Sides of Rivers, only on Ground above the Reach of Floods, no other Use being made of the Rivers than to supply occasionally the waste of water in the Canals.

Franklin's description fit that of the Bridgewater and other English canals (Hadfield, 1968, p. 39) that followed the contours along the valley sides, passing from one river drainage to another by crossing low saddle divides that separated one catchment from another. These schemes worked.

Convinced by the evidence that to use "the beds of rivers for internal navigation" was impractical and inefficient, the Commissioners of 1811 rejected that practice right at the outset of their report (p. 3–4). This decision was correct then and for the reasons given. With this decision for an independent canal, the course, profile, dimensions, and flow of the State's inland rivers no longer governed, and a choice of routes became possible. This is the kind of decision that might have been costed out; but policy issues prevailed. The route by way of Lake Ontario was rejected. A direct route to Lake Erie was adopted to avoid the feared possibility that shipping afloat on Lake Ontario might be diverted by way of the St. Lawrence River to market at Montreal. An independent canal as a waterway across the State then created a need for numerous subsidiary yet still major decisions, especially those concerning size, profile, and route.

SIZE

As a first approximation of size, the Commissioners of 1811 considered the possibility of a "sloop" (that is, ship) canal, by which was meant prism dimensions sufficient to accommodate vessels capable of navigating upon the Great Lakes and the Hudson River, thus avoiding the costs of cargo transfer to and from small canal barges. However, it was evident to the Commissioners of 1811 that

> "If the passage were only a few miles, the propriety of bringing vessels of 8 feet draught of water across, if practicable, would be readily admitted; but it may well be questioned whether to save the expense of lading and unlading at each end of a canal three hundred miles long, the expense of cutting two yards deeper than would otherwise be necessary, ought to be encountered." (p. 20)

The canal was therefore to be designed for barges. As will be described, the ship-canal idea remained viable during the 19th century and into the 20th century.

PROFILE

A canal leading directly to Lake Erie, some 570 feet above the level of the Hudson River, offered the prospect of a bold, single-stroke resolution of decisions as to profile and water supply. Such indeed had been recommended by the Commissioners of 1811 in the following terms:

> "The difference in level (from Lake Erie to the Hudson) being upwards of five hundred feet, all the descent which can prudently be obtained by an inclined plane, is so much saved in the expense of lockage; and in all human probability, the transportation for centuries to come, will be of so much greater burden from the interior country than back from the sea, that a current from the lake is more to be desired than avoided, more especially as it will, in some degree, counteract the effect of frost." (p. 21)

With depth and width considered in a qualitative way so that the friction would counteract the tendency for velocity to accelerate, and with preliminary caution, the Commissioners assumed hypothetically that a canal should have an average descent of 6 inches per mile (p. 24). According to their levels, the grade would pass above Cayuga Lake outlet by some 150 feet and clear above the Rome summit by 42 feet. The canal would follow the hillsides above the river valleys (especially the Mohawk) and when it was necessary to cross major river valleys, as, for example, the outlets of the Finger Lakes, or the Schoharie, a major tributary of the Mohawk, rather large embankments and aqueducts would be required. This grade would leave about 350 feet to be accomplished in locks or an inclined "railway" in the reach between Schenectady and the Hudson where (p. 35) "water used for machinery would probably yield a rent sufficient to keep the canal in repair."

They rejected the plan of a locked canal fed by rivers along the route in order to avoid any dependence of the canal upon rivers for supply and especially to avoid the effects of the anticipated decrease in the flow of the streams to result from deforestation and farming (p. 20). Therefore, in further explanation of a graded canal, they state:

> "In a word, if, on due examination, a thing of this sort should be found practicable, instead of depriving the country of water, every drop of which is needed by its inhabitants, they will gain a great addition from the canal." (p. 26–27)

Thus, in 1811 the notion was already afoot to use the canal to convey water as well as traffic.

To save lockage, the Commissioners took the greatest slope they considered wise, and in a canal 4 feet deep, at a grade of 6 inches per mile, the velocity would be about 1.5 feet per second (1.0 mph)—somewhat large for a horse-drawn barge. Had the Commissioners included locks to accomplish part of the fall, their profile could have been significantly lower and still have cleared the Rome summit. Another factor also made the scheme impractical at that time. One can now calculate that to supply the water needed for leakage over a 360-mile length from Lake Erie would have required a cross section at its western end sufficient to convey a flow of the order of 600 cubic feet per second. If velocity were to be kept below 1 mile per hour, a section about 5 times larger than that actually built would have been necessary. The Commissioners had little comprehension of the hydraulics of their scheme.

Although the Commissioners of 1811 repeatedly emphasized the need for more detailed study and examination and modified their profile in their report of the following year, the proposal became the subject of considerable ridicule that put the whole project in jeopardy. The Commissioners of 1816 (1816–17 As. Jour. 40th sess., p. 313–355) therefore adopted the more practical scheme of a locked canal that closely followed the terrain. The profile shown on figure 4 follows the general land surface and, although generally downward from west to east, has a pronounced sag in the central part of its profile. This dip prevented the flow of water from Lake Erie eastward, and created the need to develop feeders from rivers along the route in order to cope with the never-resolved water-supply problem, as will be described.

ROUTE LOCATION

After the decision to build an independent locked canal from the Hudson River to Lake Erie had been made, the job was to fit the route to the terrain. The main features of the topography to affect the choice of location were the narrowness of the Mohawk River valley leading from the Hudson River at tide level to the summit level at Rome (elev 420 ft msl); the sag in the profile to about 360 feet elevation in the middle or lake division; the north-facing Niagara escarpment in the western region; and finally the elevation of Lake Erie at about 570 feet above msl. (See fig. 4.)

The route itself was examined in detail by the Commissioners of 1816, who resurveyed and marked the whole route and sank test pits at a number of places to ascertain the nature of required excavation. The Commissioners' report laid out section by section the yardages of excavation and fill, the kind of excavation (earth, marl, rock), and gave directions for many details such as location of the towpath (north or south) and stone work for the culverts. Warnings were given about possible problems with floods and stability of embankments, and of the possible need for feeders (water supply) along the route in addition to that to be fed at summit levels.

Among the many difficulties presented by the terrain to the construction of the canal, there were three of major proportions—the "Noses" or promontories along the Mohawk River where the river flowed against the steep rock wall; the extensive swamps in the middle or lake division; and the deep rock cut in the western or dry division. The broad, flat saddle composed of alluvial deposits at the Rome summit was recognized at the start as the most favorable feature of the terrain. The strategy was to begin there, and

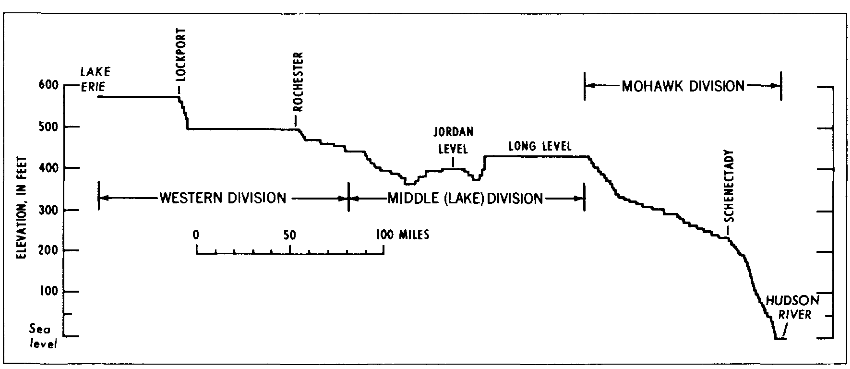


FIGURE 4.—Longitudinal profile of the Erie Canal.

so quiet the residual opposition to the canal project by rapid progress.

MOHAWK VALLEY

In keeping with the decision for an independent canal, a route was sought along the narrow valley separate from the river. The canal followed the south or right side of the river for it offered the fewest difficulties. The main challenge was to find space above the flood levels of the river. In 1817, when construction began, the Mohawk River valley was subject to extensive inundation "as if, to indicate at the commencement, by the height, impetuousity, and durability of the greatest floods, the exact dimensions and strengths of the works necessary to discharge or resist them" (1818 As. Jour. 41st sess., p. 68). In modern terms, the flood of 1817 became the design flood. In adhering to the south or right bank, the canal had to pass by rock spurs such as the Noses that crowded against the river. In these places, the canal had to be built up along the river upon a foundation laid on the river bed and protected by stone work against cutting by the river. In such exposed locations the canal was also subject to damage by wash of loose rock and overburden from the steep valley sides.

In retrospect, the problems encountered in the Mohawk Valley inspired the Commissioners to observe in their report for 1824 (As. Jour. 47th sess., p. 547), that

> Had this section been commenced originally while information on the subject of constructing canals was merely theoretical, it is probable that the attempt to complete it would either have been entirely abortive, or so imperfectly executed as to have defeated, and perhaps postponed for a century, the accomplishment of the great work of internal improvement * * *

MIDDLE (LAKE) DIVISION

For some 60 miles west of the long summit level where the canal crossed the saddle from the Mohawk at an elevation of about 420 feet, the valley bottoms lay below 400 feet elevation and below the levels of the Finger Lakes whose outlets flowed northward through extensive swamps. This region is a sag in the generally uphill profile from the Hudson River to Lake Erie. It is poorly drained. The valley bottoms are composed of marl—a limy clay—of post-glacial origin. "The marl varies in color from a pure white to a yellowish white. It is handled readily when dry or plastic, but becomes very slippery when wet." (Landreth, 1900, p. 576.) Coupled with standing water, this material was troublesome and the builders of the original canal wisely tended to follow a side-hill position at the edge of the swamps, closely hugging the hills composed of glacial sands and gravels (fig. 5).

The Commissioners made repeated reference to the difficulties encountered in excavation along these wet lowlands—along the Montezuma-Cayuga Swamp, and along those that border the Seneca River which receives the outlets of Finger Lakes and is the master stream of the region.

The difficulty of cutting through 11–12 miles of wet meadows from Ninemile Creek (outlet of Otisco Lake) to Skaneateles Outlet induced the builders to raise the level of the canal in that reach, a decision that required the introduction of a short summit level called the Jordan level (see fig. 4) (1819 As. Jour. 42d sess., p.

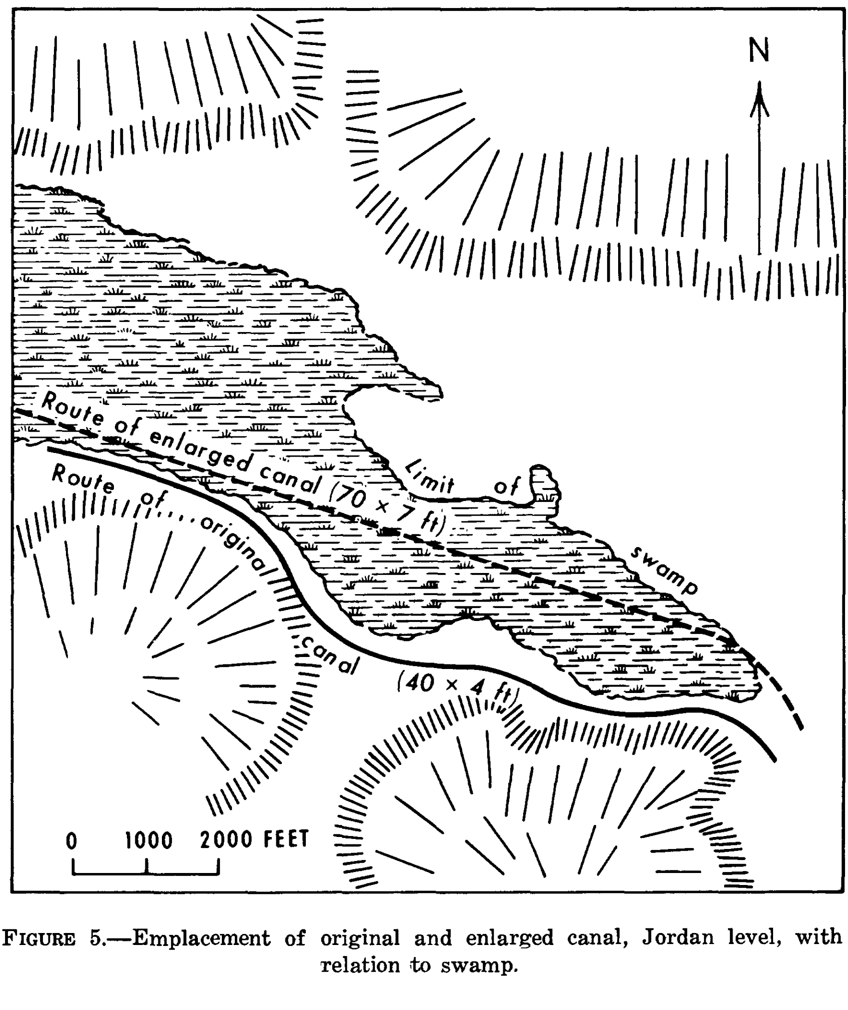


FIGURE 5.—Emplacement of original and enlarged canal, Jordan level, with relation to swamp.

201–202). The Jordan summit level—a local summit in a sag in the profile—was retained throughout the 19th century period of operation of the canal. Soil and water problems did not end with construction because difficulties were created by bank slides and rising bottoms. Continued maintenance was required for navigation.

WESTERN DIVISION

The Commissioners of 1816 had laid out a route from a connection with Lake Erie at Buffalo, thence along the shore of the lake and of Niagara River to Tonawanda Creek. The proposed route then went up Tonawanda Creek (see fig. 2), and crossed the divide between that creek and the drainage basin of the Genesee River at an elevation 75 feet above Lake Erie. This route would introduce a summit at that level with additional locks up and down. It was recommended in lieu of an alternate route to the north that avoided the intermediate summit and its added lockage, presumably to gain the advantages of shorter length, easier construction, and lesser cost. In addition, the route passed through the lands offered by the Holland Land Company, owners of a large tract in the western part of the State.

Water supply at the summit level was, however, a critical matter as the Commissioners had warned. They accepted the measurements of flow made by Joseph Ellicott, one of the Commissioners, with a vested interest as a sub-agent of the Holland Land Company (Whitford, p. 79). The Commissioners reported that Ellicott

"had the sources of this supply gauged, with great care, during the driest part of the last season, which has been more remarkable for severe drought than ever before experienced in that part of the State. Independently of waters deemed sufficient to repair the waste occasioned by evaporation and soakage, these sources consist of ten streams naturally flowing or capable of being conducted to the summit level." (1816–18 As. Jour., 40th sess., p. 315.)

He found the flow of these 10 streams (not named) totaled 253,435 cubic feet per hour (70 cfs), an amount sufficient to "fill 673 locks every day." It was also suggested that the summit pound (see glossary), which covered 1,000 acres, would provide a reservoir of water to supplement the natural flow. The natural flow plus draft on the reservoir was then judged to be adequate for lockages (no account at that time was made of that required for leakage). The southern route was retained in the plan until 1820, when experience with the canal section already built at the Rome summit gave some indications that "more water has been wasted, in it, by evaporation, soakage and leakage than we had anticipated. And this discovery we deem, in itself, sufficient to settle the question, between the two routes." In further support of this decision, they added their fears that the flow of the streams available as feeders will diminish as the land is cleared for farming (1821 As. Jour., 44th sess., p. 868).

Choice of the northern route required crossing of the "mountain ridge" as the prominent north-facing Niagara escarpment was then called (why "mountain" is not clear—the escarpment is of the order of 60–70 feet). Still, there remained the question of levels. For the next year the Commissioners noted that

> "ideas about raising level in approach to the mountain ridge to save rock excavation and to have bottom of the canal at the same level as the surface of Lake Erie were abandoned when local feeders were deemed inadequate * * * after much pains, however, to gauge the streams during the last autumn (1821) we determined to adopt the lowest level and to construct the canal in the first place, so as to receive its supply of water from the lake." (Canal Commissioners' report dated 27 Feb. 1822, p. 11–12.)

Hence, a northern route was adopted that "nowhere rose above the level of Lake Erie," thus to maintain the lake as a source of water for the western division; but as explained in section "Hydraulic Computations," the flat slope from the lake to the escarpment limited the amount of water that could be drawn from the lake.

From Tonawanda Creek the northern route headed for a low point in the ridge, the notch made by a stream that the surveyors had named "Eighteen Mile Creek." With some 60 feet of fall to be taken in one step at the locks descending the ridge, of the 68 feet between the lake and Rochester, not much fall remained to give the necessary slope to the canal in order that, as will be explained in further detail, it could convey the water needed to maintain navigable depth. The remaining slope was literally to be measured in fractional inches per mile. Since lock lifts were then limited by hand-operated timber miter gates to about 12 feet, a tier of 5 chambers in timber was required to descend the escarpment. (See fig. 6.) Called "combined" locks, the upper gate of the lower chamber serves as the lower gate of the chamber next above. To save time and water (as will be explained under water supply), a double tier of combined locks was built at this point. The Lockport combines soon became one of the marvels of the canal.

Together with the rock cut for the approach, their construction involved the largest amount of rock excavation on the route, an important consideration in the days of hand drilling and black powder explosives. The removal of about 600,000 cubic yards of rock was the last excavation in the construction.

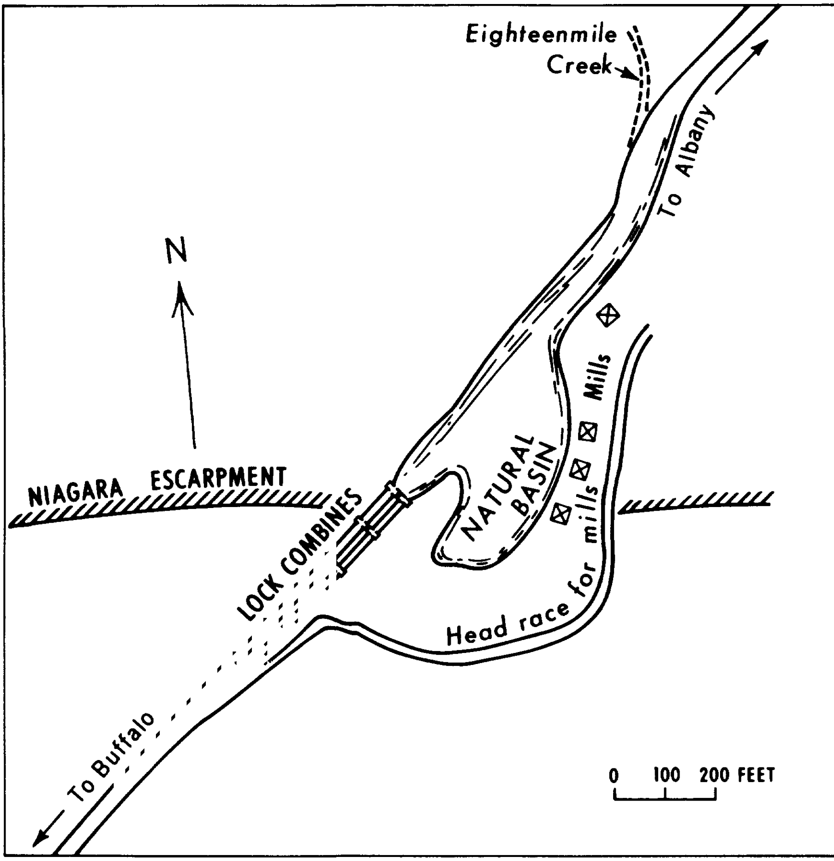


FIGURE 6.—Lockport.

The connection with the lake was made on the lake itself rather than along the Niagara River which was closer and which had been urged by the citizens of Black Rock (now incorporated with the city of Buffalo). This decision gained an extra 5 feet of elevation and so reduced the amount of rock excavation required into the hard Lockport limestone in the approach to the "mountain ridge." Even so, the Deep Cut, as it was known, extended for some 2 miles west of the Lockport combines. It became part of the tourist attractions at that point.

CHANGES

Aside from some canal shortening and reduction in the number of locks, the 1817–25 choices of route and profile remained throughout the 19th century. With independently powered barges and greatly advanced construction engineering, the 20th century alinement was changed to follow a canalized Mohawk River, and thence across Oneida Lake. The only change in profile was the elimination of the Jordan level. Canal building in New York State during the 19th century is outlined in the section "New York Canals in the 19th Century" along with a record of the decline of canal traffic for commerce and its growth for recreation.

DIMENSIONS OF THE CANAL—OPTIMALITY

Included among the decisions on route and profile there lay the issue of size—how wide and how deep? Should the canal be built with a small prism to wind easily about the hills and valleys and so to require only relatively low investment, or should the canal be built more substantially to profit by the economies of scale and to be more attractive to shippers?

At the time, canals in Great Britain were either "narrow" or "broad." Narrow canals were built for the passage of 30-ton barges, 7-foot beam by 70 feet long and 3 feet 6 inches draft; broad canals were for the passage of 100-ton barges of 13 feet 6 inches beam, 90 feet long and 3 feet 6 inches draft. The Commissioners of 1811 (p. 32) thought in terms of a canal prism 15 yards wide and 2 yards deep. The Middlesex Canal, built in 1793–1804 between the Merrimack River and the Charles River in Massachusetts, was designed for boats of 9.5-foot beam, 70 feet long, and 2-foot draft.

With this information available to them, the Commissioners of 1816 faced the problem of optimization among elements of costs that were relatively certain and expected revenues that were uncertain. The principles are classic: capital cost as well as maintenance cost increases with size of the prism; traffic capacity increases with size of prism as does the delay and uncertainty of actually putting that capacity to use. Estimates of cost were made at several reports in the range of $5 to $6 million, and in 1812, the Commissioners compared their estimated cost of $6 million with annual revenues expected to be $1.25 million and reasoned that income would be sufficient to cover costs. Some rough computations or at least imputations of how costs would vary with prism size were surely possible and may have been sketched by the design Commissioners of 1816. Nothing of that sort is referred to in their report, but one can piece out a schedule of costs from the record, as follows:

Prism (width by depth, in ft)	Annual capacity (million tons)	Estimate of construction cost (million dollars)	Amortization at 6 percent for 25 yrs (million dollars)	Estimate of annual operation and maintenance [1] (million dollars)	Total annual cost (million dollars)
30 × 3	0.5	3.5	0.27	0.03	0.3
40 × 4	1.5	6.0	.47	.06	.53
50 × 5	3.0	12.5	.98	.12	1.1

[1] Estimated at 1 percent of construction cost.

The costs were to be paid from revenues collected as tolls which, at the planning stage, would have been highly uncertain. The 1816 estimate of anticipated revenue of $1,250,000 per year would have been adequate for a 50×5-foot canal. But, recognizing the uncertainty of that estimate, comparisons would need to be made using conditions of traffic significantly smaller and larger than first assumed.

Prism (width by depth, in ft)	Annual cost (million dollars)	Revenue (million dollars) 50 percent smaller		Revenue (million dollars) 50 percent larger	
		Gross	Net	Gross	Net
30 × 3	0.30	0.62	+0.32	[1] 1.25	+0.95
40 × 4	.55	.62	+.07	1.62	+1.05
50 × 5	1.1	.62	—.48	1.62	+.52

[1] Limited by capacity to 500,000 tons per year at $2.50 per ton.

According to these results (1) a 50×5-foot canal would have been risky; (2) a 30×3-foot canal with a low traffic capacity, would have been fiscally "safe"; and (3) a 40×4-foot canal would have been fiscally solvent over a wide range of variation in revenues and had potential to accommodate a growing traffic if that might materialize. Some analysis such as this may have preceded the following recommendations of the Commissioners of 1816:

"The dimensions of the western[3] or Erie canal and locks, ought, in the opinion of the commissioners, to be as follows, viz. width on the water surface, forty feet, at the bottom, twenty-eight feet, and depth of water, four feet; the length of a lock, ninety feet, width, twelve feet, in the clear. Vessels carrying one hundred tons, may navigate a canal of this size; and all the lumber produced in the country and required for market, may be transported upon it." (1816–17 As. Jour., 40th sess., p. 313–314)

As shown on figure 7, the canal was built to these specifications, except that the locks were built 15 feet wide. (All locks except those in the Lockport combines were single.) In 1824 the Canal

[3] "Western" to distinguish the Erie Canal from the "northern" or Champlain Canal, constructed at the same time.

Commissioners (1825 Sen. Jour., 48th sess., p. 289–291) projected tolls to reach $1 million by 1836 and $2 million by 1846 with a potential annual revenue of $9 million. Enlargements were planned in 1836 when tolls had exceeded the projected $1 million and when traffic carried was about 700,000 tons, 50 percent of its capacity, and growing at an annual rate of about 45,000 tons. Thus encouraged, the Commissioners in 1841 projected revenues to increase from the then current $1.8 million to $3.5 million by 1852 (1842 As. Doc. 18, p. 9). Using the latter figure as the anticipated revenue for the enlargements, and with due regard for the higher costs of operations, one can set the following comparisons among alternate canal prisms based on data in the record.

Prism (width by depth, in feet)	40 × 4	50 × 5	70 × 7	80 × 8
Annual capacity ------million tons--	1.5	3.0	8.0	12.
Enlargement cost ---million dollars--	0	13.	32.	48.
Amortization (25 yrs at 6 percent) million dollars--	0	1.0	2.4	3.7
Operations and maintenance million dollars--	.35	.55	.75	1.0
Total annual cost ----million dollars--	.35	1.55	3.15	4.7
Anticipated revenue -million dollars--	[1] 3.0	3.5	3.5	3.5
Net revenue --------million dollars--	2.65	1.95	.35	—1.2

[1] Limited by traffic capacity of 1.5 million tons per year at $2 per ton.

The optimal economics would have been to retain the 40×4-foot canal. But optimism, one may judge, led to a decision to build a canal at the upper level of solvency—not the optimal net revenue, but the largest canal for which projected revenues would defray the costs. The results in the table may explain the decision to build a 70×7-foot canal.

This analysis omits consideration of the "secondary" benefits—that is those accruing to shippers and others benefiting from lower costs of transport. At a toll of $2 per ton (about 1 cent per ton mile) canal revenues captured only a small part of the benefits. Before the canal was built, wagon transport in the region ran about 20 to 70 cents per ton mile (Goodrich and others, 1961, p. 227–228). It was probably this latter point that showed in the political rhetoric of the day, but could not be included in any optimization scheme. The canal lost this competitive margin as railroads came into operation. Revenue from tolls averaged about $1.75 per ton until about 1850, it decreased to $1.17 by 1860, and to $0.75 in 1870. Tolls were eliminated in 1882.

As a result, the enlargement was not fiscally solvent as manifest in table 1 showing totals of revenues and costs (in millions of dollars) for the period through 1882 when tolls were eliminated

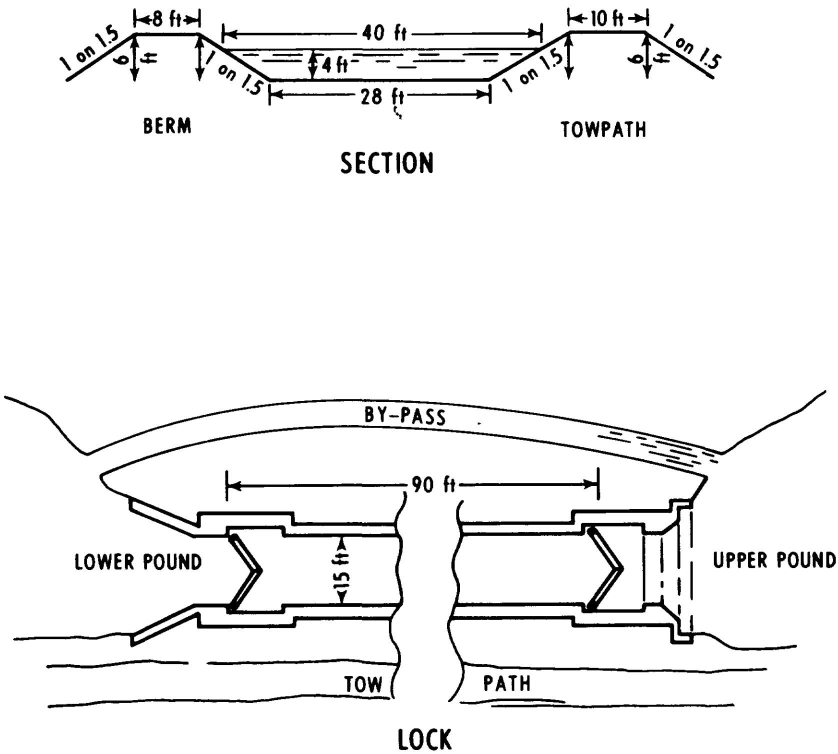


FIGURE 7.—Section and lock of original Erie Canal.

from the State canal system, and when tonnage carried had reached its historic maximum.

The upshot seems to be that the 40×4-foot original canal was efficiently sized considering the revenue constraints; that of the enlargement was designed at the margin of anticipated revenue.

TABLE 1.—*Revenues and costs for the original and enlarged canal (millions of dollars)*

	Revenue	Construction and improvements [1]	Interest on canal debt	Operation, maintenance, and ordinary repairs	Net
Original canal (1817–50 midway through enlargement)	42	9.0	7.5	7.5	+18
Enlarged canal (1850–82)	79	40.5	18.5	21.8	—2
Total	121	49.5	26.0	29.3	+16

[1] Includes extraordinary repairs.

Source: 1883 As. Doc. 4.

SUMMARY

The clear and present advantages of a canal to the general economy surmounted sectional opposition and a prediction of technological obsolescence. The weight of experience that inland rivers had proved unsatisfactory for dependable navigation led to a decision to build an independent canal which freed the location from the constraints of the river system and made possible a route directly to Lake Erie. With a connection to Lake Erie in prospect, it was natural enough to propose a canal profile as an inclined plane leading directly from Lake Erie at elevation 570 feet to the summit at Rome at elevation 420 feet and thence down the Mohawk Valley to the Hudson River at tide level. In concept, the scheme had two advantages; it would tap a copious supply of water for the canal which could serve as a source of water for future development of the State; it would avoid dependence of the canal for water supply upon the rivers along the route whose flow was expected to diminish as a result of deforestation. Far beyond the engineering capacity of the times, the inclined-plane scheme was rejected in favor of a profile that followed the terrain, thus introducing a sag in the lake or middle division, and requiring a continuous development of new feeders from the rivers to maintain navigation.

Terrain problems were difficult; the Mohawk Valley was narrow and offered little space for locating a canal above flood levels. The sag in the lake or middle division required excavation through swamps and wet ground. The western division involved either rock excavation through the 60-foot Niagara escarpment or a route up Tonawanda Creek introducing another summit in the profile which, in addition to eliminating Lake Erie as a source of water, created a new requirement for water. Faced with this choice, the decision was made to cut through the 60-foot rock escarpment, the last and hardest part of the 8-year construction project. The flat slope of the canal from the lake to the crest of the escarpment greatly limited the amount of water that could be drawn from the lake.

The decision on the dimensions of the canal—chiefly width and depth—involved a balance between a fear of building too small and thus not achieving the economic advantages sought, and a fear of building too expensively. The constraints proved effective and for the first part of its history the revenues collected were sufficient to repay all costs. So great was the economic advantage of the canal at the time that the rising trend in traffic soon induced an enlargement of the canal, this time with a new but riskier objective—build as large as the projected trend in toll revenues would finance. The expected revenues did not materialize.

SEQUEL

The two imaginative proposals considered when the canal was in the early planning but rejected in the design, were not entirely without merit as they surfaced again during the ensuing century. The first of these was that for building the canal as an "inclined plane" from Lake Erie to the Hudson. The scheme as it was presented by the Commissioners of 1811 would make the lake a source of water for the State. The same proposal was made again in 1883 by State Engineer Silas Seymour in his proposals to improve the canal, and then by his successor, Elnathan Sweet (1885 As. Doc. 38, p. 11). Its omission in the major alteration begun in 1905 was criticized in 1927 (Thompson, 1927) when the need for additional water supply for New York City was becoming a problem.

The Commissioners of 1811 also considered whether to build the canal to convey ships or barges. In view of the limited traffic expected, they recommended a canal built only for barge traffic, by inference leaving the option open when added traffic might make the construction of a ship canal feasible. Later, when the canal authorities sought means to prolong the usefulness of a canal, the proposal was made again by State Engineer Elnathan Sweet in 1885, without reference to his predecessors of 1811, as follows:

> "It is clear to me that the Erie canal, to become the permanent highway of this commerce, must have sufficient capacity to float the largest vessels navigating the great lakes (sic) from Lake Erie to the deep waters of the Hudson * * *" (1885 As. Doc. 38, p. 11.)

The proposal was reviewed again by the Federal Board of Engineers on Deep Waterways in 1900 (H. Doc. 149, 50th Cong., 2d sess., Dec. 7, 1900) and, still more recently, a news item in Civil Engineering for August 1974 states that the Great Lakes Commission is looking into the possibility of rebuilding the Erie Canal for ocean shipping and, for the same reasons the original canal was built, as a competitive alternative to the St. Lawrence route through Canada.

As will be described in the next section, water power competed with navigation for the water supply of the canal throughout the 19th century. All of these water powers were for direct mechanical drive at the mills. In a later time, when hydroelectricity became feasible, the potential for power generation was enhanced. It was then considered to combine a new and enlarged ship canal with power generation as a built-in facility, rather than a byproduct. In fact, Rafter (1905, p. 821) refers to a scheme for a "Great Eastern Canal" that would roughly occupy the route of the Erie on a graded profile (=inclined plane) from Lake Erie to Schenectady, where a dam across the Mohawk would impound water to a high enough level that a direct diversion may be made into the Esopus and Rondout Creeks, where further impoundments would divert water into Wallkill River and thence into the Delaware River, which would be dammed at Easton, and leading by other impoundments would link together the Erie Canal, the Delaware, the Susquehanna, the Potomac, and finally the James River, with waterway connections to New York, Washington, Baltimore, Richmond, Philadelphia, Trenton, and other cities in the region. But the canal was also to be the vast headrace of a hydroelectric scheme to develop 15 million firm horsepower. The idea is an early precursor of the recently proposed NAWAPA scheme (Sewell and others, 1967) proposed for building dams and canals of continental scope for water storage and water transport from Yukon Territory and British Columbia of western Canada to the central part of that country, to the western United States and to northern Mexico.

OPERATING THE CANAL

It is often said of public works that operations must repair the errors of design. And so it was for the Erie Canal. There were several major difficulties that related to its hydrologic and hydraulic character—the perennial gap between water requirement and water supply, the limitations of the canal section to convey needed water, the inefficiencies in the movement of traffic due to such unanticipated factors as hydraulic drag and flow blockage, and especially the frequent "detentions" of traffic caused by washouts of culverts.

Water to fill the canal and to refill the empty locks as boats passed from one level to another was the most obvious but not the major requirement. Although the Commissioners of 1811 warned that "more [water] will filter through the sides and bottom of a canal than those of a river, which are generally saturated" (p. 18), neither they nor the Commissioners of 1816 made any estimate of the quantity of water required to make up for the leakage and evaporative losses. Nor did a review of British experience (Sutcliffe, 1816) emphasize the matter of leakage, discussing water requirements mainly for lockages. The amount of water required for the operation of the Erie Canal proved to be far greater than first provided and additional supplies were sought over the years.

Annual maintenance, repairs, and improvements kept the canal viable, and the cost of these operations totaled to a sum that equaled the base investments in the building of the canal.

LOCKAGE

To fill the canal at the beginning of each navigation season was a single operation. But each time a barge moves through a lock, water moves from the upper to the lower level or pound. The same or equivalent volume of water can be used in a succession or flight of locks provided that the pounds are long enough to store—to impound—the lockage volume. (See Glossary for explanation of hydraulic terms.) Lockage volume, therefore, for each flight from summit to a sag or low point equals the prism of the largest lock times the number of boat passages, if all in one direction, or one-half the number of boats if the up-and-down passages alternate. Since the same volume of water can be used successively in each lock between summit and trough in the profile, and since the largest lock need only clear the largest vessel, the volumes of water required for lockage need not be great. The higher the lifts in each single lock (on the Erie, lifts averaged 8 feet), the fewer are the number of locks that are needed and hence the shorter the transit time, but at the expense of greater volume of water for lockages.

The amount of water for lockage was easily calculated. A typical lock chamber (see fig. 7) contained about 10,000 cubic feet. A total of 20,000 lockages alternating in direction represented a busy 220-day open-water season. These numbers are equivalent to a water flow of only about 10 cubic feet per second in each tier of locks. However, the demands at a summit for lockage could be critical, as water must be discharged in two directions. Consider two barges following each other ascending to the summit. Boat 1 leaves the top lock full as it enters the summit pound. After passing through the summit, it leaves the top lock on the down side empty. Following boat 2 then approaches the summit and finds the lock full (as it was left by boat 1), empties it, and then refills it, drawing off the necessary water from the summit pound. At the other end of the summit, boat 2 finds the first lock down to be empty, as boat 1 left it, and therefore fills it, goes down, and leaves it empty. Boat 2 therefore drew two lockfuls of water from the summit. A succession of boats in one direction could overdraw the available supply at the summit. At times, therefore, barges were detained at the summit, so that locks were filled or emptied only when occupied by a barge.

Time was saved at the cost of water by a process called swelling, that is, flushing "down" boats out of the locks by discharge of a small flow through the upper gate paddles. (Rafter, 1905, p. 792.) Although swelling was frowned upon when water was in short supply, it was sometimes necessary at just such times to produce a wave or swell in the lower pound to get grounded barges moving.

Water usage in locks separated by long pounds was minimized when up and down barges alternated. When the pound reaches were short, or as in the combined locks at Lockport where the lock chambers were in a tier without any intervening pounds or storages, then water use was minimized by having boats follow one another in the same direction. The tier of combined locks was built in parallel; an up staircase and a down staircase. Here, of course, one lock chamber of water is used for each up and each down boat. If, however, alternating passages were used on a combined lock, then the whole set of chambers would need to be filled or emptied for each passage.

The conspicuous leakage at the timber miter gates was not normally a serious problem, save at the last or bottom lock in a tier. A good flow of water was needed down the canal and what did not leak would otherwise spill over by by-pass weir at the lock. Depending on details of construction and fit, the quantities involved were highly variable; reported figures for gates in the old 40×4-foot canal with 8-foot lift (12-ft bottom gate) ranged between 380 and 1,000 cubic feet per minute (6 and 17 cfs). To give some idea of the looseness of the gates, these rates are those associated with orifices of 0.5 and 1.2 square feet, respectively, at a 6-foot average head on a 12-foot bottom gate. Yet the gate leakage was sufficient, as will be evident, for only 3.8 to 10 miles of canal seepage losses, and therefore it rarely, if ever, approached the flow required down the canal. Although considered a problem when the canal was low, lock leakage was rarely a basic cause of low water, as water retained to maintain levels in an upper pound would be at the expense of lower levels down the canal.

CANAL LEAKAGE

The volume of water for lockage was minor compared to the volume that seeped out of the canal bed and banks. In the level situation (see fig. 7) the embankments (berm and towpath) would be formed of excavated material—that is, there would be a balance between cut and fill. With a freeboard of 2 or 3 feet between top of the banks and the water surface and a water depth of 4 feet, the surface of the water would stand above the original land surface and would abut the fill material. In side-hill emplacement (see fig. 8) the contact between water and fill on the downhill side would be even greater. Leakage was noted as a problem on the first sections built. The 25-mile reach from the "Nose" to Schenectady was found to leak so badly in 1822 that it was drained and lined with clay (1823 As. Jour. 46). As leakage was still a problem, measurements of this loss in selected reaches were made in 1824. (An account of methods of flow measurement is given in the section "Measurement of Water Flow.") Measurements of total or aggregate loss of water from the canal were continued because leakage was a continuous problem. The results, as compiled by Rafter (1905) are given in table 2. These data indicate that the rate of loss ranged from a low of 2.89 inches per day in the Clyde level to more than 10 inches in the reach along the Mohawk River from Amsterdam to Schenectady, with a general average of about 8 inches per day. The low figure for the Clyde level probably corresponds to the fact that it is the sag point on the profile that includes the Montezuma-Cayuga Marsh, a region of high water table.

These data on water losses were obtained by measuring rates of flow at the ends of long reaches of the canal between feeders, and ascribing the difference to a loss of water. This loss would include net leakage and evaporation. Of these losses, leakage is the dominant factor, for evaporation would be only 0.2 inch per day even in midsummer.

TABLE 2.—*Summary of the results of observations of water loss from the original Erie Canal*

[After Rafter, 1905, p. 832]

Locality	Date	Length of reach observed (miles)	Canal losses (inches per day)
Brockport to Ninemile Creek	1824	----	8.18
Brockport to Cayuga	1824	75	8.28
Brockport to Rochester	1824	20	8.58
Amsterdam to Schenectady	1824	18	10.22
General	1838	----	8.18
Lodi to Little Falls	1841	61.8	4.74
Palmyra level	1841	8.3	8.89
Clyde level	1841	27.7	2.89
Both levels	1841	36.0	6.88
Lockport to Pittsford	1841	69.0	5.97
Lockport to Pitlock	1847	122.0	7.0

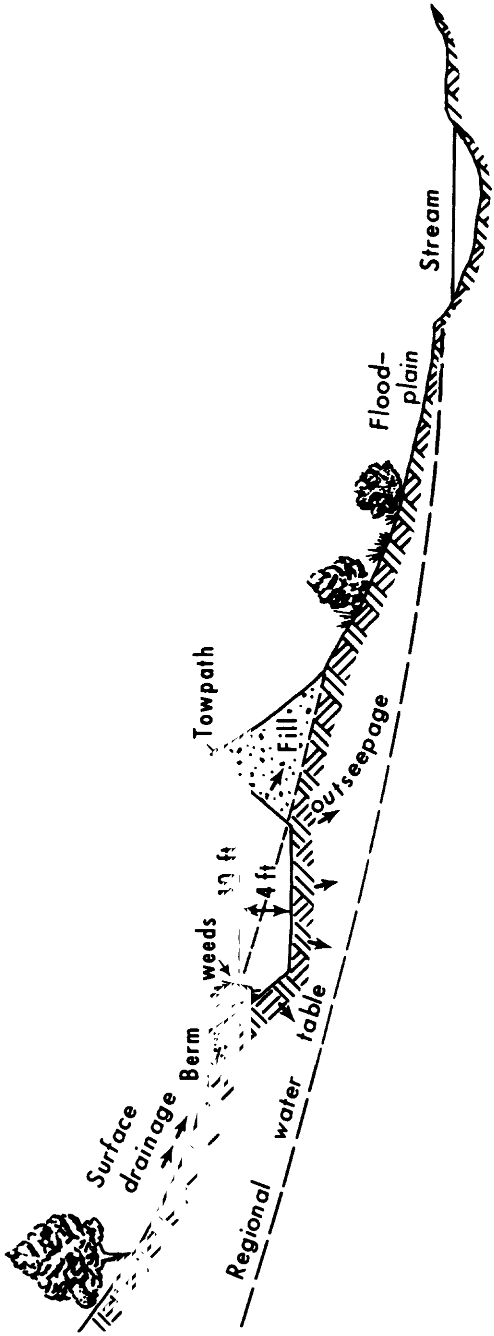


FIGURE 8.—Schematic side-hill section.

It might be expected that siltation or swelling of clay particles of the bed and banks would in time decrease the rate of seepage, yet the data seem to indicate no progressive change. A comparison of the 1824 with 1841 and 1847 measurements in the western division (say, Brockport-Rochester, 1824, with Lockport to Pittsford, 1841) shows a 30-percent reduction, as noted by Rafter (1897, p. 178). However, slope-area measurements (by hydraulic formula) for the Lockport-Rochester reach in 1877 (Searles, 1877) some years after that channel had been enlarged, indicated a rate of water loss of 7.5 inches per day, not much less than that reported in 1824.

These data were cited for many years and appear among the data on loss of water from American canals compiled by Woodward (1930, p. 1578), all of which relate to 19th century measurements. In that list, water loss from the Erie is within the range of experience of other canals, albeit a bit on the high side.

A seepage loss of 8 inches per day for a 40-foot wide canal amounts to about 100 cubic feet per minute (1.7 cfs) per mile, as reported by Blake as early as 1823 (see section "Measurement of Water Flow"). With a canal section of 136 square feet, the amount of water required to replenish the losses is the same as if the canal were refilled every 5 days.

DIVERSIONS OF WATER FOR POWER

The Erie Canal combined a source of mechanical energy with means for transport of supplies and products. Numerous useful differences in head were created either between the canal and a natural drainage course in which case power generation depended on surplus canal waters, or between a feeder and the canal, in which case the tailrace discharged into the canal. In fact, each lock contained the required characteristics for a waterpower site although the ordinary single lock with a 7- to 9-foot head offered only low horsepower (hp).

The combines at Lockport offered great possibilities for there was not only the 60 feet of head on the canal itself, but also the difference in level between the canal and the bed of the creek that passed under the canal. (See fig. 6.)

Beginning with sawmills, manufacturing uses of waterpower increased at Lockport, particularly after the canal was enlarged in the 1840's, increasing the diversion of water from Lake Erie. In the 1890's nearly 400 horsepower was developed using flow diverted from the canal and returned to the canal below the locks. An additional 2,600 hp was developed using surplus waters that would otherwise overflow a waste weir into Eighteenmile Creek that crossed under the canal a short distance to the east of the foot of the locks. (See fig. 6.) A measurement of the diversion to Eighteenmile Creek from the canal made in 1887 was reported by Rafter (1897, p. 214) to be about 19,000 cfm or 320 cfs.

Other waterpowers were developed along the canal, as at Black Rock, Medina, Syracuse, and Little Falls. Although, beginning with the idea of using "surplus waters," waterpower began to exercise a claim on diversions of the water from the canal and thereby to diminish navigable depths. Waterpower along the canal became a matter of public controversy (1870 As. Doc. 133) as being extraneous to the primary objective of the canal—navigation. Later critics, such as Rafter (1897, p. 213), saw the possibility of combined use that would optimize total benefits and recommended a clear statement of policy to achieve it. But nonelectric waterpower (that which is directly connected to factory machinery) was soon to be technologically obsolete.

WATER SUPPLY TO THE CANAL

Water for lockage and to replenish leakage along the way was brought into the canal by gravity diversions from rivers and creeks. A dam, typically of rock and brush, was built across a stream to a depth sufficient to divert water into the feeder canal that led into the navigation canal. The amount that could be diverted depended not only on the amount of water in the streams but on how much leaked through the dams which were usually tightened or improved during periods of water shortage in the canals. In order to minimize disruption of canal navigation by floods, the feeder canals contained a guard gate that was closed during period of high water on the rivers. Diversion dams and guard gates were built of timber, brush, earth, and stone—local materials which permitted an ad hoc response to experience, and favored an easy accommodation to the environment.

In 1825, when the canal as a whole began operations, water supply was obtained from 12 sources including Lake Erie, as listed in the section on "Feeders, Locks, and Stream Crossings." On the original canal the total quantity of water used for a tier from summit to sag averaged 1.7 cfs per mile of canal for leakage (0.5 cfs/mi in the region of the Montezuma-Cayuga Marsh) plus 25 cfs for the water let out at the bottom lock. For the original canal system as a whole, therefore, the following quantities of water were needed:

Lake Erie to Montezuma (145-mile leakage, plus 25 cfs)	300 cfs
Clyde to Jordan level (25 miles, plus 25 cfs)	35
Jordan level to Syracuse (12 miles, plus 25 cfs)	30
Syracuse to Rome summit (60 miles, plus 25 cfs)	125
Rome summit to Hudson River (110 miles, plus 25 cfs)	215
	700 cfs

By 1862 the total flow to the enlarged (70×7 ft) canal had increased to 1,900 cfs when the number of feeders had about doubled (see section "Feeders, Locks, and Stream Crossings.") There were 40 feeders in operation in 1891. The quantities of water handled by the Erie rank it as the major water project of the 19th century.

The increase in the rate of intake from 700 cfs to 1,900 cfs may be largely accounted for by the increase in the leakage and related losses. These quantities would be approximately proportional to the product of the surface width of the canal by the square root of the depth of water in the canal. As between the 70×7-foot section and the original 40×4-foot section, the ratio of losses would be 2.3 to 1, nearly as much as the increase in flows noted above.

RESERVOIRS

The first reservoirs (1830 As. Doc. 47, p. 32) built on the canal system were those constructed in the 1830's to supplement the low flows of the small streams that were used as feeders at the high summit level of the Chenango Canal, a lateral to the Erie Canal at Utica, which led up the valley of Oriskany Creek (see section "Hydrologic Data and Analyses"). Although the Chenango Canal was later abandoned, the reservoirs were maintained to augment the low seasonal flows of Oriskany Creek, an Erie Canal feeder (see section "Feeders, Locks, and Stream Crossings"). Lakes, however, were used for the major part of the storage capacity by putting control works at the outlets. Total storage capacity by decades is given in table 3 (1892 As. Doc. 75, p. 72). A large amount of capacity came into operation in the 1850's as a result of the construction of the Forestport feeder to the Black River Canal which discharged into the Rome summit level.

Some idea of the magnitude of the total volume can be obtained by expressing it in terms of the number of days of operation. Considering the water intake was about 2,000 cfs, the capacity built by 1890 amounts to a reserve sufficient for about 55 days operation.

TABLE 3.—*Total reservoir capacity on Erie Canal feeders, by decades*

Up to	*Capacity (millions of cubic feet)*
1840	1,275
1850	3,470
1860	6,290
1870	9,090
1880	9,460
1890	9,900

WATER SHORTAGES

Leakage, lockage, and the diversions for power over the years added to the need for water. The potential supply of water was adequate as the canal commissioners correctly judged in 1818—"With a country of from fifteen to sixty miles wide, stretching its whole length, and abounding with lakes and streams, which all seek their natural discharge by crossing it, no deficiency of water can ever be apprehended" (1819 As. Jour. 42nd sess., p. 207). New York State is favored with a humid climate and copious water resources, and the low flow from 7,000 square miles (equivalent to a strip along the canal about 20 miles wide) would indeed supply the 700 cfs needed, and 19,000 square miles (55 miles wide) to supply the 1,900 cfs used by 1862. The problem was to develop the supply and to convey the water down the canal to maintain navigable depths.

Despite the continual addition of feeders and the impoundment of water in reservoirs, shortages of water led to delayed traffic because shallow water increased hydraulic drag on the barges or because barges had to lay by to await other barges to share the lockage volume—that is, an up barge on finding a lock full would have to await a down barge before the lock was emptied. The annual reports of the Canal Commissioners and later the State Engineers repeatedly refer to water shortages, particularly in dry spells, and report efforts to shore up the supply to the canal by such measures as tightening the diversion dams. A short historical summary of water shortages is given in the State Engineer's report for 1883 (1884 Sen. Doc. 9, p. 24).

Even as late as 1891, by which time there were 40 feeders, the State Engineer reported (1892 As. Doc. 75, p. 127) "During the latter half of the month of August and the whole month of September, the water in the Mohawk River was very low, and it was with difficulty that navigation could be maintained * * *" And again (p. 196), "This fact gives additional force to the remarks in previous reports on the necessity for additional sources of supply and additional storage reservoirs," a startling admission after 65 years of trying to cope with water shortages. The scheme of adding a new feeder as river flows receded during dry spells never seemed to measure up to the job. Rafter (1905, p. 829) came to the conclusion that the fault lay with inadequate data. "In the absence of systematic information as to the yield of streams, the general tendency has been to overrate the summer flow, with the result of shortage frequently at points where the supply was believed to be ample."

To judge the adequacy of the streams to meet the requirements, the canal engineers measured their flows during the late summer and autumn seasons when streams were usually at their annual minima. (See section "Measurement of Water Flow".) These measurements were made during the year or so of planning that preceded construction. As is now well established from continuous records of streamflow, rivers are highly variable in flow from year to year as well as seasonally. A single set of measurements by themselves cannot give an indication of the low-flow regimen of the river. As a demonstration, assume that measurements made during a 3-year period of planning and design succeed in determining the lowest flow during that period. How does that flow compare with the experience of say the next 50 years? The current records of the flow at five different long-term gaging stations show that the low flows during any 3-year sample would have a fourfold range and, on the average, would be from 2 to 3 times greater than the lowest flow in the record. This comparison indicates that the isolated measurements gave optimistic indications of low flows. It was just this kind of experience that beset the canal during the 19th century.

Despite awareness of the potential for flows lower than measured, there were no means for knowing how much. For example, in connection with estimates of water supply for the Chenango Canal (1834 As. Doc. 55, p. 57) Jervis reduced measurements made during a period of questionable dryness by an arbitrary 25 percent. But measurements made in 1838 (1840 As. Doc. 96, p. 24) gave results "36½ percent less than in 1834 and 48 percent less than in this year (1839)." Even today there is no reliable way to determine the rates of flow of a stream that are likely to occur during extended spells of dry weather in the absence of continuous records of flow for use as a reference base. Methods have been evolved to use the spot measurements of the flow of streams otherwise ungaged for this purpose, by comparing the measurements with the long-term records of flow at continuous gaging stations. (Riggs, 1972.)

HYDRAULIC INEFFICIENCIES, TRAFFIC DELAY

When the canal opened, 30-ton barges made the 363-mile round trip between Albany and Buffalo in 16 days (equivalent to a barge speed of 2 mph, allowing 10 minutes per lockage). By 1841 the average time for a round trip for 70-ton barges had become 22 days, a third longer than originally (1842, As. Doc. 24; p. 15), subtracting significantly from the advantages of the larger payloads. The chief villains that decreased efficiency were inadequate hydraulic capacity, flow blockage, and hydraulic drag. Losses in efficiency also resulted from the introduction of larger barges that caused collisions when passing. Unscheduled barge traffic was the cause of waiting-line delays at locks. The adverse economic consequences of all these inefficiencies were doubtless considerable as they led to pressures to enlarge the facilities, rather than measures to abate them at the source.

HYDRAULIC CAPACITY

Besides low flows in the streams that were diverted into feeders, shallow depth for navigation also occurred as a result of insufficient capacity of the canal prism to convey the necessary water down the canal, particularly when the hydraulic capacity was decreased by the presence of barges.

As the Commissioners of 1811 had anticipated, some slope was needed to convey water to maintain navigable depths. Moreover, slope could save lockage, provided that velocity induced by the slope was not excessive. The original canal was built without benefit of formal hydraulic computations to assure that these conditions were met minimally, let alone optimally. In Great Britain a slope or fall of about 1 or 2 inches per mile in the pound reaches was about right, but that would depend on the rate of channel losses and the spacing of feeders. If losses are low, water conveyance is low and a flat slope would be satisfactory. In the Erie, water sufficient for about 35 miles of canal could be conveyed with a slope of 1 inch per mile and for about 50 miles with a slope of 2 inches per mile.[4]

The western division of the canal offered a classic hydraulic problem which is treated in some detail in the section "Hydraulic

[4] Based on Manning's formula with roughness coefficient estimated at 0.025, canal cross section as shown on figure 8 and a water requirement for losses and lockage of 2 cfs per mile. Cross section here is assumed clear of barges.

Computations." In concept, that division—from Lake Erie to the sag point in the profile in the lake district (fig. 4)—had a copious source of water in Lake Erie. However, the original canal could not meet the objective of conveying a supply of water from Lake Erie because of a lack of hydraulic capacity. The grade of the canal from the lake to the mountain ridge was held at 1 inch per mile to avoid the added rock excavation that would have been required to increase the slope and therefore the flow. Because a slope this flat would convey only enough water from the lake for about 35 miles of canal, a feeder was introduced in 1823 from Oak Orchard Creek which was crossed by the canal 40 miles along its length from Lake Erie. The upper Tonawanda Creek was diverted into the north flowing Oak Orchard Creek at a point where there is only a low saddle between them. (See fig. 2.)

Later in the experience of the canal (see section "Hydraulic Computations"), it was also recognized that a uniform canal cross section (1842, As. Doc. 24, p. 14–15) was not appropriate for long pound reaches. Considerable difficulties because of insufficient water to float boats were reported to occur in the long levels in the western division and in the long summit level at Rome. There was insufficient hydraulic capacity at the upper end to convey the water needed to maintain navigable depths in the lower end of the reach. Hydraulic capacity needed to be proportioned to the flow and distance from the supply.

Beginning in the 1840's with increasing traffic there were many reports of flow blockage by boats on the canal. The hydraulic capacity of the 40×4-foot canal would be reduced by more than half when part of the section was occupied by a barge and more so when passing boats wedged together. Further, the blockage effect was even greater when the canal was only partially full, and thus, the effect was compounded down the canal. For example, it was noted (1842 As. Doc. 24, p. 14) that after a break in the canal banks had been repaired the time required to refill the canal was lengthened because the flow down the canal was obstructed by 215 boats. State Engineer McAlpine (1854 Sen. Doc. 50, p. 77 and 80) reported that when the canal was crowded with boats there was difficulty in "sending forward the requested quantity of water to keep up the levels and supply the locks." Sand bars had a similar effect (1845 As. Doc. 28, p. 52; Rafter, 1905, p. 850). In addition, aquatic vegetation, chiefly Potamogeton, growing in the canal impeded the flow; even when cut the stubble added considerable resistance to the flow of water (1850 Sen. Doc. 41, p. 8).

HYDRAULIC DRAG

Barges were initially of the narrow type—7 feet wide, 3½ feet draft, and 60 to 70 feet long, and carrying 30 tons, or 1,000 bushels of wheat. (See fig. 9.) Increasing traffic soon led to introduction of broad 70-ton barges, limited only by the 15-foot width of the locks, and canal enlargements were planned in 1832 after only 7 years of operation.

As previously mentioned, it appeared to be a simple matter to estimate canal width and depth, when given the size of a barge: one needs only to provide clearance on bed and banks for a pair of passing barges. But the problem of hydraulic drag soon emerged as it had in Europe. A vessel that moves with little clearance above the bed or about its sides is retarded by increased hydraulic drag. The moving vessel creates a reverse flow of water that must take place in the confined space between the barge and the bed and banks. And because of the narrow space, the velocity gradient between barge and channel is steepened, which adds to the shear resistance. Hence a barge in a canal moves more slowly for a given motive power than the same barge in a water body of considerable extent.

B. Franklin in 1768 (Willcox, 1972 p. 115–118), after noting the drag encountered by vessels when rowed over shallow water, made tank experiments to demonstrate and measure it. The work was done in England and as his report was published among his observations on electricity, it was probably not known to the canal designers. It was not until a decade after the completion of the

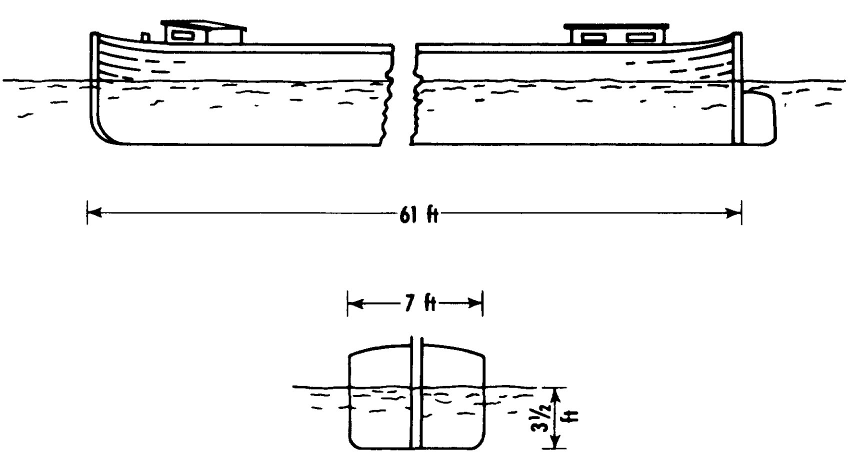


FIGURE 9.—First barges used on canal.

canal, the hydraulic elements of design became evident from research that had been published by DuBuat in 1786. Thus, in 1835 the problem was examined by John B. Jervis, Holmes Hutchinson, and Nathan S. Roberts. (Their reports are reprinted in 1863 As. Doc. 8, p. 198 et seq.) Hutchinson (1835, As. Doc. 143, p. 42), referred to the experiments of DuBuat to the effect that the cross section of the canal ought to be, with moderate velocity, "6 and 46/100 times" the cross section of the boat, and the water line 4½ times the breadth of the boat. Hutchinson included the following data from DuBuat (order changed):

Ratio of sectional area of canal and boat	*Observed resistance (in a water body of indefinite extent)*
2.106	2.11
2.476	1.90
3.192	1.62
4.212	1.33

Apparently these data define a smooth curve, which extended, indicates a resistance ratio of 1.0 for a section ratio of 6.46 which accounts for the above recommendation. Jervis ascribed to the old Erie Canal a 40 percent excess in resistance; Hutchinson made it 59 percent, referring to the above table.

"The resistance in a fluid of indefinite extent being equal to 1, would give to the present Erie Canal boats of the largest class a resistance of 1.59 or 59 percent more than in a fluid of indefinite extent." Hutchinson stated that for the largest boats then (1835) on the Erie (14 feet wide, and 3.5 feet draft) "to move to the greatest advantage, as on an indefinite extent of water, the canal should be 63 feet wide at the surface, 5.11 feet deep, and have a cross-section of 271.32 feet." (sic) For boats 14 feet wide but of 4 feet in draft, the canal should be 63 feet wide at the surface and 6.08 feet deep.

Jervis recommended a canal section 42 feet wide at the bottom, 70 feet at the surface and 7 feet deep, for a barge 13½ feet wide and 4½ feet draft. Nathan S. Roberts on January 17, 1835 (quoted in 1863 As. Doc. 8, p. 201) proposed a section 48 feet at the surface, 30 feet wide at the bottom, and 6 feet deep, effectively adding more to the depth than to width.

However. in the following year Jervis and Mills (1836 As. Doc. 99, p. 282–283) expressed the opinion that to accommodate the growing trade, a canal 80 feet by 8 feet would be most suitable for the enlargement (see also 1863 As. Doc. 8, p. 202).

DuBuat's rules are equivalent algebraically to a specification that barge draft not exceed 70 percent of the canal depth. So much was known in 1835. Yet the practice of building barges to occupy

85 percent of the depth was continued in the enlargement—3.5-foot draft in a 4-foot channel of the original; 6-foot draft in a 7-foot channel in the enlargement. For such drafts resistance was at least 50 percent greater than for DuBuat's recommended 70 percent.[5]

Drag was particularly sensitive to shortages of water that made difficult the maintenance of full depths. For example, when water depth decreased from 4.0 to 3.9 feet, then drag on a vessel drawing 3.5 feet was increased by about 25 percent.

CANAL SLOPE AND CURRENT

The section "Feeders, Locks, and Stream Crossings" lists the locks on the original Erie Canal as obtained from various published sources. Assuming that the lifts as given are correct, the net difference in levels between the Hudson River and Lake Erie, accounted for by the locks, totals 542 feet as against a difference in elevation of 572 feet between these two levels. This arithmetic leaves 30 feet or 1 inch per mile to be accounted for by friction slope in the reaches between the locks. This slope in a well-formed canal, 4 feet deep, would produce a mean current (west to east) of about 0.5 foot per second or about 0.35 mile per hour.

It was early understood that a current in the west to east direction could be a net advantage, since the heavy tonnage was carried in that direction. In principle, optimal advantage exists only when the downstream current is one-half the difference between the speed of a fully loaded barge and a lightly loaded barge when drawn through still water. However, the advantage is small and later as the boats were heavily loaded in both directions, the current was a distinct disadvantage. As Garrity recollected (1966), the westbound trip over the 62-mile level from Rochester to Lockport took 50 hours, or a speed of only 1¼ mph.

WEDGING

As wider barges were introduced (see table 4), collisions in passing became more frequent as State Engineer McAlpine re-

TABLE 4.—*Barges during the 19th century*

Period	*Dimensions (feet)*					*Capacity (long tons)*
	Width		*Length*		*Draft*	
1818–30	7	×	61	×	3½	30
1830–50	12	×	75	×	3½	75
1850–62	15	×	90	×	3½	100
1862–99	17½	×	98	×	6	240

[5] In the 1870's when enlargements were again considered, canal engineer E. Sweet conducted experiments on tractive force in relation to barge velocity, draft, water depth, and canal cross-sectional area. (1879 As. Doc. 41, p. 11.)

ported in 1854 (Sen. Doc. 60, p. 77)—"the wedging of boats is a daily occurrence." By impeding the flow of water, the wedging of boats tended to ground those boats below the wedge. This experience was apparently not sufficient to deter the Commissioners from adopting 18-foot wide locks in the enlarged canal despite Jervis' recommendation that they be held to a 16-foot width in order to limit the width of barges. Jervis (1877) had this to say of the Commissioners' decision which was impelled by a desire to float barges capable of carrying a load of 250 tons:

> No one appreciated more than I, the importance of substantive and durable works, but unfortunately at that time, there was so high an estimate of the value of the canal, that the ideas of men were extravagant, and advocated work of an expensive character, that was in no way more substantial or useful. This induced a more or less expensive policy, that increased the cost of the work much beyond that necessary. I had recommended, that the chambers of locks for a canal 7 feet deep by 70 feet top width, should be 16 feet wide and 115 feet between the gates. The Canal Board, on the petition of navigators, increased the width to 18 feet, which I regarded a decided error. A navigation with few boats may be conducted on a comparatively narrow channel; but for a large traffic, there is a proper relation between the area of boat and area of channel that secures the best economy in transportation. The boatman will make the boat as wide as he can pass the locks [sic], with simply room to pass on the open canal. They analyze nothing, but suppose the acme of economy is in the largest possible load they can carry; very much on the theory of most railway superintendents who consider the largest possible train as securing the best economy in transportation with no more attempt at scientific analysis than that of the boatman. It is now the opinion of the most intelligent navigators of the canal, that locks are too wide for the best economy of transportation.

DELAYS AT LOCKS

Waiting lines formed at locks, despite the fact that total capacity for service was well in excess of the demand. The waiting lines occurred simply because barges were dispatched at intervals during the day that suited the convenience of shippers and because slow barges tended to impede those behind. Both factors tended to increase grouping along the canal and concurrent arrivals at the locks.

Some data on detention and service times at locks (1844 As. Doc. 16, table p. 27) provide a classic example. With an average rate of arrival of 100 boats per day at a lock, well within service capacity, 40 percent needed to wait for service, yet the lock was idle 16 out of the 24 hours. Costs in time and temper were high and proper queue discipline became difficult to preserve.

Although unscheduled traffic was the cause, the response of the canal authorities was to enlarge the facilities. The improvement of the canal (1836–62) included the doubling of locks (in parallel) first in the heavily traveled and heavily locked section between Albany and Syracuse, and ultimately throughout.

FLOODS, WASHOUTS, AND TRAFFIC DETENTION

The flood hazard to canals, as generally to linear transport systems including roads and railroads, was of two kinds: that due to rivers paralleled by the canal and that due to streams that are crossed by the canal—the cross drainage. Neglect of the first proved catastrophic on the later built Chesapeake and Ohio Canal (Sanderlin, 1946) that paralleled the Potomac River for most of its length; neglect of cross drainage proved to be an expensive nuisance on the Erie. In the absence of record keeping, it is fairly difficult to judge the flood potential of a stream when it is in its low-water state, with sufficient confidence to justify what might then seem to be an inordinate construction cost. The builders of the Erie Canal were fortunate at least in that respect for, as previously mentioned (p. 16), severe floods in 1817 before construction began provided clear and persuasive evidence of the flood danger.

MOHAWK RIVER

Potentially the most hazardous location of the canal was the 110 miles that paralleled the Mohawk River. Destructive drainage here could potentially destroy the canal as a viable artery of commerce. That the canal was not subjected to general disruption as it might have been, proved that the indications of the flood of 1817 were apparently as satisfactory as they were assumed to be, even though the canal did not escape flood damage during the 19th century. Floods in 1821, 1832, 1833, 1846, and 1866 were reported to have reached the canal at one or more places, namely: November 1821 "raised the waters in the canal in some places above its banks" at Little Falls (1823 As. Jour. 46th sess., p. 504); March 13, 1832, at Schenectady—(breaks in the north bank of the canal) ice and flood damages to feeder dams across the Mohawk in March and April 1832; flood of May 1833 "covered the Erie Canal, in the valley of the Mohawk, to an uncommon extent, and for a few days partially interrupted the navigation." (1834 As. Doc. 55, p. 45.); Feb. 1842, extensive injuries to banks (1843 As. Doc. 25, p. 67); March 1846—Mohawk River ice laden, pours into bad break at Schenectady; June 1866—break 5 miles west of Schenectady—300 feet of towing path swept into Mohawk River (record not clear as to origin of washout—whether main river or side stream).

In their report for 1821, the Canal Commissioners (dated 27

Feb. 1822, p. 23) refer to their route down the Mohawk River valley which they attempted to put

"in all places above the floods of the river; and avoid on the other hand, as far as was practicable, the sides of steep banks where the soil is liable to slip, and the canal to be otherwise injured by the torrents from the hills. The correctness of this location was tested by the great flood of November last (i.e., 1821), which suddenly raising the Mohawk to an unusual height, was not observed anywhere to approach within many feet of the top of the banks, or to do any injury to the works which were completed."

Basil Hall (1829) who traveled on the canal along the lower Mohawk River noted (p. 119) "our perpendicular height above the stream may have been 30 to 40 feet." Based on traces of abandoned sections on the topographic maps, author's calculations show that the canal banks were placed about 20 feet above the river bed in the upper reach, 25 feet in the middle reach, and 35 feet in the lower reaches.

Except in the vicinity of Schenectady, the canal banks were as high or higher than the maximum levels reached by the Mohawk River during the 70 years or so of regular record keeping on that river. The exception at Schenectady was caused by an ice jam in 1914. It must be concluded that the engineers succeeded in locating the canal if not, as claimed, "above the floods of the river," at least beyond the reach of ordinary floods.

CROSS DRAINAGE

Continuing with their report of the flood of November 1821, the Commissioners add (report dated 27 Feb. 1822, p. 23)

"On the land side [i.e., cross-drainage] more damage was sustained; the flood from the hills filled the canal and in some places broke down the new and unfinished bank, destroyed the wing of the dams and injured several unfinished culverts."

Thus it was that the numerous small creeks that caused the major damage were a potential hazard early recognized by the Commissioners in the following language:

"To secure our work from injury, by floods and freshets, that will often suddenly collect, from the extensive land drain, and the abundant waters, above alluded to, we have been compelled to make numerous culverts and waste weirs. The office of a culvert is, to pass waters, not wanted for navigation, under the canal; that of a waste weir, to discharge the extra waters, that may be in it." (1819 As. Jour. 42d sess., p. 207.)

The object was clear, but it was not achieved. Disruption of traffic and costly repairs vexed the canal throughout its period of operations. A canal washout usually suspended traffic for a period of 7 to 15 days, as neither detours nor temporary service could be arranged. Even traffic on pounds not directly involved had to be suspended, for in order to save water the locks could not be opened.

A report (1853 As. Doc. 128,[6] p. 5) on suspensions of navigation in the Erie Canal over the 10-year period 1843–52 showed an average annual rate of 10.7 days—5 percent of a 220-day season—nearly all because of cross drainage. The State Engineer and Surveyor in 1882 when the canal was having a hard time in meeting rail competition, reported an average suspension of navigation in the State canals of 37 days per year:

"It is a matter of surprise that no regular record or account of the casualties has been kept in any department of the State canals; but a careful examination of the different reports shows, that from 1858 to 1882, inclusive, embracing a period of twenty-five years, the detentions from breaks in all the canals of the State, so far as any record can be found, amounts to nine hundred and twenty-five days; and that their cost to the State has amounted to $2,042,183, and there can be no doubt that a large percentage may be added to these figures with perfect safety." (1883 Sen. Doc. 9, p. 11.)

The problem began with choice of grade elevations for the canal as these fixed the clearance over streambeds. Raising the local elevation to improve clearance was not feasible on a canal as on a highway or even on a railroad. The adopted alternative was to excavate river and streambeds "for the purpose of free and safe discharge of water under aqueducts and culverts" (Hutchinson, 1834). This procedure could not work. River channels in nature are adjusted in elevation, slope, depth, and width to carry their loads of water and sediment. Any excavation of the bed can only be temporary as the stream sediment will return the bed to the original profile and choke the culvert.

In the building and in the rebuilding throughout the 19th century, emphasis was put upon structural solidity, as, for example, this report on construction:

"Stone culverts of different sizes, all to be arched and placed upon permanent foundations, and more than half of which are now finished with great solidity and beauty" (1821 As. Jour., 44th sess., p. 870). Later, during the enlargements, the specifications were as follows:

"All culverts are to be built upon timber and plank foundations, except where rock occurs of sufficient solidity and durability to support the structure permanently. Ten of the small culverts, with three-feet openings, are to have side and end-walls of cement masonry, and a covering of timber and plank. Eleven others of the same size to be covered with stone flagging. Culverts, with openings exceeding three feet in width, to have semi-circular arches, and such height of jamb walls as may be adapted to their location. The masonry to be of good, durable stone, and so dressed that the horizontal joins

[6] There are two Assembly Documents for 1853 numbered 128.

of face and arch work will not exceed a quarter of an inch." (1854 Sen. Doc. 60, p. 74).

(See fig. 10.)

Yet the design of a device to render the simple service of a culvert is now known to be complex, involving not only the structural details but their hydraulic properties and the flood discharges that are likely to be experienced. Without this information, repair and enlargement became surrogates for design. When a culvert washed out, the tendency would be to rebuild it larger so far as was possible. Several washed-out sections in the abandoned canal were observed by the author where the bed of the canal was but 1 or 2 feet above the bed of the stream crossing. Such culverts could only be widened, but widening would be hydraulically less effective than adding to depth. Even so, a practice of enlarged replacement could not cope with the problem. Stream crossings averaged about one per mile; thus the 360-mile canal contained that number of exposures to risk. If, say, as many as 25 culverts washed out in a 5-year period, and were enlarged, there would still remain 335 culverts. A century would not be long enough to remove the difficulty.

Any glamour in a culvert is hidden. Out of sight to the boatman on the canal as it is today to the motorist on a highway, it serves to carry the flow of a stream under the canal or road. Although each culvert may represent a very modest investment, their very

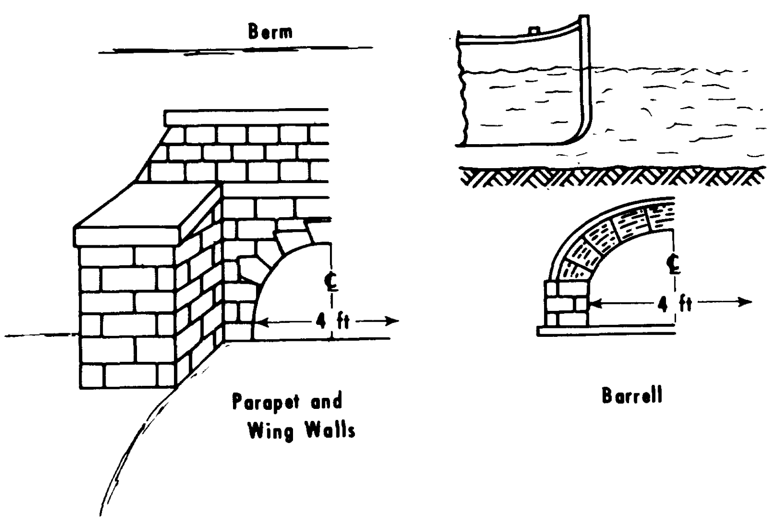


FIGURE 10.—Four-foot stone culvert.

great number and the disruptive effect of a single failure upon the entire transport system warrants a very great attention indeed.

OPERATIONS, MAINTENANCE, AND REPAIRS

A grasp of the operational problems and of the magnitude of the work needed to maintain the canal may be obtained from a comparison of costs. The base investment in the construction of the canal came to $39 million ($7.1 million for the original and $31.8 million for the enlargement (Whitford, 1906, p. 1366)). By 1882 total costs including operations, improvements (such as added feeders and locks), maintenance, and repairs came to $78.8 million (see table 1), indicating that added costs duplicated the original investment. Looking only at annual costs, the total for operations, maintenance, and ordinary repairs on the original canal came to about $280,000 or 4 percent of the $7 million investment cost; on the enlarged canal these averaged about $700,000 per year or 2 percent per year of the $32 million investment. Costs of operations, maintenance, and repairs on modern hydraulic public works are usually 1 percent or less.

SUMMARY

Water required for lockage, although the most obvious to the planners of the canal, proved to be relatively minor compared with the amounts of water that were required to compensate for the leakage through the bed and banks of the canal. The total water intake of 700 cfs in the original canal increased to 1,900 cfs by 1862 as the canal was enlarged. The total quantities of water taken into the canal made it the largest hydraulic undertaking of the century in the United States. The diversion of water for the generation of power in factories attracted to the canal as a source of hydraulic power and means for the transport of goods added to the water requirements. Although new feeders and reservoirs to extend the supply were built throughout its history, these efforts to cope with water shortages were never fully successful. The primary cause of the persistent deficiencies in supply was the method used to estimate the flow of the streams available during extended dry spells. Dependence on spot, *ad hoc* measurements of flow consistently overestimated the supply.

Water shortages in the canal were also created by a lack of hydraulic capacity to convey the water needed to maintain full depths over long distances between feeders. Failure to maintain depth in the canal increased greatly the hydraulic drag encountered by the moving barges and lengthened the travel times.

A decrease of the bottom clearance normally 0.5 foot, by only 0.1 foot added to the drag by 25 percent. The hydraulic and traffic problems of the canal were exacerbated by the practice to build and operate barges as large as possible, which then led to enlargement of the canal. Unlike the railroads, the canal was not viewed as a unified traffic system, a fact that contributed to its second place in that competition.

What might have been known beforehand of some of the water problems of canals is contained in a critique of British canals that was published in 1816 (Sutcliffe, 1816). Almost a polemic, this report found fault with economics and engineering nearly everywhere in Great Britain. As to economics, Sutcliffe concluded (p. 74), "If the average of profit and loss, of all canals that have been projected and executed within the last twenty-five years were accurately taken, I am inclined to believe, that the balance would be found greatly against them." ["The last twenty-five years" would refer to the final or second generation of British canals.] As to engineering, he offered his critical judgment on construction and on inadequacy of water supply, noting (p. 77), "It is difficult to say, whether the estimates of canal engineers for supplying them with water, or their estimates for executing, are the more erroneous," following the observation (p. 73) that "many of them are little better than so many dry ditches." The earliest reference to Sutcliffe's treatise found in the Erie Canal literature was some 20 years after publication as part of the newly learned hydrologic computations for the enlargements.

The major flood problem was caused by cross drainage—the small creeks that crossed under the canal in culverts. Washouts of culverts were a never-ending source of sporadic disruption of traffic, each occurrence being of 1 or 2 weeks duration and adding greatly to shipping costs. Repairs and replacement could not cope with the problem created by deficiency in information about the flood potentials of the small streams.

A fortunate occurrence of a severe flood in 1817 when construction began provided such clear and present evidence of the flood potentials of the Mohawk River, which the canal followed for 100 miles, as to compel putting the canal at a high level in difficult terrain. Otherwise, there can be little doubt that the Erie Canal would have been of no more use for transport than the Chesapeake and Ohio Canal, which was put out of service repeatedly by floods on the Potomac River.

The canal survived its persistent operational problems, which were the inevitable consequences of moving ahead on a grand scheme without having obtained and analyzed some of the pertinent data.

THE CANAL AND THE ENVIRONMENT

Optimistic and keenly aware of the economic stimulation that a canal would provide, the Canal Commissioners of 1811 were apprehensive and assertive that the resulting land development would have adverse environmental impacts, as one would say today. In the main, their anxieties centered upon their fears that land development would have serious adverse effects on the hydrology of the area and thus on the canal. Thus their concern was limited to only one part of the whole story; but the environment is as broad as all out-of-doors.

Environmentally, a canal is more than a cross-country ditch; it collects water from one place and takes it to another; it receives and transports sediments and pollutants; it affects land use in the area influenced by its commerce; it is affected by floods and droughts; it may enhance or detract from the landscape. The difficulty in addressing environmental impacts begins with simple listing of the possibilities, and requires identifying the major factors out of a potentially endless number of possible effects. Even in this report that looks only at the hydrological aspects, it becomes difficult enough to identify most of the major interactions between the canal and its environment, let alone all of them. Within constraints of available information, account is taken of the impacts posed in the report of the Commissioners of 1811 such as water supply, floods, sedimentation, and water quality, and of other consequences that emerged during the operations and after abandonment.

WATER SUPPLY

The Commissioners of 1811 expressed their apprehension about the water supply very clearly

"the true character of a river (for water supply) cannot now be known. Large tracts, for instance, west of the Genesee, which appear as swamps, and through which causeways of logs are laid for roads, will become dry fields, when no longer shaded, as at present, by forests impervious to the sun. In the progress of industry, swamps, the present reservoirs of permanent springs, that burst out on a lower surface, will be drained, whereby many of those springs will be dried. Of such as remain, a part will be used to irrigate inclined plains. Moreover, in every place tolerably convenient, ponds will be collected for mills and other machinery, from whose surface as well as from the soil, the sun will exhale an ample tribute of vapour. Thus the summer supply of rivers will be in part destroyed, and in part consumed, whereby their present autumnal penury must be impoverished * * *." (p. 19)

The same belief must have been widely held at the time. John Stevens, of Hoboken, the well-known inventor who foresaw the rapid obsolescence of the canal, also warned the Commissioners that its water supply may fail: "It is a notorious fact that tracts of country become more or less arid as they become cleared of timber."

The Commissioners of 1816, who prepared the final design, tried to resolve the uncertainty about the future of the water supply, not in disputing the adverse effects of deforestation, but in arguing that springs and lakes are immune to it. They referred to the feeders in the following terms: (1816–17 As. Jour. 40th sess., p. 340) "some of which are outlets of lakes, and others originate from perennial springs in high lands, and will never be affected by the clearing of the country," an ad hoc argument that may reflect some lingering medieval mystery about the sources of springs (Biswas, 1970).

The anxieties over the adverse effects of deforestation expressed by the Commissioners of 1811 were frequently restated by the others who followed. Indeed, one of the reasons given for setting aside the Adirondack Forest Preserve in the 1880's was to maintain a steady flow of water to the Erie Canal. By that time contrary opinions had emerged, as stated, for example by the State Engineer. "An idea seems to have found lodgment in the public mind, that the preservation of the forests in the Adirondack Region, is the only means by which an adequate supply of water for the State canals * * * can be secured for all time." Although preservation would be justified for game, health, and recreation, the benefits would not include water supply which could be obtained from impoundments by dams. "The facts show most conclusively that, from forty to fifty years ago, when the forests of the Adirondack Region were in their primitive state, they were much less reliable as a source of water supply, than they have been during the past few years." (1884 Sen. Doc. 9, p. 22 et seq.).

Despite the assurances of the early Canal Commissioners "Now all experience shows" (1821 As. Jour. 44th sess., p. 868), Rafter's definite assertions near the close of the 19th century (1897 As. Doc. 73, p. 667) that deforestation "has materially reduced the minimum runoff," and the contrary certitudes of the State Engineer, just quoted, that "The facts show most conclusively," very little certainty actually was possible; facts and experience were and in some ways remain few and inadequate.

The extensive and intensive deforestation and land development of the 19th century kept the subject alive and the lack of systematic records kept it controversial. Experience with attempts to resolve the effects of land-use changes upon stream regimen has shown that the effects of manmade changes are heavily masked by those variations in flow caused by the natural recurrent storms and droughts. To screen out—to separate—the artificial from the natural requires long series of observations, and it was only after these land developments had taken place that there was sufficient interest in the potentials of power generation, in availability of water supplies, and in flood protection to warrant continuous stream gaging.

The many spot measurements of streamflow that were made to estimate the available supply of water, if compared with modern data could be instructive on this point. Difficulty arises even for the few flow data that were actually reported, because these spot measurements were higher than the minimums that they were taken to be. For example, Daniel Marsh (1854 As. Doc. 63, p. 147) reported measurements of the flow of the Genesee River at Rochester which he made during July and August 1846 in the course of litigation as to water rights on that river, giving, as he stated, "24,842 cubic feet per minute (414 cfs) for the whole volume of the river at low water."

Marsh also measured a flow of 14,370 cfm (240 cfs) on August 24, 1846, (p. 156), but he averaged this figure with several higher measurements and, because diversions were made from the river to the Genesee Canal, the calculation of natural flow became so complex that it is difficult to judge from the facts given what the reported flows actually represent. Nevertheless, the reported flows can be compared with later records. A flow of 414 cfs is exceeded by two-thirds of the flows of the Genesee River at Rochester during July and August, and is about twice the minimum of record. Rafter (1905, p. 182, 494) saw in this fact that the low flows of the Genesee River had been markedly reduced by reason of the deforestation of the catchment during the 19th century. It would be simpler to conclude from the precipitation and flow measurements that 1846 was not a particularly dry year: annual precipitation at Rochester in 1846 from climatological records was 37 inches, average of record is 32 inches; precipitation for July and August 1846 totaled 6.34 inches, average of record for this 2-month period is 5.5 inches.

A further comparison can be made. The systematic record reported by Jervis on Madison Brook (Madison County) for the year 1835 gave a total runoff of 18.5 inches. Modern records on streams in that region indicate a range in annual flows from 15 to

30 inches, about a mean of 22 inches. The record for the single year, 1835, falls well within the modern range.

Considering the extent and duration of controversy that the subject engendered and the assertions made, an answer through research was long delayed. The Wagon-Wheel Gap deforestation project in Colorado (Hoyt and Troxell, 1934) demonstrated that deforestation increased water yield.

In the 1930's, the Department of Conservation of New York State and the U.S. Geological Survey began a project to determine the hydrologic effects of the reforestation of abandoned farmland that had been acquired by the State for the growth of trees in the central part of the State. Three small experimental catchments were established together with a control catchment in which land-use practices remained substantially unchanged in an unforested condition. Measurements were made of the rainfall and runoff from each of the four catchments. The results of some 20 years of observation showed that the total annual runoff from the three study areas (partially reforested) was decreased by a significant amount. Peak (that is, flood) rates of flow were also decreased but only in the dormant season; summer floods were unchanged. No changes were noted in the seasonal low flows of the streams in the partly reforested areas. The reduction in the total runoff was attributed to the increased interception and transpiration by trees in the reforested areas; the reduction in the peak flows during the dormant season was attributed to the evaporation of snow caught in tree branches and to the delayed melting of snow in the forest relative to the open areas (Schneider and Ayer, 1961).

A summary by Hibbert (1967) of the results of many studies was simple and direct: "Taken collectively, these studies reveal that forest reduction increases water yield and that reforestation decreases water yield." All answers are not at hand or obtainable. For example, one can no longer determine the hydrologic effects of clearing the virgin forest of New York State or whether these effects are just the opposite of reforesting farmedout land. Nevertheless, the fears expressed by the Commissioners of 1811 and their successors proved unnecessary.

EXTERNAL EFFECTS OF CANAL LEAKAGE

Since the water level of the canal generally stood higher than the countryside through which it passed (see fig. 8 and section on "Canal Leakage"), bank seepage occurred generally over the entire length of the canal. Burrowing animals were especially troublesome. The absence of wide reaction at first to the effects of the leakage from the canal suggests that it did not create a significant external problem. Few accounts of damage were found in the early record, as the canal was put through while the country was still open, and settlers would naturally enough adjust to conditions as they found them, considering the canal as a benefit. Such claims as were made were small as, for example, 4 acres of farmland between the canal and the Mohawk River near Fultonville were waterlogged by bank seepage. The legislative report on the claim (1848 As. Doc. 45) noted that special legislation to indemnify the farmer was needed because there was neither precedent nor authorization for action in this case. The major problems emerged later.

State Engineer E. Sweet (1888 As. Doc. 25, p. 13) referred to extensive damages to private property arising from leakage, concluding that the large sum paid annually for damages could be avoided "by moderate expenditures for drains and ditches." Landreth (1900, p. 568) reported extensive swamps were formed on both sides of the Jordan summit level during the navigation season. Many wet low places were noted by the author in 1974 where the canal alinement had been rectified so as to leave space between the natural hillside and the banks of the canal.

OPEN SEASON FOR NAVIGATION

Unlike the anxieties expressed by the Commissioners of 1811, the environmental hopes of the 19th century settlers often exceeded their fears. For example, the settlers of the Western Plains expected that "rain will follow the plow"—or if not, then the "magnetic telegraph," or at least the railroad tracks (Powell, 1878, p. 70). So it was that the Commissioners of 1824–25 viewed the canal's climatic handicap—winter ice. The builders of the Erie Canal expected that the ice-free season of navigation would become longer,

"if the same changes of climate are produced in our country (and those changes appear to be rapidly progressing), by the cutting down of the forests, as have been produced in France, Germany, Italy and other countries, by the same process, our annual seasons of navigation will ultimately be extended to 250 or 275 days" (1825 Sen. Jour., 48th sess., p. 290).

On the average, the Erie Canal was open for navigation between late April and early December, making a navigation season of about 220 days. Actual dates of opening and closing varied from year to year, and were necessarily defined officially, based on appearance. The date defined for official opening (completion of repairs, refilling, lock services, and so on), caused some chafing among boatmen anxious to start; but choosing a date for closing the canal was a degree more troublesome. Too early and navigation suffered; too late and a sudden freeze entrapped loaded barges enroute, as happened on a few occasions,[7] namely:

1824 "15,000 bbl. of flour detained month of December by ice between Utica and Hudson" (Report dated 4 Mar. 1825, p. 8).

1828 Longest navigable season, March 27 to December 20, 269 days.

1871 Canals suddenly closed by extreme cold; 800 boats laden with merchandise frozen in.

1875 Shortest navigable season on record; opened May 18, closed on account of snow and ice, November 24, 191 days.

1880 Closed November 21 by ice.

During its earliest days, in the 1820's, the open season averaged about 240 days. Contrary to the expected effect of deforestation, the season progressively shortened to about 212 days in the 1880's. The closing date, more sensitive to temperature then the opening date, averaged around December 14 at the beginning of operations, and December 1 at the end of the century. The trend corresponded with the worldwide cooling during that epoch which reached minimum temperatures during the 1880's (Hoyt and others, 1935).

FLOODS

Floods present the greatest environmental danger to inland canals, a fact anticipated by the Commissioners of 1811, who noted (p. 19) that "floods, which pouring a torrent into a canal and tearing down its banks, might at once destroy the navigation and inundate the country" (p. 18) and "in the spring, the careful husbandman and miller will open every ditch and sluice to get rid of that water which, though at other times a kind friend and faithful servant, is then a dangerous enemy and imperious master. Of course, much of what is now withheld for many days will then be suddenly poured out. The torrents must, therefore, rage with greater fury hereafter than they do in the present day."

Increases in floods as a result of land development and deforestation have remained a controversial subject, but the intensity of argument seems to be abating in the light of accumulated

[7] A sudden freeze in 1962 that trapped barges for a couple of weeks ended most commercial use of the upland canals in Great Britain.

evidence that the effects of land use on floods are greater on small streams than large; and are greater for small floods than for large floods. (Hoyt and Langbein, 1955.)

For some of the small streams, such as those that passed under the canal in culverts, forest cutting may indeed have affected flood discharge. According to the experiments in New York (reported by Schneider and Ayer, 1961, p. 59) most of the effect of forest cover on flood peaks is on timing of snowmelt. Partial clearing, for example, might reduce flood peaks by desynchronizing snowmelt. These hydrologists, who found no effect of forest cover on floods during the growing season, also reported (p. 60) that their results agreed with those of other studies. Modern data would account for no great change in the flood regimen of major streams along the Erie Canal, and none seems to have occurred.

SEDIMENT AND ACCELERATED EROSION

Accelerated erosion that might destroy the canal was anticipated. "When the country shall be cultivated, streams swollen by showers will bring down mixed with their waters, a proportion of mud, and that, in the stillness of a level canal, will subside and choak it up" (Commissioners of 1811, p. 18–19).

The concerns of the Commissioners were not misplaced; sediment was troublesome, but not disastrous. The erosion of natural earth materials depends on the vegetal cover, rainfall intensity, rock types, and topography. The net effect of these factors is to put upper New York State among those areas of the country where problems of sediment are not especially severe.

Any accelerated erosion caused by farming was carried off in the runoff of the streams that drained the region. As an independent canal, it was insulated from these effects. Some of those streams were developed as feeders, and sediment would be diverted with the water. Taking the feeders supplying about 700 cubic feet per second and a sediment concentration of low summer streamflow, as indicated by modern records, to be about 10 parts per million, it appears that some 8,000 cubic yards of sediment were carried into the canal each season, amounting to an average of only 0.002 foot of deposition in a 200-day season. The feeders therefore were not a significant source of deposition. That problem was created rather by the side-hill location of the canal (see fig. 7), so advantageous in avoiding other difficulties—such as floods. The canal became a trap for the deposition of the sediment carried by the numerous runnels that were led into the canal through the berm bank, because they were too small to be carried under the canal in culverts (1832 As. Doc. 42, p. 4). Wash and slides along the steep walls of the Mohawk River valley were a continuous problem (1839 As. Doc. 86, p. 10), as they were along the deep earth cuts in the western division (1845 As. Doc. 28, p. 52–53; 1846 As. Doc. 14, p. 50).

Although, as previously stated, the velocity in the canal was too low to erode the bed or banks, the motion of the boats was a significant factor in causing bank wash on the one hand and was a help in maintaining navigable depth along the towpath bank on the other. Deposition tended to take place along the berm bank (1888, p. 134, 233).

The deposition of sediment was sufficient to retard the flow of water (1845 As. Doc. 28, p. 52) as well as the movement of the boats. Cleaning the prism—or "bottoming out" as it was sometimes called—was an annual part of the process of preparing the canal for the spring opening (1843 As. Doc. 25, p. 64; p. 80). Records of amounts of sediment removed were not reported nor were surveys regularly made. Soundings carried out in 1876 in the western division, where apparently sedimentation seemed more troublesome, indicated that 544,000 cubic yards had accumulated in the canal despite the annual spring cleaning. A volume of 376,000 cubic yards was excavated in 1882 (1883 As. Doc. 9, p. 2). In 1885 the division engineer again reported that annual cleaning could not keep pace with volume deposited. By 1886 the volume of deposition was estimated to be 800,000 cubic yards, equivalent to 0.6 foot on a 130-mile length of the canal bed—a rather large amount, some of which must have been carried from the deep earth cut above the Lockport combines (the canal at that time in the western division was 7½ to 8 feet deep) (1887 As. Doc. 38, p. 92). Only a very minor part could have been carried in by the feeders.

Erosion and sedimentation produced by engineering works may be a source of esthetic as well as physical damage. Erosion induced by the works of man is subject to a threshold which, if exceeded, exacerbates the process. The threshold is low in arid climates where the soil has little vegetal protection and a disturbance of the natural land surface tends to enlarge. In contrast, the threshold in humid, cool climates, like that in upper New York State, is quite high; land scars caused by construction, left alone, tend to heal. The banks of the canal became grassed and weedy and clearing the banks became a maintenance task. Vegetation has clothed and protected the banks of the abandoned canal.

WATER QUALITY

The quality of water had great significance to the Commissioners of 1811 who did the original planning. They saw the canal as a potential source of pure water, pointed (p. 21) to that "inexhaustible stream of limpid water which flows out of Lake Erie," and added there "is a strong temptation to use it exclusively until auxiliary supplies can be drawn from reservoirs equally pure."

In contrast, buoyancy was the only property of water of interest to the later commissioners during the 19th century operations, and that property was not in question. The operational view of the canal was economic and not ecologic. The successive annual reports of the commissioners responsible for its operation and maintenance were attentive mainly to traffic, trade, and costs, and had little to say of pollution or sanitary conditions except insofar as garbage or sewage mud may have interfered with navigation. According to recollections of Garrity (1966, p. 15) a covered pail was the toilet. Waste was "easily disposed of by throwing it overboard." Trash thrown into the canal, particularly at cities, became a common problem in the latter part of the 19th century, and open drains carried domestic and industrial wastes into the canal, for the canal was the sink—the low point—for many of the communities built up along its banks. There was therefore a sizable pollution load imposed on the canal (1887 As. Doc. 37, p. 145–156), even if only with respect to that transient population which lived on the canal and who dumped into it directly or indirectly their untreated wastes. An estimate of their pollution load may be made from the average number of boats operating on the canal. Although the number of boats registered during the 1870's numbered between 5,000 and 6,000 (Finch, 1927, p. 857) only about 2,000 were in operation at any one time. Since each operating boat required at least two persons and as many draft animals, and taking the pollution load of a horse or mule as four times that of a person, the population equivalent (p.e.), excluding the resident population, was of the order of 30,000. This population equivalent would impose a daily biochemical oxygen demand (BOD) load on the canal of about 5,000 pounds. This calculation does not include the load imposed by domestic wastes, little of which in the early and mid-19th century would have reached the canal, as each home had its own source of water and a privy. Later, however, warehouses, mills, and factories that were built directly along the canal, discharged wastes into the canal. Nevertheless, there were no reports of septic conditions (in distinction to nuisance) which would doubtless have attracted notice even in the 19th century.

The canal water, as pointed out in several places, was not stagnant. There was a decided flow through the system, maintained by feeders, bypass weirs, lockages, and leakage. Seepage, the main effluent from the canal, amounted to 8 inches per day, and so the residence time of the water in the 4-foot canal (average depth, 3.4 feet) was of the order of 5 days, and about 8 days in the 7-foot canal of the latter half of the 19th century. As calculated previously, the total flow into the 360-mile canal was about 1,900 cfs or about 10,000 million pounds of water per day during the height of its use in the 1870–80's. With water intake saturated with respect to oxygen (10 parts per million of oxygen), the available oxygen supply would be 100,000 pounds per day, many times the oxygen demand imposed by the canal operations. This intake of oxygen to the canal, sufficient, as it turned out, to avoid septic conditions, may be considered to be a byproduct of the inordinate inflow of water required to make up the leakage from the canal. A watertight canal would be a septic canal.

Rafter (1897, p. 191) described the situation at Buffalo, which apparently discharged its sewage effluent into the canal, because as the city authorities claimed, "the Erie Canal along the waterfront had cut off the natural line of drainage [to Lake Erie] of a large portion of the city." Rafter calculated the population equivalent to be about 61,000. On the basis of a dilution of 500 cubic feet per minute (8.3 cfs) per thousand population equivalent (p.e.), a canal flow of 50,000 to 60,000 cubic feet per minute, there should be no septic nuisance, although the "sanitary side of the question either as to the effect on health of people living along the line of the canal or on those navigating it, is not taken into account." (p. 192–193.) The problem at the time was rather the necessity to dredge about 15,000 cubic yards of sewage mud each year. Rafter stated that similar but lesser problems also existed at Lockport, Medina, Holley, and other places in the western division.

The canal was not a source of drinking water. Each barge carried one or two barrels of drinking water; canal water was used for washing and to water the draft animals. It must have been considered polluted in its later years, as the Act of April 15, 1889 (chapter 141), with reference to the adulteration of food, drugs, and liquors, prohibits (section 3) the sale or transport of ice cut from the canal for any purpose other than cooling of beer unless the ice is contained in a building or cart plainly marked "canal ice."

The canal had fish, and fishing was popular. From repeated reports of breaks ascribed to the tunneling activity of muskrats, the canal must have offered a favorable habitat for these animals, which made their home most often in the bank and fed on vegetation growing on the bank and along the canal margin.

Swamps and wet, low places were viewed as health hazards and so, in 1833, Jervis omitted construction sites for proposed feeder reservoirs because of the expressed apprehensions of their injurious influence on the health of the adjacent country (1834 As. Doc. 55, p. 61). Blodgett's climatology (1857, p. 477) recorded that "Sources of malaria of artificial origin—reservoirs for canals, and ponds in streams—constantly produces severe intermittent and malignant fevers." Somehow the canal itself aroused no such fears—perhaps because it contained flowing water, although that could not be as evident to the casual observer as it must have been to the straining mule bound for Buffalo. The visual appearance of flow depends not only on the absolute velocity but on the depth as well. Deep waters do not run still, they only appear to do so.

ESTHETICS AND HUMAN INTEREST

A canal is an improbable alteration of nature. A trough of water is built where not only was there no water before but often in the most unlikely places—very commonly following along the brow of a hill. Yet, as we know, these highly artificial works of the 19th century "sit easily and comfortably into the landscape" (Burton, 1972).

The Erie hastened the development of lands that had been only recently open to settlement. The settlers sought not beauty from the canal but cheap transport for their produce and their supplies. Although little, if any, attention was given to esthetics in the construction of the Erie (as distinct from structural workmanship), the intrinsics of the situation introduced elements of a pleasing design. To reduce changes in level and to minimize the need for aqueducts or other stream crossings, the canal followed along a contour, winding up a valley and returning back down on the other side, to avoid a major crossing of the stream in the valley bottom. Cutting along the contour tended to produce an alinement in harmony with the landscape. The 25-percent sinuosity [8] of the original Erie corresponds to that of mildly meandering rivers (Leopold and Wolman, 1960). Although the canal was straightened in several places in an attempt to eliminate bends, by 1862 the canal length had only been reduced to 350 miles, 13 miles shorter than its original length.

[8] Canal length = 362.8 miles; linear distance along canal course as measured on a map of 1:500,000 scale (8 miles per inch) = 290 miles; sinuosity = $\frac{362-290}{290}$ = 25 percent.

From firsthand observation, the British traveler, Basil Hall (1829, p. 127), noted an agreeable degree of curvature that tended to remove the "formality as well as the ditch-like appearance which generally belongs to canals." His impressions were generally favorable. Of his trip along the Mohawk River (p. 119) he wrote "we commanded a range of prospect both up and down of great extent and variety." His countryman, the acerbic Mrs. Frances Trollope, found her travels in 1830 to be a boring experience on crowded packets adding that "From the canal nothing is seen to advantage, and very little is seen at all" (Domestic Manners of the Americans, chap. 32).

Scale had something to do with appearance, as Mrs. Trollope also observed (chap. 19),

> I strongly felt the truth of an observation I remember to have heard in England, that little rivers were more beautiful than great ones. As features in a landscape, this is assuredly the case. Where the stream is so wide that the objects on the opposite shore are indistinct, all beauty is derived from the water itself, whereas when the stream is narrow, it becomes only part of the composition.

The dimensions and scales of the old canals were such that in a sense they fit the terrain—tucked, as it were, into the landscape. Those few canals of the 19th century that continued in horse-drawn use until such recent times have grown old enough to have become part of the landscape. Amenity and recreational values of these canals seem to have become treasured assets (Burton, 1972). To preserve them for this use and because of their historical interest, several old canal sites have become State or National parks.

The Chesapeake and Ohio Canal, which extends 185 miles from Washington to Cumberland, was built in 1825–30 in response to the success of the Erie, and operated with mule-drawn barges until it was put out of service by floods in 1924. It has been restored in part by the National Park Service. Justice William O. Douglas had this to say in 1954: "it is a refuge—a long stretch of quiet and peace at the Capitol's back door—a sanctuary where man can commune with God and with Nature * * *" (Quoted in Washington Post, Oct. 1, 1972, p. E1). The relatively simple technology available forced the builders into greater conformity with the natural scene than modern builders find necessary. This accommodation to the environment led not only to such pleasant effects as the contoured sinuosity previously noted, but also the use of more natural structural elements such as the stonemasonry of the locks and aqueducts. There is powerful esthetic appeal in handicraft. (John Graves, personal commun.)

THE CANAL AND ECOLOGIC RELATIONS

In a recent accounting of the ecological impacts of water projects in California, Hagan and Roberts (1972) list the following six items with respect to "canals" which might be examined in regard to the Erie Canal, although they are not strictly hydrological and their treatment here is very sketchy.

1. "Interferes with land access across right-of-way." Cutting access was the first "people" problem faced by the canal authorities. A liberal policy was adopted to provide bridges across the canal for just about every footpath and cowpath, let alone roads. With clearance of only 7½ feet above the water level, these numerous low bridges (averaged 3 to 4 per mile in the eastern or Mohawk division) gave the canal its "Low-Bridge" reputation, and probably hastened its disuse for extensive passenger service.
2. "Spread pests and disease." Other than to observe that the canal as a vector of pests would be confined between each summit and sag points—the subject is beyond the hydrological. As a channel for transport of goods and persons, the canal did doubtless aid in the speed with which infectious disease was spread—for example, cholera spread along the canal in 1832 while it was still used for passenger travel (Shaw, 1966, p. 223–224), but it would be no different in this respect from other means of public transport.
3. Effects on fish. Feeder dams across the streams affected the migration of fish—by obstruction and by diversion to a feeder canal that led water as well as fish to the navigation canal. The obstruction effect was only considered a problem where there was commercial fishing as along the Seneca and Oswego Rivers. The engineer's report on the proposed works along those rivers stated that the fisheries "will be overwhelmed by the process of damming and locking the river" (Canal Laws, v. 1, p. 501), and suggested that some consideration be given to the fishermen displaced.

   But the main effect of the canal on fish was through the regional interconnections of waterways. For example, De Witt Clinton, in his discourses on the natural history of the region (Clinton, 1820, p. 53–54) stated that "I expect great changes from the junction of the western and eastern waters on the subject of fish. Already have several kinds penetrated the canal at Rome into the Mohawk River," listing pickerel, black sucker, catfish of the lakes, chub or dace. He added

"The canal will bring the western fishes into the eastern waters * * *."

Marsh (1864, p. 116) saw the Erie Canal as enhancing the variety of fishlife because it enabled the intermixing of freshwater fish and vegetation of the Hudson and the upper lakes. Marsh concluded from this possibility that these two regions "have now more species than before the canal was opened."

Such intermixing was not necessarily advantageous as might be inferred from Marsh's language. The occurrence of two troublesome species of fish, the alewife (*Alosa pseudoharengus*) and the sea lamprey (*Petromyzon marinus*) in Lake Ontario and their subsequent spread into all of the Great Lakes has been attributed to the construction of the Erie Canal and the Welland Canal (first constructed 1824–33 by Canada between Lake Erie and Lake Ontario—to bypass Niagara Falls possibly to minimize diversion of traffic from Lake Erie to New York by the then new Erie Canal). In an assessment of the aquatic effects of ship canals, Aron and Smith (1971) state "The alewife was first recognized in Lake Ontario in the spring of 1873, when at least three observers reported it was present in abundance. The best evidence suggests that it entered through the Erie Canal," (Oswego Canal). Christie (1974, p. 840), who also reviewed the various alternatives—marine relicts, inadvertent input during attempts to introduce shad, the Erie Canal, and the St. Lawrence River—could only conclude: "The origin of the alewife in the Great Lakes has not been established with certainty."

With respect to the destructive sea lamprey, Aron and Smith conclude: "Although evaluation is not complete, available evidence gives strong support to the possibility that the sea lamprey entered Lake Ontario drainage via the Erie Canal." They observe that the sea lamprey "probably became established first in Cayuga and Seneca Lakes during the mid-1800's and then moved down into Lake Ontario as the alewife did" and conclude that "If it had not been for the Welland Canal these marine invaders and the havoc they caused might have been contained in Lake Ontario."

The role of the Erie Canal in introducing the destructive sea lamprey to Lake Ontario seems to be less clear. Aron and Smith indicate that there were no reports of the sea lamprey in Lake Ontario before 1880, but Lawrie (1970), citing Dymond (1922), observed that "Although the sea lamprey (*Petromyzon marinus* Linnaeus) is generally conceded to be native to Lake Ontario, it is an unwanted and inadvertent introduction to the remaining Great Lakes. Apparently it passed Niagara Falls through the Welland Canal sometime not long before it was first reported from Lake Erie in 1921." Wigley (1959) wrote that "Several lakes in New York, including Cayuga Lake, have supported landlocked populations of sea lampreys for centuries." The hypothesis of a long presence in Lake Ontario as well is given added credence by a record of a breeding population of sea lamprey in Duffins Creek just east of Toronto in May 1835 (Lark, 1973). Either the sea lamprey was in Lake Ontario before the connection with the Hudson River through the Erie and Oswego Canals (the latter completed in 1829), or it penetrated the 150 miles of canal and invaded the lake in the relatively brief period of time between 1829 and 1835.

If the sea lamprey did penetrate the Erie Canal rapidly and by an early date, why did they not continue on to Lake Erie by the same means? Perhaps they did. As already noted, velocities in the canal were low and the Lockport combines would seem to have been no more an obstacle than the locks on the Welland Canal. In the absence of direct evidence of the presence of the sea lamprey either in the canal system or in Lake Ontario prior to the opening of the Erie Canal, the possible invasion through the canal remains a conjectural though viable alternative to the possibility of a pre-canal presence in Lake Ontario.

There were other migrants. For example, Hubbs and Bailey (1938, p. 28) state that "The small-mouthed bass is known to have invaded the Hudson valley together with the large-mouth after the opening of the Erie Canal about 1825." Trautwine (1957) includes several citations of 19th century statements of the role of the canals on the migration of fish, but the association is usually based on inference rather than on direct evidence. With reference to migration, he noted further (p. 184) the possibility that the presence of a fish specie may be overlooked until a cyclic peak of abundance brings them to notice.

The 19th century fish record seems no more complete than the hydrologic. Taken together with a complex ecosystem, the haphazard record obscures conclusions as to the extent and manner in which the canal was implicated in the spread of undesirable fish species.

4. "Results in loss of wildlife." No mention of such loss in the record; however, the canal provided a favorable habitat for water-related mammals—for example, muskrats. (See Clinton, 1820, p. 43–45.)
5. "Creates safety hazard for children."—unfenced.
6. "Provides opportunities for parks and recreation where developed." Numerous sections along the abandoned canal have been developed for these purposes.

EFFECTS AFTER ABANDONMENT[9]

When canal reaches were abandoned as a result of relocation during the enlargements of 1836–62, or 1905–17, most were simply drained to become open ditches, although some sections were refilled to serve as ponds for fish culture (Titcomb, 1920). In the absence of an organized plan for disposal or protection (Supt. of Public Works, 1916, p. 19–20) the vacated lands were adapted to local purposes. Their linear character made travel the major use as before. As a minimum, the towpaths have been used as footpaths or as local roads. The old 40×4-foot canal winding along the drumlins in the lake district, abandoned for the 70×7-foot enlargement (see fig. 5), became roadways, usually starting with the towpath and gradually widened by filling in the canal until the road occupied nearly the whole right-of-way. Since much of the 70×7-foot enlargement followed the same general alinement as the older canal, little of that can be found. Large-scale abandonment of the 70×7-foot canal occurred during the 1905–17 enlargement (see section "New York Canals in the 19th Century"). Although over the years the abandoned 70×7-foot canal became subject to many changes, about 100 miles of open ditch between Rochester and Albany still appear on the topographic maps. (West of Rochester the existing 1905–17 enlargement occupies the same alinement as the earlier sections.) In cities the open ditch was filled to become city streets, and a few towns made the old canal site into parks. Most of the open mileage contains the marks of cutting, filling, or dumping so that there are relatively few sections of abandoned canal that are sufficiently distant from habitation and roadways to have regressed naturally. Several of these sections (including one of the 40×4-foot canal) were examined in 1974 to see the kinds of changes that took place.

[9] Assistance of R. S. Sigafoos, Geol. Survey, in the fieldwork is acknowledged.

As shown on figure 11, changes in cross sections from natural causes were small when compared with the design section. In fact, it is surmised that the fill along the bottom edges and the filleting of the corners may have taken place by sedimentation while the canal was in use. (See 1888 As. Doc. 25, p. 63.) Alternatively, from the evidence, one might question whether some sections as built conformed to the design sections as noted by Whitford (1906, p. 1037–1043). The time for active erosion after the canal was drained must have been short. Bank wash could occur only for a few years as rapid growth of a succession of weeds, brush, and trees in the moist soil gave protection to the side slopes. The bank rip-rap of 10–12-inch boulders would also serve to lessen erosion, although many of these were generally found to have moved downhill, probably as a result of frost action. As seen today, the open ditch is heavily overgrown by brush and trees, such as willow and ash, and where there is standing water the bed contains dense growth of cattails and rushes.

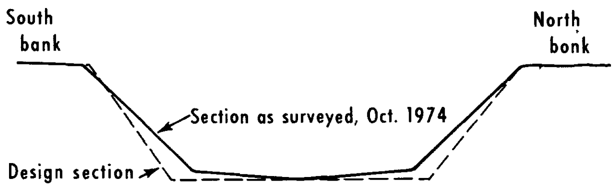
There is a stark contrast between a full and flowing canal and an abandoned open ditch. The former is a source of water flowing, in part, into the ground, the latter a sump for surface drainage and for outseepage from the ground. With a few exceptions, the open ditch contains near stagnant water, about 12 inches or less in depth, derived from seepage of ground water through the banks or from drainage of rain water down the side slopes. The ditch itself, being nearly level and being at an elevation above that of the streams that cross or parallel it, has not been captured by the active river system, and there is no large-scale erosion of the ditch such as might have occurred by river erosion. Even though some sections, especially in the Montezuma swamp, are put to use to convey water drained from agricultural lands, velocities are too low to erode the banks or bed. Some surface pondage was noted back of the banks where the canal was built away from the side hill, such as where the canal alinement was straightened.

The canal was built as a shallow ditch in or upon till or alluvium; major aquifers were not cut and the scale of operations did not constitute an irreversible change upon the hydrology. Although far from an asset, the present condition of the abandoned ditch falls short of being a hydrologic threat to the well being of the contiguous lands.

SUMMARY

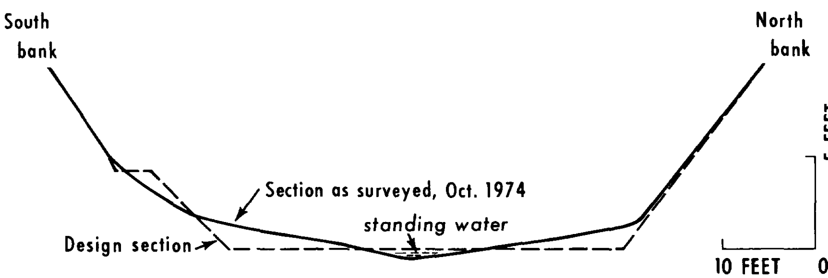
Today's concern with "environmental impact" centers upon the external effects of proposed projects. The promoters and planners

CAMILLUS QUADRANGLE, EAST OF NEWPORT, N.Y.
Looking West



Notes: Grass meadow, some shrubs and small trees; no rip-rap on banks.

JORDAN QUADRANGLE, EAST OF JORDAN, N.Y.
Looking West

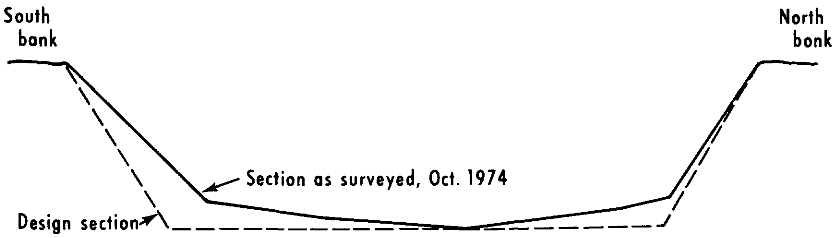


Notes: Heavily vegetated shrubs, some trees 4 to 12 inches in diameter. Banks paved, 12- to 18-inch boulders.

FIGURE 11.—Comparison of cross sections of abandoned canal reaches with original design cross sections. (See also cross sections on opposite page.)

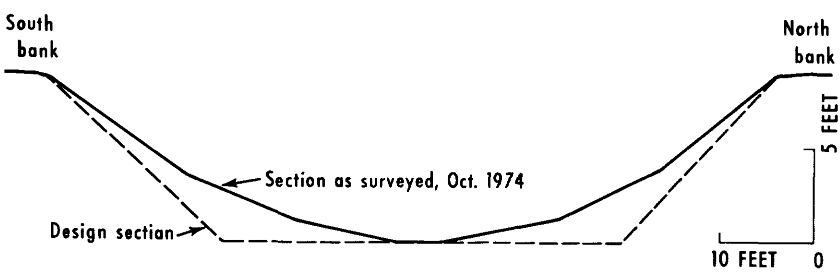
of the Erie Canal also were heedful of environmental effects, but centered their attention on those that might effect the proposed canal. For example, the record repeatedly details their apprehensions about the forest cutting and farming to be expected as a result of the canal, but aimed at the possibility that such changes would affect streamflow and erosion in ways that would damage canal operations. The flow of rivers did not decrease as originally feared. The planners feared that land use would increase the

SAVANNAH QUADRANGLE, WEST OF EVANS CORNER, N.Y.
Looking West



Notes: Shrubs, forbs, cattails on bottom, small trees on north bank, transmission-line clearing on south bank. Rip-rap in place on south bank, no standing water on bed at time of survey.

LYONS QUADRANGLE, EAST OF LOCK BERLIN, N. Y.
Looking West



Notes: Forested, hardwoods (12 inches in diameter), banks paved, bed dry.

intensity of flooding and so endanger the canal. Floods were indeed a serious problem, but not for the anticipated reason. Although "bottoming out" was necessary to remove sediment carried in by the feeders or brought in by bank wash, sediment was not generally a major difficulty.

The dissolved oxygen brought into the canal with the feeders was sufficient to inhibit the development of septic conditions despite the pollution load imposed by canal operations and by towns or cities along the way. The great amount of water inflow required because of the leakage from the canal was an asset in maintaining a flow of oxygen through the canal.

Nevertheless, there were many external effects of the canal. River flow and ground water were affected by the canal. Streamflow was reduced as large quantities of water were diverted from the rivers into the canal. The canal was built above the regional water table and therefore the canal acted as a linear source of recharge to the ground, deriving water from the upland streams. In addition, there were significant effects on migration of fish. The Erie Canal may be implicated in the spread into the Great Lakes of the sea lamprey and the alewife, two troublesome species of fish.

Looking only at the hydrology, the canal was by no means an environmental disaster. The external effects were neither systematically adverse nor systematically beneficial. For example, consider water flow. The diversions from the rivers used to feed the canal were frequently contested by mill owners, but the seepage of that water to the streams below the canal through the ground-water system would tend to increase the dry weather flow of those streams and to that extent would be an asset to water users downstream. Land development induced by the canal was a factor of great economic benefit. Flood backwater at culverts was a source of relatively minor land damage. The operators of the canal could cope with these effects on a project of the scale of the Erie Canal. Needed corrective actions were plainly evident and could be taken at the time.

Because the early canals were constructed of local materials, and were subject to hazards as well as an uncertain supply of water, the planners necessarily had a weather-eye for the unknown relations between the terrain and their proposed works. In the building, and later in the maintenance and repair that was required by deficiencies in design, the responsibilities to make sure the scheme worked passed to the construction engineer. Predicted external effects that did not materialize could be ignored by the busy, practical engineer. The environmental projections that were so prominent in the planning reports for the Erie Canal seemed to be the last for the century. Thus, Jervis, who had built and maintained much of the Erie Canal and many others as well as rail lines, had nothing to say of environmental effects of engineering works in his memoir (1877).

Although it is evident from the discussion of water supply that the controversial topic of forest and streamflow had lively partisans, the subject as well as other hydrologic environmental effects remained apart from 19th century engineering practice. The subject did not arise in any significant way in the civil engineering literature of that century as documented in the Transactions of the American Society of Civil Engineers. An 1885 paper on "Preservation of forests" dealt with the maintenance of a supply of timber for builders. A 1909 paper on "Forests and reservoirs in their relation to stream flow" was the first in this literature that was aimed squarely upon the external effects of land use. The paper was soon followed by many others on similar subjects and, for some years, engineering literature was dominant in reports on hydrology. Recent engineering literature reflects the full flood of environmental subjects, including the hydrologic, of which this report may be viewed as a part.

In more recent years, the external hydrologic and climatic effects of proposed large-scale canals have been brought into question (Nace, 1974). Modern canals of major scope and scale that transport water, heat, and entrained particulate and dissolved material from one region to another can influence the climate and the ecology, or even the crustal isostatic balance. The Erie Canal experience cannot be extrapolated over the enormous differences between the works of the 19th century and those of the 21st century soon to be at hand, save in one significant respect, the common role of information and the feedback from recorded experience.

SUPPORTIVE HISTORICAL REVIEWS

HYDROLOGIC DATA AND ANALYSES

It was the construction in the 1830's of lateral canals, such as the Genesee and Chenango Canal, leading off to the south over high summit levels, which brought about two innovations in American water development—the construction of artificial impoundments to serve as reservoirs for water supply, and the collection and analyses of hydrologic data, albeit on a spot or *ad hoc* rather than a systematic basis.

The reservoirs were needed to augment the low flows of the small streams at the summit levels which were over 1,000 feet in elevation. Having definite measurable capacity, a reservoir would naturally enough arouse questions as to whether the entering streamflow was enough to fill it. As the first reservoirs were proposed to supplement the flows of some small brooks to be used for feeders on the high summit level on the Chenango Canal (lateral built in the later 1830's to connect the Erie Canal at Utica with the Susquehanna River at Binghamton), British practice was to be followed in estimating the flow available from rainfall. Jervis (1834 As. Doc. 55, p. 57), after referring to "Sutcliffe in his Treatise on Canals, &" (sic), goes on to say that the greatest amount they have been able to obtain from the Blackstonedge reservoir (on the Rochdale Canal in England) is one-third of the rainfall, and this over a very tight uncultivated soil. Dalton (John Dalton of England, well known for his studies of molecular theory and evaporation) estimated the average entire fall of rain in England at 36 inches annually, and the evaporation on land and water at 23 inches, which allows over one-third to drain off and find its way to the ocean by running streams. Later, Jervis(who 16 years before had begun as a surveyor's axman) added (p. 58)

I propose to take, as a basis of calculation, one-fifth of the downfall water for the quantity that will descend to the reservoirs. The observations above quoted from Sutcliffe, together with those that have been made on general evaporation from the surface of the earth, induce me to believe this ratio will will be fully realized. I have accordingly made a tabular statement of as many reservoirs as I consider necessary to supply the balance of water wanted to supply the longest section from the summit.

The reservoir sites considered are shown in table 5 (1834, As. Doc. 55, p. 59).

The quantities listed in the final column of the above table are equivalent in each case to about 5 to 7 inches over the contributing drainage area, and because annual rainfall in that region is about 35 inches, one can see how Jervis derived the water supply. The column headed "Number of times filled in year" seems to have been a derived item rather than a step in the calculation. It shows how the reservoir would operate. Looking at those figures today, one might question whether reservoirs of these capacities having

TABLE 5.—*Reservoir sites, Chenango summit*

Reservoir site	Drainage area (acres)	Reservoir area (acres)	Capacity (million ft³)	Number of times filled in year	Supply after deducting 5 percent loss by evaporation (million ft³)
Leland's Pond	3,594	90	43.1	2	82.0
Madison Brook #1	----	100	39.6	1¼	47.1
Madison Brook #2	6,005	180	70.4	1¼	83.7
Eaton Brook #1	2,493	56	37.0	1½	52.7
Eaton Brook #2	2,034	76	52.6	1	50.0
Eaton Brook #3	4,253	205	103.2	1	98.1
Bradley Brook #1	2,079	32	15.7	2½	37.2
Bradley Brook #2	1,246	60	31.1	1	29.6
Hatch's Lake	----	---	----	---	30.0
					510.4

NOTE.—(Some rounding off of numbers and modernization of table headings.)

filled during the spring at the onset of the canal season, would fill again during the season of low runoff when the canals would draw upon them.

For example, Bradley Brook #1 reservoir, listed to fill 2½ times to yield 37.2 million cubic feet, has a capacity equivalent to 0.11 of the total annual runoff as indicated by modern data. A reservoir of that volume could be counted on to yield about 1.4 times the capacity rather than 2½ times, as assumed (Langbein, 1959, fig. 1).

Six reservoirs were built in 1835–36 as shown in table 6 (1840 As. Doc. 96, p. 22).

TABLE 6.—*Reservoirs built, Chenango summit*

Reservoir	Area of reservoir in acres	Depth (ft)	Capacity cubic ft ($\times 10^6$)	Drainage area (acres)
Leland's Pond	173	8	43.1	----
Madison Brook	235	45	[1] 80.0	[2] 6,000
Eaton Brook	284	50	[1] 162.7	[2] 6,000
Bradley Brook	134	25	56.0	----
Hatch's Lake	136	10	61.6	----
Kingsley Brook	80	[3] 35	80.0	----

[1] Not consistent with surface area and depths as given. Listed by Rafter (1905, p. 765) as 460 million cubic feet for Madison Brook reservoir, and 553 million for Eaton Brook reservoir, but these figures do not appear to be right as they are disproportionately large for the drainage area.
[2] 1836 As. Doc. 65, p. 57, 58.
[3] Depth given as 45 feet in 1844 As. Doc. 16, p. 70.

These reservoirs were maintained through 1905 as part of the feeders to the Erie Canal. Kingsley Brook dam was washed out by a flood in April 1843 (1844 As. Doc. 16, p. 70). It was repaired and restored to service in 1867.

Subsequently, additional reservoirs were built, mainly by controlling the outlet of lakes, such as Skaneateles Lake, Otisco Lake, and Owasco Lake, that fed streams used as feeders. Rafter (1905), who describes in some detail the water supply of the Erie Canal as of the 1890's, lists 26 reservoirs (p. 765) with a total storage capacity of about 10,000 million cubic feet, a volume whose size can be judged by equating it to 60 days' river diversions.

Inconsistencies in the published account make it impossible to judge the adequacy of these reservoirs, but the matter must have troubled Jervis because in 1835 he instituted what is believed to be the first set of observations of rainfall and runoff in the United States (1836 As. Doc. 65, p. 57–59). In later years (1877, p. 51) he described this work in the following terms:

> I decided to establish a rain gauge and a sluice for measuring the water that flowed from the valley (the Chenango). On one of the valleys, this

was attended to daily for one year [1835], and on another valley, from June to December. Mr. William J. McAlpine was the Resident Engineer on the Summit Section and had charge of the rain and sluice gauges. The matter was diligently attended to, and the result from these gauges was to establish 40 percent as the proportion of rainfall which on an average soil could be secured in a reservoir.

Although Jervis gave a table of the results (republished in U.S. Geol. Survey Water-Supply Papers 24 and 109; respectively, by Rafter, 1899, and by Hoyt and Anderson, 1905), he did not describe the methods used other than to say that a rain gauge was obtained from Hamilton Academy nearby, and that the flow measurements were made below the two reservoirs which had just been built, and which "equalized" the flow as footnoted. There seems to be no record of how the measurements of flow were made (most likely by timed floats), whether a record was kept of stages in the reservoir, or of depth of water in the sluices, whether a rating curve (that is, a relation between depth of water and rate of flow) for the sluice was prepared, or of how the water equivalent of the snow on the ground "which fell * * * November and December of 1834" was measured. Such an account would be useful in establishing the accuracy of the data and the history of the development of hydrologic measurements, for, as noted, this work is believed to be the first study in the United States of the relations between rainfall and runoff, one of the long-standing problems of hydrologic research.

Shortly after, W. H. Talcott (1840 As. Doc. 96, p. 53) adjusted the observed record of flow of Madison Brook for the effects of the impoundment, and he referred to Jervis' account as follows:

It is there stated, that Madison Brook reservoir 'retained the flood waters, and discharged them nearly uniform through the reservoir.' The gauge sluice was below the reservoir dam, so that the gauging indicated only what was discharged through the pipes each day, instead of what drained off from the valley.

Talcott was quite correct in this assessment, but not in the adjustment of the measured flow. His adjustment consisted of two parts: (1) that filtration from the lake from June through October amounted to 30.6 millions of cubic feet from an average area of water surface of 100 acres and (2) that about 20 millions of cubic feet remained in the reservoir at the end of October, making an addition of 50 million cubic feet, to the 105.7 million of runoff that was measured during June–October period. Since the precipitation for this 5-month period totaled 429.5 million cubic feet, Talcott then concluded that the "ratio of drainage" should be 0.364, rather than 0.246 as given by Jervis.

A review of this adjustment raises several queries—the June-October filtration of 30.6 million cubic feet on 100 acres is equivalent to 7 feet in 5 months (half inch per day) which seems inordinately high in the light of modern experience, though perhaps quite conservative to a canal engineer with keen awareness of a rate of "filtration" from the canals of 8 inches each day. A linear canal perched along the hillside, with rather large perimeter-area ratio offers a hydrologic setting quite different from a compact reservoir centered on the valley thalweg. Although Talcott was quite correct in adding in the reservoir content remaining at the end of October, he should also have deducted the contents at the beginning of the 5-month period when the reservoir was probably full. Both of these considerations would have decreased the adjustments as made by Talcott and probably decreased it to zero, as the reservoir was in a generally lowering trend during the 5-month period.

Talcott reported his adjustment of the flow record of Madison Brook in connection with a study of the water supply for the summit of the Genesee Valley canal in 1839—a study that shows how far hydrologic design had come in the few years since the Erie Canal was built, for the concepts and procedures he used are quite modern.

Talcott's analysis (1840 As. Doc. 96, p. 41 et seq.) very properly began by setting down and estimating the essential elements of the "demand,"

> for initial filling,
> losses by evaporation and filtration (seepage) from the canal,
> losses at mechanical structures,
> lockage for the trade of the canal, and the
> evaporation from the reservoirs.

His report follows that of F. C. Mills (1840 As. Doc. 96, p. 23), who observed that "In order, therefore, to estimate very correctly the extent and cost of a reservoir that will supply a given quantity of water, it is necessary, first, to determine the annual fall of rain in the vicinity, the extent of the basin, and the proportion of the annual fall of water that may be drained from it into the proposed reservoir; also, the loss of water after thus collected, referable to evaporation, filtration, and absorption, and the leakage at the fixtures for the discharging of water. To do this requires time. A series of daily observations should be kept, for the period of one or more years. This in 1834 was impracticable, for the want of the requisite time and assistance." The estimates of water supply would need to be based on precipitation, for which Jervis' measurements were available. The question was how? Talcott expressed disagreement with Jervis' use of estimating runoff from precipitation by multiplying the letter by a coefficient, stating (p. 54) "Nor does it follow, either from the experiments quoted above, or from any we have ever seen, that there exists any constant ratio between the fall and drainage." It was his judgment that the difference between precipitation and runoff, which is taken as the "demands," is the more uniform, citing as evidence the data for Eaton and Madison Brooks (the latter as corrected), as follows:

June to December, differences between precipitation and runoff

Eaton Brook	12.05 inches
Madison Brook	13.30 inches

He then noted (p. 54) "The demands (that is, the differences between precipitation and runoff, the evapotranspiration in modern terms) are much more uniform than the falling water and since they must be supplied first, it is evident that the drainage (that is, the runoff) will depend altogether upon the excess of fall (that is, the precipitation) over what is required for their supply." He added (p. 55) "We do not claim that these facts are sufficient to establish any general rule, although they seem to confirm the views herein taken of this question."

This is a classic argument, of some importance, because the estimate of the runoff in a dry year would be proportional to the precipitation according to the coefficient method; the estimate of the runoff calculated as a residual would be much less.

Talcott then calculated the annual drainage (=runoff) in the Genesee Valley during a dry year by the residual method as follows (p. 56):

	Inches
Precipitation[1] ("falling water")	28.36
Natural consumption	21.63
Drainage = Difference	6.73

[1] At Hartwick, N.Y., for 1837 where the 10-year average precipitation was 38.44 inches.

Examination of long-term records of streamflow in the Genesee River drainage area indicates that the annual lows are quite variable, ranging from 5.2 inches for Canadice Lake outlet near Hemlock to about 10 inches for the Genesee River itself.

A few years later, Henry Tracy (1850, Sen. Doc. 40, p. 17) assembled the following available data on annual rainfall and runoff:

	Rain and snow (in.)	*Water that ran off (in.)*	*Evaporation from surface of ground (in.)*	*Ratio of drainage*
1835 Madison Brook	35.26	15.83	19.43	0.449
1837 Lond Pond (Mass.)	26.65	11.70	14.95	.439
1838 Long Pond (Mass.)	38.11	16.62	21.49	.436

which tended to show the ratio to be more uniform than the difference between rainfall and runoff.

Tracy's estimate of inflow to Hemlock Lake, south of Rochester, which it was proposed to control as a storage reservoir, employs the coefficient method (1850 Sen. Doc. 40, p. 29).

Hemlock Lake, 1,544 acres surface area, 29,525 acres of contributing area

Least annual fall of rain, 22 inches

Ratio of drainage, 0.4, or 8.8 inches inflow to lake=943 million cubic feet

Loss from the lake (1,544 acres)

Total evaporation per year=49 inches

offset by rainfall on the lake of 22 inches making net loss of 27 inches.

Hence annual loss from lake=151 million cubic feet giving 943—151=792 million cubic feet as the amount available "in the year of least fall of rain."

Unfortunately, probably following British practice of the times, the idea was left there—that the yield of streams could be accurately inferred from rainfall, whether by the ratio or residual method. For Rafter (1897, p. 174), noting the lack of attention by canal authorities to measuring the flow of streams, added that Jervis' "results, while covering too short a period of time to furnish safe averages, have still been, as regards the yield of small streams in the State, the handy stock in trade of the New York Canal Department from that day to this." The writer recalls an interview in 1935 with Frederick Stuart Greene, then Superintendent of Public Works, who said that he still favored the estimation of streamflow from rainfall records. He emphasized the difference in cost between rainfall and flow measurements. Talcott's note of inadequate time and resources to collect hydrologic data was perhaps the first appearance of an apology that has been written again and again in project reports in this country for over a century and still appears today.

In view of the high cost of error in modern public-works practice, major reliance is placed upon a national, systematic network of continuous records of streamflow. The controversy regarding the estimate of annual runoff by the coefficient or the residual method is now moot. Precipitation data are used to extend records of daily flow or to synthesize the daily flow of ungaged streams by the use of complex hydrologic formulas or models that depend for their calibration on flow data from the systematic network.

HYDRAULIC COMPUTATIONS

The hydraulic difficulties that developed during the operations of the original canal were to be corrected in the enlargements that were begun in 1836. By that time formulas for the velocity of water in open channels became generally known from European research, which were then applied in canal design, especially as greater quantities of water had to be conveyed. The hydraulic problem was the following.

To design a channel section and profile that will convey a flow of water sufficient to maintain a prescribed navigable depth, with a known rate of channel loss per mile and to supply lockages, and not exceed a maximum mean velocity of 1 mile per hour. This is a standard hydraulic problem, easily solvable with a number of possible combinations of depth, area, and slope, provided the channel is stable—that is, the channel does not react to the flows carried. The prescription of a limiting velocity of 1 mile per hour assures that this condition of stable bed and bank is met.

O. W. Childs (1848, As. Doc. 16) and Henry Tracy (1850, Sen. Doc. 41) carried out these analyses for the western division. A hydraulic problem was created in that division by the desire to obtain as much water as possible from Lake Erie to supply the canal all the way to the sag point in the profile at the Montezuma marshes. The key to the problem was a velocity formula, and at the time, the best known (Rouse and Ince, 1957) was the Prony formula.

$$av + bv^2 = DS$$

where

v = mean velocity, in feet per second,
D = hydraulic mean depth, in feet,
S = slope of the water surface, and
a and b are constants determined by experiment.

According to Childs (p. 150), Prony gave the following values for the constants:

$$a = 0.0000444499$$
$$b = .0000942772$$

and as defined later by Eytelwein:

$$a = 0.0000242651$$
$$b = .0001114155$$

(The 6-figure precision of the constants probably came about in the conversion of the formula from metric to English units. The general concept of reporting calculations with regard to their real accuracy did not seem to be part of the mid-19th century engineering practice.)

One may note that because of the decrease in the a term and an increase in the b term, the later Eytelwein version approaches the Chezy formula in which the product DS varies only as v^2, embodied in the Manning formula of present practice.

It is interesting to compare the Prony-Eytelwein formula with the Manning formula now in common practice:

$$v = \frac{1.5}{n} D^{2/3} S^{1/2}$$

where v, D, and S are as before and n is a coefficient of roughness. (The constant 1.5 arises because of the conversion of the formula from metric to English units, and some relic of false precision is found even today where it is usually reported as 1.486, the cube root of the number of feet in a meter).

For slopes and depth encountered in the Erie Canal, the Prony-Eytelwein formula gives about the same results as the Manning formula with a value of the roughness factor n of about 0.025, not far above what is now considered applicable to a smooth artificial channel in good condition.

Measurements in the improved outlet channel of Onondaga Lake were used (1848, As. Doc. 16, p. 172) as a check. The Prony formula (with Eytelwein coefficients) gave a velocity of 1.82 feet per second. The velocity as measured was reported as follows:

Surface velocity	1.45 feet per second
Reduced to the mean	1.13 feet per second

The difference was to be accounted for by the irregular and rough section of the outlet.

Based on the Prony formula (with Eytelwein coefficients) Tracy (1850, Sen. Doc. 41, p. 10) presented four plans for the canal between Lockport and Rochester.

1. Constant width, vary depth and slope so that mean velocity = 0.5 mi. per hr.
2. Constant depth (7 ft), vary width and slope.
3. Depth at 8 ft for first 40 mi west of Lockport, thence gradually decreasing to Rochester.

4. Level bottom to have such depth at Lockport as to give sufficient slope to the water surface.

(In each case, flows were to be as follows: Pendleton, 31,000 cfm; Lockport, 29,600 cfm; and Rochester, 17,000 cfm; depth at Rochester was kept at 7 ft.)

Tracy carried out a series of calculations based on these conditions, and for a low and high water level. He favored plan number 4 mainly because the level bottom would not exclude the possibility of supplying the canal from the Genesee River in an emergency.

The channel as built on the 62.5 mile pound from Lockport to Rochester (Searles, 1877) conformed more nearly to Tracy's plan number 2, with depth nearly uniform.

Section below Lockport combines	
Surface width	96 feet
Depth	8 feet
Slope	.068 foot per mile
Section midway	
Surface width	87 feet
Depth	7.6 feet
Slope	.050 foot per mile
Section at Rochester	
Surface width	70 feet
Depth	7.8 feet
Slope	.028 foot per mile

The standard section east of Rochester at the time was 70 feet wide by 7 feet deep.

Because of the continuous leakage from the canal, the flow decreases and therefore the hydraulic capacity must decrease. Of the indicated 50 percent decrease in hydraulic capacity, from Lockport to Rochester, one-third was made by reduction in width and two-thirds by reduction in slope. As in natural rivers, the profile was concave.

Lake Erie Levels.—Variations in the level of Lake Erie would necessarily affect the flow into the canal. Considering the low gradient from the lake to the "mountain ridge" (total fall, at average lake levels, of 4 feet) even small changes in level and therefore in slope would significantly affect the flow down the canal.

The Commissioners of 1811 (p. 21) suggested "that it is impossible there should ever be a considerable variation in the surface of Niagara River. * * * Indeed, we know from experience, that a greater difference of elevation at the mouth of Lake Erie is occasioned by a change of wind, than by any variation of seasons."

They had ascribed an elevation of 525 feet to Lake Erie; those of 1816 made it 564.85 feet; more accurate levels run during the construction placed its level very close to the presently adopted mean level of about 572.5 feet. Nevertheless, the lake was soon known to change its levels, seasonally and from wind. These levels are also subject to secular changes owing to climatic fluctuations over the contributory area of the Great Lakes. Isostatic readjustment taking place following retreat of the glaciers (Flint, 1957, p. 250) would not affect the canal, first, because it emerges on the lake near its outlet; thus the canal and lake levels would maintain their same relative position, and, secondly, because it is small in the Lake Erie region (about 1 mm per year).

Continuous records of lake levels are available only since 1860, but Horton and Grunsky (1927, p. 276) show a historic high of 575.1 feet in June of 1838. The levels had receded considerably by 1841 when the Commissioners of the canal gave the low levels some attention because of the resulting difficulty. They reported (1842 As. Doc. 24, p. 53, 60) that the level reached in 1838 was 5 feet 1 inch higher than in November 1820, when the lake was at its lowest known stage. This would make the 1820 level 570 feet. Commissioners go on to say that the level in November 1841 was only 9 inches higher than in 1820, or 570.7 feet. At that time the lake was lower than the level of Tonawanda Creek and water in the canal flowed toward the lake rather than out of it. Water in the western division of the canal was again low in the 1890's. (1892 As. Doc. 15, p. 133.)

MEASUREMENT OF WATER FLOW

The Erie Canal was begun on faith that water supply would be sufficient for the need. There was, of course, superficial justification for this faith in the generality—the Mohawk River and Lake Erie seemed to offer quantities of water far in excess of that needed and, in addition, the canal crossed other streams that could be used for incremental supplies along the way. Accordingly, few measurements of flow were made before construction began. However, soon after sections of the canal were filled, measurements of flow became commonplace as problems of leakage and water supplies became manifest, particularly in the lateral canals which were built in terrains and at a time less favorable than that of the Erie Canal. The streams available for water supply were smaller and had become subject to claims by mills which had developed them for waterpower.

The first set of measurements was used to resolve the critical question of the water supply available for the proposed Tonawanda Creek summit—the Commissioners of 1816 stated that the flow of 10 streams "gauged with great care," totaled 253,435 cubic feet per hour, then judged to be sufficient. Additional measurements (no data given) were made in 1820 (1820–21 As. Jour., 44th sess., p. 866), as were measurements of leakage of water from the middle section of the canal that had already been filled. As already mentioned, these measurements led to the abandonment of the Tonawanda route in favor of a route to the north.

Leakage from the canal was an unanticipated problem that led to measurements of flow (leakage being the difference in rates of flow over a suitably long reach of the canal), and it was natural enough that reference be made to the results of these measurements in the design of the new canals. In his report on the proposed Chenango Canal, D. S. Bates (1830 As. Doc. 47, p. 31) referred to his measurements of canal leakage made in 1824 in the several reaches of the western division of the Erie Canal (see table 1 for results). John B. Jervis' report on the same proposed Chenango Canal (1834 As. Doc. 55, p. 54) referred to his measurements of canal leakage in the eastern division, particularly the section from Amsterdam to Schenectady.

Bates (1830) used floats to measure flows in the canal, but details are not known as field notes are not available. A report by D. S. Bates, quoted by Sherman (1932) on flow measurements made in Ohio in 1823 in connection with canal proposals inspired by the Erie, states that he used weirs with rectangular notches on the smaller creeks and floats in the larger streams. In that report Bates mentions the results of his measurements in New York as follows (Sherman, 1932, p. 157): "Quantity of water expended in the New York canals has been found to be 100 cubic feet per minute[10] per mile in ordinary cases," a result based on his gagings in 1823 and 1824 (Bates, in 1830 As. Doc. 47, p. 31).

The Chenango Canal, built in 1834–36, one of the new canals that entailed serious questions about water supply, followed the valley of the Oriskany Creek from Utica, reaching a summit level at an elevation of 1,050 feet, where it crossed the saddle between Oriskany Creek and the Chenango River. The canal then followed

[10] In canal practice at the time, water flows were reported in cubic feet per minute rather than cubic feet per second as has been customary in hydraulic practice.

down the valley of that river to Binghamton. Uncertainties about the water supply came about because of the high summit and because water could not be taken from Oriskany Creek owing to objections from the established mill owners. Hence, all water north of the summit had to be supplied from the streams at the summit, making it necessary for the promoters of the canal to store the high runoff of the spring season for use during the low-water period. A scheme of storage reservoirs was proposed for six of the small streams that otherwise flowed south to the Chenango River. Jervis, the engineer, arranged for the measurements of precipitation and of the flow of Eaton and Madison Brooks that were described in the section on "Hydrologic Data and Analyses."

Assessment of the adequacy of streams to be used as feeders was carried out by *ad hoc* spot gaging during the summer or autumn season of low flow. Thus, in 1841 when "streams were unusually low," O. W. Childs (1843 As. Doc. 25, p. 40–41) was directed "to make accurate gauges of streams to be used as feeders for the enlarged canal, from the lock at Geddes to the Seneca River." Because the results indicated insufficient flows it was decided to lower the bed of Skaneateles Lake outlet by 5 feet in order that the lake could be drawn down by that amount through a gated bulkhead.

Jervis (1834 As. Doc. 55, p. 56) observed that 1833 was too wet a season to gauge for low flow determinations and "sluices were put in all of the streams to be gauged and every opportunity was improved to procure a measurement of the lowest water." No account was given of what the "sluices" were like. He expressed a correct view; the "lowest gauge (i.e. measurement) was the one in which there was the best evidence of the regular flow of the stream" or, in modern terms, when the streams had receded to base flow. He then added "various opinions were expressed in relation to the comparative condition of the streams when gauged and at the lowest state of the water. It is believed, however, that a deduction of 25 percent from the gauged quantity would not essentially vary from the minimum flow."

Little was published concerning methods of making measurements of flow, even though in contrast to the long-established methods of land surveys, flow measurement was still exploratory and uncertain. Timed surface floats were used. The following description of flow measurements is contained in a hearing on claims made by mill owners for damages caused by diversion of water of the Genesee River to canal purposes (1854 As. Doc. 63,

p. 84). The testimony was given by Daniel Marsh, a civil engineer previously employed by the State, then appearing for the claimants.

> I found the width and depth, and multiplied these into the velocity; to find the velocity I used a pine stick of lath 3 feet long to float upon the surface; I tried it within 18 inches of each side and so quite across the stream at about equal distances of each other * * *

The floats were timed over a reach, an assistant dropping the floats on signal at the upper end. Depths were measured at several places at equal distances. Marsh noted that "the velocity above stated is the surface velocity," and then, after some remarks that seem unclear, he added, "so I deducted one-tenth from the surface velocity."

In the measurements of the flow of the outlet of Lake Onondaga (1848 As. Doc. 16, p. 172) a coefficient of 0.78 apparently was used to reduce surface velocities to the mean. The shallow streams probably discouraged if not precluded the design of deep floats that would move at the mean velocity in lieu of surface floats. The use of current meters and systematic records lay in the future. (1888 As. Doc. 25, p. 25; Rafter, 1889.)

FEEDERS, LOCKS, AND STREAM CROSSINGS

Feeders.—In 1825, when the canal as a whole was first in operation, water supply was obtained from (east to west):

- Mohawk River at Johnsville (Minden)
- Schoharie Creek
- Mohawk River at Little Falls
- Steeles Creek
- Oriskany Creek
- Mohawk River at Rome (Rome summit)
- Wood Creek
- Skaneateles Creek (Jordan summit)
- Genesee River
- Oak Orchard Creek (including diversion from upper Tonawanda Creek)
- Tonawanda Creek (lower)
- Lake Erie

By 1862, the list of feeders or sources of supply was as follows (1863 As. Doc. 8, p. 442):

Feeder	*Date*	*Supply (cubic feet per minute)*
Rexford Flats	1844	10,979
Schoharie Creek	1845	6,800
Rocky rift	1856	10,602
Little Falls	1843	12,643
Ilion Creek	1838	800
Chenango Canal	1836	750
Butts Creek	1838	1,400
Mohawk feeder at Rome	1858	10,979
Black River Canal at Rome	----	708
Oneida Creek	1835	1,500
Cowassolan Creek	1858	320
Erieville reservoir	1850	2,130
Chittenango Creek feeder	1840	250
Cazenovia Lake reservoir	1857	2,631
De Ruyter reservoir	1863	3,972
Limestone Creek	1852	210
Orville (Butternut Creek) feeder	1858	450
Camillus feeder	1843	1,500
Skaneateles Lake reservoir	1844	7,520
Genesee River feeder	1826	350
Genesee Valley canal	1842	861
Oak Orchard Creek	1840	1,400
Lake Erie, Buffalo	1856	35,000
		113,755 cf, (1,900 cfs)

The list includes the inflow from the later-built Genesee and the Chenango Canals that led off to the south, reaching high summits en route. The lateral canals were continued as feeders after they were closed to traffic.

Lift Locks on the Original Erie Canal

[Published sources give differing figures]

East to West No.	*Total lift (ft)*	*Approximate mileage from Albany*	
2	22	----------	Up
2	22	----------	Up
7	56	8	Up
2	15	----------	Up
3	26	----------	Up
4	32	----------	Up
1	7	20	Up
1	35	----------	Up
5	40	34 Schenectady (elev 225)	Up
1	4	----------	Up
1	6	----------	Up
1	7	----------	Up
1	6	60	Up
1	7	----------	Up

Lift Locks on the Original Erie Canal—Continued

East to West No.	*Total lift (ft)*	*Approximate mileage from Albany*	
1	8	----------	Up
1	8	----------	Up
1	8	----------	Up
5	40	81	Up
1	8	----------	Up
1	9	----------	Up
5	40	----------	Up
Long Level	--	110	----
	--	165 Long Level (elev 414)	----
2	20	----------	Down
1	6	170 Syracuse sag (elev 382)	Down
1	6	----------	Up
1	11	175–182 Jordan level (elev 399)	Up
1	11	----------	Down
1	9	----------	Down
1	9	----------	Down
1	7	219 Montezuma sag (elev 363)	Down
1	8	----------	Up
1	6	----------	Up
1	7	----------	Up
1	6	----------	Up
1	15	----------	Up
3	24	----------	Up
2	20	235	Up
1	8	----------	Up
5	37	----------	Up
--	--	270 (Rochester)	----
--	--	325 (elev 490)	----
5	60	Lockport (elev 560)	Up
81	604	Total up lockage	
	62	Total down lockage	
	676	Total lockage	
	542	Net	

Stream Crossings.—Hundreds of streams had to be crossed either by bridging or fording along the route of the canal, and because this was to be an independent canal, some form of bridging in an aqueduct or culvert was to be preferred to fording the stream at grade. Aqueducts were viewed as structures for carrying the canal over a natural waterway; culverts, on the other hand, were viewed as structures that conveyed watercourses under the canal embankment.

Aqueducts were bridges—the canal was carried in the material of which the bridge was built, stone or timber. Most aqueducts on the original canal were timbered structures upon masonry piers, but a few were major stone arch bridges, as at Rochester. They were narrow, only as wide as a lock, that is, only wide enough for a single boat.

Fording where the canal crossed the stream at grade was used in those cases where an aqueduct appeared too expensive. A low dam was built downstream from the crossing impounding water to a navigable depth and trestles were built across the pool to carry a towpath. Guard gates or locks were usually installed along the canal on either side of the pool to isolate the canal in the event of flood in the stream. Because of its economy (the dam was usually of rock and brush construction), the pool crossing method was advocated and adopted in several places in the original plan, for example, Tonawanda Creek, Oriskany Creek, and Schoharie River. One of the advantages was that the stream could serve also as a feeder but, being uncontrollable, the flow could work either way. In one case, Oriskany Creek, which at first formed part of the navigation, was disconnected from it by an aqueduct as early as 1822, because the connection enabled the mills and factories to draw water from the canal whenever the creek failed to give them their accustomed supply (1823 As. Jour. 46th sess., p. 503). Violating the primary rule of independence, such crossings other than on the Tonawanda were eliminated by converting the crossing to aqueducts and thus maintaining the independence of the canal from the vagaries of river floods. The 12-mile reach on Tonawanda Creek remained the only natural channel on the canal after the improvements of 1835–62.

Some small streams, including nearly all those dry at the time of construction were admitted directly into the canal (Jervis, 1877, p. 55). Waste weirs were provided at intervals to permit the overflow of flood waters as well as the excessive flows diverted from the feeders.

CANAL CROSS SECTION

The trapezoidal cross section specified by the Canal Commissioners of 1816, as shown in figure 7, is such that about 3 feet of excavation or cut would produce sufficient material or fill for the berm and towpath embankments. The banks were constructed by scrapers drawn by horses and cattle (oxen) which, together with the hundreds of laborers, served to compact the fill. The side slopes of 1½ to 1 followed practice "often adopted in England" (1820 As. Jour. 43rd sess., p. 451).

There was no reason to expect erosion by flowing water since velocities were less than 1 foot per second (0.7 mile per hour). However, wave wash produced by moving boats was found to erode the earthen banks. This unanticipated erosion seriously narrowed the towpath and shoaled the bed. The response to this serious problem was of two sorts—administrative and engineering. (1) A speed limit of 4 mph (6 ft/sec) was enacted in 1822, and (2) the canal banks at the water surface were faced with stone, a program begun in 1824 (1825 Sen. Jour. 48th sess., p. 278) and continued from year to year throughout the length of the canal and adopted at the outset of the enlargement that was begun in 1835.

A side-hill location above the valley bottoms was preferred; and the topography was such that this was usually along a north-facing slope (see fig. 6), so that to the south, the land was nearly always higher, and this became the berm bank. The fill embankment was used as the towpath. Each bank had its characteristic problem. The berm bank was subject to erosion and soil wash from the higher ground to the south; the towpath bank to leakage. The section itself was above the regional water table to which the water in the canal drained. Small runnels, normally dry, were allowed to fall directly into the canal and discharged water together with some sediment during wet weather. Also, the cut-bank intercepted some perched or wet-weather springs.

It is of some interest to note how conservative the width-depth ratio remained. It was 10 to 1 in the two stages of the 19th century, and is 11 to 1 in those parts of the present canal that are in earthcut section. With barges customarily built in width-depth ratios of 3 or 4 to 1, it would mean that a canal built to permit passing and with side slopes of 1½ to 1 would have a width-depth ratio of about 10 to 1 and so it remains.

NEW YORK CANALS IN THE 19th CENTURY

The early success of the Erie Canal induced not only its own enlargement (see table 7), but a canal building epoch in the country after that kind of transport facility had become obsolete. Several additional lines were built in New York, the following being those listed as in operation in 1853 in the State Engineers Report on the canals (1854 Sen. Doc. 60, p. 13):

> The main trunk of this system is the Erie canal, occupying the valley of the Mohawk and the southern slopes of Lake Ontario, running east and west nearly through the centre of the State, and connecting the chain of western lakes with the navigable waters of the Hudson.

TABLE 7.—*Statistics of the original and enlargements of the Erie Canal*

	Original [1]	First enlargement [1]	Barge canal [2]
Dates of work	1817–25	1836–62	1905–17
Canal prism:			
Width at water surface (ft)	40	70	133
Width at bottom (ft)	28	52½–56	75–94
Depth (ft)	4	7	12
Length (miles)	363	351	340
Locks:			
Number	83	[3] 72	34
Total lockage (ft)	676	655	680
Length (ft)	90	110	300
Width (ft)	15	18	44.5
Depth on sill (ft)	4	7	12
Boats:			
Length (ft)	61; 75	98	250
Beam (ft)	7; 12	17.5	40
Draft (ft)	3.5	6	9–10
Load capacity (tons)	30; 75	240	2,000
Annual traffic capacity (million tons)	[4] 1.4	[5] 8	[6] 20+

[1] Animal power was in use throughout 19th century; steampower was introduced in 1870's.
[2] "Barge" canal has no towpath, mechanical power only.
[3] By 1875 all locks were doubled.
[4] 20,000 barges at 70 tons average burden.
[5] 40,000 barges at 210 tons average burden. See also 1866 As. Doc. 4, p. 36.
[6] Finch, 1927, p. 856.

The Chenango canal, occupying the valley of the river of that name, running from the southern border of the State, northward, connects the waters of the Susquehanna with the Erie canal, near the middle of the State.

The Black River canal (nearly completed) extends from the navigable waters of that river, and connects with the Erie canal, near the outlet of the Chenango.

The Oswego canal connects the most easterly harbor in the chain of great lakes with the Erie canal at the centre of the State, and forms of the shortest line between the most easterly of those lakes and tide-water.

The Cayuga and Seneca canal connects the Erie with the lakes of those names, and by means of the Chemung canal, extends the navigation of the Susquehanna.

The Crooked Lake canal completes the navigation between the lake of that name and the Seneca.

The Genesee Valley canal (nearly completed), occupying the valley of that river, running south nearly to the southern borders of the State, connects the Allegany river with the Erie canal about one hundred miles east of Lake Erie.

The Champlain canal constitutes an independent route, extending the navigation of the Hudson to Lake Champlain, and thence by the improvement of its outlet to the St. Lawrence, in the province of Canada.

Of these New York canals, only the Erie, Oswego, Cayuga-Seneca, and Champlain are now in operation as the New York State Barge Canal System.

Figure 12 shows the record of traffic on the Erie during the 19th century. The tonnage carried continued to increase until the 1880's after which it slowly decreased, despite the enlargement and the elimination of tolls in 1882. In order to stem the loss of traffic to the railroads, further efforts were made to improve the canal as, for example, by lengthening some locks so as to service two barges at one time; but the impact was gone. On completion of the canals in 1825, a boat carrying 30 tons pulled by a single horse or mule at the rate of 2½ mph was a great improvement over a wagon hauled by a team carrying 1 ton at a speed, if that is the word, of 1 mile per hour, provided the road was dry. The improvements could not duplicate that impact. In 1882 the State auditor reported that the canals were viewed as antiquated and their continuance a subject for ridicule. (1883 As. Doc. 4, p. 16–17.)

Less than 2 million tons were carried on the Erie division of the State Barge Canal system in 1972, about as much as was carried by the horse and mule drawn barges in the 1850's.

With the decline in commercial use, the assets of the barge canal for recreational boating have been increasingly recognized, albeit reluctantly at first. In 1905, for example, it was reported (Whitford, 1906, p. 405) that pleasure craft had become a "problem"—over 1,000 permits for such boats had been granted, nearly twice the number of barges then operating for carrying freight. The attitude was then that canal cruising constituted a necessary evil—necessary to maintain the principle that the canal was to

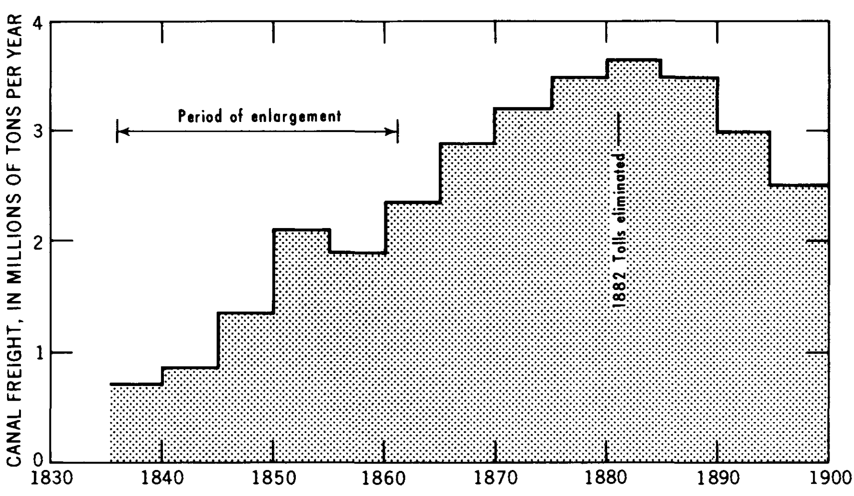


FIGURE 12.—Tonnage carried on Erie Canal during 19th century.

be open freely; evil because overpowered pleasure craft tended to disobey the 4-mile speed limit (now 6 to 10 mph) with attendant bank wash, and required rather frequent opening of busy street bridges. Recreational boating is now (1974) actively encouraged. The State currently reports 100,000 lockages of pleasure craft annually, compared with about 30,000 lockages of commercial barges.

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