2 Dam Designers and Builders

> The secret fountains to follow up,
> Waters withdrawn to restore to the mouth,
> And gather the floods as in a cup,
> And pour them again at a city's drouth . . .
> Rudyard Kipling

Humans may have been building dams for thousands of years, but they were not the first creators of dams on earth – the earth got there first. Retreating glaciers leave behind the rubble of rock, stones and pebbles they have carried. Termed 'moraines', such rubble impounds the glaciated valleys upstream to form lakes. The corrie lakes of Snowdon in North Wales are examples of these, as are the lakes of the English Lake District. In Croatia the lakes in Plitvice National Park are still being formed by deposits of travertine which form dams connecting a series of lakes in this karst limestone region.

And humans are not the only inhabitants of the earth to build dams. The North American and European beaver is an eco-engineer that can build up to 200 kilograms of dam in a day. The longest one measured was 1.5 kilometres. By creating lakes, beavers gain access to tree bark – their favourite food – and provide safe havens for their homes or lodges. They create mosaics of habitats for other wildlife as well as recreational areas in the resulting wetlands for bird-watching and fishing, and they provide attenuation ponds for melt-water in spring.

The earliest known man-made dam is at Java some 100 kilometres north of Amman in Jordan, built in 3000 BC for water supply. The builders and designers of this structure are long forgotten, but what

Plitvice Lakes, Croatia, a UNESCO World Heritage Site.

do we know of the dam builders of the modern era? In Samuel Smiles's definitive *Lives of the Engineers*, admittedly written in 1862 before the major water-supply reservoirs were created, we are introduced to Rennie, Smeaton and Telford.[1] Angus Buchanan, the British industrial historian and biographer, in his *Engineers – A History of the Profession in Britain 1750–1914*, added Rankine, Bateman, Simpson and Hawksley – and this handful is only mentioned in passing.[2] L.T.C. Rolt, in his *Victorian Engineering*, additionally refers to George Deacon, who implemented Hawksley's designs for Liverpool's Lake Vyrnwy, and James Mansergh, who designed the Elan Valley dams.[3] Yet dam engineers surely must rank among the most important of professional engineers since, without adequate water supplies, public health and the welfare of nations are threatened to the point of unsustainability. Accordingly, this chapter will examine the biographies of these creative and determined individuals, drawing on the specialist works of Geoffrey Binnie and Donald Jackson.

Schoolchildren inspecting a beaver dam, *c.* 1899.

We might pause to reflect briefly on the reason for the apparent lack of prominence among dam engineers. Perhaps the reason is not too difficult to find. Dams have tended to be, at least since the nineteenth century, sited far from population centres – one thinks of the Elan Valley dams buried deep in the Cambrian Mountains and supplying the city of Birmingham more than 100 kilometres away, or the Hoover Dam in the remote Arizona desert. Dams were, of necessity, structures which were not in the public gaze (although admittedly some have become visitor attractions), unlike the bridges, tunnels, roads and railways used daily by the general public.

Dams were built in eighteenth-century Britain by landscape gardeners to create ornamental lakes for estate owners to enjoy. As we have seen, 'Capability' Brown thought nothing of moving a village to create a lake as a component of the view. Such dams were usually earth dams faced with puddle clay – clay thoroughly mixed with water and compacted with tampers. At Blenheim, Brown placed the clay as a central core, a technique initiated in Britain by John Grundy in Leicestershire in 1741 and at Grimsthorpe in 1748. This method, learned from the German experience of mining dams in the Harz Mountains in the sixteenth century, had been reported on by the Surveyor General John Taverner in 1600.[4] It became the trademark for the next generation of British dam engineers, particularly for reservoirs to feed canals. William Jessop and John Rennie were early exponents of dam-building for navigation with Rennie's specifications for a puddle-clay core the standard for more than a hundred years.

Arch spillways in ashlar masonry were perfected by John Smeaton for ironworks mills such as that for the Coquett Ironworks in Northumberland in 1776. This was an arched dam 50 metres wide with a radius of 52 metres. The curved wall had an outer skin of bonded and cramped masonry with a rubble core. As Smeaton said, 'There is not a more difficult or hazardous piece of work within the compass of civil engineery than the establishment of a high dam upon a rapid river.'[5] The dam on the Coquett still stands as testimony to the soundness of the design of this self-taught engineer.

Angus Buchanan termed these early pathfinders 'heroic engineer-s' since they had limited training and were largely self taught. Smeaton, the son of a solicitor, founded engineering (or 'engineery', as he called it) as a profession. Rejecting his parents' plans for him to follow in his father's footsteps, he was determined to pursue mechanics as a trade. He taught himself instrument-making and was elected as a Fellow of the Royal Society at the age of 29. In that same year he turned to engineering and with no previous experience was commissioned to design a water-mill in Lancashire. He went on to be responsible for bridges, river and canal navigations, mills, harbours and fen-drainage schemes.

In 1760 Smeaton met and became friends with John Grundy. Together they worked on the Louth Canal and the Witham Navigation. In 1771 Smeaton was instrumental in setting up the Society of Civil Engineers (known after his death as the Smeatonians). Most of the early members were associated with navigation or drainage schemes, but Grundy was the only one of the original eleven with any engineering training. The fact that they were almost all involved with such projects is not a coincidence: in this golden age of canals, Acts of Parliament were required and the engineers promoting them were called to London to give expert evidence. As a result, they would get together over dinner to discuss matters of mutual interest, and the Society was born. Smeaton coined the phrase 'civil engineer' (as distinct from the military Royal Engineers who received training at, among other locations, the Woolwich Royal Academy at Woolwich Barracks), but the Society was always seen as exclusive: 'gentleman engineer' would have been more accurate. On

Smeaton's death, Jessop, Rennie and others reorganized the Society (although it still only had 24 members) into three classes: Engineers, Gentlemen as honorary members, and Artists. The senior engineers were not keen to attract young engineers to their dining club. However, as Buchanan put it, 'they [the young engineers] found an ally . . . in . . . the person of Thomas Telford', who disliked the élite of the Society.[6] The Institution of Civil Engineers was formed in 1818 with Telford as its first President (which required a change of the rules restricting the age of members to 35).

By 1930 some 260 embankment dams more than 15 metres high had been built in the UK to Telford's design – mostly for water supply. The same technology was exported to the Empire, particularly India, where some 80 similar structures were built for water supply or irrigation.

Many of these dams were designed and supervised by a handful of engineers, including James Leslie, George Leather and his nephews John Towlerton Leather and John Wignall Leather, Thomas Hawksley, John F. La Trobe Bateman and Sir Robert Rawlinson. In the words of Schnitter, 'this resulted in a strong concentration of know-how and a remarkable degree of standardisation.' Schnitter suggested that this sound experience – rather than theory – explains why the British embankment dams were so safe and suffered only a handful of failures compared with the experience of the US, where 9 per cent of dams failed between 1850 and 1930.[7]

Buchanan extended this theory to what he perceived as 'dynasties' of engineers. Thus there were the Leathers, the Manserghs and especially the Binnies, starting with Alexander (later Sir Alexander) Binnie and continuing with his great grandson in the twenty-first century. The same applies to the family construction firms of Cubitt and McAlpine. There were also surrogate dynastic relationships when close and personal apprenticeships were served. Examples include John Smeaton's accommodation and pupillage of William Jessop, the son of his supervisor on the Eddystone Rock Lighthouse; William became resident engineer on the Aire and Calder Navigation for Smeaton, and later designed the East and West India Docks in London's Isle of Dogs.

We shall meet these names again in connection with the structures they designed, but mention must be made at this point of Edwin Chadwick, an Assistant on the Poor Law Commission of 1832. Chadwick became Secretary to the Poor Law Board in 1834, and the blame for much of the new system's severity was laid at his door.

Following an outbreak of typhus in 1838, Chadwick instigated an Inquiry that demonstrated the relationship between environment and health. This motivated him to investigate the living conditions of the poor – principally on the basis that funds could be saved if the poor could be kept from becoming a charge on the parishes in which they lived. The sanitary conditions of the labouring classes in Britain in 1842 revealed the true horrors of urban living at that time. The Health of Towns Commission was set up by the government under the chairmanship of the Duke of Buccleuch – the engineer Sir William Cubitt, who was to receive his knighthood in 1855 for his work on the Crystal Palace, was one of the Commissioners – with Chadwick as unofficial secretary. Evidence was given by a number of witnesses including Thomas Hawksley and Thomas Cubitt (no relation to William, he founded the contracting firm), who confirmed the inadequate condition of water supplies to major towns and cities.

The Inquiry led to many towns initiating water-supply schemes and to the engineers mentioned above supporting and designing schemes for Leeds, Nottingham, Sheffield, Liverpool and Manchester, as well as London. Chadwick, however, despaired of the piecemeal approach of these towns and formed the British, Colonial and

Foreign Drainage, Water Supply and Towns Improvement Company, which he persuaded Hawksley (then Engineer of the Trent Waterworks in Nottingham) to join as an engineer. This company gave Chadwick the opportunity to benefit from the works the Inquiry was recommending, and gave Hawksley the introduction to towns needing his services. Indeed Hawksley was soon to be approached by Boston (Lincolnshire), Lincoln and Coventry. His evidence to the Inquiry is often quoted:

> The most cleanly female . . . will invariably . . . relax her exertions under the influence of filth . . . and sink into a dirty, noisy, discontented and perhaps gin-drinking drab – the wife of a man who has no comfort in his house . . . The improvements certain to result from the introduction of water . . . into the houses of the working classes are far beyond the pecuniary advantages.[8]

Unfortunately for Chadwick, this was now also the time of railway mania with competition for funds, materials and labour, so commissions did not materialize as quickly and satisfactorily as he hoped. His company was wound up in 1849. Following accusations of self-serving interest, he resigned from the Board of Health in 1854 and never held public office again. However, in response to the identified need for a clean, reliable water supply, dam engineers prospered.

As we have seen, they were largely practical men who relied on their experience. That is not to deny that theory did not exist. As early as 1717, Henri Gautier of the French Corps of Bridge and Highway Engineers had published a treatise on the 'Slope of Repose' for earth retaining walls. Gautier recommended a mean thickness of 25 per cent of the height for an air-face inclination of 20 per cent – revised to 33 per cent by Bernard Forest de Bélidor in 1729. This became the standard reference for civil engineers in France, Germany and Britain. A formula for calculating the stability of slopes in clay soils was proposed by the French military engineer Charles A. Coulomb in 1773, substantiated by the field observations of a slippage at Grosbois by Alexandre Collin, another member of the Corps. Unfortunately, despite these advances, French engineers were attracted to the emerging science of statics and consequently preferred masonry dams. Although Collin's concepts were to be revisited some 80 years later, the construction of embankment dams was effectively discontinued in France.

Other writers also had theories based on observation rather than rational mechanics. Don Pedro Bernardo Villarreal de Berriz, a Knight of the Order of Santiago and a Basque nobleman, owned mills in Vizcaya which were supplied with water by means of diversion dams. In 1736 he published *Maquinas Hydraulicas de Molinas y Herrerias*, in which he proposed the use of arch dams: 'when the river is narrow, one arch is sufficient and when it is wide, 2, 3, 4 or 5 will be needed.'[9] His dams still exist and are in use. He advocated a vertical water face and air faces sloping at 45 degrees for straight gravity dams and also gave meticulous instructions on construction including preparation and mortaring of joints.

As Norman Smith put it, up until 1850, while there had been a number of works written on dams, only Bélidor had adopted a rational scientific approach as opposed to empiricism. However, another member of the Corps of Bridge and Highway Engineers, J. Augustin Torterne de Sazilly, demonstrated a method of gravity-dam analysis showing that the most effective profile for such a dam is a triangle with a vertical upstream face. In his paper, published after his death in 1853, he visualized vertical slices through a dam and surmised that for the profile to be safe there should be equal compressive stress when the dam was empty as when it was full.

In 1858 Torterne de Sazilly's theories were put into practice when it was decided to protect Saint-Etienne in eastern France from flooding by the River Furens. The engineers were F.X.P. Emile Delocre and M. I. Auguste Graeff, again members of the Corps. The Furens Dam is 60 metres high and was built between 1859 and 1866 in a narrow gorge to a slight curve in plan. It is still in perfect condition – a monument to the engineers who made the first attempts to *design* dams. It revolutionized dam-building since it was so economical in terms of materials and labour.

Construction of earth embankment dams was still being carried out by means of pick and shovel at this time (with horsepower), but, in California in the 1860s, a Canadian, Anthony Chabot, used a technique borrowed again from the mining industry. Rather than excavating material by hand, a hydraulic method was employed. Earth and gravel were sluiced to the dam site by water jets and transferred by pipes, flumes or channels, then built up against the core of the dam. This technique reached its height in 1937 at Fort

'First dirt being pumped': Fort Peck Dam on the Missouri River, Montana. The largest hydraulically filled dam in the USA, completed in 1940.

Peck, which contains 95 million cubic metres of material – a quantity that would never have been economical to shift by hand.

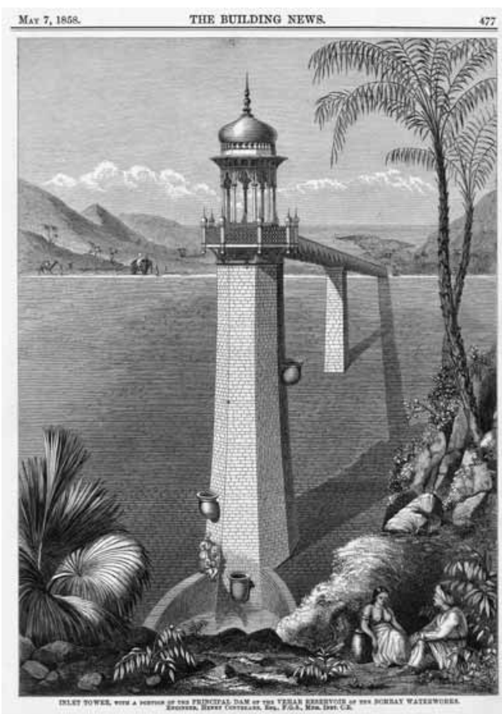
Whatever the form of dam, it must be founded on competent rock foundations, and boreholes or trial pits are required to determine the depth of foundation needed. In the Harz Mountains in Germany, gunpowder was used in 1715 for the preparation of the Oder Dam, with the waste material having to be hauled out with shovel and barrow. The efficiency of the excavations for dams was improved by the invention of dynamite by the Swedish engineer Alfred Nobel in 1863 – and by the use of percussion drills to create holes for charges in the US from 1865. From the middle of the nineteenth century, work was made much quicker by the use of steam-powered shovels and narrow-gauge railways.

To avoid deep excavations, reinforcement of subsoil by the injection of cement was first tried in 1879 by Hawksley at Tunstall Dam

An Osgood steam-shovel building Morman Flat Dam, Arizona, in 1923.

(near Newcastle); the method was adopted by the US Bureau of Reclamation from 1915. (This technique, known as grouting, was to become standard throughout the world, reaching its zenith in 1990 at the 184-metre-high Ataturk Dam on the Euphrates in south-eastern Turkey. There, by means of 10 kilometres of tunnels and 1,200 kilometres of drill holes, 1,200,000 square metres of 'grout curtain' were placed to prevent leakage.)

Returning to the work of British engineers in India, the first masonry dam for water supply was completed in Pune in 1868. Henry Conybeare – who seems to have had a wide brief during his time in India, submitting designs for St John's Church in Bombay as well as



The Vehar Dam built for Bombay Waterworks, 1858.

the Bombay Great Eastern Railway – became Superintendent of Repairs of Bombay in 1852. His plans for a water-supply scheme were approved in 1855, at which point he left for England never to return. He was consulted (with others) in 1865 by the Sheffield Corporation on the failure of Dale Dyke Dam, as we shall see. He does not appear to have had further involvement with water supply, becoming primarily a railway engineer.

As we have seen, it had been planned as early as 1808 to provide an irrigation scheme on the River Periyar for Madurai. This ingenious proposal envisaged storing the water flowing to Kerala in the west in a reservoir from where it could be discharged to Tamil Nadu in the east. The thought was revived by Major Ryves, RE, District Engineer at Madurai, in 1862. Ryves spent several seasons surveying the dense jungle, fighting fever and leeches. He eventually submitted a proposal in 1867 for an earth dam 49 metres high. The working conditions were clearly going to present a major challenge, but, following the example of the energetic British engineer Arthur Cotton, who built dams on a number of Indian rivers, the Government of Madras was encouraged to proceed. It commissioned Capt. John Pennycuick and Mr R. Smith to develop a proposal for a masonry dam. The proposals were sent to the Government of India, which sought 'the best English opinion' in 1870. Professor W.J.M. Rankine, a Scot, was consulted to determine the form of the profile.

William John Macquorn Rankine had been appointed to the Chair of Civil Engineering and Mechanics at the University of Glasgow at the age of 35. Having left school at ten, he nevertheless entered Edinburgh University at sixteen and was a brilliant student. A four-year pupillage with Sir John Macneill, a leading civil engineer, followed – with Joseph Bazalgette (engineer of the London Embankment, incorporating main sewers and underground railways) as a fellow pupil. During this time Rankine worked on river schemes, waterworks, harbours and railways, principally in Ireland. In 1842 he was back in Edinburgh, where he was a consultant for six years, after which he devoted his time to a prodigious output of theoretical and original physics. However, he did not neglect the practical purpose of civil engineering, being involved in the water-supply scheme for Glasgow.

Glasgow's water supply in 1845 was drawn from the Clyde. Owing to the polluted nature of this source, Lewis Gordon, Professor of Civil Engineering at the University of Glasgow, proposed a scheme based on Loch Katrine, 65 kilometres north of the city. The private Glasgow Water Company employed spoiling and delaying tactics, suggesting an alternative scheme from Loch Lubnaig which received parliamentary approval in 1846 but was never implemented. Rankine entered the fray in 1852, claiming that the Loch Lubnaig scheme had been put forward as an obstacle to the success of better projects. The Glasgow Corporation appointed J. F. La Trobe Bateman to report on the feasibility of Loch Katrine, which he did in 1853. Lewis Gordon's original suggestions were ignored, and Bateman (supported by Robert Stevenson and Isambard Brunel) was appointed engineer to the scheme, which was opened in 1869 and functions to this day. This episode illustrates the public role engineers were prepared to play at the time – and the critical attitude they took towards each other.[10]

Rankine published a paper in 1857 on earth stability, building on (and criticizing) Coulomb's earlier work. As we have seen, this was a time in Britain for the application of theory and reflection on the results. Work continued in France meanwhile, although there was a move towards masonry dams there. It was not until 1881 that Sir Benjamin Baker, in a paper to the ICE, responded to and denounced Rankine's theories with the proclamation that 'Earth pressure theory stood . . . on the same scientific basis, and of the same practical value, as the weather forecasts for the year in *Old Moore's Almanack*.'[11] Since Rankine had been dead for some nine years, he was no longer in a position to defend himself; engineers are more polite to one another these days. This is not the place to discuss the disparities and emphasis on theory and practice, but in Rankine's *Civil Engineering*, published in 1862, he referred to a method of creating a puddling-clay reservoir embankment: a flock of sheep was driven backwards and forwards along it several times! It was to be some 75 years before the Sheepsfoot Roller based on this 'principle' was developed.

After Rankine took the Chair at Glasgow in 1855, he eventually succeeded, in 1872, in establishing a degree in science. He published 111 papers prior to his early death, the last being on the design and construction of masonry dams in the *Engineer* (1872). Rankine developed a profile for a dam that almost completely eliminated tensile stress on horizontal sections, the first time this had been achieved by the application of scientific principles to dam design. His detailed *Report on the Design and Construction of Masonry Dams* (1872) explains the theories of stress in gravity dams and was put into effect at Periyar.

In 1877–8, a drought in Tamil Nadu led to widespread starvation, and many people died through lack of food and water. The Periyar scheme was revived by Pennycuick in 1882 for a concrete dam and received formal approval in 1887. The dam was to be made of concrete due to the absence of suitably skilled masons, and the concrete was faced with a thin skin of masonry. The project was formally inaugurated in September 1887 by Lord Connemara, Governor of Madras, by the felling of a tree: 'there could perhaps be no better symbolic function in a situation where the engineer is trying to find a way through dense uninhabited jungle.'[12]

And this was the problem. The dam site was kilometres from anywhere, in jungle inhabited by wild animals and where there would be a perpetual struggle with disease. Camps and quarters for the coolies and officers were laid out, together with first-aid posts. Initially there was no shortage of labour, but acclimatization took a long time, and 'many succumbed to malarial fever and the rest ran away as fast as they came in.'[13] The coolies were paid a day rate, but they always returned to their villages to attend to ploughing, sowing and harvesting. This, coupled with an eight-month working season to avoid the monsoon, meant that progress was slow. In 1889 and 1890 detachments of the First and Fourth Pioneer Corps were lent by the army for service on the construction, but the quality of their work was variable, and they were often withdrawn for military service so were not used again. However, a band of Portuguese carpenters arrived from Cochin – 'these were sober, quiet, religious men who were a pleasure to work with.'[14]

There were difficulties attracting and keeping masons, but, although their skills were often lacking, the quality of the materials more than compensated for this, and the dam remains in excellent condition (see illustration on p. 28). The dam site itself was 13 kilometres from the camp and depot at Thekkadi, and various options were considered for access over the Ghats. A canal with eleven locks was chosen, but this brought its own problems of working in isolated locations: 'the terror of wild beasts had to be faced.' Elephants were scared off with tom-toms and firebrands, and one man was killed by a tiger. Once tamed, the elephants were used for haulage. However, fever was the biggest problem: 'Deadly fever lurks behind the smiling countenance of Periyar.'[15] The combination of sun, rain and forest bred ideal conditions for malaria, but the coolies did not help themselves by their recklessness. Good food, warmth and filtered water would have helped, but they spent their wages on ‘cheap jewellery, tinsel and “Manchester” goods’[16] (another example of British technology transfer). The importance of health and sanitation was recognized from the beginning.

Not all deaths were reported since the sick were often removed by relatives to either recover or die. Between 1892 and 1895 about 450 men died in the camps. It was to be expected perhaps that the camping of 5,000 people in a relatively small jungle area would lead to dubious sanitation conditions, and cholera epidemics occurred on two occasions. In a letter to the Chief Engineer, the Superintendent of Works reported on 11 March 1894: ‘I have the honour to report that labour has fallen in consequence of the cholera to such a point that it is impossible to carry on work any longer.’[17] There were 45 fatalities in three weeks, and the camps were closed and moved to a new site. Despite disinfecting, burning and liming the ground, the cholera persisted, and when the number of men fell to 200 there was no alternative but to give up for the season.

Accidents were also common. The majority were associated with nitroglycerine or detonators – the labourers would remove the red flags indicating a misfire in the drill holes and claim payment, only to cause an explosion when their colleagues made a fresh charge. Deaths were so numerous that separate graveyards were earmarked for Indians and Europeans. As Pennycuick (now Col.) reported in 1893, he had anticipated that the work site would be declared a British Territory, but the Government of Madras did not agree; ‘consequently the conditions of life . . . are by no means such as should prevail among a community of 6000 British subjects.’ Twice construction works were washed away during the monsoon and the Madras Residency decided to abandon the project, but Pennycuick was determined to complete it. Allegedly, he returned to England and sold his property in order to raise the necessary funds to do so.

The dam (365 metres long plus a 'baby' dam of 73 metres and a 76-metre earth dam) was 54 metres tall (a world record for a concrete dam at the time) and constructed of a lime-*surki* concrete (lime, sand and *jaggary* – sugar pulp made from palm sap) faced with granite masonry set in a similar lime-*surki* mortar. The dam was completed in 1895 and inaugurated on 11 October by the Governor, Lord Wenlock. In 1931 the Maharani of Travangore built a lake palace for the Maharajah (Sree Chithira Tiuvnal) as a summer residence on a promontory in the resulting Periyar Lake – centred today on one of India's largest tiger reserves. Col. Pennycuick only guaranteed the dam for 50 years, and in 1990 it was reinforced by additional concrete on its air face and by cable-anchoring vertically through the masonry water face. A 2-kilometre tunnel through the Cardomom Hills to the other side of the watershed to irrigate the fields of Tamil Nadu was integral to the project; in the 1960s the water was piped to a hydroelectric plant, adding to the usefulness of Kerala's Periyar Lake for the benefit of Tamil Nadu. This fact is not lost on the State of Kerala, in dispute as it is with Tamil Nadu, which wants to raise the dam's height.

The conditions at Periyar can be compared with those arranged for workers elsewhere – for example, on the contemporary Elan Valley scheme for Birmingham, which was started in 1892. The Birmingham Waterworks Company was granted parliamentary powers to supply water in 1826. The company's first engineer was John Rofe, who was succeeded by his son Henry in 1829 (the consulting engineers Rofe, Kennard and Lapworth were later responsible for many British reservoir schemes between the 1960s and the 1990s). In the course of representations for the adoption of the Public Health Act of 1849, the government-appointed inspector, Robert Rawlinson, reported that the town's water supply was unsatisfactory, and the company extended the area of constant supply in 1853.

The Mayor of Birmingham, Joseph Chamberlain, obtained powers to acquire the Waterworks Company in the interests of public health in accordance with the Birmingham Corporation Water Act, 1875. During the period preceding the acquisition, the Corporation had concluded that it would be necessary to look elsewhere for supplies large enough to meet the needs of the rapidly growing city. In 1870 attention was drawn to the mid-Wales mountains as a potential source, and, in 1871, Rawlinson was instructed 'to inquire as to the Water Supply of Birmingham compared to other Towns . . . and to avail [himself] of the services of [consulting engineers] Lawson and Mansergh to make such surveys as required'.[18]

James Mansergh had been apprenticed to Lawsons, engineers of Lancaster, at the age of fifteen. At 21 he had gone to Brazil and worked on the Rio de Janeiro railway. He returned to England in 1859 and worked for a while on the railways of mid-Wales before entering into partnership with his brother-in-law John Lawson in Westminster. During his career he gave evidence at some 300 public inquiries and made more than 600 appearances in both Houses of Parliament.

Rawlinson examined the existing water quality and yields from boreholes, streams and potential new sources from rivers around Birmingham. He concluded that nearby sources were all too polluted or in catchments which were agricultural and heavily manured, and therefore likely to be of unsuitable quality in the future. His criteria for site selection, and his recommendations, were that ideally the water provided should be capable of delivery to storage areas in Birmingham under gravity and that, in order to provide for future expansion of the city, an area of watershed on uncultivated land in excess of current requirements should be selected – criteria which could well apply today.

Rawlinson looked at five river catchments in mid-Wales and concluded that the Elan and Claerwen were ‘much superior and in fact nothing better can be found in the country nor could better be desired’, being ‘almost utterly devoid of human habitation . . . and other sources of pollution . . . [and] . . . almost totally uncultivated’. Although his estimates for development of the various catchments identified the Elan and Claerwen as the most expensive, he recommended their utilization for the purity of supply in an area unlikely to be developed – i.e. a ‘remote corner of Radnorshire far away from any large town or great line of traffic [thus ensuring] its remaining in its present condition for many years’. He described the area as ‘a solitude, tenanted only by a few straggling flocks of sheep’.[19]

The Corporation was unable to promote and secure a new supply source until it had acquired the Waterworks Company. Local extensions to the supply system proved satisfactory until 1890, when Mansergh was consulted (Rawlinson was 80 and retired by this time); he still recommended the Elan and Claerwen scheme. In his Proof of Evidence in support of the Bill to the House of Lords Committee in 1892, he set out the grounds for his preference, describing the area’s population, the catchment, water sources and future requirements. Again he looked at alternative sources but concluded that they ‘all ran through highly-manured agricultural country, with towns, villages and farms and are inevitably polluted’. The area he recommended was very sparsely populated, ‘and the extent of cultivated land is exceedingly small’. Clearly the requirement for good-quality water directed the engineers towards catchments where there was little cultivation: ‘it is a good source of supply (I should have been a noodle to suggest any but the best I knew of).’[20] A Water Bill (to secure the finances for the scheme) was authorized by a poll of burgesses of the city on 9 December 1891.

For a description of the area in which the dams were to be built, the most useful source is Eustace Tickell, who, before work could begin, was sent by Mansergh along with Mansergh's two sons to carry out the surveying. Tickell later became the engineer in charge of Pen-y-Gareg (Above the Stone) Dam and made pen-and-ink sketches of the river valleys prior to inundation. He compiled these, together with his own commentary and contributions by Mansergh and William Rossetti (Shelley's biographer), into a commemorative volume that was presented by the 'Water Committee to those landowners who co-operated with Birmingham in allowing the pipeline to be carried through their estates'.[21] After completing work on the dams, Tickell went to Ceylon to build railways.

Two houses in the valleys that were destroyed by the reservoirs had 'some pretensions and literary interest, namely Cwm Elan on the bank of the Elan . . . and Nantgwillt on the bank of the Claerwen . . . Both of these houses . . . were associated with the poet Shelley'.[22] Shelley had originally arrived at Cwm Elan, a remote house at the top of the valley, on 9 July 1811, and had written to his friend Thomas Jefferson Hogg that the scenery was 'divine, but all very stale flat and unprofitable – indeed this place is a very great bore'.[23] He clearly suffered a mood swing the next day when he wrote to Elizabeth Hitchener, 'rocks [are] piled on to each other to tremendous heights, rivers formed into cataracts by their projections, and valleys clothed with woods, present an appearance of enchantment'.[24] In April of the following year, on his return from Ireland with his first wife Harriet, Shelley negotiated for the lease of Nantgwillt but only stayed for two months.

Given this association, Tickell focused his sketches on these valleys and houses, and in his preface to the plates he described the locality as

> one of the most charming valleys in Great Britain, scenes which are soon to be lost for ever . . . And the valleys where now the river flows through moor and bracken, woodland and meadow, will in a few years be converted into a chain of lakes. Beautiful lakes they will doubtless be, winding up the valleys with sinuous margins, wooded promontories such as are seen on Derwentwater, frowning crags and screes which will remind one of Wastwater. But their construction dooms many a picturesque and interesting spot to destruction and it would be indeed a pity if they should be allowed to pass away without some record.[25]

Tickell's words provide an insight into the perception of the valleys by an engineer at the time. He recorded the future loss of Nantgwillt and Cwm Elan together with the chapels, schoolhouse and about twenty farmsteads:

> But in reviewing this roll call it must be remembered that, *sad as it is* [emphasis added] it would be more difficult to find in this island a place

Cwm Elan, Powys, where Percy Bysshe Shelley briefly stayed, sketched by Eustace Tickell, resident Engineer on the Elan Valley scheme, in 1894.

> where more than 70 square miles of land could be taken for a public purpose without dispossessing very many more people and destroying many more houses. At the same time, the seclusion of the valley is one of its greatest charms. It lies hidden away amongst the mountains and leads to nowhere. The valley is visited by few . . . but those who have known it will never forget the charm of the scenery . . . [26]

Mansergh described the proposed 'Birmingham Water Scheme' in the following terms:

> The determination of the area of watershed to be acquired was a comparatively easy problem [considered from a water engineer's point of view] because the contraction of the valley at Caban Coch and the opening out above of the wide expanse of flat land fixed at once the position of the dam of the lowest reservoir.

While recognizing that

> the mansion and beautiful grounds of Nantgwillt [will] be drowned . . . when more than full, the water will overflow from all the reservoirs in picturesque cascades down the faces of the dams . . . [in maximum flood] forming probably the finest waterfall in this country.[27]

Mansergh as the designer therefore was aware both of the loss of features and of what would be put in their place.

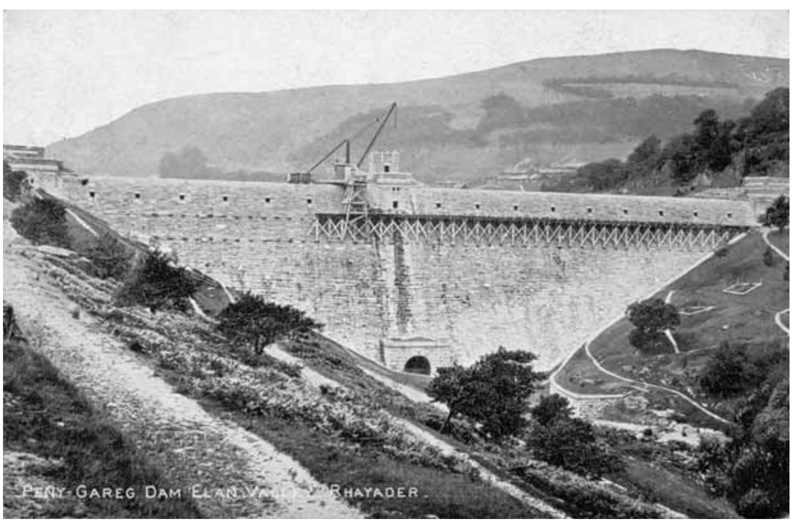
The Birmingham Corporation Water Bill met with opposition in Birmingham itself, along the route of the aqueduct and in areas affected by the construction of the reservoirs. Provision for supply to adjacent counties within 15 miles of the aqueduct had already been agreed – this arrangement became known as the Birmingham Conditions. However, Welsh MPs objected to the Bill on the grounds of the effects on Wales and the River Wye. Mr Shaw-Lefevre MP, 'champion of the Preservation of the Commons' and founder of the Commons and Open Spaces Preservation Society in 1865, proposed access to the hills and common rights on the watershed. At the second reading of the Bill, the Corporation accepted his conditions.

The Corporation sensibly reached an agreement with Mr Lewis Lloyd, the principal landowner in the watershed, and the withdrawal of opposition from landowners greatly accelerated the passage of the Bill through Committee. It was finally approved, receiving Royal Assent on 27 June 1892. It would appear that landowner opposition fell away once compensation was agreed; as Thomas Barclay put it, 'the local opposition . . . was of a very feeble character.'[28]

In his evidence to Parliament, Mansergh had stated that 'all dams shall be built of masonry because there are sound rock foundations for all of them . . . and because material for earthen dams with puddle cores is not procurable in the district.' Mansergh died in 1905, and it was left rather belatedly to his sons to present a paper to the ICE in 1912 in which they described the design and construction of the dams. 'The first three dams were all to be of a greater height than any previously in this country and cross section demanded careful consideration. In 1895 the Bouzey dam near Epinard in France gave way and margins of safety were built into the design.'[29] The dams serving Birmingham were built of cyclopean rubble, faced with block-in-course masonry. The rubble 'plums' – up to 10 tons in weight – were set in Portland-cement concrete. This technique was an innovation at the time, replacing the use of dressed blocks bedded in mortar. The valve tower, part of the masonry structure of the dam, was described as being 'surmounted by a handsome octagonal valve house with a domed roof'.[30] The Foel Valve Tower is circular with a domed roof covered with copper and marks the entrance to the 117-kilometre aqueduct to Frankley Service Reservoir in Birmingham.

In addition to these works, the Corporation built a temporary railway and permanent highway, a church, a Baptist chapel and a school to take the place of those submerged in Caban Coch. Alexander Binnie remarked that when he and James Mansergh had been working on the mid-Wales railway in 1862–3, they had imagined dams on the spot where they were eventually built. Walter Hunter (a Director of the Grand Junction Company), purporting to represent 'the mouth of an artist', noted that

> the appearance of ugliness was due to critics not understanding that adaptability had beauty of its own and that it was rather lack of education which caused a man not to appreciate engineering works even though outwardly they might not seem to be as beautiful as some other works. The works of engineers could be carried out to harmonize with



The Pen-y-Gareg Dam in the Elan Valley, nearing completion in 1905.

> their situations, and the reservoirs of the Birmingham works had added to the beauty of the scenery.[31]

The scheme was opened in July 1904 when King Edward VII opened the valves at Foel Tower.

The overall engineer in charge had been George Yourdi, son of an Irish mother and a Greek father. Yourdi had been in charge of the labour force, which at times numbered as many as 1,500 navvies ('navigators') and engineers. He was a strict disciplinarian; an engineer who went for a few beers in the local town of Rhayader was dismissed on his return since 'someone in his position should not frequent public houses.'[32] Unusually for the time, Yourdi had degrees in arts and engineering and was a Fellow of Trinity College Dublin. For eight years this single man never spent a night out of the valley. He lived in Nantgwillt House – previously occupied by Shelley and his wife Harriet – which is alleged to have inspired Francis Brett Young to write 'The House under the Water'.

The opening of the Elan Valley scheme by Edward VII and Queen Alexandra, 21 July 1904. A special train ran from Rhayader station along the tracks laid for construction.

The work force was comparatively well looked after: a complete 'model' village was built, comprising huts for the the workers and public buildings including a school, hospital, mission room, canteen, police station, fire station with engines and post office. There was a full range of services, including sewerage, water supply, lighting and fire hydrants (all buildings were constructed of wood). The huts came in four classes, ranging from those for ordinary lodgers (for up to eight men, a hut keeper and his wife) to those for officials and married men. Visitors from Rhayader were amazed to see that the navvies 'slept in beds. With sheets. Like *people*'.[33] In 1897, Queen Victoria's Jubilee Day was a paid holiday and the whole village descended on Rhayader, where they consumed the victuals for the day provided by the Jubilee Committee in less than an hour.

Many of the navvies were Irish (two-thirds working on the Cray Dam for Swansea in 1900 were Irish), and at Elan, unusually, one was black – he is recorded as having died of exposure in the hills above Rhayader in 1897. Another death was of Thomas Pugh, who accidentally shot himself with a pistol he was repairing in the blacksmith's shop in 1898. The canteen was only open for five hours a day, and customers were limited to six pints (Allsopps Single X or bottled Bass) and no women, singing, juggling or marbles. The village was strictly policed, and access was only possible via a single suspension bridge with a bridge janitor. (Although it was reported that the men built a small footbridge across the Elan so that, having been thrown out of the canteen, they could cross down to Rhayader to get truly drunk and then spend the night in the hedgerows – this was fine during the summer, but many died from hypothermia during the winter).[34]

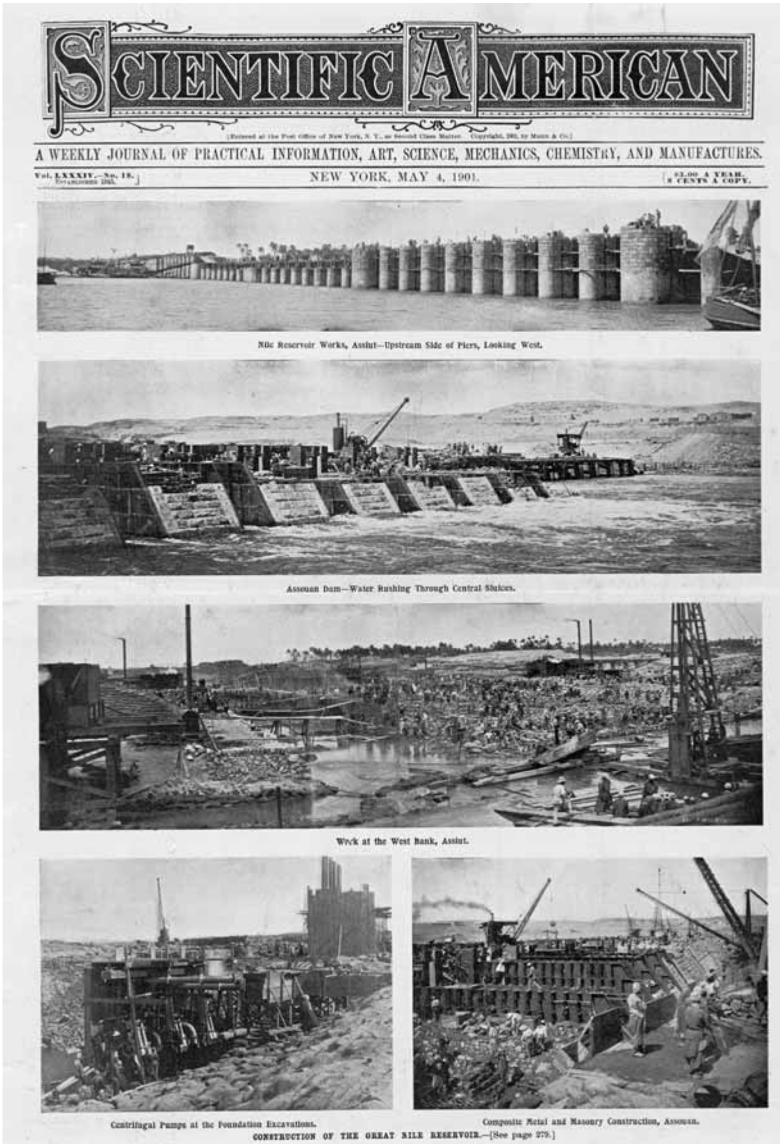
How many men died in the construction of the first phase of the Elan Valley dams is not recorded, but Yourdi's records show his expenses for telegrams to next of kin for 1902, during which three men died, including John Jones in January (falling from a gantry at Caban Dam) and Samuel Davies in December (as a result of an explosion in the quarry). In 1903 Yourdi paid a total of £9 10s to Evan Jones for the loss of ten sheep killed by the supply train. That same year, there was a smallpox outbreak – five cases were reported, one of which was fatal.

Of the proposed six dams only three were built, with the intention of adding the others as the need arose. In the event, it was decided that one additional dam would suffice. This received approval in 1939 but, due to the war, was not begun until 1950, when Birmingham Corporation invited tenders for the new Claerwen Dam. Various options were proposed, but the Corporation opted for a masonry-clad curved gravity dam 'to match the appearance of those existing'.[35] (There was a shortage of skilled masons in Britain at this time; they had to be brought from Italy to work on the dam.)

At the end of the nineteenth century, British expertise moved from its proving ground in India to another country in need of agricultural advancement – Egypt. As Norman Smith put it, '[This is] a particularly interesting case of technology transfer in the sense that expertise passed from one country to another without ever having been an activity indigenous to the native land of its engineers.'[36]

In 1883 Colin Scott-Moncrieff, who had been an irrigation engineer in British India, arrived to take charge of Egypt's Irrigation Department and Works. He brought with him William Willcocks, who, at the age of 31, had never set foot outside of India; as Willcocks himself put it, he had been born 'in a tent on the bank of an irrigation canal in India'.[37] After engineering college, he had spent ten years on drainage works on the Ganges and the construction of the Paricha weir on the Betwa Canal. In 1890 he began his study of Egypt's irrigation under the title of Director General of Reservoir Studies. In three years he surveyed the 1,200 kilometres of the Nile and its desert margins – an extraordinary achievement in such a short time. During the final season he dispensed with the luxury of a tent. Every morning he is alleged to have memorized lines from Bunyan or the Bible (eventually committing the whole of the New Testament to memory). A colonial misfit in the narrow social world of the expatriate British, Willcocks had no time for dinners and dances and probably related more to the farmers along the Nile than to his supervisors. It was said that 'every fellah in Egypt knows the name of Wilguks.'[38] As Scott-Moncrieff said, 'he is not the conventional type of man.' Willcocks selected a site at Aswan for a dam and an 'International Commission' was appointed to assess his choice. The commission comprised Sir Benjamin Baker, President-elect of the ICE, Auguste Boulé of France and Giacomo Torricelli of Italy. Although they agreed on the choice of dam site, the three are reported to have had different reactions to their assignment. Boulé liked good food, Baker ate anything, while Torricelli's staple diet was Chianti and macaroni. Willcocks lived on apricots, rice and whisky.[39]

The dam as proposed was 1,950 metres long with 180 sluices which could be opened in sequences to allow the silt-laden floods to pass through for irrigation and then to hold back seasonal flows in the reservoir for later release. Storage was an issue, however, and environmental concerns played an important role even in 1895: the proposed storage of 2.5 cubic kilometres was reduced to 1 cubic kilometre to prevent the flooding of the Temple of Isis. Winston Churchill pronounced that 'the State must struggle and the people starve in order that professors may exult and tourists find some space on which to scratch their names.'[40] Willcocks's original design was influenced by the Betwa Dam with its 'long sweeping curves'. However, the Commission decided on a straight alignment. Willcocks disagreed, believing that an arch dam would



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Nile Reservoir Works, Assiut—Upstream Side of Piers, Looking West.

Assouan Dam—Water Rushing Through Central Sluices.

Work at the West Bank, Assiut.

Centrifugal Pumps at the Foundation Excavations.

Composite Metal and Masonry Construction, Assouan.

CONSTRUCTION OF THE GREAT NILE RESERVOIR.—[See page 279.]

First Aswan Dam under construction, 1901.

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be stronger in the event that its height would have to be raised – which eventually happened twice!

As at the Elan Valley, a factor in the Aswan design was the recent collapse of the Bouzey Dam. Baker – now the dam's engineer – drew the conclusion that the recent theories of gravity-dam design were not at fault but that they had been disregarded at Bouzey. However, the Aswan design was complicated by the need for so many sluices.

The workforce in this desert location approached 15,000 on occasion, comprising mostly native workers and a contingent of skilled labour from Britain and stone-cutters from Italy. The camp built for them was impressive: this 'European' village included shops, a restaurant and a hospital. An ice-making machine was provided, principally for the hospital. Neither was it all work and no play with cricket, football and tennis pursued enthusiastically. On Christmas Day 1901 a football match was held between the Scottish and English members of staff. Sir Murdoch MacDonald was centre forward and the game ended in a 1–1 draw despite three members of the Scottish team having to be carried from the field in the first quarter of an hour when the after effects of the Christmas festivities proved too much. In contrast to Periyar, no serious epidemic occurred; the hospital was principally kept busy attending to cases of sunstroke and accidents with explosives.

An added bonus of the first Aswan Dam was that it provided a series of locks to negotiate the Aswan Cataract. Although he was knighted for his contributions, Willcocks left the project in 1897 when his relationship with MacDonald, the new Resident Engineer, deteriorated. The finishing stone was laid on 10 December 1902 by Princess Marguerite Louise of Prussia, but already there were plans to raise the dam to its original proposed height (and flood the Temple of Isis). Baker now had the task of raising the dam and, at the same time, ensuring the free flow and operation of all 180 sluices.

A further complication was the publication in 1904 of a paper by Pearson and Atcherley entitled ‘On Some Disregarded Points in the Stability of Masonry Dams’ and proposing that previous calculations based only on horizontal stresses did not tell the full story since they ignored vertical ones. This alarmist paper was based on tests on strips of wood and was not really applicable to dams. However, it gave rise to a controversy that lasted for four years with full exposure in the engineering journals. Factions were formed favouring the ‘mathematician’s dam’ and the ‘engineer’s dam’, and the controversy was eventually resolved by India-rubber models constructed by J. S. Wilson – an assistant to Baker at Aswan – and William Gore, who had assisted George Deacon at Vyrnwy. The models proved that the prevailing methods of designing dams were sound and also pioneered the tradition of dam design by the use of models which prevailed throughout the twentieth century.

Baker, who died in 1907, realized that fixing a ‘new’ dam to the old one at Aswan would cause problems due to differentials in temperature in the desert; a space for expansion was therefore initially left between the two structures. On 23 December 1912 many of the attendees at the first opening of the Aswan Dam were called back to witness the second inauguration ten years and two weeks after the first.

By 1918 Murdoch MacDonald had established that both Egypt and the Sudan could be irrigated by management of the Nile. However, Willcocks, whom MacDonald had replaced as Director General of Reservoirs, did not agree and became increasingly virulent in his opposition, accusing MacDonald of falsifying the flow records. He turned a ‘serious situation into a disastrous one with the publication in Cairo of *The Nile Projects*.’[41] This document stretched to 200 pages of criticism of the honesty and competence of Willcocks's fellow professionals. It is without equal in the history of engineering both in its vitriolic attacks and in its effect on its author.

Willcocks's obsession with MacDonald's figures ended with his being found guilty of criminal slander and libel in the Consular Court in Cairo in 1921. It has been said that at this point 'an illustrious career came to a tragic end',[42] but Willcocks returned to India, where in a report published in 1930, two years before his death, he explained the irrigation-canal system of the Ganges – which previous British engineers had thought were for navigation. (The British police, mistakenly but forcefully, tried to stop the peasants breaking the canal banks at night to fertilize and irrigate their fields). Willcocks proposed the restoration of these ancient works to 'bring in again the health and wealth which . . . Bengal once enjoyed'.[43] On his death, the *Spectator* wrote that the Aswan Dam was 'as great a memorial as Cheops' Pyramid, and of considerably more use to Egyptians'.

The single most important milestone in embankment-dam theory was the publication in 1926 of 'Principles of Soil Mechanics' by Karl von Terzaghi. Terzaghi was to dominate approaches to the stability of earth dams from then on. By 1940 the elements of earth-dam theory were established, enabling the construction of higher and bigger earth dams. This process was also encouraged by improved methods of construction.

From the 1930s on, earth-moving machinery replaced horsepower. Embankment dams were particularly amenable to the mechanization of construction, and changes accelerated in the 1930s and '40s due to advances in construction equipment. Bulldozers were attached to caterpillar tractors and used for excavation work as well as for the spreading of material. Advances in both power and tyres meant that vehicles could work on embankments as well

as excavation sites and on haul roads. Sheepsfoot rollers were used for compaction from 1905 and had become standard by the 1930s.

Dam-building in the US in the 1900s was largely the result of home-grown talent – again mostly self taught. However, while the British sphere of influence did not extend beyond the Empire, later émigrés from Europe did add to the rich variety of dam structures produced.

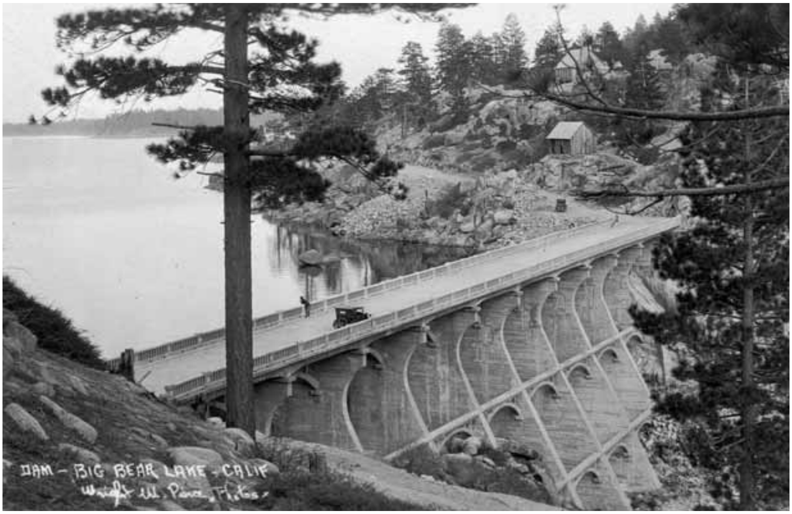
The innovative and self-taught model is epitomized by the career of John S. Eastwood. Eastwood was motivated by one principal interest – economy – but this led to two other attributes of what David Billington described as 'Structural Art': efficiency and elegance.[44] Eastwood created more than 60 dams in his career but was frequently faced with opposition from conservative-minded engineers who sought to stir up public concern at his 'airy arches'.[45]

Horse teams were still used, especially for embankment dams, in the early part of the twentieth century.

Eastwood had been born in Minnesota in 1857 and on leaving college had gone out to the Pacific Northwest, building railways. Eventually in 1883 he settled in Fresno, California, and explored the Sierra Nevada. He became involved in the logging of the Giant Sequoia, which – in contrast to John Muir, who saw beauty – he saw as a resource to be utilized.

The 1887 Wright Act had authorized the creation of Irrigation Districts through bond sales. Eastwood succeeded Hermann Schussler as engineer to the Sunsea Irrigation District south of Fresno. In the 1890s he became one of the pioneers in hydroelectricity, which was to transform California's culture and economy; he formed the San Joaquin Electric Company in 1895. This failed when the competing Fresno Gas and Electric Company diverted water away from Eastwood's sources – at the time of one of California's severest droughts. The lesson was learned: adequate water storage was mandatory. In 1901 Eastwood proposed a dam on the San Joaquin River to enlarge several lakes in the catchment in order to supply the Mammoth Power Company, which sold electricity to San Francisco. This scheme never materialized, but in 1902 he became involved in the much larger Big Creek power scheme, for which he proposed an arch-buttressed concrete dam – what he later described as a multiple-arch dam. The design was based on an aspiration to save on concrete, and in this Eastwood succeeded.

An earth-fill dam would have used 49,000 cubic metres of concrete (and 1,025,000 cubic metres of earth), a gravity dam 245,000 cubic metres, but Eastwood's proposal only envisaged 59,000 cubic metres of concrete. The scheme was delayed since it was in the Federally owned Sierra National Park, and President Theodore Roosevelt sought protection of this natural resource. While he waited for the consent to be negotiated, Eastwood built a dam of similar



design for the Hume-Bennett Lumber Company. This was 200 metres long and 20 metres tall and had twelve arches. Remarkably, it was built in 114 working days. On the basis of Hume Lake he accepted a commission to build a replacement for Frank E. Brown's Bear Valley Dam in San Bernadino. James D. Schuyler had proposed a rock-fill dam at an estimated $140,000, but Eastwood's design was costed at $80,000. It was to be 110 metres long and 24 metres tall with ten arches and with strut tie-beams through the buttresses.

Rather than timber formwork for the arches, Eastwood used corrugated steel, which was left in place and covered with a cement plaster. Big Bear made his name as a dam engineer – he was now associated with one of the world's most famous thin-arch dams. As he himself put it, he had seen Brown's dam as 'a long step in the right direction' and his own contribution as 'further strides towards the Ultimate Dam'.[46] In the event, Big Creek was built by Stone and Webster to a curved-mass gravity design, but this rebuff did not concern Eastwood – he had arrived. Big Bear withstood overtopping by floods in 1916 and an earthquake in 1918, which

'The Ultimate Dam'. John S. Eastwood's ten-arch concrete dam, which replaced (and submerged) the Bear Valley Dam, California, in 1901.

went a long way to raise the confidence of Eastwood's clients in the 1920s. In 1924 a road was built over the dam.

In 1911 Eastwood prepared a design for Big Meadows Dam upstream from Sacramento for the Great Western Power Company (GWPC). Despite positive reviews from Schuyler and Alfred Noble, the GWPC also sought the opinion of the East Coast hydraulic engineer John R. Freeman. Freeman was much in favour of gravity dams:

> it does not pay to carry economy to excess in dam building and there is nothing quite so satisfying as a big solid mass of concrete – Eastwood's airy arches and lace curtain effect [are] not well suited to inspire public confidence; [he] has become so impressed with multiple arch designs that I presume he will ultimately have his hair trimmed in scallops.[47]

Eastwood responded that 'the solid dam would soon be placed with other relics of the dark ages where it belongs – in the junk heap.'[48] Nevertheless, Freeman succeeded in persuading the GWPC that the arch dam was unsound, and – with half of it built – it was abandoned.

Eastwood was never to be involved in hydroelectric schemes again and promoted himself purely as a dam builder – 'the Eastwood Multiple Arch Dam – the Last Word in Dams'. He moved to Oakland in 1911, and at the 1914 Internal Waterways Congress in San Francisco he pronounced (echoing Churchill) 'the Californian slogan e're should be, that 'tis a crime to let our rivers reach the sea.' He had to search for work at this time but, following the successful construction of the Mountain Dell Dam for Salt Lake City in 1917, gained a number of commissions from the Mormon community, including his longest multiple-arch dam – the 792-metre Fish Creek Dam in Carey, Idaho (1919).

Eastwood always sought to refine and improve his designs and in 1921 conceived the curved-face concept for the Cave Creek Dam in Phoenix, Arizona. Cave Creek was usually dry but in rainstorms became a torrent, and the dam was needed to protect Phoenix from floods. It was 515 metres long and 36 metres high with 38 arches, which were only 0.5 metres thick at the top and 1 metre at the bottom – thus having a curved profile and saving even more concrete. Construction started in March 1922, and, despite being held up (ironically) for lack of water for the mixing of concrete, it was completed in February of the following year. Almost immediately it stopped a flood, and, as the *Arizona Gazette*[49] reported, 'already more than paid for itself'. Concrete was carried from a central mixing plant in a Ford truck, and then the hopper was lifted from the truck by a Brown hoist crane and the concrete placed in the formwork.

More dams followed, including the Anyox Dam in British Columbia, which was Canada's tallest dam for many years and of which it was said that 'it's a pity [that such a pleasing design] is in such a remote place.'[50] Eastwood's last project – still searching for that 'Ultimate Dam' – was a 'triple-arch' dam at Webber Creek near Placesville in Northern California. His design was still founded on economy since, although his dams were cheaper than other forms, unit costs were higher, so he sought more efficient construction techniques. This had just one large centre arch of 43 metres with smaller arches of 33 metres on either side. It was 27 metres high and was impounding water in March 1924 when Eastwood inspected it a few months before he died.

His most ambitious project – like so many – was never built: a 915-metre-long, 92-metre-tall dam at Balojaque in Mexico. His plans for a triple-arch dam 122 metres tall on the Colorado River would have flooded the Grand Canyon. His obituary in the *Southwest Builder and Contractor* recorded 'always the seer, the prophet of things to be, the

dreamer who saw far into the future, and who happily for us, was able to make some of his dreams come true'.[51]

Back in the UK, earth dams were still largely the order of the day, but one stands out for a number of reasons. The 457-metre-long Silent Valley Dam was built between 1923 and 1932 in the Mourne Mountains to supply Belfast. The Belfast City and District Water commissioners had recognized the need for increasing water storage to meet the requirements of the growing industrial city in the 1890s and had purchased the whole of the 3,600-hectare catchment by 1899. They then took the extraordinary step of building a 35-kilometre-long wall round the catchment! This was started in 1904 and was a double-thickness rough granite structure 1.75 metres in height. It was known as the Back Ditch to the men who built it –

Eastwood's concrete dam at Cave Creek, Phoenix, under construction in 1922.

they worked from March to October, camping out overnight in the summer months. It was finally completed in 1922, and the contract for the dam was signed in March 1923 – a year after Ulster's partition. Designed and supervised by Fred W. McCullough (until his sudden death in 1927, when William Binnie, Edward Sandeman and H. Prescot Hill took over), this dam was notable in that the contractor's engineers team included Dorothy Buchanan, the first woman to become a corporate member of the ICE. Gangs of labourers were hired by the contractors to walk back and forth over the clay core to heel it in. They wore special boots with steel tips and heels which had to be 'Vaselined' every night to stop the clay from sticking to them. Belfast men apparently didn't like the puddling:

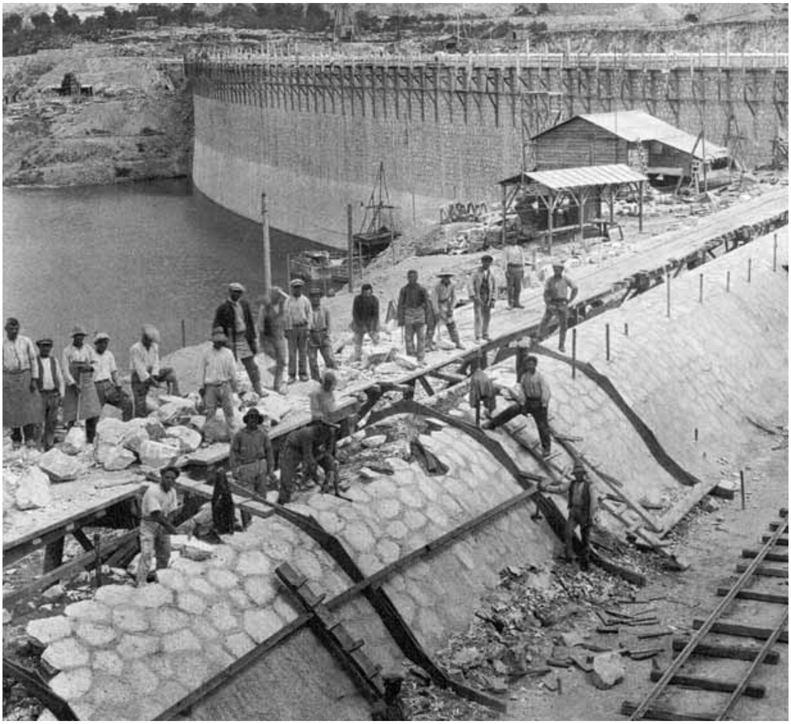
> They're working in the puddle clay
> They're working night and day
> The men who come from Belfast
> We know they will not stay[52]

The Silent Valley reservoir, Co. Down, for Belfast, completed in 1928. In 1951 a two-and-a-half mile brick-lined tunnel was dug (by candlelight) to transfer water from the adjacent Annalong catchment to Silent Valley.

While men were still employed for the puddling of clay, mechanization was gradually entering the field of dam-building in Europe as in the US. Dan Dooley, who had joined the Silent Valley project from the irrigation scheme on the Blue Nile, was a master operator of his Ruston steam excavator and filled 500 trucks in a day (including breaks for bacon and eggs fried on a shovel in the firebox), for which achievement he received a watch and a £15 bonus at a time when skilled wages were only £2 a week. (C. S. Lewis's Narnia in *The Lion, the Witch and the Wardrobe* comprised the Mournes and the Silent Valley: 'I feel that at any moment a giant might raise his head over the next ridge.' The men who built that wall *were* giants indeed.) For the placing of stonework, however, there was never going to be a substitute for labour.

Concrete was first used in dam-building in the 1870s in the US and Switzerland but was still mixed by hand. Mechanical mixing was used at the Abbeystead Dam for the water supply of Lancaster in 1881, and in 1890, at Crystal Springs, San Francisco, Hermann Schussler devised a method of mixing in drums turned by steam power and then transporting the concrete in hand-carts on rails to the dam site, where it was formed into interlocking blocks. It was spread in thin layers and rammed manually. The engineers realized that the cement content of the concrete had to be limited due to the heat it developed during curing. Consequently, contraction joints were provided (which were later filled); these also acted as cooling slots.

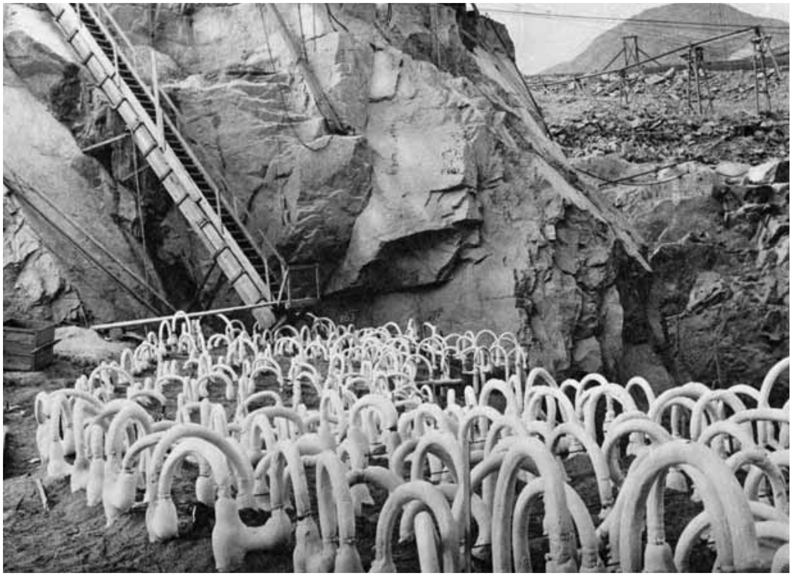
The use of water circulated through pipes in the concrete was first introduced at the Merwin arch dam in Washington State in 1931, and later ice was used instead in the concrete mix. At the Presa de Rules Dam in southern Spain, completed in 2002, the daytime temperatures reached 42 °C and cooling pipes (nicknamed 'pythons')



were incorporated within the concrete. (From the mid-1950s, fly ash from power stations was used in the concrete mix to reduce the cement content and the heat generated.) Compacting of the concrete was achieved at the Morris Dam east of Los Angeles in 1932 by the use of immersed vibrators. All of these technical developments were embodied in the Hoover Dam.

Even though dam projects became larger, they were naturally only as good as the designers or the engineers driving them. The Hoover Dam on the Nevada–Arizona border was designed by John L. Savage of the Bureau of Reclamation before being put out to tender in 1931. (Savage went on to help on the Three Gorges dam in the 1940s.) It was such a major task that it would use as much concrete as all of the projects in the Bureau's previous 29 years put

Placing stonework by hand on the 54 m high Marathon Dam in 1928 for the water supply of Athens. The stone is pentelikon marble as used for the Parthenon.



together. The Six Companies consortium (comprising some now household names such as Bechtel and Kaiser) brought in Frank T. Crowe as General Superintendent, first to prepare the bid (he came in at $48,890,996 – just $24,000 more than the Bureau's engineer's estimate) and then, having won it, to see it built.

Men like Crowe were more than resident engineers. 'I was wild to build that dam – it was the biggest dam ever built by anyone, anywhere', he said in a 1943 interview. Born in 1882 in Quebec, he was a student at the University of Maine when a guest speaker from the newly formed Reclamation Service inspired him to sign on for a summer job – he stayed for twenty years. Having become the Bureau's General Superintendent of Construction – and having devised efficient methods of construction such as cableways for concrete distribution – he left to join Morrison-Knudsen to do what he liked best: build dams. A driven man, Crowe had already supervized dams in Wyoming, California and Idaho when the big one came along. He features in Bruce Murkoff's novel *Waterborne*.[53] He

The reaction of cement with water causes heat to be liberated. At Grand Coulee Dam, Washington State, cold water was circulated through miles of pipe embedded in the dam. During excavation a mud slide was halted by freezing it with secondhand ice-making machinery.

also took the men (made infamous by John Steinbeck) who were fleeing west in 1931 in search of work and fortune – Murkoff's 'dam bums', skilled men who only knew dams — and turned them into builders of one of the era's greatest industrial monuments.

When Crowe arrived in Las Vegas on 11 March 1931, at the age of 49, a week after the bids had been opened, he set about building Boulder City. He completed (Boulder) Hoover Dam two years ahead of schedule in February 1936 but not without a few short cuts. He allowed ordinary motor vehicles to be used in the construction of the diversion tunnels, and many men were gassed by the carbon monoxide. The State of Nevada took Six Companies to court where Crowe swore that no one had been gassed working underground — eventually the company settled out of court.

Hoover Dam introduced a number of innovations. Men were taken to the work site each day from Boulder City in 150-seat wagons. Once on site, they were carried across the canyon on cables — as was the concrete from the batching plant. However, the dangerous job of removing loose rock and making 'keys' for the abutments had to be carried out by hand. For this, men called 'high scalers' swung and abseiled themselves down the face of the canyon.

After Hoover Dam, Crowe worked on Parker Dam, Copper Basin and Gene Wash dams on the Colorado, and the kilometre-long, curved gravity Shasta Dam in Northern California. He retired in 1944 and died two years later.

By the time the Grand Coulee Dam was started by Roosevelt in 1934 in Washington State, contractors were accomplished in their organization of such multi-million-dollar schemes. Grand Coulee was not as high as Hoover but was to be three and a half times longer and would use as much concrete as it would have taken to build three ancient Egyptian pyramids. In *The Dam* by H. M. Newell, an army of men struggles against rock and mud, burning sun and

crippling cold, against the unappeasable strength of the 'Mighty Squaw' (the Columbia River) in flood. The construction engineer Jeff Tunnicliff wonders if 'such a country might conceivably resent the impertinence of temporary little men meddling with its topography, but that was a fanciful idea, unworthy of a construction man'.[54]

In 1941, as work on the Grand Coulee was nearing completion, the Bonneville Power Administration (BPA), who would market the power from the dam, decided to make a documentary film, *The Columbia*, to promote the scheme and public power projects in general. Woody Guthrie was hired to put words and music together for the soundtrack. While the film has faded into obscurity, the songs live on. Guthrie submitted 26 songs to the BPA, and one, 'Roll on, Columbia' ('Roll on Columbia, roll on. Your power is turning our darkness to dawn'), was designated the official Washington State folksong in 1987. It was appropriate that Guthrie, famous at the time for his 'Dust Bowl' ballads about the plight of the Midwest, should have been selected since the dams were part of the New Deal, which not only brought cheap power to rural communities but also gave jobs to those from the Dust Bowl itself. In 'Guys in the Grand Coulee Dam' he describes Old Uncle John Turner and the others (to the tune of the English folksong 'Widdicombe Fair') as:

150-seat wagons transported workers between Hoover Dam and Boulder City.

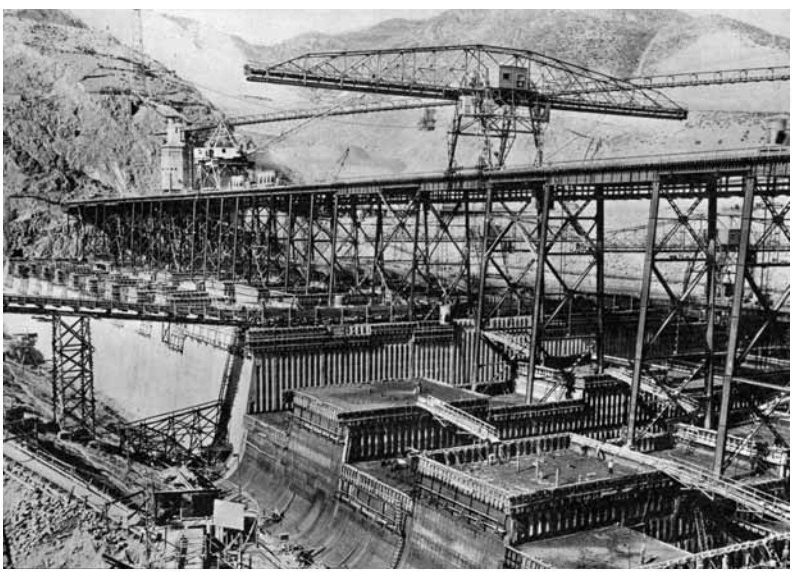
hard sweatin', hard fightin', hard workin' men,
All along down on Grand Coulee you'll see;
Blasting the canyon and damming her in . . .[55]

'The Grand Coolie [sic] Dam' was also adapted and recorded by Lonnie Donegan in Britain in 1958. The Grand Coulee provided electricity to power the factories that produced aluminium (principally to build aircraft for the war effort); the early Scottish hydro-electric schemes had been built for the same purpose. After the war, the British government, taking a lead from the TVA, set about bringing power production to the Highlands.

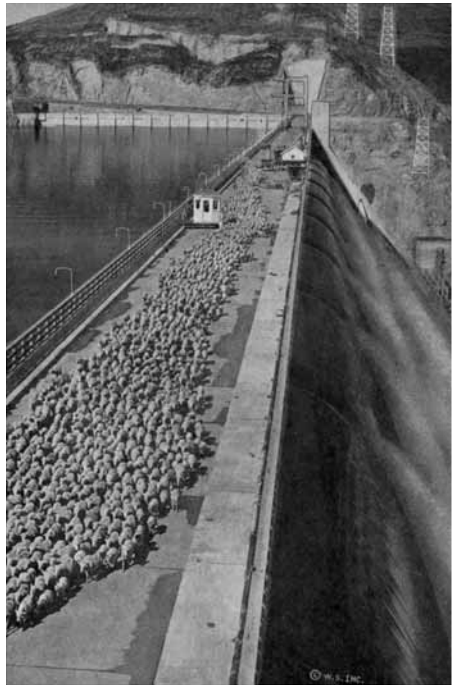
The promotion of major development projects often relies on special people, and the harnessing of Scottish water power by a public authority was the brainchild of Tom Johnston. A patriot and Red Clydesider, he had been elected to Parliament as an Independent Labour member in 1922. Although he lost his seat when Ramsay MacDonald's first administration fell in 1924, he was in and out of

An engineers' town built by the Bureau of Reclamation for their staff and families. A model community compared with Grand Coulee town, 'a centre for sin and vice' and known as the 'Cesspool of the New Deal'.

Parliament and government for the next fifteen years. On the outbreak of war in 1939 he was responsible for Civil Defence in Scotland until summoned to Downing Street by Churchill in 1941 to be appointed Secretary of State for Scotland. Johnston accepted on condition that he received no payment for as long as the war lasted. Churchill is recorded as replying, 'Nobody can prevent you taking nothing.'[56] In the words of Emma Wood, Johnston was the political godfather of the North of Scotland Hydro-Electric Board and Churchill the unlikely political sponsor of Britain's first nationalized industry.[57] Between 1945 and 1975 the Board built some 50 dams, 34 of which are on the ICOLD Register of Large Dams. If Johnston was the godfather, the surrogate 'midwife' for the Scottish schemes was James Williamson, who was responsible for the design of many of the early ones, including Loch Sloy, the first buttress dam in Scotland.



The Grand Coulee Dam, Washington.



While dam-building was largely mechanized by the 1930s, in countries where labour was plentiful it could still be used to advantage. At any one time on the fifteen-year construction of the Nagarjunasagar Dam in Andhra Pradesh (completed in 1970), between 30 and 70 thousand labourers worked on the site.

Scheme promotion, however, was often in the hands of single design engineers – with the carrot of designing and overseeing the eventual construction. This was exemplified by Julius Kennard at Cow Green in the 1950s and 1960s. As we shall see, the engineers had to tolerate not only opposition but also interference by their political masters.[58] Scheme promoters didn't always trust their engineers, however; Floyd Dominy, an economics graduate, rose from land development at the US Bureau of Reclamation to Commissioner: 'If Dominy harboured a lifelong grudge, it was

Sheep crossing the Grand Coulee Dam: settlers were allocated farm units, and by 1955 there were 10,000 people living on farms within the project area.

against engineers.'[59] He recognized their 'mystical ability to erect huge structures' but only had faith in his own ability to get them built. He did not have much respect for rivers either, having remarked: 'The unregulated Colorado River is a son of a bitch.'[60] Dominy presided over dozens of big dams, including Glen Canyon, but Marc Reisner maintains that his legacy is 'not so much bricks and mortar as a reputation – a reputation and an attitude. The attitude is his . . . arrogant indifference to sweeping changes in public mood'.[61] Of course, dams are big structures and maybe they need big men to make them real.

From the 1950s the introduction of vibratory rollers for the compaction of concrete, gravel and rock fill advanced the techniques available for dam-building. Embankment dams proliferated from this time[62] since the rollers reduced any settlement. This led to world

Haweswater, Lake District. This 470-metre-long dam is unusual, being a concrete buttress dam, but the 44 buttresses are widened at their end so that the dam's air face, while appearing uniform, is in fact hollow, comprising a series of linked pyramid chambers, thus saving concrete.

records in dam-building: the Tarbela Dam (1976) on the Indus in Pakistan (at 105 million cubic metres, the record for embankment volume) and the Nurek Dam (1980) in Tajikistan (at 300 metres the tallest dam in the world). An even taller rock-fill dam, the Rogun, also in Tajikistan, was started in 1976 but was stalled on the break-up of the USSR and then destroyed in a flood in 1993. A deal was signed with RUSAL, the Russian aluminium producer, in 2004 to complete the Rogun in order to power the aluminium smelter that RUSAL is hoping to build. It will be 335 metres high when complete. The dams of Tajikistan have been somewhat controversial in that they have the potential to starve neighbours such as Uzbekistan, Turkmenistan and Kazakstan of water, as well as turning off the tap to the rapidly depleting Aral Sea.

This chapter has been principally about the designers and builders of dams, but the story would not have been complete without reference to technical advances introduced by engineers. Dam projects are now so big that no one person can be identified as being the 'dam engineer'. Ever since the Six Companies combined to tender for Hoover Dam in 1931, consortia have grown, and the creative engineer has been lost in a sea of anonymity. Even consultancies which still bore the names of their famous founders – Binnies, Babtie, Hawksley, Rofe and Kennard – have been swallowed up by international organizations in recent years. Now even these are but cogs in the wheel of larger project funders and development corporations – the Three Gorges Dam will cost $25 billion when complete. We may well ask, 'What do these organizations or governments care about the beauty of their dams?' This is the subject of the next chapter.