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# ROBERT STEPHENSON (1803–59) – THE FIRST GROUNDWATER ENGINEER

**Author: M Preene**

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# ROBERT STEPHENSON (1803–59) – THE FIRST GROUNDWATER ENGINEER

**Martin Preene, Arup, Leeds**

## Abstract

From a humble background in the mining communities of Tyne and Wear, with little academic education, Robert Stephenson followed in the footsteps of his father, George, and became one of the foremost civil and mechanical engineers of the early nineteenth century. While he is primarily associated with railways, Robert Stephenson had considerable dealings with groundwater during his professional life, applying a rational, empirical approach that would be familiar to modern practitioners.

Stephenson's approach to groundwater issues was probably shaped largely by the years spent battling water-bearing quicksands during construction of the Kilsby Tunnel near Rugby on the London to Birmingham Railway. Careful observations allowed him to conclude that local drainage by use of arrays of wells was possible, without the need to drain the whole aquifer body. Later in his career he advised on public water supplies from the Chalk for London and the Sherwood Sandstone for Liverpool. His careful observations and reasoned interpretation, allowed him to advance the concept of a 'cone of influence' around a pumped well, and to develop tests and monitoring programmes to assess the impact of new abstractions on existing water features.

Today, his work may seem basic, even obvious, but, in the days before the work of Darcy and Dupuit, there were many who disputed his findings. Stephenson preferred to let the facts to speak for themselves, but where this was not possible he vigorously publicised the benefit of applying a scientific approach to the management and control of groundwater.

## Introduction

By any reasonable measure, Robert Stephenson was one of the foremost civil and mechanical engineers of his time. Furthermore, he was one the most prominent figures in professional society. There can be few contemporaries from science and engineering who were so fêted with awards and honours. Stephenson was elected a Fellow of the Royal Society, was President of the Institution of Civil Engineers in 1855–7, was awarded the *Legion de Honneur* by the French Emperor, received an honorary Doctor of Civil Law at Oxford University (in company with Isambard Kingdom Brunel and the explorer Dr Livingstone), and was twice elected as the Member of Parliament for Whitby, North Yorkshire, serving there until his death in 1859. Even in death he was honoured, being laid to rest in Westminster Abbey. A contemporary obituary (Anon, 1860) describes the funeral as being 'conducted with fitting solemnity…in the presence of several thousand persons, amongst whom were not only his professional and private friends, but also the most distinguished representatives of the literature, science and art of Great Britain in the nineteenth century'.

The esteem with which Stephenson was held, by business, science and the public was based on his work on the development of the railway network and locomotive technology in Britain, building on the pioneering work of his father George. This is fully documented in contemporary and modern biographies (Jeaffreson, 1864; Rolt, 1960). However, what is much less well known is that Robert Stephenson developed considerable practical expertise in the management of groundwater, both as a source of supply and when it posed an impediment to construction works. That Stephenson developed groundwater sources and groundwater lowering systems which would be recognisable to modern practitioners is a tribute to his skills, especially when it is considered that most of his work pre-dates even the publication of Darcy's law (Darcy, 1856).

Stephenson's groundwater work had three main elements: fighting against groundwater during the construction of the Kilsby Tunnel on the London to Birmingham Railway (1835–8); work on developing water supplies for the metropolis of London (1841 onwards); and study of the water supply for the City of Liverpool (1850). That this work is not widely known among the hydrogeological community is perhaps because Stephenson did not publish papers in the scientific or learned journals – one of his few formal contributions being the section on 'iron bridges' in the *Encyclopaedia Britannica* of the time. However, Stephenson produced numerous professional reports and contributed to technical discussions minuted by the Institution of Civil Engineers and others. The remainder of this paper will use those sources to document the range of Stephenson's work with groundwater. This will include his work developing sources in major aquifers such as the Chalk and Sherwood Sandstone, his epic groundwater lowering exploits at Kilsby, and his conceptual understanding of the 'cone of depression' around a well source, and the interaction between wells.

To better understand how Robert Stephenson was perhaps uniquely equipped to manage and manipulate groundwater to his will, with little contemporary theoretical support, it is worthwhile considering his background and early work.

## The making of Robert Stephenson the engineer

It is well documented that Robert Stephenson did not have an especially academic upbringing (Jeaffreson, 1864; Rolt, 1960). Born in 1803 at Willington, Tyne and Wear, Robert was the only son of George Stephenson, who at the time was the brakesman of a local colliery engine. Robert was involved with his father's work at the pit from an early age, and in this way received much education of a practical and mechanical nature. On leaving school he was apprenticed to his father's friend Nicholas Wood, the mining engineer at Killingworth Colliery, but was released from this on grounds of ill health. In 1822–3 Robert spent one term (probably of less than six months duration) at the University of Edinburgh studying natural philosophy, chemistry and natural history. These studies included geological excursions with Professor Jamieson, which Stephenson recalled fondly in later life. An award by Professor Leslie in recognition of his mathematical skills was perhaps a sign of a latent analytical skill that would prove useful later.

In his early years of his professional career, Robert (Figure 1) was naturally in the shadow of his father, who by the 1830s had become the driving force behind the development and implementation of railway systems and steam locomotive technology. During this time Robert travelled to Venezuela and Colombia to act as Engineer to the Colombian Mining Association. This was not the most fruitful relationship, and after three years he returned to Britain to continue his work as a railway engineer. His chance to establish himself in his own right came from 1830 during the construction of the London to Birmingham Railway, where he was Engineer-in-Chief. At the time he could not have predicted how groundwater would play such an important role in the construction of the project.

## The London to Birmingham Railway

The idea of a railway linking London and Birmingham had first been seriously considered in the 1820s. In 1830 the London and Birmingham Railway Company was formed, and subsequently appointed the company of George Stephenson and Son to make plans and surveys and to carry the line through the parliamentary process. The surveys and plans were made by Robert himself. In 1833 the railway act was passed by the Commons and the Lords and Royal Assent was granted. In the same year Robert Stephenson was appointed Engineer-in-Chief at an annual salary of £1,500 plus expenses of £200 per year. The directors of the company stated that 'they are persuaded that to no one could this charge be more safely or more properly confided' (Jeaffreson, 1864). This view was to be ultimately confirmed by the works at Kilsby.

The London to Birmingham Railway was the first of the railways in the modern pattern, allowing high speed travel between major cities. The railway covered 180 km between the cities, with its metropolitan terminus on a vacant piece of land at Euston Square, now known as Euston Station. The quality of the chosen alignment, minimising steep gradients and sharp curves, is illustrated by the fact that the railway now forms part of the West Coast Main Line. Until recently, very few major engineering works have been necessary to allow trains to travel in excess of 160 km per hour along a line where the original rail traffic was to average 30 km per hour.

It was the desire to have a line with minimal gradients that resulted in the alignment with a number of substantial cuttings, tunnels, embankments and viaducts to carry the railway through or over geographical obstacles. With hindsight the most notable and challenging of these was the tunnel at Kilsby.

## The Kilsby Tunnel

The construction of the Kilsby Tunnel has been thoroughly documented by Lewis (1984). It was an epic undertaking. Required to carry the railway through a ridge of high ground, the tunnel itself, located approximately 8 km southeast, of Rugby is 2,217 m long, 7.6 m wide and 8.5 m high, with two huge ventilation shafts (Figure 2). The tunnel was up to 63 m below the summit of the ridge. Constructed between 1835 and 1838 at a final cost of £291,030, 1,250 labourers were employed at the height of the works. Twenty six men lost their lives building the tunnel.

As Engineer-in-Chief Stephenson was determined that the project would be planned, programmed and costed in a rational manner, an approach that would be familiar to the modern construction industry. At the time this was a revolutionary approach. The entire line was divided into thirty separate contracts, each with their own drawings, estimates and specifications. Most of the works were supervised by an Assistant Engineer (responsible for a section of line), reporting to Stephenson as Engineer-in-Chief. The contract for the construction of the Kilsby Tunnel was let to the contractor Joseph Nowell and Sons of Dewsbury, Yorkshire in May 1835.

As will become apparent, groundwater posed a great obstacle to the construction of the tunnel, but a key question is – had Stephenson considered this in advance? It seems likely that he had, at least to some degree; his alignment had been pushed slightly to the west to avoid 'quicksand' problems encountered nearby during the earlier construction of the Union Canal. Furthermore, Stephenson indicated in correspondence that 'symptoms of quicksand made their appearance [in trial borings]' (Lewis, 1984). Very early on in the site works four trial shafts were sunk to allow the contractor to judge the nature of the ground. Very little water was found in these shafts, and the tunnelling work was expected to be easy. The reality was to prove rather different.

*Early construction problems*

A number of working shafts were to be constructed, from which the tunnel would be driven. However, early in the works the contractor hit water in the working shafts and was flooded out. Conditions were worst between two of the trial shafts, leading Stephenson to believe that a basin of sand 400 m long had been missed by the investigation.

Pumping engines were hurriedly procured and two shafts were sunk to the level of the water, with a 180 m long drift to aid draining of the sand. There were a number of inflows of sand and water into the drift during construction, including one event where the drift was filled with sand over a length of 80 m.

Matters were complicated by the death of the contractor, Joseph Nowell, in January 1836. By late February it was clear that Nowell's sons could not carry on the contract in the necessary manner. In March 1836 Joseph Nowell and Sons relinquished their contract, and construction works were taken over by London and Birmingham Railway Company. Stephenson was now fully in charge.

*Geological setting*

Accounts based on contemporary records (such as Boyd Dawkins, 1898) describe the strata through which the tunnel was driven as Inferior Oolite, based presumably on the original records and geological mapping of the time.

However, modern mapping (British Geological Survey, 1980) indicates a different geology. This indicates the tunnel was driven through Middle Lias Silts and Clays comprising silts, mudstones and thin silty limestones. These strata form the ridge of high ground which was the obstacle requiring the railway to pass through a tunnel. The ridge is shown to be capped by sand and gravel and glacial till, and to be underlain by the Lower Lias, comprising mainly mudstones with a few very thin limestone bands. The modern mapping is apparently consistent with William Smith's early mapping (Smith, 1815), which pre-dates the construction of the tunnel and identifies the strata at Kilsby as 'Blue Marl of the Lias'.

A crude conceptual model of the ground through which Stephenson drove his tunnel might be as follows. The tunnel was driven through the Middle Lias Silts and Clays, which contained horizons or lenses of water-bearing silts and sands. These strata were underlain by the Lower Lias, which is generally of low permeability, so the water in the Middle Lias Silts and Clays would have been perched above the Lower Lias. Stephenson's tunnel would have intercepted this water, and the flow through the silts and sand horizons would have given the quicksand conditions so feared by the tunnellers. That the flows did not significantly diminish with time is consistent with the presence of a mantle of sand and gravel over part of the ridge. This may have acted as a reservoir providing recharge to the silt and sand layers, with vertical flow perhaps facilitated by cambering features.

*Stephenson's observations*

By the end of July 1836, a total of eleven shafts had been constructed, some for tunnelling (where water was not a problem, Figure 3), but mostly in wet ground where pumping was necessary. Stephenson's reports, quoted in Lewis (1984) state:

> ‘The distance between the shafts to be sunk in the quicksand must be governed by the advances made in the draining. It is probable that distances will not exceed 100 yards [91 m] from shaft to shaft…. The diagram [Figure 4] shows the line of the tunnel in the quicksand and the relative positions of the three shafts by which drainage has been attempted, and its progress observed. When one pump was put to work in No.1 Pumping Shaft, the water immediately fell in No.2 Working Shaft, but No.2 Pumping Shaft being nearer the pump than No.2 Working Shaft, the water level fell lower than in the [other] shaft. This is precisely what might have been anticipated, and demonstrates in the most conclusive manner that the supply of water at this level to the quicksand is very moderate – and that the sand throughout it is so open as to admit freely the passage of water.’

Stephenson then outlines his plans to complete the works:

> ‘From the commencement of pumping on even a small scale, we have been able to lower the general level of the water in the quicksand gradually, notwithstanding any falls of rain which have from time to time taken place. When we first attempted the drainage by drawing water in buckets, a rapid thaw took place, with a considerable quantity of snow on the ground – in this instance the water rose in the shaft. Nothing of the kind has occurred since the pumps were worked; on the contrary, the general level of the water has been lowered at the rate of 10 inches [250 mm] per week. Previously when only one pump was worked, the fall was at the rate of 6 inches [150 mm] per week….That local drainage by shafts will be effectual seems placed beyond any reasonable doubt by the complete sympathy existing between the levels of the water in the shafts at a considerable distance from each other, and by the simultaneous effect of one pump in different shafts. As an example in sinking the two pumping shafts, the sinkers were compelled to work in them alternately, for the moment one shaft was sunk a few inches deeper than the other the water flowed into it and left the other in a fit state for sinking. It was in this manner that they were sunk to their present depths. Precisely the same thing has taken place within the last few days in No.2 Working Shaft. The men were some time since driven out of the shaft by the rapid influx of water. The general level of the water having gone on lowering, it is now quite dry, and fit for sinking again to commence.’

Stephenson’s method of ‘local drainage by shafts’, where it is recognised that several wells act in concert achieve more drawdown than from a single well, and where the spacing between wells is an important parameter, controlled by ground conditions, is the ancestor of modern ‘construction dewatering’ methods. Shafts may have been replaced by boreholes, and pumps are now driven by electricity, rather than by steam (Figure 5), but the principle remains exactly the same.

### *Resolution*

Stephenson’s use of shafts and pumping engines allowed the tunnel to be completed in June 1838, at a cost of £291,030 (nearly three times the original estimate).

It must have been a very heavy workload for Stephenson to be Engineer-in-Chief for the entire railway, while personally managing the works at Kilsby following the loss of the contractor. Many men would have lost themselves in action, and would have had little time for reflection on what could be learned from the observations at Kilsby. However, in Stephenson’s case, the evidence suggests he gave considerable thought to groundwater flow through the sand. The following statement of his Kilsby experience is from one of his reports on the water supply to London (Stephenson, 1841).

> ‘I was soon much surprised to find how slightly the depression of the water level in the one shaft influenced that of the other, notwithstanding a free communication existed between them through the medium of the sand, which was very coarse and open. It then occurred to me that the resistance the water encountered, in its passage through the sand to the pumps, would be accurately measured by the angle or inclination which the surface of the water assumed toward the pumps, and that it would be unnecessary to draw the whole of the water off from the quicksand, but to persevere in pumping only in the precise level of the tunnel, allowing the surface of the water flowing through the sand to assume that inclination which was due to its resistance.
>
> If this view were correct, it was evident that no extent of pumping whatever would have effected the complete drainage of the bed of sand. To test it, therefore, boreholes were put down at about 200 yards [183 m] from the line of the tunnel, when it was clear that, notwithstanding that pumping had been going on incessantly for twelve months, and for the latter six months of this period, at the rate of 1800 gallons per minute [137 litres per second], the level of the water in the sand, at a distance not exceeding 200 yards [183 m] had scarcely been reduced.
>
> The simple result, therefore, of all the pumping, was merely to establish and maintain a channel of comparatively dry sand in the immediate line of the intended tunnel, leaving the water heaped up on each side by the resistance which the sand offered to its descent to that line on which the pumps and shafts were situated.’

Put in modern language, Stephenson had identified that water flowing through granular soil experienced a resistance (which we now call hydraulic conductivity). When water is abstracted at a point, the water flowing to that point must overcome the resistance. The groundwater head distant from the abstraction point must be greater than at the abstraction itself, with the slope of the groundwater head (which we call the hydraulic gradient) being controlled by the hydraulic conductivity of the material. This might be interpreted as an alternative formulation of Darcy’s Law, fifteen years before it was formally published (Darcy, 1856). Stephenson had also identified that the lowering of groundwater levels extended only a finite distance from the point of abstraction, and reduced with distance. This may seem self-evident today, but at the time there were many who disputed it.

## The water supply for the Metropolis

### *London’s water in the early nineteenth century*

In the first part of the nineteenth century the water supply to the population of London was a mess. Much of the city’s drinking water was drawn from the Thames, which also received almost all the sewage from the metropolis. The river became a foul, stinking pool, the tides conveying putrescent material up and down the tidal stretch of the river. The city’s inhabitants were literally drinking dilute sewage (Halliday, 1999).

But society was changing and London was growing rapidly; there was need for more wholesome water, and lots of it. Barlow (1854) paints a vivid picture:

> ‘This marvellous extension [the growth of London’s population from 865,00 in 1801 to 2,362,000 in 1841] would have demanded improved means of supply, even if there had not been any change of social habits; but when civilisation and luxurious habits advance

> with equal strides, baths become necessaries of life for all classes, and sanitary measures enforce the copious use of water in all ways'.

The opinions of the time are articulated in Stephenson's own words 'the present mode of supplying London with water, has, for a length of time, been anything but satisfactory to the public' (Stephenson, 1840). Following his first hand experience of groundwater at Kilsby, from around 1840 Stephenson became involved in schemes to supply water for the Metropolis, by means of wells. At this time there were many schemes to improve the water supply and drainage of the capital. Many companies were formed in the speculative hope of making money from this opportunity. Stephenson's contribution is recorded in his two reports to the London Westminster and Metropolitan Water Company (Stephenson, 1840; 1841) and various responses and rebuttals by others.

*Stephenson's first report*

Stephenson's first report (Stephenson, 1840) was published in the Morning Advertiser of 29 December, 1840. The report proposed a groundwater supply to the city on the basis that:

> 'Nature has supplied us with the means of substituting a pure and unceasing flow of spring water for the out-pourings of filthy drains, and that this can be done without encountering difficulties of any but an ordinary nature'.

Following the Royal Commission of 1828 the distinguished engineer Thomas Telford had been appointed to report on new sources of water for London. Other engineers and companies had also proposed water supply schemes. Stephenson begins his report by commenting on these schemes and says 'it is indeed surprising that…every scheme, including Mr Telford's, should have contemplated using the water of streams which are all subject to be affected by the surface drainage of a more or less extensive tract of country, and, consequently, only a very few degrees better than that already in use'.

Stephenson differentiates these surface water schemes from proposals for groundwater use, which 'obtain the water by perforating the London clay' – in other words schemes to sink wells into the confined aquifer beneath central London. However, Stephenson does not look favourably on these proposals, and he explains why this is so using what we would nowadays call a 'conceptual model' of the hydrogeology presented in the report:

> 'The group of strata, designated as the lower tertiary, or eocene and consisting of two divisions, the upper called the London clay, and the lower composed of various coloured sands, and argillaceous deposits, distinguished as the plastic clay [in modern terms the Lambeth Group and Thanet Sand Formation], lying immediately upon the chalk formation, may in general terms be described as a huge mass of clay resting upon a still more extensive bed of chalk….the surface of the country occupied by the clay is surrounded on all sides by a belt of chalk, excepting to the east, where the German Ocean [the North Sea] for some distance interrupts the continuity, and you will perceive that this cretaceous circle is, generally speaking, higher in level that the deposit of clay which fills the centre of the basin.
>
> It is almost needless that I should inform you, that of the water which descends as dew or rain upon the surface of the London clay, little, if any, can be considered as absorbed into the earth, and that whilst a part either again reascends into the atmosphere as vapour, or enters into the composition of animal and vegetable bodies, by far the greater portion flows off into the main drain of the district of the river Thames.

> In this respect there is a most material difference from that portion of the surface where the chalk comes to light, divested of any covering which could intercept the passage of the moisture; being not only extremely porous, but also full of fissures in every direction, a very rapid absorption takes place, and we accordingly find that there are but few streams carrying off the surplus surface water, and that these are insignificant, and, indeed, many of them dry during the greatest part of the year…The lower part of the cretaceous group, and the gault which immediately succeeds it, again presents an impermeable stratum of clay, causing the water to accumulate through the lower regions of the more porous chalk. An enormous natural reservoir of water has thus been formed, and the level to which it might be considered as quite full of water is the lowest point where it can find a vent and overflow; therefore, as the chalk communicates under the coasts of Norfolk, Suffolk and Essex with the ocean, this level, in the present case, may be considered as the same as the mean height of the sea.
>
> That there is, however, an extensive accumulation of water above this level will be obvious, when it is considered that the friction, which from the nature of the small fissures and pores must exist, will necessarily prevent the water from exerting rapidly its hydrostatic pressure…The greater or lesser facility, which from lines of fissures, soft strata, and pores, the water may encounter if flowing towards the centre of the basin, will also govern its surface, and cause it to assume an inclination, the angle of which will represent the friction; and in this manner we may readily account for the different levels, which often appear anomalous, at which water will be found to stand in wells.'

Stephenson does not claim to have done the geological investigation and study that allowed this conceptual model to be developed (he refers to work by Dr Buckland) – his skill was interpreting what this meant in practical terms. His comment on the inclination of the groundwater surface (and by implication the hydraulic gradient) being related to the friction or resistance to flow of the aquifer pores and fissures (a measure of hydraulic conductivity) results from his careful observations at Kilsby, and, again, could be interpreted as a formulation similar to Darcy's law.

Stephenson then uses this conceptual model to present his view against the proposal to obtain water supplies by perforating the London Clay and installing wells into the Chalk. He states that because the Chalk beneath the clay cannot receive recharge easily, large and excessive drawdowns would result:

> 'whenever a large quantity is extracted, the wells in the vicinity, which derive their water from the same strata, are sensibly affected…the level for some distance around this focus will be temporarily reduced'.

From our modern perspective, Stephenson seems to have been remarkable prescient; the excessive lowering of piezometric levels beneath London during the twentieth century is indisputable (Marsh and Davies, 1983).

Being unhappy with the idea of abstraction from the confined Chalk, Stephenson became involved with a scheme to abstract water from the unconfined Chalk north of Watford, proposed by a Mr R Paten. Stephenson states 'The abundance of springs which overflow into the Colne valley, above Watford, and the apparent purity of the water, had long attracted [Mr Patens's] attention'. Various investigations had been done, and Stephenson was 'requested to examine whether the experiments were well grounded'. The remainder of the report seeks to 'explain the proposed method of procuring the water and conveying it to London; and lastly, to submit such remarks as will enable you, in my opinion, to present the project before Parliament'.

In essence, the proposal was for large-scale abstraction from shallow wells in the unconfined Chalk in the Colne Valley. A modern geological map (British Geological Survey, 1999) shows this area is near the feather edge of the Tertiary deposits overlying the Chalk, an environment where we would expect enhanced transmissivities and the potential for high yielding wells. Stephenson's report makes it clear that he understood the geology of the area. However, his estimate of the effective recharge to the chalk is less satisfactory. Stephenson uses data from others to assess precipitation, and conjectures that two thirds of the precipitation would be available as recharge. Today we would expect only around one third of the precipitation to act as recharge. From his recharge calculations, plus his belief that the bed of the river was formed of low permeability alluvium, Stephenson believed that the proposed abstraction would not 'produce any visible effect upon the springs which feed the Colne'. While parts of his analysis may be questionable, Stephenson's next step – a practical experiment – was not.

A well of 10.4 m depth, and 3.81 m diameter at its base, was sunk in Bushey Hall meadows, near the Colne and equipped with four pumps, powered by two steam engines. The test, whereby 'The water of the well was now repeatedly pumped out, as low as the power of the engines admitted, and the height of the Colne at those times carefully noted' is clearly a pumping test of the modern pattern. Stephenson concluded that pumping of the well had no discernable effect on the Colne, and that the well could yield approximately 5 Ml/day. Further borings showed that, below 24 m depth, the water supply became 'prodigiously plentiful'. Stephenson also noted that the water was very clear and

> 'indeed, there was abundant ocular demonstration ([the water] was so beautifully transparent as to admit of the bottom of the well being seen when the water was upwards of 30 feet [9.1 m] deep'.

This is a key point as the alternatives to groundwater sources were from surface waters that were often turbid or worse.

Stephenson concluded that the scheme to abstract water from the Chalk near the Colne had many advantages in forming 'the supply to London with facility and economy' and 'in making use of the enormous reservoir which nature has supplied us with in the chalk, and effecting this at a spot where no existing interests can be injured'.

### *The response to Stephenson's first report*

There were objections to the proposals. Barlow (1854) later summarised the arguments as:

> 'This project was opposed by the millowners in the neighbourhood, who contended, that this quantity of water [46 Ml/day] must be obtained from the same source whence the springs which feed the mill-streams were derived…On the other side of the question it was argued, that the springs were derived only from the upper stratum of chalk, and that if the well was made watertight to the depth of 60, or 70 feet [18–21 m], it would have no effect on the surface streams; the supply being obtained from the lower water-channels, which had no connection with the upper supply'.

As was the convention of the day, the objectors produced pamphlets (such as Anon, 1841) stating why Stephenson's opinions of his first report were wrong. Parts of the pamphlets can seem vitriolic by modern standards, attacking Stephenson in quite a personal way. It is useful to view the major objections in light of Stephenson's response.

*Stephenson's second report*

Stephenson answered his, apparently numerous, detractors in a second report (Stephenson, 1841). One of the objectors, a Mr Webster, had a rather major objection, in that Stephenson says Mr Webster 'denies, emphatically, that the chalk underlying the stratum of London clay is the "great water-bearing stratum"'. Stephenson rebuts this from a geological perspective, and then from a practical one, by outlining how the cities of Winchester, Arundel, Brighton, Dover, Deal and Walmer, Canterbury, Gravesend and St Albans derive their water supply from the Chalk.

Some of the objectors had added a slightly demeaning air; Stephenson's practical upbringing did not tolerate this well, although he preferred the facts to speak for themselves. When Mr Webster (he who did not consider the Chalk to be the major aquifer beneath London) said of Stephenson 'many are old in years, yet young in geology', Stephenson responded thus of Mr Webster:

> 'Some are old in years, yet young in mining. When Mr Webster has spent as much of his time underground as I have done, and not till then, will he understand the exact truth of this remark….However,…I am convinced any observations of a personal nature never, in a question of this sort, can be substituted with proprietary, for sound arguments or fair deduction'.

One of the principal objectors was the Reverend J C Clutterbuck (Clutterbuck, 1841), who was concerned for local interests that may be injured by the proposed abstraction. Stephenson says that Clutterbuck and his relatives owned property in the vicinity of the abstraction. In response to Clutterbuck's objections Stephenson (whose previous report had said that there would be no noticeable effect on river and spring levels) invited Clutterbuck 'to suggest any experiments which he conceived were calculated to decide whether the views I entertained were correct or incorrect'. According to Stephenson, Clutterbuck proposed continuous pumping from the well for three days, having first accurately determined initial levels in surrounding water features, with levels monitored during the test. These tests were carried out in March 1841, and Stephenson reports that there were no perceptible effects on water levels in any of the wells that were monitored.

Stephenson expressed the hope that Clutterbuck would accept that his and other local interests would not be affected, but this was not to be the case. Apparently, in addition to water level observations taken jointly by Clutterbuck and Stephenson and his assistants, Clutterbuck had some observations taken by him alone. Stephenson believed, not withstanding the unwitnessed nature of some of the observations, that Clutterbuck was using the data selectively, ignoring nearby wells that were not affected, and attributing movements in water levels in distant wells directly to the influence of the test pumping. Stephenson is dismissive of Clutterbuck's hypothesis:

> 'He adopted a theory at variance with all hydrostatic laws. To discuss it, would really be a waste of time, and I think I shall be justified in treating it thus summarily, by stating that it follows, from his theory, that pumping at any point in the chalk is not so likely to affect the neighbouring as the distant wells…he gives a diagram where the level of the water in the chalk is shewn to be influenced to a far greater extent at fifteen miles [24.1 km] distant than at one mile [1.6 km] distant'.

Stephenson, by reference to his observations at the Kilsby Tunnel, reiterates his view that the effect of pumping must reduce with distance from the point of abstraction. He then makes the following statement:

> 'The result of pumping at a deep shaft, in chalk or other similar porous material, would be the drainage of a portion of the district, represented by an inverted cone, the point being at the bottom of the shaft; the upper surface, or what is generally designated the base of the cone, occupying an area depending on the inclination which the fluid assumed in passing through such porous mass.'

This statement is remarkable in that it almost perfectly describes the concept of a circular 'cone of influence' around a source, which is implicit in all radial flow models beginning with Dupiut (1863) and the workers that followed. As with many things that Stephenson did, a modern perspective makes Stephenson look remarkably precescient.

*Later developments*

The variance of views between Stevenson and Clutterbuck did not end there, with Clutterbuck responding in another pamphlet (Clutterbuck, 1842) and also in a number of papers and discussions in the *Minutes of the Proceedings of the Institution of Civil Engineers*. Nevertheless, later workers have supported the conclusion of Stephenson that large-scale abstraction from the unconfined chalk was viable, and that the impacts of abstraction will reduce with distance. It is not clear whether the scheme proposed by Stephenson was ever implemented, but Boyd-Dawkins (1898) states that Stephenson's views 'bore fruit at the time, in the sinking of numerous wells in the chalk, and notably in those of the New River and Kent Companies'.

**Work in Liverpool**

Stephenson was appointed in 1850, by Liverpool Town Council, to report on and recommend the best plan to secure an adequate supply of water for the town. His report (Stephenson, 1850), describes the sources of water at the time, and discusses options to procure additional water, not just from groundwater, but also from surface water schemes, such as expansion of the Rivington Works.

As with his previous studies, Stephenson did not do any original geological work himself, but invited representations on such matters by others, and discussed them in his report. What he did commission specifically was a series of pumping tests on wells and groups of wells, and the gathering of much more detailed groundwater level data than was previously undertaken.

*The wells supplying Liverpool and the hydrogeology of the sandstone*

Stephenson's report contains considerable detail of water levels at the seven 'pumping stations' where wells supplied the town. These were: Green Lane; Windsor; Park (also known as Water Street); Hotham Street; Soho; Bush (also known as Bevington Bush); and Bootle. Records are also presented from sixty-three private wells, where Stephenson was interested in the impact of pumping from the public wells. Stephenson's data show the maximum yield of all the public wells as 23.5 Ml/d, although he interprets the data to give a more typical output as 18.2 Ml/d.

In his review of the geological submissions put before him, Stephenson states that his aim was:

> 'to ascertain correctly the quantity of water yielded by the existing wells, the influence which they exert upon each other, and the mode by which the water contained in the mass of sandstone is transmitted from one place to another'.

The details of all the submissions are not recorded, but Stephenson says that some of the evidence was:

> 'very conflicting, some of the witnesses maintaining, that however large a quantity might be pumped from one well, little or no effect was found to be produced upon those in the vicinity; and of this several authenticated instances were certainly adduced, but a careful consideration of the whole mass of facts leads me to believe that these cases form rather the exception than the rule; and that they are occasioned by local geological faults, partially or wholly water tight, which are known to be interspersed throughout the new red sandstone formation [now known as the Sherwood Sandstone Group] in the neighbourhood of Liverpool'.

In the face of conflicting views on the practical importance of fissures, Stephenson believed, as we do today, that fissures can significantly affect the hydraulic properties of the sandstone, and states:

> 'Different degrees of porosity unquestionably exist, satisfactorily accounting in my mind for the different degrees of influence which wells are found to exert on each other. The facility with which the water will pass from one part of the sandstone to the other, depends principally on the size of the fissures, their character and direction; and hence it is quite consistent with the existence of a very large number of fissures, that two wells at a great distance may affect each other while two that are near may show little or no connection'.

Stephenson concludes that the sandstone forms a very productive aquifer. Furthermore, based on various pumping tests and consideration of monitoring data, he estimates that the maximum long-term yield of a well in the sandstone is unlikely to be greater than 4.5 to 5.4 Ml/d.

*Interference between wells*

When planning to develop new groundwater resources, Stephenson realised that the spacing between wells, and their influence on each other, was an important factor. His report re-states the concept of an inverted cone of influence centred on a well, with the diameter of the cone being controlled by the frictional resistance to flow (i.e. the hydraulic conductivity of the aquifer). He expands on this concept and introduces the idea of non-circular areas of influence:

> 'looking upon the area drained by a well as represented on the surface by a circle is not strictly correct, because its form will be of course modified by the relative sizes, characters and directions of the fissures through which the water finds its way to the well. The area ..will, therefore, most probably be very irregular in outline'.

Again this statement would not seem out of place in a modern textbook on modelling of zones of depletion around wells.

The report considers the increase in total yield that could be obtained by drilling additional wells relatively close to existing ones. Stephenson did a test on the sixteen boreholes at the Bootle works, which flowed into the base of the reservoir (Figure 6). The test involved temporarily capping all the boreholes. The first was unplugged, yielding 4.2 Ml/d. Then, in the form of a step test, the other boreholes were opened in turn, with the yield measured at each stage. Stephenson determined that the final yield, from all sixteen bores was 4.7 Ml/d, little more than 10 per cent greater than the yield from one well. He considers that, unless wells or bores are widely spaced, drilling of additional wells is unlikely to result in a dramatic increase in total yield, as the new wells will merely tap into the same network of fissures as the existing ones, and that their areas of influence will overlap and interfere. He than draws an interesting analogy:

> ‘This group of boreholes at Bootle present a complete epitome of what is actually going on upon a large scale throughout the town of Liverpool. The difference is only one of degree, consisting in the intervention of a large mass of rock between the wells, which offers more difficulty to the free passage of water from one to the other’.

Stephenson also arranged an extensive series of pumping tests on the existing wells, devoting much effort into obtaining accurate flow measurements by the timed volumetric method. He surmises that the yield of an individual source in the sandstone is unlikely to be greater than 4.5 to 5.4 Ml/d, and that wells should be located considerable distances apart to ensure such yields can be attained. These studies led Stephenson to recommend that the additional water needs of the town be met by ‘a system of independent wells, placed throughout the district, and lying generally to the east of Liverpool’, rather than by drilling additional wells beneath the town itself, an area already well populated with abstractions.

### *Saline intrusion*

The report also dealt with the question of brackish or salty water appearing in the wells of Liverpool. A review was made of the presence and concentration of chloride of sodium in the wells across the town to, according to Stephenson, determine ‘the disputed point regarding the existence and extent of the connection between the river and wells’. Stephenson concludes that the salinity of the wells is due to connection with the river, albeit with the process of saline intrusion being very gradual, and that the particularly high salinity of a group of wells was the result of them being in or near a buried river channel. Comparisons are made between data from 1846 and 1850 and Stephenson interprets that levels of salinity were rising, and attributed the deterioration of water quality to the continued and extensive pumping from beneath Liverpool. Stephenson recommended against deepening existing wells beneath the town, which will create greater drawdown and draw in saline water. His preferred option was to locate new wells to the east, away from the River Mersey.

## Conclusion

Robert Stephenson’s achievements as a civil and mechanical engineer are manifold. However, his more arcane work to control and exploit groundwater also reflects well upon him.

The works to complete the Kilsby Tunnel through the treacherous quicksands were an epic engineering task of its day. Stephenson was able to observe and interpret characteristics of groundwater flow, that allowed him to develop a groundwater lowering system, based on principles that are still valid today.

His later work on water supply for the cities of London and Liverpool showed his understanding of the concept of the ‘cone of influence’ around a well, and of the importance of the interference of drawdown between wells. He devised and carried out pumping tests and monitoring to assess the impacts of abstractions, using approaches that would be familiar to modern practitioners.

That his work was done before the publication of the work of Darcy and Dupuit is remarkable. The methods and conclusions of Stephenson may seem obvious today, but the objections he faced at the time remind us that Stephenson's rational approach was many years ahead of its time.

**Acknowledgment**

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Robt Stephenson

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Fig. 1. Robert Stephenson as a young man (from Jeaffreson 1864)

Fig. 2. Great ventilating shaft, Kilsby Tunnel (Bourne 1839: courtesy of the Institution of Civil Engineers Library)

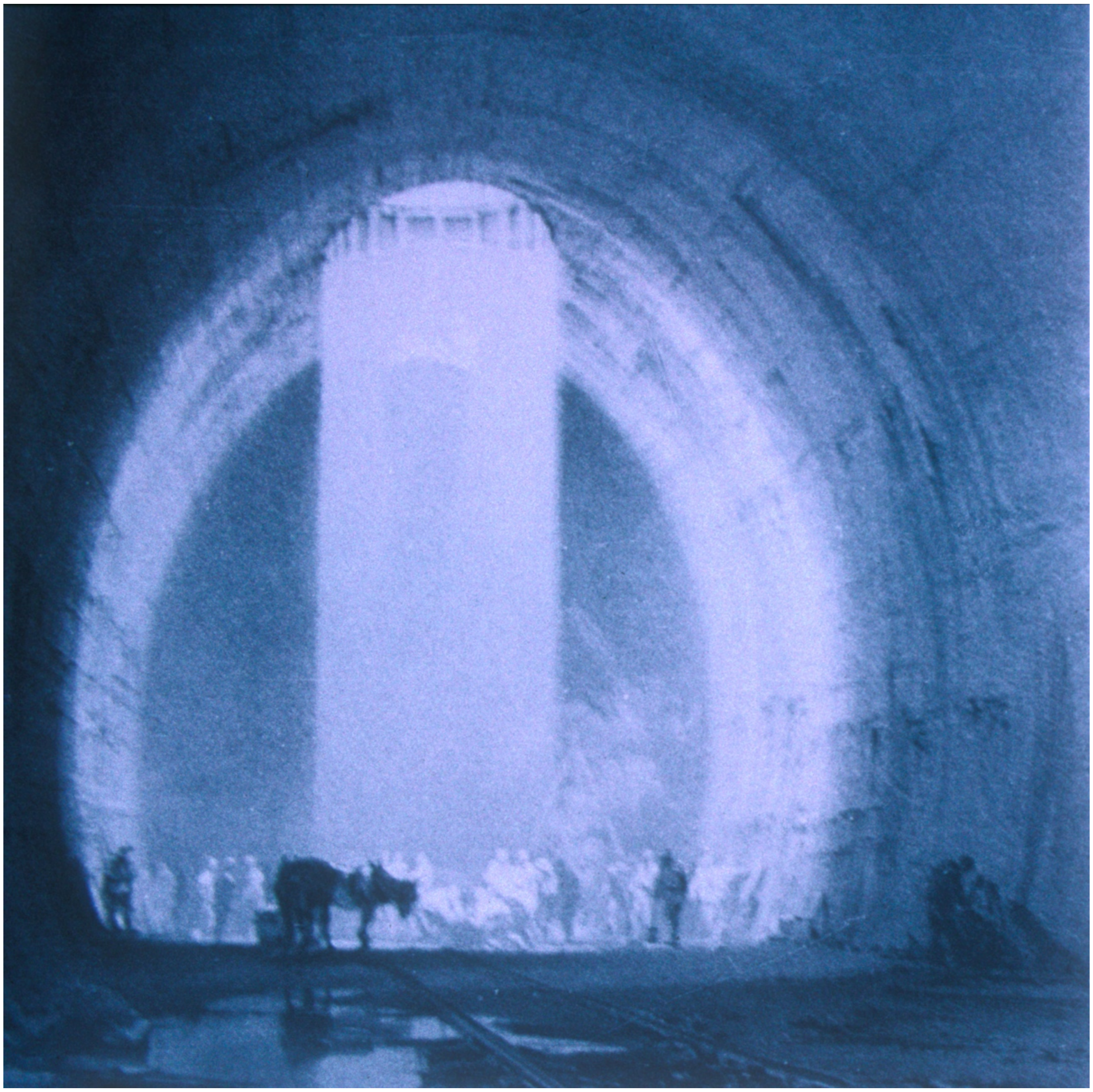

Fig. 3. Working shaft, Kilsby Tunnel (Bourne 1839: courtesy of the Institution of Civil Engineers Library)

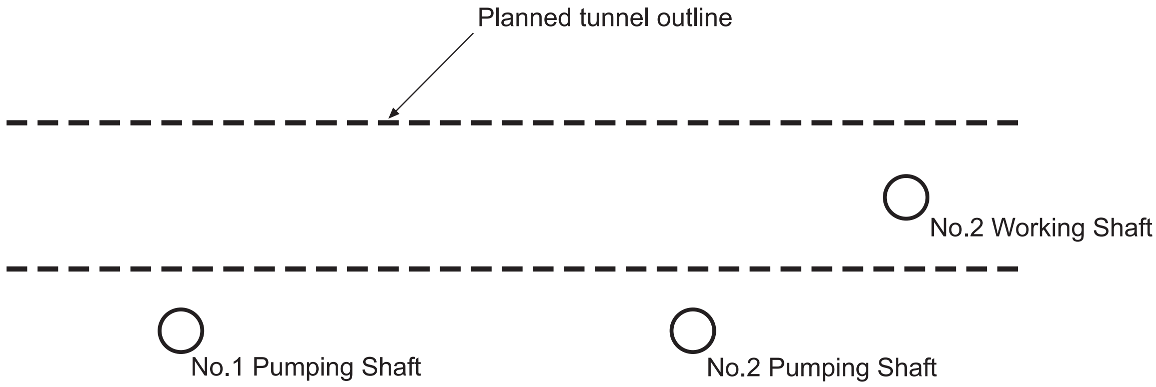

Fig. 4. Kilsby Tunnel, location of Working and Pumping Shafts

Fig. 5. Pumps for draining the Kilsby Tunnel (Bourne 1839: courtesy of the Institution of Civil Engineers Library)

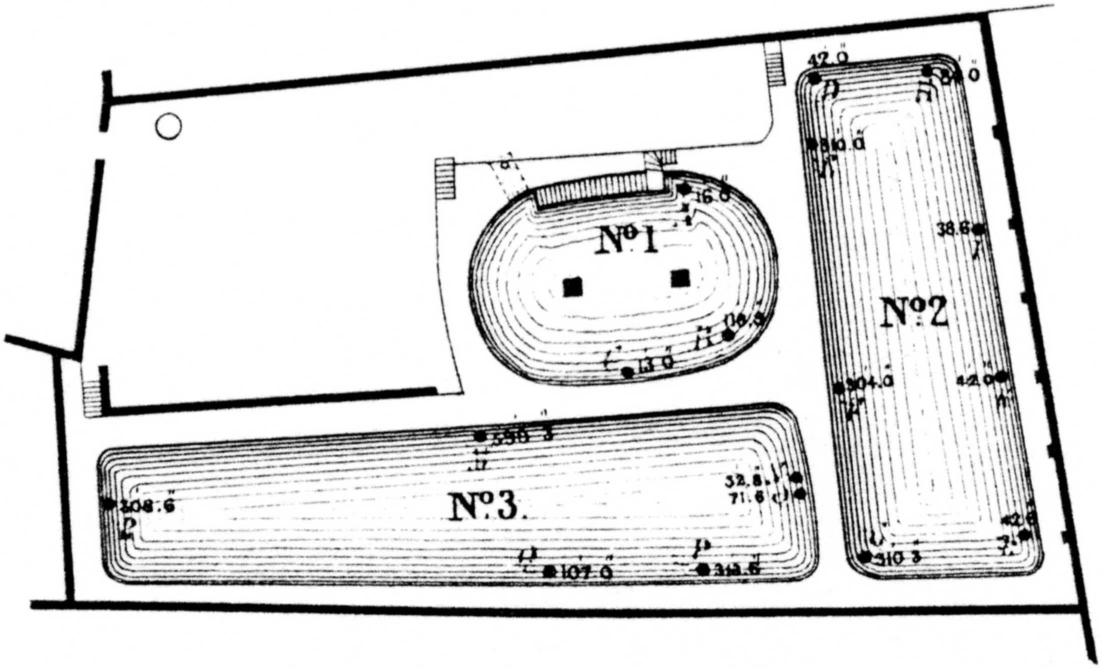

Fig. 6. Well group at Bootle, Liverpool (from Stephenson 1850: courtesy of the Institution of Civil Engineers Library)

Fig. 7. Robert Stephenson (from Jeaffreson 1864)