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The Abbey Mills pumping station renewal project

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ABSTRACT

This paper describes the project to provide a major new sewage pumping station in east London with a highly innovative design of utilising very large submersible pumps. It covers the historical background to the project and the extensive hydraulic modelling carried out to develop the concept. Details are given of the engineering and architectural elements of the project which have led to substantial cost reductions, while addressing the environmental and heritage aspects of the site.

Key words | cost reductions, hydraulic modelling, submersible pumps

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INTRODUCTION

The Abbey Mills site was first selected by Joseph Bazalgette as a key part of his great scheme for the main drainage of London in the 1860s. 'Abbey Mills Pumping Station' is in fact a complex of five pumping stations by the river Lee, near Stratford in east London. It forms the largest pumping facility on the sewerage system north of the Thames and is one of the largest sewage pumping installations in the UK.

The stations serve two main catchments (Figure 1), primarily the area of central London bordering the river as far west as Hammersmith and approximately south of a line drawn along Oxford Street, although this extends also north to Chigwell along the river Lee valley. The secondary catchment is the low lying areas of West Ham and the Isle of Dogs (IOD). The resident population is one million, and commuters add significantly to numbers during the day.

The stations lift the sewage from these catchments into the Northern Outfall Sewer (NOS) where it joins the gravity flows from the higher areas of north London to pass to Beckton Sewage Treatment Works. Storm flows discharge into the adjacent Abbey Creek, a tributary of the tidal River Lee.

At the outset, most of the plant was old and manually controlled. The main stations were becoming increasingly expensive to maintain and operate reliably. The Abbey Mills Pumping Station Renewal Project was conceived to replace most of this decrepit plant and provide reliable and economical service well into the 21st century.

HISTORICAL BACKGROUND

Bazalgette built the main facility now called station A in the 1860s. This lifted the flow from his new Low Level Sewer, now called Low Level Sewer No 1 (LL1), draining central London and the IOD up to the NOS and had no storm overflow arrangement. Consequently if the station failed or was overloaded flows simply backed up into London and would gravitate to the Thames from the old sewer outlets along the north side of the river. The lowest point of this large catchment was the IOD and sewage flooding occurred several times in the 1870s and 1880s.

This led in 1885 to the construction of a storm relief pumping station in the Island itself, and in 1894 to the construction of Station B at Abbey Mills which separated the IOD catchment from the central London area.

Throughout the period up to the 1920s London continued to develop and the impermeable area spread greatly, increasing the run-off during wet weather so that backing up and flooding continued to occur. In 1912 the storm outlet into Abbey Creek was provided and the storm Station C was built. This coincided with the construction

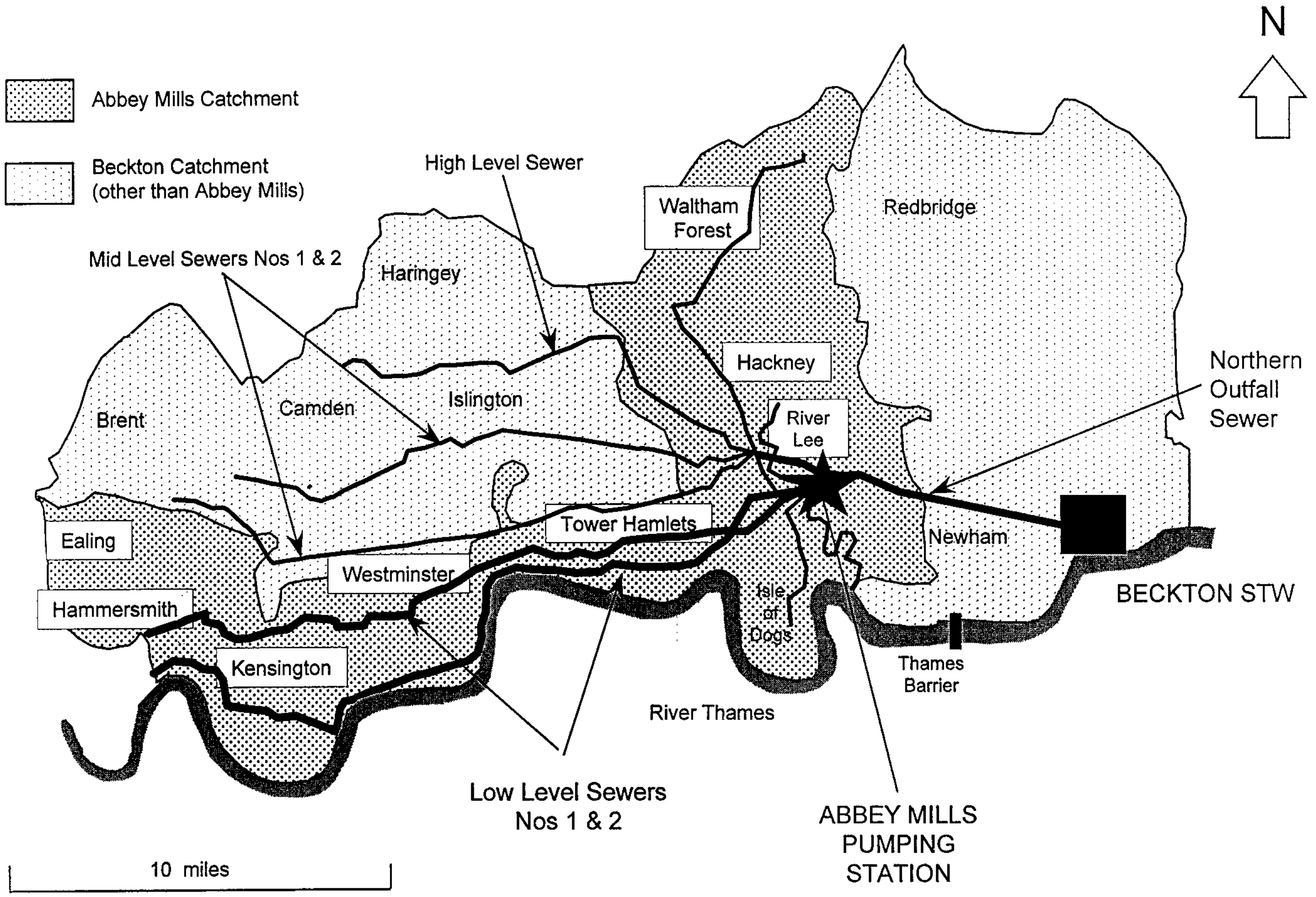

Figure 1 | The catchment area of Beckton STN and Abbey Mills Pumping Station.

of Low Level Sewer No 2 by the London County Council (Figure 2).

Station D was built in 1972 as a short-term storm relief measure when the WHDS (West Ham Diversion Sewer) was built, permitting the closure of the nearby West Ham Pumping Station. The new sewer was connected into Station B combining the West Ham and IOD catchments and was to have been the first phase of a comprehensive redevelopment of Abbey Mills but the rest of the scheme was abandoned due to capital spending restrictions, and Station D was still in service until 1997.

In the 1980s development in the Isle of Dogs area of London's Docklands was taking place. These works increased the strain on the already overloaded local sewerage. So the London Docklands Development Corporation and TWUL (Thames Water Utilities Ltd) jointly promoted a new deep tunnel sewer from the Isle of Dogs to a new pumping station E at Abbey Mills. Commissioned in 1994, Station E offered a novel compact design to fit within the tunnel's terminal shaft. The design of the new Station F developed from this concept.

During the 1930s electric and diesel pumps replaced the steam engines in Stations A and B. The pumps in Station C still dated from 1912 although diesel prime movers replaced the original gas engines in the 1970s. Station D had electric dry well pumps and E had electric submersibles.

The site has great heritage interest. Apart from Station D, now gone, the buildings are magnificent examples of the industrial architecture of their time. Stations A and B

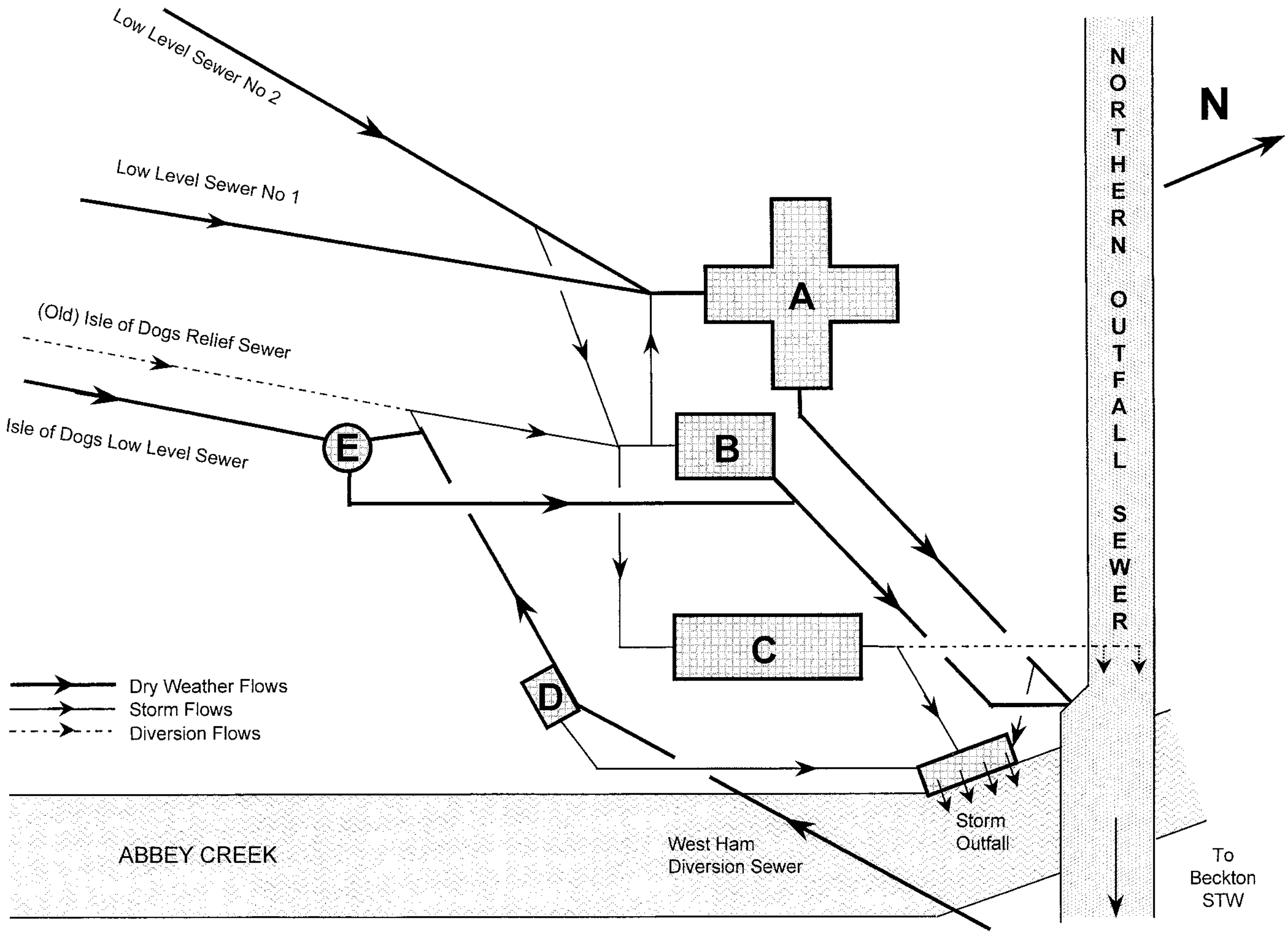

Figure 2 | Schematic layout at beginning of project.

are Grade 2 Listed. The whole operational site lies within the curtilage of the Listed Buildings and within a Conservation Area.

EXISTING SITE

The layout of the site before work on the project commenced is shown schematically in Figure 2.

Sewers

Five large sewers between 2.5 m and 3.5 m in diameter drain to the site. Low Level Sewers Nos 1 and 2 (LL1 and LL2) serve central London and enter the site from the south-west. To the south of these is the old Isle of Dogs Relief Sewer of 1894 (old IOD), now largely redundant since the construction of the adjacent Isle of Dogs Low Level Sewer (IODLLS) which terminates at Station E. The West Ham Diversion Sewer (WHDS) comes in from the north-east through Station D to join the old IOD near Station E.

The NOS runs along the north of the site in a raised embankment. Upstream of Abbey Mills it has four linked brick barrels. A fifth starts at Abbey Mills. They are horseshoe-shaped, roughly equivalent to 2.6 m diameter.

Pumping stations

LL1 and LL2 emptied via a coarse-screen chamber into Station A whose eight pumps draw straight from it with no sump. Dry weather flows passed directly through a 2.6 m rising main which becomes barrel 1 of the NOS. In times of storm a penstock is opened causing *all* flow to go to Abbey Creek.

The old IOD fed directly to Station B, which delivered only to the NOS and did not normally deliver to the Creek. The WHDS was later connected to station B via a large junction chamber to the old IOD just upstream of the screenhouse.

Station C's main duty was to pump storm flows to Abbey Creek although it could deliver to the NOS.

Station D only pumped storm flows direct to Abbey Creek from the WHDS when it surcharged.

Station E is connected to the above-mentioned junction chamber and was designed to pump the dry weather flows from the WHDS as well as the IODLLS to the NOS through either the Station B or Station C mains up to a maximum of about 2 m^3/s. Storm flows above this level surcharged overflowed to Station B via the chamber and ultimately could be pumped by D to the creek.

Pumping capacity before the start of the project

A curious feature of the Abbey Mills site and the arrangement of the sewers is that the dry weather flows are pumped to a higher level than the storm flows. Consequently the pumps in Station A and C delivered more to the Creek than to the NOS. The capacities were as shown in Table 1 (m^3/s).

Thus the theoretical total maximum pumping capacity of the whole site was 44 m^3/s.

THE RENEWAL PROJECT

The objective of the project was to replace all the defective plant and to increase the pumping capability to the level required for future duty as predicted into the 21st century.

Table 1 | Pumping station capacity (m^3/s)

Station	To NOS	To Creek
A	15	20
B	4	—
C	9	12
D	—	6
E	2	—
Total	30	38

Planning study

Between 1989 and 1992 a Planning Study was undertaken to establish flow parameters and examine options to provide reliable operation until 2010.

The catchment is so large and complex that contemporary modelling techniques could only give unreliable estimates of maximum storm flows. The Planning Study had to limit its flow estimates to the theoretical capacity of the incoming sewers. On this basis the maximum inflow lies between 50 or 60 m^3/s depending on the surcharge assumed. A large-scale catchment study of the Beckton and Crossness sewer networks is developing a mathematical model of the whole of the London sewerage system, which will eventually give a more accurate estimate of the flows.

The Planning Study found three viable overall solutions, each having two elements in common: a low level culvert to intercept the incoming sewers, and an open-channel delivery culvert to take the flow to the NOS.

Where the options differed was in the method of pumping.

Option 1 entailed refurbishment and uprating of Stations A, B and C, including new sumps in B and C.

Option 2 had a single new total duty station to replace all the stations except E.

Option 3 was a phased solution with a new station of about 30 m^3/s capacity to do all the dry weather and most of the storm pumping. In the interim, Station A would be retained to assist with maximum storm flows. This would

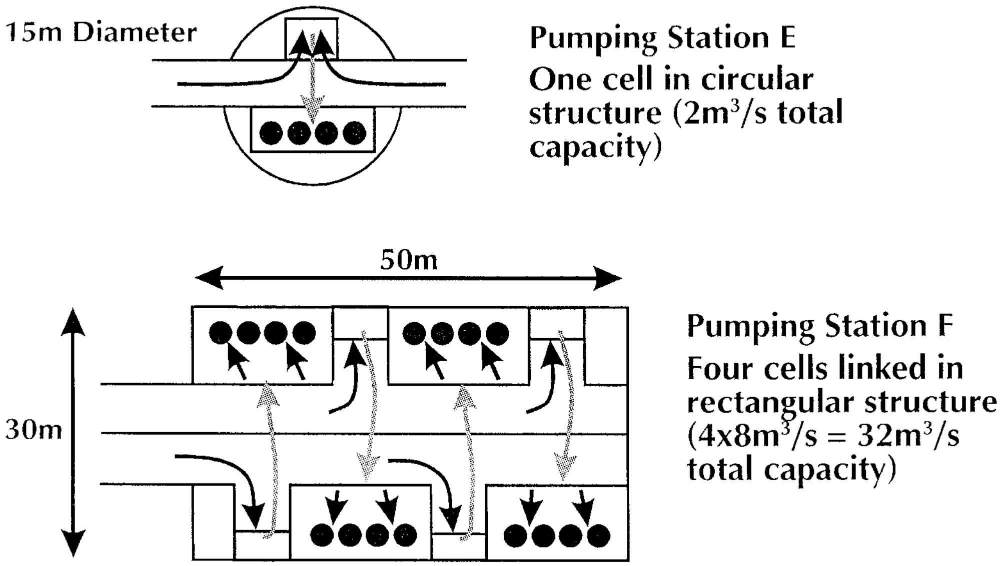

Figure 3 | Stations E and F sumps compared.

provide sufficient reliable capacity for the short to medium term. Stations B, C and D would be abandoned. Depending on the outcome of the Beckton/Crossness Catchment Study, in the second phase either Station A would be refurbished and uprated, or a further station built to give the full capacity. The decision as to which was the more economical would be taken at the appropriate time in the future.

Compared on Net Present Value the options all worked out to roughly the same overall cost. However, Option 1 had more risk during construction during reduced pumping capacity.

With the doubt as to the precise capacity required, Option 2 would have been impossible to size accurately.

Option 3 quickly tackled the reducing reliability of the existing plant and allowed a later, more accurate, assessment of the long-term flows. It also had a lower initial capital cost.

In late 1991 TWUL's Capital Expenditure Committee decided that Option 3 should be developed into a firm proposal. The estimated cost at the time was £45m.

Implementation

In May 1992 the project was passed to TWUL's Engineering Division for implementation. A Project Proposal was prepared, which re-examined the Planning Study Options with a more rigorous consideration of the preferred phased option, in particular the types of pump to be used.

The main feature of the proposal was the new large pumping Station 'F'. Operations staff at Abbey Mills had experience with large submersible pumping stations in Docklands and were enthusiastic that such pumps were included in this evaluation. The trend in operations practice was away from heavily manned sites with much on-site intervention and maintenance of *in situ*, usually dry-well mounted plant. Modern thinking preferred a modular approach with many similar pumps, which could be swapped over and with spare units quickly slotted in by itinerant maintenance gangs so that defects or maintenance could be by in-house or contract personnel in remote large-scale centralised workshops.

Station E uses four submersible units in this manner and has a novel 'folded over' design which evolved so it could fit into the smallest possible terminal shaft of the IODLLS sewer. This idea was adapted for Station F. Using our Station E shaped sumps intertwined, a very compact layout was possible for the new station (Figure 3).

It would have been possible to achieve the modular approach with dry-well pumps which were available but 16 equal-sized (2 m^3/s) submersibles gave a smaller footprint. As the largest element of cost was the civil

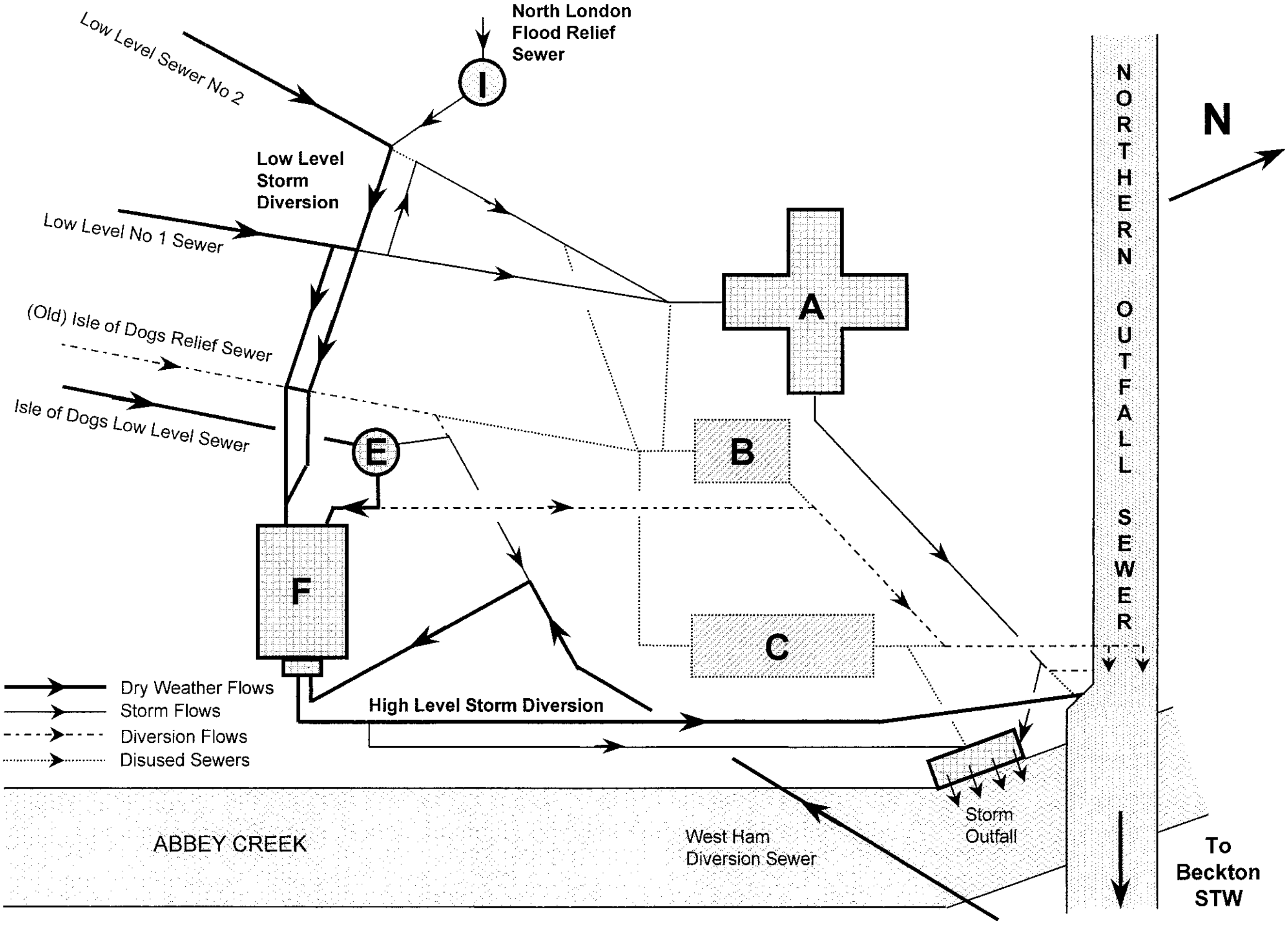

Figure 4 | Schematic layout proposed (and on completion).

engineering which is proportional to plan area, the lowest cost was clearly with submersible pumps. The final site layout is shown in Figure 4.

GENERAL DESIGN ISSUES

Pumping energy considerations

The primary function is to raise up to 32 m^3/s of sewage through a fairly modest head of 12–15 m. This requires large quantities of energy, and any superfluous head loss is expensive both in energy and capital terms. With fixed levels for the incoming sewers and the discharge, the only way to provide for system head losses is to deepen the station with consequent increase in the cost of civil works. It was calculated that the marginal capital cost of each 100 mm of pumping head was about £50k and the capitalised energy cost added a further £30k. This statistic was used to evaluate the effectiveness of eliminating head losses: if it cost less than £80k to remove 100 mm of head loss it was cost effective!

Separation of main and small catchments

At first the new station design envisaged four sumps from a single inlet channel. However, it was soon realised that this would recreate the original problem of linking the London and IOD catchments together again. A described above, it would then be possible to flood the Isle of Dogs, and now also West Ham, with sewage from the main catchment! Station B and the old IOD Sewer were constructed to avoid this.

To overcome this the Station F inlet channel was divided into two halves. Two pump wells on one side of the station serve the main catchment. These operate at a high control level to minimise pumping costs. This is now called the 'hot' side. The two pumps wells on the other 'cool' side serve the smaller catchments. They have a control level low enough to allow Station E to overflow without flooding the Island.

However, this caused a secondary problem. Although the pumps were divided in two equal halves the flows were much heavier on the London side in approximtely a ratio of 3:1, wet or dry. So that the hot side would not be denied the excess capacity of the cool side, a weir in the dividing wall allows storm water from the main catchment to overflow and be pumped by the cool side. Although this reconnects the catchments it should only occur in extreme storm conditions and any flooding risk would only re-appear once the entire enlarged capacity of the whole site was called upon.

Low level storm diversion

If during a storm all the Station F pumps are running and the levels continue to rise, Station A is brought into service. The layout in Figure 4 shows the storm overflow chamber at the west end of the new inlet culvert. It is fed through the lengths of LL1 and LL2 downstream of their intersection with the new culverts. Penstocks and cloughs allow operational control and flow diversions for access and maintenance.

Future provisions: Station G, screening and storm tanks

The second phase of the renewal of Abbey Mills will depend on future experience of operation. It may be accomplished by re-equipping Station A. Alternatively a Station G may be required. The minimum of provision for this has been made in the first phase without increasing construction problems for the second.

Allowance was also made for the future installation of both storm tanks and fine screening of storm discharges. Storm storage is still an unknown quantity but it is now likey that fine screening of discharges to Abbey Creek will be required within the next five year period. These will have to be located on Mill Meads, an area of TWUL owned land to the south of Station F. These requirements influenced the design of the High Level Storm Diversion.

High-level storm diversion

Station F has to be able to pass storm flow to Abbey Creek. To allow for screening and storm tanks, the High Level Storm Diversion is sited immediately outside Station F. This means a long storm culvert was required to connect to the existing storm outfall structure. This was simply achieved by stacking the high level channel on top of the storm culvert in a double deck arrangement with storm flows to the Creek underneath and normal flow to the NOS on top.

Stations A and C used to discharge their flows either all to the NOS or all to the Creek. Better control has been provided so that discharge to the Creek occurs only when the NOS is full or Beckton STW is at capacity. Flow to the NOS is measured and controlled by modulating penstocks with flow to the Creek passing over fixed weirs.

MODEL TESTING

Physical hydraulic modelling of pump wells of this size is essential, particularly with the innovative ideas for Station F. With the complex hydraulic layout of the inlet culverts and delivery channels and the importance of minimising head losses, there were good reasons to model the whole system.

In association with Sir William Halcrow and Partners, Hydraulic Models Ltd (HML) were engaged to develop

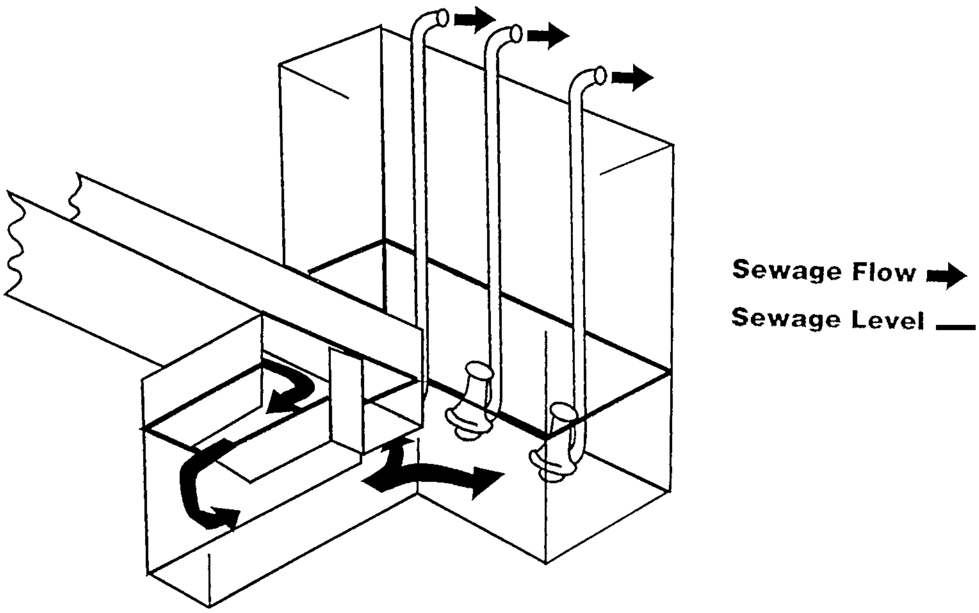

Figure 5 | The folded-over Sump Wells of Stations E and F.

the hydraulic design. Three separate models were constructed by HML in Leeds: the inlet and outlet systems at 1/20 scale and a 1/10 model of a one pump well designed so that it could represent any of the four wells.

The inlet and outlet models verified that the layout was sound and that grit deposition would give no problems at any point within the range of flows.

Pump well design

The pump well design developed significantly during the modelling to produce the final highly compact but remarkably efficient layout.

Figure 5 shows the principles behind the pump wells for Stations E and F (although neither station looks exactly like this).

In both Stations E and F the flow to the pump well is turned through a right angle from the culvert to pass through an isolating penstock and Rotating Bar Interceptor (RBI) Screen. The flow is then turned through 180° in the vertical plane passing below the incoming sewer and into the pump well.

In Station E the pumps are sited on the far wall. However, in Station F the high-level delivery channels are sited centrally within the station, and so therefore, are the rising mains. To avoid a clash between these and the overhead cranes, it was necessary to turn the pumps the 'wrong way round' as presented to the flow.

Station E has a sump tapered in plan, but the modelling showed that in Station F the tampered sump would have problems with horizontal swirl together with grit deposition at low flow. The latter was overcome by amending the sump to '***T***' shape in plan but at the expense of an obvious increase in horizontal mass rotation.

To overcome this, a vertical ***T***-shaped baffle was introduced. This diverts some of the flow through the ports in the baffle but most of the flow is directed up and over the top. The mass rotation is thus changed into a vertical sense and the flow hits the outer wall before returning to the pumps in an ideal presentation. Velocities through the channels are quite high with no significant deposition, as attested by recent inspection of the wet areas. There is significant surface disturbance, which should minimise the build-up of floating debris and scum.

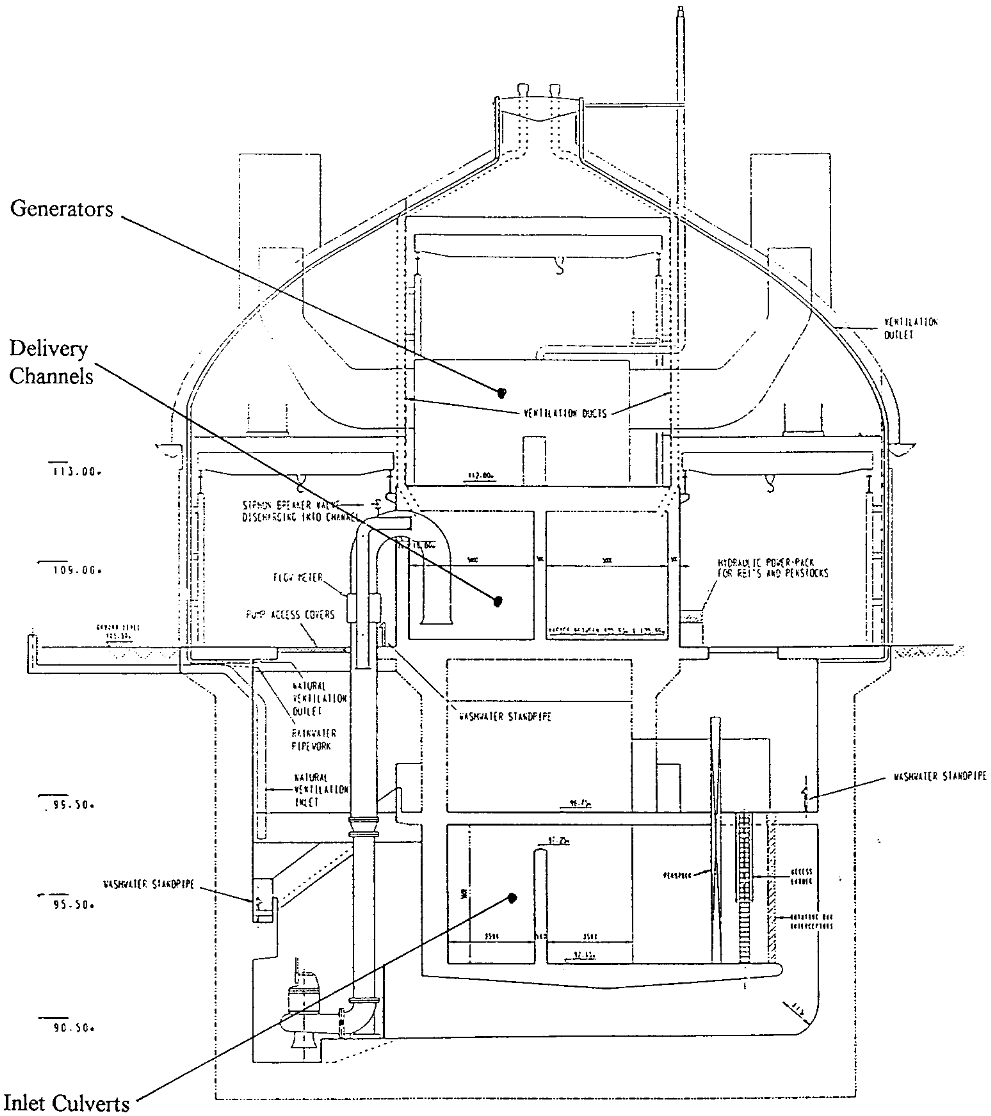

Figure 6 | Section through Station F.

Hydraulic dynamics

The steady-state hydraulics can be covered by calculation and physical modelling. However, there are very significant dynamic hydraulic effects. It was reported that during severe summer thunderstorms the existing stations had gone from a single pump running to every one running in 15 minutes! These effects cannot be modelled or calculated but must be accommodated! Plant and control systems had to be capable of rapid response to these conditions.

STATION F: ENGINEERING

Figure 6 shows a cross-sectional view of Station F, illustrating its important component parts.

Civil engineering

The civil engineering is the most expensive element of the station, but is actually only there for two reasons:

- to contain the sewage on its way in and out (hydraulics). This was covered by the hydraulic modelling;
- to support the other engineering and architectural elements (structural).

The nature of the site and the basic project objective meant that extensive deep excavation was the main constructional problem. A comprehensive geotechnical investigation confirmed the expected ground conditions and indicated several possible structural solutions including:

- diaphragm walling;
- contiguous or secant piling caisson;
- conventional construction within temporary supports (e.g. sheet piling).

The contract strategy was determined as a single design and build contract using the IChemE Green Book to allow individual tenderers to propose their own preferred method. Detailed structural design was therefore not required before issue of tenders. However, a preliminary design was needed for costing and to validate the design. A simple approach was adequate became substantial member thickness is required in any event to provide the mass to resist flotation.

Another problem depending for a solution on the contractor's expertise was the connection to the existing sewers. In the catchment upstream of Abbey Mills, diversion of dry weather flows was possible. The residual flow at site could then be dealt with by on or off-line diversion or by over-pumping. Storm flows, however, can be so great that they might have to use all the available sewer capacity. The design and construction of the sewer connections temporary works had therefore to be planned to allow storm flow to pass through the works when necessary, but with minimum setback to the construction.

Penstocks and rotating bar interceptors

Each of the pump wells has twin inlet channels isolated by penstocks. These must open very quickly to react to the dynamic hydraulic effects and are therefore fabricated in stainless steel. Because the actuators will be in a Zone 1 Hazardous Area, they will have hydraulic actuators.

Downstream of each penstock is a Rotating Bar Interceptor (RBI) to protect the pumps from large objects either floating or carried on the invert. The bars have a 125 mm clear opening.

The space between the penstocks and the RBIs holds any trapped large material for removal by a grab from the overhead crane.

Pumping system

At the heart of the station are the pumps, which are the largest submersible sewage pumps available. The Flygt type 3800 have fixed speed 350 kW motors, operating at 660 V and weighing 8.5 tonnes. They have a capacity of about 2 m^3/s each, although this varies as the pumping head varies with the flow conditions. They are able to pass a solid sphere of 140 mm diameter. In all 17 pumps were procured: 16 for duty and 1 non-installed standby.

Each pump has a separate rising main without isolating or non-return valves. The mains are inverted ***U***-tubes dipping into the flow in the delivery channel to give a siphonic discharge minimising the head loss. Back-siphoning is prevented by siphon break valves at the crown of the inverted ***U***.

The success of a big submersible pumping station depends largely on the ability to remove and replace the pumps efficiently. Overhead travelling cranes are provided on each side of the station. Handling the trailing cables in the pump well when pumps are removed can also be a problem. In Station F, after a pump has been raised to ground level, the cables are disconnected at the pump, and left, suitably protected, in the well. Final details of the handling system were developed in conjunction with the contractor. A cradle is provided to hold the pump when it is removed from the well for transport off site for maintenance. The spare pump is stored within Station F.

Each pump well has a drainage pump to empty it when not in use. These have to pass all the solids that settle out after the main pumps have stopped and if they block the pump well cannot be emptied. Accordingly they were required to pass a solid sphere of 180 mm diameter. The principle is that the main pumps can pass solids larger than the bar spacing of the RBIs and the drainage pumps can handle larger solids still. This does have a disadvantage, however, because such pumps are large in their own right, with a delivery of 250 l/s.

Ventilation

The open sides of the station give good natural ventilation at ground level and a forced ventilation system ensures a safe atmosphere below ground for personnel access. It gives six air changes per hour but only operates when access is required.

A low rate of air change is provided by a simple natural ventilation system to prevent any build up of hazardous gasses in the wells.

Power supply and generation

The former installation at Abbey Mills had a mixture of electric and diesel pump drives, but no standby either in pumping capacity or electrical generation. Security came from the diversity of the drives.

These principles continue although now all the drives are electric. The total pumping capacity is only needed infrequently and to supply this entirely from the grid would have led to very high reserve capacity charges. It is more economic to provide some of this capacity by generation on site. Similarly, because of the infrequency of maximum pumping, standby electrical capacity (i.e. more total power availability than pumping capacity) cannot be justified. At any flow below the maximum, standby exists: the lower the flow, the greater the standby power capacity.

The balance between imported and site generated power was studied in detail. The most economical solution was shown to be provision of as much site generation as possible provided it did not require extra civil or building costs. This occurs when roughly half the total power is from the Grid and half from four 1.25 MVA diesel generators. Having provided the generators for these reasons, they can be used to minimise the tariff charges by peak lopping in winter and to avoid Triad charges.

The generators are sited on top of the delivery channels which provide a solid foundation at little extra expense. Demountable acoustic enclosures keep external noise to acceptable levels. Large volumes of cooling and aspirant air are required. Radiator fans are used to draw this air through sizeable ductwork from and back to the outside. The exhausts go through chimneys extending above roof level. A crane is provided over the generators to service them.

Switchgear

There are two switchgear rooms above the east end of the channels. HV switchgear and transformers are in the lower room with the LV gear in the upper one.

Control and instrumentation

Station F is unmanned and fully automatic under the control of the SCADA system. A small control room is provided but control is normally monitored from a centralised pumping station control centre at Beckton STW some four miles distant.

In normal operation the incoming sewers are used as extensions of the pump wells with the pumps controlled to maintain a constant level. As the level rises, more pumps are started until all the running.

The SCADA has to be capable of reacting to the dynamic hydraulic effects particularly during peak storm intensity. During such events the electrical demand requires the generators to be used, providing a further twist to the complexity.

The SCADA also controls the electrical tariff management system and brings the generators into play at appropriate times. This part of the system has been made capable of easy reconfiguration when electrical tariff structures change.

Location identification

The below-ground elements of each pump well's layout is similar. It has been observed in other stations that this can lead to disorientation for personnel. The pump wells have therefore been colour coded: red and yellow serve the large catchment, and blue and green the small. This is in keeping with the 'hot' and 'cool' sides philosophy mentioned above. Marking all the elements of each well with its colour avoids disorientation. So the rising mains, RBIs, their power packs, and the penstocks are all coloured.

STATION F: ARCHITECTURE

Why a building?

In modern pumping station practice with submersible pumps it is possible to have a completely underground station with no building. However, switchgear and generators need housing. More significantly, however, craneage is fundamental to handling and maintaining large submersible pumps. There is little extra cost providing a roof over the cranes compared with making them fully weatherproof and covering them was more acceptable to the Planning Authority.

Planning issues

The site lies within a Conservation Area and next to the Listed Stations A and B. So both the Planning Authority, London Borough of Newham (LBN), and English Heritage were very interested in the proposals and both were consulted frequently throughout the design phase. It was expected that they would have preferred the building in sympathy with the style of the originals. Surprisingly it became clear that they would prefer a good modern building and LBN were very keen that an Architectural Competition be held. It was a basic premise of the design that operational function should come before appearance, so the functional requirements were defined before the competition entries were invited.

Location of switchgear and generators

The switchgear must be close to the pumps and by continuing the crane roof over the top of the raised outlet channels suitable housing could be provided.

Station B and C were considered as locations for the generators. However, neither was really suitable and they were rejected in favour of Station F itself, where the concrete substructure provided a solid base. To provide cover the walls are somewhat higher but with no increase in roof area.

Vehicle access

At the western end of the station is a loading dock to allow road vehicle access to remove or return the pumps or other plant. The building is longer in consequence but no higher because the dock is recessed.

Ventilation considerations

The sides of the building are essentially open for ventilation, but require a security grille. Louvres are provided in front of this to improve the appearance.

The forced ventilation plant is sited above the side cranes. The louvred walls allow ample air intake but the exhausts are at roof level to promote good dispersion. A major influence on the external appearance is the ventilation requirements of the generators.

Architectural competition

Six practices were invited to enter the competition which was in two phases.

The entrants were given three weeks to complete and submit initial ideas. They were then interviewed and given comments on the technical suitability of their entry. One competitor chose to withdraw at this stage. The rest submitted their final entries, including a cost estimate, after three more weeks.

The design team judged them for technical suitability. After this a panel, including LBN's Head of Planning, selected a shortlist of three. The final choice was made by TWUL's Engineering Director. The winning entry came from Allies and Morrison, who received the commission to design the building.

The two-stage process helped to ensure that the successful architect was a team player able to contribute to the design development without dictating the form at the expense of operability. The value of this was clearly demonstrated, with a steady development of and improvement to the design without any loss of the original aesthetic idea.

Building description

The external appearance is metallic. The walls are mainly aluminium-finish louvres with some solid aluminium coloured panels. The roofs are zinc coated standing seam aluminium, relieved by the large circular terminals for the generator ventilation. There are four chimneys for the generator exhausts and, at the apex of the roof, a raised section with louvres for internal ventilation.

Internally, the whole station is one large open expanse. All the plant and pipework is visible and the structural steelwork prominent. During the detail design work, a catwalk system evolved which gives ready access around the elevated areas. High- and low-voltage switchgear are housed in separate rooms and there is a small suspended and glazed control room.

ENVIRONMENTAL ISSUES

The heritage and listed building issues arising from the Victorian origins of the site have been covered above.

The existing operational site is characterised by extensive mature trees. Great care has been taken in the alignment of the new works, particularly the delivery channels, to avoid these. It was hoped that only two mature trees would have to be felled; in the event four had to be sacrificed!

Among other environmental considerations was Mill Meads, the area of TWUL-owned land to the south of the existing operational site. This open scrub land has never been developed. Although ecological surveys showed that there is little of rarity value in its flora and fauna, it is a substantial green site in a run-down inner city area. Construction of the IODLLS and Station E immediately preceded the renewal project and cleared a great deal of the same area, which had to be used for the Station F construction site. Therefore, great care was taken to ensure that the works did not encroach further into the undisturbed area to allow recolonisation by native species on completion of the works.

The new delivery channels are reinforced-concrete closed culverts. They could function perfectly without covering, but at 5 m above the existing ground this was not thought to be an aesthetically acceptable solution. The channels are therefore covered by an embankment just like the NOS using material excavated from the rest of the site. Where possible flat slopes minimise the visual impact and used up surplus excavated material.

An existing permitted footpath, the ‘Longwall Path’, runs along the side of Abbey Creek, connecting with the ‘Greenway’ on the top of the NOS. The opportunity was taken to realign the Longwall Path along the top of new delivery channels. This provides easier access to the path for wheel and pushchairs, and gives more extensive views both over the Creek and into the Pumping Station site.

Both the embankment and the site within the new boundary fence have been planted with trees and shrubs. The area outside the fence has been left for the existing flora to re-establish itself.

COSTS

Surprisingly the estimated cost of the project has reduced at each stage of the design!

The Planning Study costed the first phase of the Phased Option at £47 million (asset plus resource). This costing was done in the early 1990s and was thus based on late 1980s prices. Construction costs fell significantly during the early 1990s. However, this only accounts for a small part of the dramatic difference in the estimate produced at Project Proposal stage. The use of large submersible pumps and the extremely compact layout were the main reason that at this stage the estimate had dropped to £33 million (asset plus resource).

From this stage on it is usual, as definition of the scope gets more precise, for the estimated cost to rise and the contingency level to fall. The overall effect is for the estimate to rise. When the Abbey Mills Project reached the Definitive Design Report stage, the cost had fallen to £30 million! A major reduction in the electrical elements contributed significantly to this.

As the final design and contract preparation was done other savings were incorporated, particularly in the High Level Storm Diversion.

The lowest tender price (tendered target cost) was £22 million, which when added to other costs, gives the current Project Cost of £26.1 million (asset plus resource).

CONSTRUCTION

Preliminaries

The hydraulic and functional design of the station and the associated culverts was done in house by Thames Water's Engineering Division, and the building design by Allies and Morrison. On completion of the design in November 1994 tenders were invited from six contractors under the IChemE 'Green Book' conditions, with a tendered target cost. The successful tenderer was Trafalgar House who were acquired during the implementation period by Kværner.

The detailed design work was now continued by Kværner subsidiaries Kværner Technology (Civil) and Kværner Water (M, E C&I), Allies and Morrison continuing as architects, with Ove Arup as their structural engineers. All of these plus several of the chosen sub-contractors worked with TWUL personnel, both Engineering and Operations, in a highly motivated atmosphere of teamwork and co-operation. It is true that the construction phase went well and encountered no major obstacles, but the work was not completely free of difficulties, and the completion of most of the work to allow commissioning two months early in August 1997 was due mainly to the team approach. The site was occupied in May 1995 with a projected delivery programme of $2\frac{1}{2}$ years.

Substructure

After site clearance the main excavation proceeded over the whole area of the pumping station substructure and the inlet culvert to an ultimate depth of about 20 m. Four closed sheet pile cofferdams were sunk using the Giken silent vibration piling system to excavate respectively the pumping station sub-structure, the inlet culvert and junctions to LL1, and to LL2 and around the storm outlet main from Station C. These were sunk into the London clay through an upper layer of alluvial gravels level with adjacent river Lee channels. Piles were carefully driven tight around the two large 2.5 m diameter intercepting sewers LL1 and LL2 at the western end of the inlet culvert. The excavations reached bottom still within the clay but with only a thin layer remaining above the Woolwich and Reading beds. A ring of de-watering well points around the cofferdams prevented the water pressure below causing the formation to heave. Conventional welded structural steel walings were supported with 1 m diameter tubular steel struts.

Sewer diversions

By the summer of 1995 the massive concrete substructure works were underway with several pours of up to 700 m^3 stretching often into the night. During this phase it became necessary to break out large sections of the existing intercepting sewers whose flow had to be carried through the works. The top arches of the sewers could be removed in normal flow situations which meant that until the 'jumbos' could be installed the site was at risk of storm flows flooding the works. By diverting most of the flows from LL1 to LL2 and vice versa it was possible to gain short periods when the residual flows could be reduced almost to nothing. Temporary dams were fixed in the sewers by operations personnel to hold back the last residue of flow so that overpumping was avoided altogether. In the short dry periods 50 m long steel tubes 1.5 m in diameter were sealed into each end of the sewers so that flow could be released and carried through the works for over a year until the inlet culvert was completed. All flow was suspended in the old IOD so no flow control within the works was required.

In the storm outlet from Station C a fabricated steel gate was fitted to the outfall in Abbey Creek. This enabled the works to the new storm overflow from the high level delivery culvert to be connected and later for the abandonment of the station C storm delivery. While these works were in hand it was not possible to isolate the works from the need to discharge storm flows to the creek from Stations A and C. In the event of heavy rain the gate was to be opened to allow flow to reach the creek through the works which would consequently be inundated. Fortunately this happened only once during construction of the sub-structure.

The WHDS was the one sewer whose flow could not be controlled and complete over-pumping of the $1\frac{1}{2}$ m^3/s dry weather flow was necessary while the new connection into F station was formed and Station D was abandoned.

Connection to the Northern Outfall Sewer

The connection to the NOS of the high level culvert presented one of the more challenging aspects of the construction phase. There was no room in barrel No 1 for the junction and so the Station B rising mains were diverted into the junction of the C mains to provide space for the new connection. This had to be carefully arranged to avoid interfering with the start of the Abbey Creek sewer bridge. This is an iron structure which conveys the five barrels of the NOS across Abbey Creek immediately downstream of the site and with which any interference from the new work was strictly to be avoided. The 2.2 m × 2.2 m horseshoe-shaped brick barrel No 1 of the NOS had lain untouched for nearly 130 years and had at the point of the junction a double vaulted roof arch where Bazalgette had provided a cross connection to allow distribution of the pumped flow evenly across the other barrels. There was great concern about removing the entire southerly half of the structure to make the junction with the new high level culvert. The complex shape defeated all thoughts of providing adequate formwork and the men would be working with a full head of sewage in the adjacent barrel No 2 next to the weakened structure of No 1.

The site team are to be congratulated with a simple and elegant solution to this problem which they conceived. By filling the section of the brick barrel with foamed concrete, continuous support to the barrel was maintained and security from the collapse of barrel 2 and from backing up of sewage from the NOS downstream were all achieved in one operation. The foamed concrete formed a perfectly shaped shutter to marry up the new work with the old, and proved easy to then remove after the junction had been formed. A short section of the barrel remains filled in this way up to the present day separating the Station A rising main from its original pumping route.

Mechanical and electrical work

M&E installation began early in 1996 and was achieved smoothly and effectively by the team of sub-contractors assembled and managed by Kværner. The contributions by Simon Hartley, Pipeline Personnel Services, Broadcrown and Aston Dane, the main electrical sub-contractor were notable. Flygt were only contracted to supply the pumps but they were very helpful with the commissioning and with many of the inevitable niggling problems which arose including the provision of a neat parking arrangement for the power cable when a pump is lifted and the celebrated 'Doklok' remote crane hook attachment device which worked well both during the project and in subsequent operation of the station.

Superstructure

The superstructure of the building was based on a conventional structural steel frame designed by Ove Arup and erected by steel erectors Rowen. The aluminium cladding and louvred panels were designed by Allies & Morrison to be in sympathy with the appearance of the mansard roof which was the dominant feature of the external structure. Operations managers had much painful experience elsewhere of roof structures which were constantly leaking or subject to condensation and required continual expensive maintenance. Specialist Dutch contractor Hoogvens were selected to supply their 'Calzip' system which was also used on one of the Docklands pumping stations. The cladding and the roof system were installed by Entec Ltd.

Commissioning

In the late spring of 1997 the construction work entered the extensive and complicated commissioning phase which would take several months for the large array of different pumping combinations and to confirm the satisfactory performance of the different mechanical equipment, including 20 large penstocks and a similar number of cloughs; 8 RBIs, cranes, diesel generator sets, ventilation motors and fans, to say nothing of the 16 pumps themselves. It was inevitably impossible to do a real test of the whole plant running at full stretch in a storm since the weather cannot be commanded and the volumes of water involved were huge. The dry weather flow was used to commission the four sumps one at a time and this staged commissioning indicated that every separate element was working. There was considerable interest by all the contractors to watch for a significant rainfall event during the maintenance period.

A similar challenge was provided by the control and telemetry testing. The MCC had to operate the plant in a range of different automatic and semi-manual modes, and the SCADA system had to monitor this and allow remote intervention from the plant controllers who were located in the control room which remained in Station A. This was achieved with complete success and enabled the smooth translation of the site to be de-manned which occurred some months after commissioning.

CONCLUSIONS

The design and construction was a team effort with each discipline taking an interest in all the others. Operations have been consulted regularly and the design uses many of their ideas. Although formal 'Value Engineering' was not done, the design was continually questioned to seek better solutions which were often found.

By this means a very creative culture evolved within the team leading to the remarkable cost savings which have been achieved without any reduction in scope.

This process continued during the contract design phase, with care being taken to ensure that improvements are identified early enough to avoid disruption to the construction programme.

Above all, working within this innovative culture, in which the whole is better than the sum of the individual contributions, has been great fun which, in our opinion, is how engineering should be.