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National Rivers Authority

RIVER DARENT
LOW FLOW ALLEVIATION

ANNEX I

Darent Catchment Investigation
(GDC, November 1991)

National Rivers Authority
Southern Region

July 1994

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Darent Catchment Investigation
CWP/8709

Pre-Feasibility Report
November 1991

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RIVER DARENT INVESTIGATION

PRE-FEASIBILITY REPORT

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SUMMARY

Background and Objectives

The River Darent has been identified by the National Rivers Authority as one of 40 over-abstracted catchments in England and Wales. The Darent catchment, located in north Kent, is regarded as being of particular importance, owing to the severity of river flow depletion.

The river is fed by springs from the Lower Greensand aquifer lying along the northern rim of the Weald of Kent, and also from the Chalk aquifer of the North Downs. Both aquifers are sources of major groundwater abstraction for public water supply. In recent periods of low rainfall, particularly the early to mid 1970s and from 1989 to the present, the river has dried up completely in certain sections for durations of several months. The reach from Lullingstone to Hawley has been particularly severely affected in these periods.

Groundwater Development Consultants (GDC) was appointed by the National Rivers Authority (Southern Region) in February 1991 to undertake an investigation of the River Darent catchment. The main objective of the investigation is to identify the most appropriate measures from a large number of engineering options to alleviate low flow conditions in the river. This objective is to be achieved by:

- an initial water infrastructure and water balance study to assess the feasibility of various potential engineering options to alleviate low flow conditions;
- a broad costing of options;
- computer-based, integrated catchment modelling with simulation of the interrelationship between the aquifers and the river, allowing detailed assessment of the effects of engineering options;
- recommendations based on benefits to the river, technical feasibility and comparison of costs.

This report describes the first two activities listed above. A review of previous reports concerning the problem of low flows in the River Darent is also presented and an assessment made of available hydrogeological data. The integrated catchment model is discussed together with additional data requirements for modelling. The report has been produced at the end of Part 1 of the investigation.

Many of the engineering options have been described in earlier reports. Detailed modelling of the catchment has not been carried out previously, however. The present investigation therefore provides the first opportunity to assess in detail the effects of options on river flow and aquifer conditions. Environmentally acceptable flow objectives for the Darent have been the subject of a separate study for the NRA (Southern Region) by WS Atkins.

Catchment Description

The River Darent rises near Westerham about 10 km west of Sevenoaks. The upper reaches of the river are fed by springs both from the dip slope of the (Lower) Greensand to the south and the scarp slope of the Chalk of the North Downs to the north. Both the Greensand and Chalk outcrops attain heights of more than 200 m asl in the vicinity.

The river first flows in an easterly direction towards Sevenoaks. Disused sand quarries just to the west of Sevenoaks have given rise to lakes (Longford Lakes and others) which are connected with the river system. The river then follows a major valley cutting through the North Downs towards the Thames basin. Within the valley the river receives further contributions to flow from Chalk springs or seepages. The river emerges on to the Thames floodplain about 20 km north of Sevenoaks where it is joined by a major tributary, the River Cray. The Darent surface water catchment to the confluence with the Cray has an area of 262 km^2. The river is tidal to approximately 3 km above the point of discharge into the Thames.

Land use in the catchment is a mixture of pasture and arable with extensive areas of woodland on both the Chalk and Greensand outcrop areas. The main urban area in the upper catchment is at Sevenoaks. The lower 6 km of the catchment down to the confluence with the Thames is dominated by urban and industrial development in and around Dartford.

Part 1 Methodology

Many of the existing data required for the investigation have been collected and collated during Part 1. Hydrogeological data have been assessed to determine quality and completeness of records. Existing well testing data have been analysed and assessed to determine whether additional useful data could be obtained by testing at existing groundwater abstraction sources during further stages of the investigation.

Hydrometeorological and hydrological data have been used in the water balance assessment. A six year period from 1984 to 1990, which includes both dry and wet years, has been considered. The same methodology of surface water modelling has been used in the water balance assessment as will be incorporated in catchment modelling.

Study of the water-related infrastructure in Part 1 of the investigation has involved the assessment of water supply and wastewater networks for infrastructure zones within or connected with abstraction from the Darent catchment. Insight into low flow alleviation solutions previously proposed has been gained through review of existing reports. Engineering options have been assessed for impact in alleviating low flows and for broad technical feasibility. Unit rates from standard water industry and civil engineering pricing documents have been used in assessing costs of technically feasible options.

Public opinion as to the state of the river has been sounded mainly through contacts with members of the Darent River Preservation Society and a public meeting held by the society. A small exhibition was staffed at the meeting, giving rise to useful informal discussion with those attending. Answers to a questionnaire circulated at the meeting have provided a useful insight into public concerns for the river.

For short term low flow alleviation measures, consideration has been given to engineering options which might be implemented quickly at relatively low cost.

Previous Studies

Two studies concerned with the problem of low flows in the River Darent were commissioned by Thames Water Authority (TWA). In 1978 John Dossor & Partners produced a report resulting from a water management desk study. Between 1987 and 1989 Sir William Halcrow and Partners produced a series of reports on low flow alleviation, as part of a wider study of six catchments in the region. The study assessed the problems of low flows and recommended solutions, giving costings and outline designs. In the final report (Halcrow 1989), implementation of recommended solutions was set out in detail. A recent report for NRA (Southern Region) by WS Atkins (1991) defines an environmentally acceptable flow regime (EAFR) for the river based on surveys of macroinvertebrates and RIVPACS analysis combined with river flow statistics. A Catchment Management Plan has also been prepared on behalf of the NRA by Atkins. Various other reports, periodicals and surveys have been reviewed but contained limited information relevant to this investigation.

Public Perception

Some interesting trends and patterns have emerged from the questionnaire survey: 64% of the respondents live within easy walking distance of the river. Those who had lived in the Darent Valley since 1980 comprised the largest category at 46%, while 39% had lived in the valley since before 1960. Among concerns for the river, 'natural visual appearance' was listed highest followed closely by 'ecological interest'. The 'historical landscape' was next in the order of concern, while 'particular recreation' received relatively little support. This trend towards passive recreation was confirmed with the most popular recreational interest being walking, followed by 'enjoyment of Darent villages'. The majority of people visited the river daily.

The picture is thus one of general concern for the River Darent, as something to be seen and often walked beside as a generally passive but important part of everyday life. While people were obviously concerned about their immediate local reach, it is evident from the questionnaire that the whole river is valued as an important feature of the Darent Valley.

Additional concerns and attitudes were usefully expressed during the public meeting. It was regretted that numerous small weirs had been removed in the past by drainage activities and their reinstatement, it was felt, would improve the fishing and help to make the most of the existing water.

Hydrogeology

An assessment of hydrogeological data availability has been made prior to catchment modelling. Descriptions of geological formations and comments on piezometry, aquifer property data and groundwater quality are provided in the report. Sufficient geological data are available to determine the regional geological structure of the study area. Piezometry is poorly defined apart from in the central area of the Chalk outcrop. Considering the widespread development of groundwater abstraction in the Darent catchment, there are very few test pumping data on which to base an assessment of aquifer properties. Reasonably complete coverage of groundwater abstraction records is available dating back to 1974. A large number of records for non-public water supply abstractions are not available for the period after 1986 however.

Surface Water Hydrology and Water Balance

The objectives of the hydrological studies have been to evaluate the hydrological data and calibrate a surface water model (the Stanford Watershed Model) to obtain recharge and water balance estimates for the Darent catchment. The latter work has been carried out using data for the period October 1984 to September 1990.

Daily rainfall and autographic rainfall data are required for the surface water aspects of catchment modelling. The distribution and number of daily rainfall gauges are good. The length of daily rainfall record is extensive with eight of the stations dating back to 1931. For most stations, periods of missing data are relatively short.

The length of autographic data readily available on computer is poor. Autographic data for Eynsford were used in view of the station's central location within the catchment.

The Stanford Watershed Model is recognised as one of the most conceptually complete representations of the hydrological cycle and has been used in the catchment water balance assessment. The model is calibrated by comparison of simulated river flows output by the model with observed river flows.

Soil infiltration is the key process in determining catchment response to rainfall and is principally dependent on the amount and distribution of soil moisture storage, soil permeability and precipitation rate and quantity. Two soil horizons are modelled: an upper zone representing the top few centimetres of the soil which controls runoff, overland flow and interflow, and is depleted by both evaporation and interflow; a lower zone, controlling the infiltration function, which is depleted by evapotranspiration and recharge to groundwater storage. The groundwater storage zone is depleted by groundwater abstraction and by baseflow to the river which follows a Horton type recession. Variable rates of recession can also be modelled.

The flow data for the River Darent have allowed calibration and verification of the Stanford Model for subcatchments upstream of Hawley. Water balances have been prepared for six water years (October 1984 to September 1990) for the following three subcatchments:

- Otford;
- Otford to Hawley;
- Hawley to the Darent/Cray confluence.

The calibrated Stanford Model has also been used to calculate recharge for the Chalk and Lower Greensand aquifers for the period 1960 to 1990.

From these water balances it can be concluded that both the Lower Greensand and much of the Chalk aquifer in the catchment have been developed to the point where abstraction at the current level is close to long term average recharge. An area of Chalk outcrop exists within the Otford subcatchment which might be developed, possibly with groundwater augmentation schemes or summer abstraction sources. However, taken overall, total average recharge to the Chalk (101 Mld) only exceeds recent abstraction (86 Mld) by about 15%. Chalk abstraction exceeds the one in five year recharge by 30%. For the Lower Greensand, average recharge (43 Mld) exceeds abstraction (35 Mld) by about 20%. In these circumstances it seems unlikely that major low flow alleviation options could be developed which either allow for increased abstraction or even for maintenance of abstraction at current levels, unless the options involve artificial recharge.

Environmentally Acceptable Flow Regime

Atkins (1991) derived discharge values for the environmentally acceptable flow regimes (EAFR) at nine locations including the three gauging sites on the Darent.

The $EAFR_{95}$ is assumed to be the lowest flow required to maintain the abundance and diversity of macroinvertebrates expected in a theoretically pristine Chalk stream at the location. The $EAFR_{mean}$ is the mean flow desirable from an environmental viewpoint at the location.

The scope of the study by Atkins did not allow for full consideration of seasonal variation in EAFR. Further environmental studies relating to EAFR need to take into account seasonal requirements of flora and fauna, principally invertebrates, fish and birds, water quality and sediment transport, the need to maintain adjacent damp habitats and also the visual and amenity value of the river.

The $EAFR_{95}$ values derived by Atkins have been used to compute annual deficits in river discharge. The analysis shows that deficits at Otford and Lullingstone are of a limited order. At Hawley, however, deficits are of an order of magnitude higher. At Otford and Lullingstone deficits are restricted to a sequence of low rainfall years in the early to mid 1970s and in 1989 (assessment for 1990 not complete), with deficit periods never exceeding 100 days at Otford and only occasionally of this duration at Lullingstone. In contrast, at Hawley annual deficits average about 100 days with deficits occuring in every year from 1969 to 1989. Years with 100 or more days of deficit occur regularly. In 1973, deficits existed at Hawley over a period of eleven months out of twelve and deficit periods of about 250 days occurred in both 1976 and 1989.

Engineering Studies

The main objective of the engineering studies is to identify practical means of alleviating the low flow problems in the Darent. A wide range of options have been suggested and the principal aim at this stage of the study has been to screen these options, and identify those which appear to have the most promise for further evaluation, using the catchment model where appropriate.

The strategies for alleviating low river flows can be broadly categorised as abstraction reduction/relocation, flow augmentation, flow conservation, recirculation, demand management or some combination of these. Options within these strategies may involve changes in the management of existing groundwater and surface water resources, development of new groundwater sources, use of storages within the catchment, artificial recharge, use of sewage effluent, control of demand, etc. Any option which involves a reduction in current abstractions involves some assessment of the practicality of finding replacement supplies.

As indicated above, the deficits at Otford and Lullingstone are relatively infrequent, occurring only in the very dry years, and of moderate duration and volume. The problem at Hawley is clearly of a different order of magnitude and is likely to require a strategic solution whereas the problem in the Otford/Lullingstone reach may be amenable to local solutions. Any augmentation solution proposed needs to be able to provide flows for lengthy periods and deliver large volumes of water, particularly at Hawley. Suggested design requirements for augmentation flows at the three gauging stations are summarised in Table S.1.

TABLE S.1

Design Augmentation Requirements at Gauging Sites

Station	Maximum capacity (Mld)	Duration (months)	Volume (Ml)
Otford	2	3	150
Lullingstone	5	5	700
Hawley	22	9	5 000

Long Term Options

A number of options have been reviewed, some of which provide only partial solutions. The options are summarised in Table S.2. Some options are only capable of addressing the problems between Otford and Lullingstone, and would have little impact on flows in the reach between Lullingstone and Hawley. Others have potential for providing longer term solutions, while also addressing current problems. Some of the options are only used on an as-needed basis, whereas others depend on full time operation. It is thus difficult to compare options directly in terms of performance, and two benchmarks have been developed.

The first benchmark is the ability of the solution to meet the 'design' deficit period (9 months) at Hawley. In cases where the available volume is limited, performance is expressed in terms of average sustainable flow over the design deficit period. Where volume is not limited, the nominal capacity of the scheme is used.

TABLE S.2

Summary of Options Considered

Option	Comment
Construction of additional wells for direct river augmentation or for groundwater use as summer water supply sources	Relies on utilising groundwater storage in undeveloped parts of the catchment, altering the seasonal pattern of groundwater flow. Water is drawn from storage in dry periods, reducing potential groundwater flow to river at other times. With direct river augmentation has the advantage that it only needs to be used when required, thus keeping operating costs low. Effectiveness in doubt on the basis of the water balance assessment and needs to be tested using the catchment model.
Re-use of sewage effluent	Makes use of resource currently lost to the catchment. Resource options considered include use of sewage arising within the catchment (partial solution to the low flow problems) and pumping of effluent from the Long Reach treatment works (full solution feasible). Treatment options considered for both resources include tertiary standard for direct return to river or land treatment for indirect return via aquifer. Latter appears most cost effective.
Recharge of aquifer using surplus (winter) flows	Pumps surplus water from river to recharge aquifer, relying on natural seepage and/or subsequent abstraction to augment river flows or provide a summer source. Diversion at Lullingstone provides only a partial (10%) solution in average years, and would fail in extreme years such as 1972/73. Pumping from downstream of Hawley would be a possibility but is expensive. Would need to be used each winter in anticipation of a dry summer and is thus somewhat inefficient.
Seasonal storage in existing lakes	Provides only a partial (5 to 10%) solution to the problems at Hawley, but would overcome the lesser problems at Otford. Interest-group pressures would make implementation difficult.
Surface water abstraction and treatment at Dartford	Relies on closure of selected wells on the assumption that river flow will recover sufficiently to allow surface water abstraction at Dartford. Uncertain how many wells will need to be closed without modelling and reliability of river flows in dry periods may be a drawback. Expensive.
Increased conjunctive use of surface water from Thames Valley and local groundwater	Has long term potential for meeting growth, as well as providing solution to current problems. Links between surface water supplied and groundwater supplied reservoirs would allow over-stretched wells to be rested, allowing aquifer to recover. Impacts of reducing abstractions at selected locations need to be determined using the catchment model. Effectiveness of links in transferring water from west to east can be examined in the network model being developed by TWU.
Recirculation	No potential alone but may have potential in combination with other options.
Bed lining of critical channel sections	Would be effective in conjunction with another augmentation option, but difficult to implement. Problems with ecological disruption and land ownership, plus the technical uncertainty over long term performance and the need to carry out trials to establish technical feasibility weigh against this solution. Bankside wells provide a direct alternative.
Development of bankside wells	Recirculates flows lost to ground in reaches of river where losses are high. Cheap to implement and run. Requires site trials, but risk low. Impact of wells can be tested using the model. Will probably need to be used in conjunction with other augmentation options. Alternative to bed lining.
Demand management	Involves use of financial incentives to encourage abstractors to prefer alternative sources and for consumers to be more economical in their use. May not be implementable immediately, but should be pursued as a matter of policy to deal with long term resource problems.

The second benchmark is the unit cost of the solution, expressed in £/m³. Evaluation of this is complicated by the fact that some solutions have to be run full time, whereas others would only be used on an as-needed basis. In order to allow for this, the average annual deficit period for Hawley, calculated as 100 days per annum over the period of record, has been used. If an option provides a solution which has to be run full-time, this is still only considered to be effective in dealing with the low flow problems in the river over the 100 days of deficit each year. This means that 'full-time' solutions appear expensive.

The comparison of options is presented in Table S.3. These are the engineering or 'structural' options and exclude demand management which at this stage is a concept which cannot be realistically costed for comparison. The options are listed under four category headings broadly in the same order as summarised in Table S.2. Use of winter flow surpluses for artificial recharge has potential application for direct river augmentation and also for reduction of existing abstractions in the river valley through relocation of abstraction to areas of recharge. These two options are costed separately and included in separate categories.

The results indicate that options such as construction of a water treatment works at Dartford or a sewage treatment works at Otford would be expensive. The use of the Longford Lakes appears attractive in terms of unit cost but provides a very limited solution in terms of meeting the deficit in the Lullingstone to Hawley reach. The problems likely to arise given the user interests makes this option unattractive, except perhaps as a means of dealing with the problems in the river down to Lullingstone. Augmentation using groundwater has a low relative cost, but from the catchment water balance appears to have little potential unless linked to artificial recharge. Recharge of winter surplus would only be technically feasible with pumping from downstream of Hawley, which makes it fairly expensive. Bankside wells would appear to be more attractive than bed lining for conserving river flows in the Lullingstone to Hawley reach, and some combination of augmentation, recharge and conservation might have potential.

With a view to demand growth, the preferred options which make available additional resources (rather than seasonal redistribution of existing resources) are the use of sewage effluent from Long Reach (although doubts over quality would need to be satisfied if land treatment is to be adopted) and conjunctive use of off-peak water from the Thames Valley surface water system.

Short Term Options

River support pumping from wells at Brasted pumping station and Horton Kirby paper mill were arranged by NRA (Southern Region) during the summer and autumn of 1990. Amenity value was also improved at certain locations when flow was available by use of temporary sandbag weirs which increased the depth of water. There is considered to be limited scope for use of weirs however.

In addition to measures implemented in 1990 further schemes which could be implemented at relatively low cost and in the short-term include:

- additional flow augmentation schemes utilising Chalk groundwater;
- utilising drawdown in Longford Lake;
- bankside wells (artificial springs).

In view of the conclusions of the water balance assessment summarised on page S-5, there would seem limited opportunities for implementation of flow augmentation schemes. It might be possible to construct wells in the Chalk in the upper Darent (Otford subcatchment) with pumping which could

Table S.3 - Comparison of Structural Options

Option Category	Option	Sub-option	Effective Capacity	Capital Cost	Unit Cost
River Augmentation	Augmentation Wells	Chalk (Lower Darent)	24	2.1	0.09
		Chalk (Upper Darent)	8	0.6	0.08
		Greensand with Iron Removal	8	1.0	0.12
	Reuse of Sewage Effluent	Primary STW at Otford + Land Treatment	12	4.9	0.48
		Tertiary STW at Otford	12	12.4	0.95
		Ex. STW at Longreach + Land Treatment	40	6.0	0.13
		Ex. STW at Longreach + Tertiary Treatment	40	13.3	0.23
	Use Winter Surplus & Recharge (pumped from Dartford area)	Land Spreading	30	5.2	0.20
		Direct Injection	30	8.0	0.27
	Use Storage in Existing Lakes	Longford Gravity Scheme	1	0.3	0.07
		Pumped Longford plus Upstream Lakes	4	0.5	0.05
Revocation/Relocation/ Variation of Existing Licenses	Summer Sources	Chalk	24	2.1	0.09
		Greensand with Iron Removal	8	-	-
	Dartford Treatment Works	With river regulation	35	14.2	0.41
			50	19.4	0.38
		With storage of winter surplus at Dartford	35	32.5	0.76
			50	44.3	0.72
	Use Existing Off peak Capacity	Conjunctive Use/Recharge	30	6.5	0.18
	London Ring Main	Conjunctive Use/Recharge (inc off-peak)	60	-	-
		New Resource Development	60	-	-
	Other Catchments	Cray	?	-	-
		Medway	?	-	-
		Swanscombe area	?	-	-
	Use Winter Surplus & Recharge as Summer Source (pumped from Dartford area)	Land Spreading	30	5.9	0.22
		Direct Injection	30	8.6	0.29
Recirculation	Using Stored Winter Surplus		40	14.2	0.26
Conservation	Bed Lining	Lullingstone to Hawley	16	2.8	0.15
	Artificial Springs	Lullingstone to Hawley	16	0.8	0.08

Notes:

1/ Effective capacity = Average sustainable flow over design deficit period (9 months)

2/ Capital cost in £million, Unit cost in £/m3, Capacities in Mld

3/ Unit costs based on average annual number of deficit days (100) at Hawley benefit the river perhaps as far downstream as Shoreham. Benefits might be extended further downstream if combined with a scheme of bankside wells. A water balance assessment of the adjoining Cray catchment to the north of Westerham would have to be carried out before proceeding with an augmentation scheme.

Use of the Longford Lake could be strongly opposed and be very unpopular with users of this amenity. Benefits to the river would also be very limited, although these might be extended by combination with bankside wells.

Bankside wells could provide the means to maintain limited amenity and ecological value of the river both upstream and downstream of Lullingstone, on a reduced scale in drought conditions. There is little risk that recirculation of water by this means could deplete the Chalk groundwater system further to a significant degree and risk failure of existing abstractions.

Catchment Modelling

Use of an integrated catchment model which simulates flows in the aquifers and in the river and the interaction between surface and groundwater components is proposed. The integrated model has been tested during low flow studies for several Chalk catchments and proved to be an excellent technique for this type of investigation.

Owing to the varied geology of the Darent catchment and differences in piezometry between the main aquifers, a six layered model may be required, although none of the layers is present over the whole catchment. The top layer, which exists only over a small part of the catchment, will be used to represent alluvium, river gravels or the Tertiary deposits depending on location. The Chalk layer includes both the normally shallow permeable zone and underlying less productive section. Variation in permeability with depth will be modelled if there are sufficient data to define the distribution.

It is envisaged that the model network for the Darent model will be generated from a basic grid of 2 km squares, with fourth order subdivision to produce 500 m squares for maximum detail. These small nodes will be used along the river and for other areas requiring accurate representation, eg the spring zones in the Chalk and Greensand outcrops and the major abstraction points.

The Cray catchment and also the area around the Ebbsfleet catchment to the east of Dartford are required to be included in the catchment model. Extension of the model allows for simulation of the effects of abstraction from the Darent on adjacent catchments (and vice versa). It is also then possible to model engineering options which involve water resources in the extended model areas.

The model boundaries will be chosen as follows:

- southern boundary, along the southern limit of the outcrop of Hythe Beds. This can be readily defined from published geological mapping. The model will generate discharge across the boundary simulating springs on the scarp slope of the Lower Greensand. This discharge would not be included in the Darent catchment balance;

- eastern boundary along the groundwater divide in the Chalk between dry valleys of the Darent and Medway catchments. From published hydrogeological mapping (IGS 1970) this appears to coincide approximately with divides in the Folkestone and Hythe beds;

- western boundary along the groundwater divide coinciding in places with the western boundary of the Cray surface water catchment and located to the west of the surface water boundary in the vicinity of Bromley. This groundwater divide has also been identified from published hydrogeological mapping;

- northern boundary, with a fixed head aligned along the River Thames. The area downstream of the Cray/Darent confluence would not need to be modelled in detail.

A major feature of the model is the interface between the river and aquifers. The river and its tributaries will be represented by a series of specially defined polygon faces, where flows between the aquifers and river are calculated. As the river is only in contact with the superficial alluvium or the top of an aquifer, flow between the aquifer and river includes a vertical component which is simulated as a leakage flow through the river bed, controlled by the difference between the water level in the river and head in the underlying aquifer. Springflows are also calculated by the model, when water levels in outcrop nodes reach ground level.

Flow in the river is routed downstream, with the addition of contributions from tributaries, springs, river support water (if applicable) and runoff calculated by the Stanford Model.

The data input to the model will be based on the existing information and results of field measurements and hydrological studies. As interpolation between measured points and estimation of poorly defined data are inevitable, careful calibration of each component of the integrated model is essential.

For the groundwater component, preliminary calibration will consist of running the model for steady state conditions using a line of fixed head nodes to approximate the river, and average values of recharge and abstraction. The main objective of this stage will be the assessment of the leakage coefficients of the aquitards and the degree of vertical interconnection between the aquifers.

The integrated catchment model will be used for final steady state and transient calibration. Transient calibration will use monthly time steps and concentrate on the period with the best data, 1984 to 1991. The calibration obtained for this period will then be verified by running the entire sequence from the start of the period of availability of detailed abstraction returns.

Conclusions

The following conclusions have been drawn from the various aspects of Part 1 of the investigation:

(a) Public Perception

There is general public concern for the River Darent as something to be seen and often walked beside, as a generally passive but important part of everyday life. Whilst there are concerns for specific reaches, results of the questionnaire circulated at the public meeting in March 1991 indicate that people value the whole river as an important feature of the Darent Valley.

(b) Hydrogeological Evaluation

Geological data are generally sufficient for catchment modelling. Chalk piezometry is well defined in the central North Downs area but is poorly defined to the north and in the south of the outcrop area and within the Darent valley. Lower Greensand piezometry is poorly defined at present with very few observation wells currently monitored. Very little data are available to determine aquifer properties. Nothing is known of the depth of fissuring and changes in permeability with depth within the Chalk. Some post-1986 non public water supply abstraction data are required.

(c) Hydrological Catchment Water Balance

The Stanford Watershed Model has been used for catchment water balance assessment. Hydrometeorlogical data coverage required for the model is good, except for autographic raingauge records. A reasonable calibration has been obtained for the model using data for water years from 1984/85 to 1989/90.

Water balance calculations indicate that much of the Chalk aquifer has been developed to the point where abstraction at the current level is close to or exceeds long term average recharge. The Lower Greensand aquifer is also highly developed. Taken over the whole catchment, long term mean annual recharge exceeds mean abstraction by only:

- 15% for the Chalk aquifer;
- 20% for the Lower Greensand.

For the Chalk aquifer abstraction exceeds the one in five year recharge by 30% whilst the Lower Greensand abstraction is at the same level as the one in five year recharge.

An area of Chalk outcrop exists within the Otford subcatchment which, depending on abstraction within the Cray sub-adjacent catchment, might be developed with groundwater augmentation schemes or summer abstraction sources. It seems unlikely however that major low flow alleviation options could be developed in either aquifer which either allow for increased abstraction or even for maintenance of abstraction at current levels, unless the options involved a compound of artificial recharge.

(d) Engineering Options for the Low Flow Alleviation

A broad assessment of engineering options, both full and partial solutions, has been made and a methodology for comparing cost and effectiveness of options has been developed.

None of the options considered at this stage can be dismissed outright. However it was concluded that the following options merit detailed assessment during catchment modelling, in some cases in combination with other options:

Long term strategic options:

- artificial recharge using surplus winter flows from downstream of Hawley, with subsequent abstraction for public supply as a means of reducing abstractions from existing wells on a seasonal basis or for river augmentation;

- pumping of secondary effluent from Long Reach STW for land treatment within the catchment as a means of augmenting river flows;

- conjunctive use of off-peak surface water from the Thames Valley via the existing trunk main system through the creation of links between reservoirs and, in the longer term, through use of the London Ring Main and reinforcement of the trunk main system;

- replacement of current abstractions from the Darent catchment with supplies from elsewhere, for example through use of the London Ring Main.

These options have potential in terms of meeting longer term demand growth. Effluent quality and public perception could effect the feasibility of the secondary effluent recharge option however.

Short/medium term options:

- use of bankside wells (artificial springs) as a means of conserving flows in the Lullingstone to Hawley reach;

- seasonal redistribution of flows using new Chalk wells as summer sources;

- artificial recharge using surplus winter flows from downstream of Hawley, with subsequent abstraction for public supply as a means of reducing abstractions from existing wells on a seasonal basis or for river augmentation;

Options just for the river upstream of Lullingstone worth further consideration are:

- augmentation wells in the Chalk aquifer to the north of the valley between Westerham and Sevenoaks;
- use of storage in Longford and upstream lakes.

Recommendations

Recommendations for additional fieldwork to provide data for catchment modelling are:

(a) An observation borehole and test well construction and testing contract (as already planned by the NRA) to provide piezometric data and test pumping data. It is recommended that wells in the Lower Greensand should be designed to permit sampling of both the Hythe and Folkestone Beds and measurement of the changes in piezometric head with depth.

(b) A programme of test pumping of existing public water supply wells at all the public water supply sites in the catchment. The winter of 1991/92 would be a suitable time, when demands are low and there may be spare capacity at the sites. The programme should consist of step-discharge tests on at least one well per site with some additional three-day constant discharge tests.

(c) During the testing programme, downhole flow and TV logging are recommended in large diameter wells where access to the aquifer zone is available past pumps, rising main etc. Locations of fissures and the main aquifer zone and variation in permeability with depth could then be assessed.

CHAPTER 1

INTRODUCTION

1.1 Background and Objectives

The River Darent has been identified by the National Rivers Authority as one of 40 over-abstracted catchments in England and Wales. The catchment, located in north Kent (Figure 1.1), is regarded as being of particular importance, owing to the severity of river flow depletion.

The river is fed by springs from the Lower Greensand aquifer lying along the northern rim of the Weald of Kent, and also from the Chalk aquifer of the North Downs (Figure 1.2). Both aquifers are sources of major groundwater abstraction for public water supply. In recent periods of low rainfall, particularly the early to mid 1970s and from 1989 to the present, the river has dried up completely in certain sections for durations of several months. The reach from Lullingstone to Hawley has been particularly severely affected in these periods, with flow losses along a length of several kilometres of river bed.

Groundwater Development Consultants (GDC) was appointed by the National Rivers Authority (Southern Region) in February 1991 to undertake a water resources investigation of the River Darent catchment. The main objective of the investigation is to identify the most appropriate measures from a large number of engineering options to alleviate low flow conditions in the river. This objective is to be achieved by:

- an initial water infrastructure and water balance study to assess the feasibility of various potential engineering options to alleviate low flow conditions;
- a broad costing of options;
- computer-based, integrated catchment modelling with simulation of the interrelationship between the aquifers and the river, allowing detailed assessment of the effects of engineering options;
- recommendations based on benefits to the river, technical feasibility and comparison of costs.

Many of the engineering options are well established and have been discussed in detail and costed in existing reports (see Chapter 2). Detailed modelling of the catchment has not been carried out previously, however. The present investigation therefore provides the first opportunity to assess in detail the effects of options on river flow and aquifer conditions. The catchment model also provides a means to simulate aquifer and river conditions without the effects of abstraction. The 'naturalised' flows derived will provide useful data for comparison with the flow objectives. Environmentally acceptable flow objectives for the Darent have been the subject of a separate study for NRA (Southern Region) by WS Atkins.

For the investigation, great importance is attached to the presentation of results, both to interested local parties and also to bodies within the water industry which may be affected by options to alleviate low flows in the river. A major aspect is therefore the presentation of results in a clear, readily understood form through the use of computer colour graphics.

1.2 Catchment Description

The River Darent rises near Westerham about 10 km west of Sevenoaks (Figure 1.1). The upper reaches of the river are fed by springs both from the dip slope of the (Lower) Greensand to the south and the scarp slope of the Chalk of the North Downs to the north. Both the Greensand and Chalk outcrops attain heights of more than 200 m asl in the vicinity.

The river first flows in an easterly direction towards Sevenoaks. Disused sand quarries just to the west of Sevenoaks have given rise to lakes (Longford Lakes and others) which are connected with the river system. The river then follows a major valley cutting through the North Downs towards the Thames basin. Within the valley the river receives further contributions to flow from Chalk springs or seepages. A series of flooded gravel pits is located close to the northern end of the river valley. The river emerges on to the Thames floodplain about 20 km north of Sevenoaks where it is joined by a major tributary, the River Cray. The Darent surface water catchment to the confluence with the Cray, which has an area of 262 km^2, is indicated in Figure 1.1. The river is tidal to approximately 3 km above the point of discharge into the Thames.

Land use in the catchment is a mixture of pasture and arable with extensive areas of woodland on both the Chalk and Greensand outcrop areas. There are some water meadows in the valley bottom. The main urban area in the upper catchment is at Sevenoaks. The lower 6 km of the catchment down to the confluence with the Thames is dominated by urban and industrial development in and around Dartford. Greater London urbanisation has spread to dominate the western side of the Cray catchment.

The Darent catchment has an average annual rainfall of about 700 mm. There is considerable variation in rainfall from less than 600 mm along the Thames floodplain to more than 900 mm in some upland areas of the North Downs.

1.3 Scope of Work

The investigation programme has been divided into three parts. Part 1 comprises a pre-feasibility study and includes the following activities:

- the infrastructure and water balance study;
- broad assessment of engineering options with costing;
- catchment model specification;

Figure 1.1

Location Map

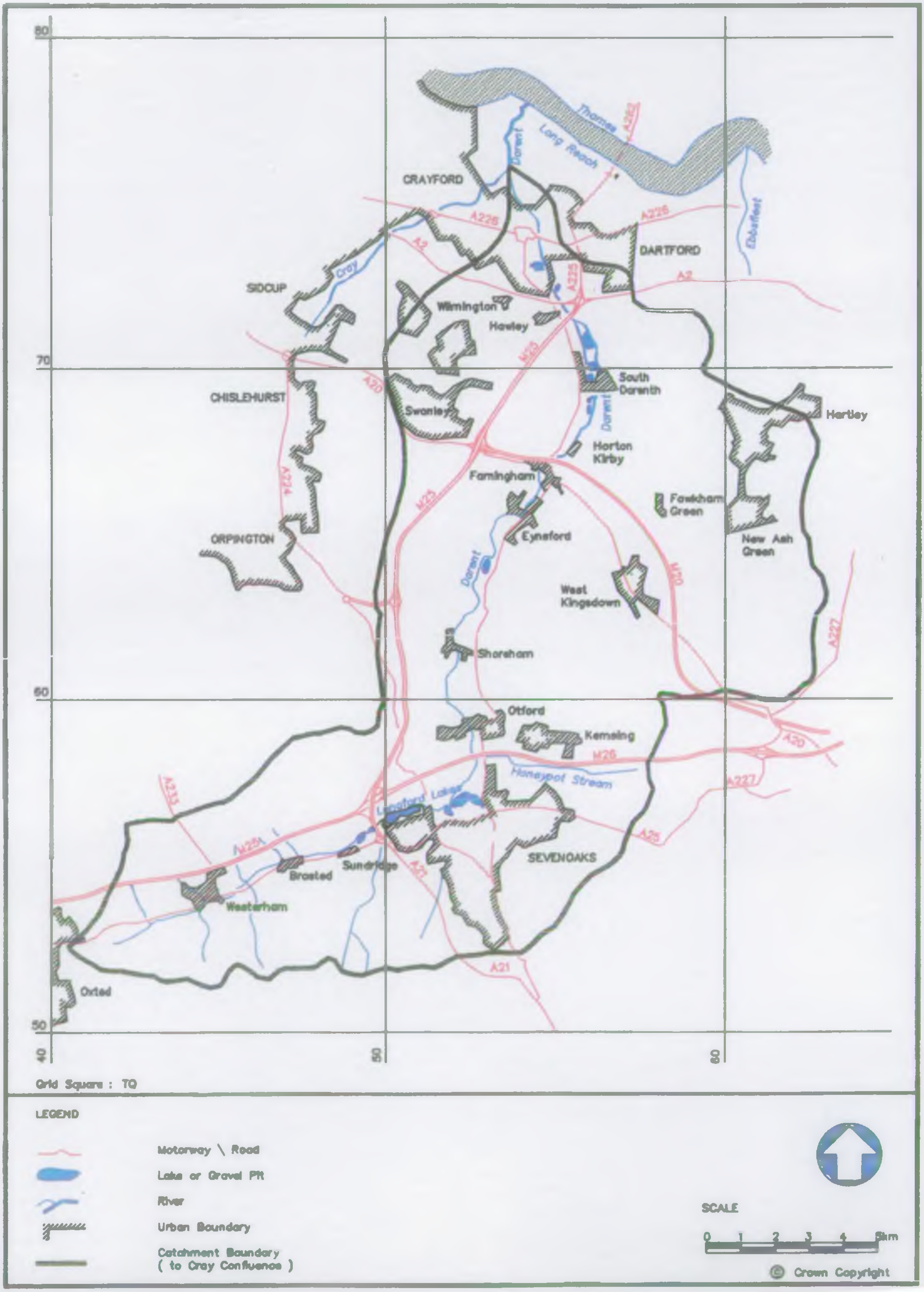
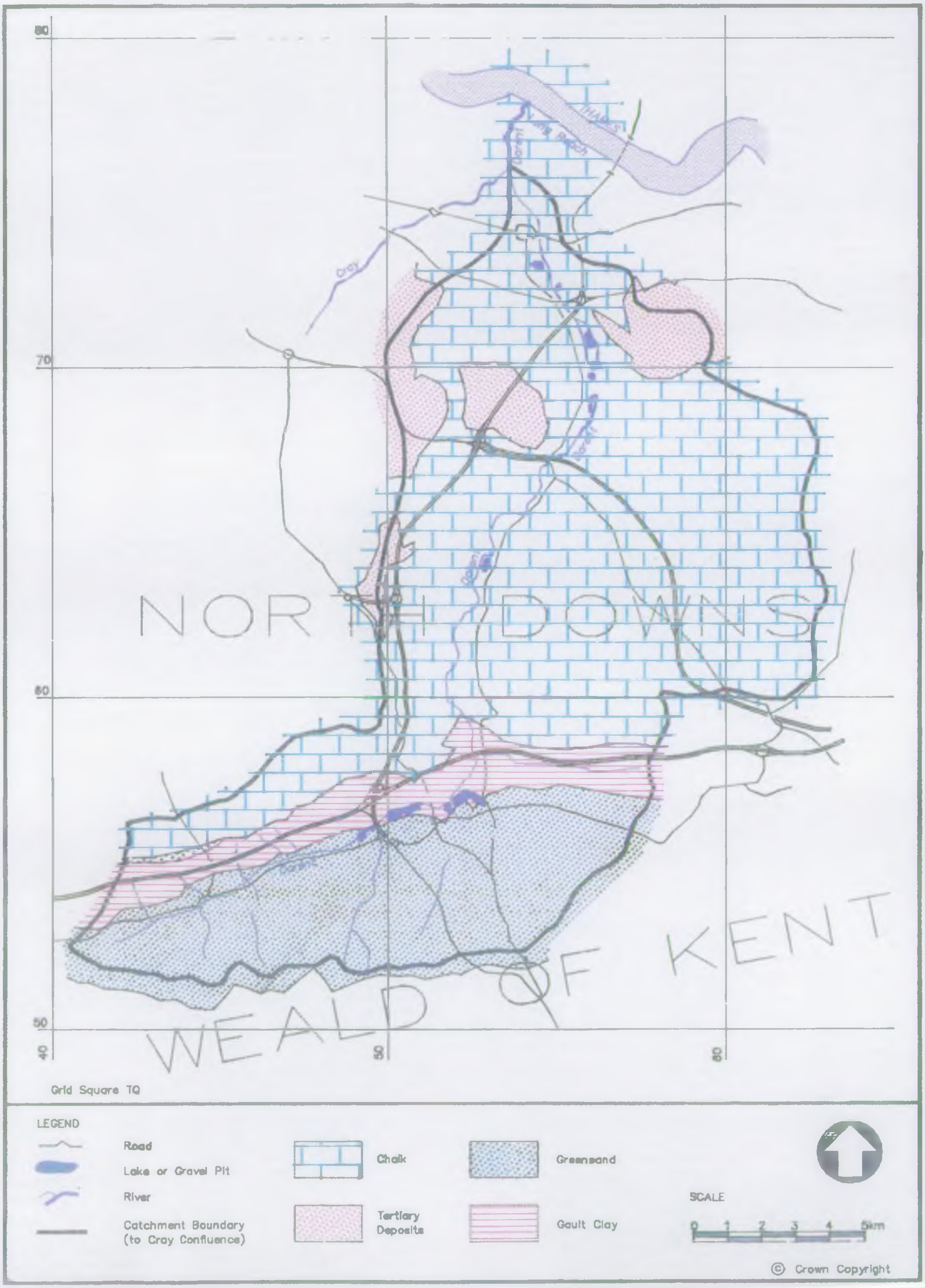


Figure 1.2

Solid Geology



- assessment of data to be used in catchment modelling, providing an opportunity for specifying any further data requirements;
- review of previous reports and gauging public opinion as to the state of the river and the perceived requirements for action;
- assessment of any short-term options for low flow alleviation.

Part 2 of the investigation is mainly concerned with establishing the catchment model and preliminary model calibration. At the end of Part 2 the model is required to be in a form suitable for demonstration at a public exhibition in November 1991. Part 3 includes full model calibration and use of the model for assessing the effectiveness of engineering options. Final technical and financial comparisons and recommendations will be presented at the end of Part 3 of the investigation.

In Part 1 the assessment has concentrated on the Darent Catchment to the confluence with the Cray as this is the focus for concerns regarding flow depletion. The Cray catchment and also the area around the Ebbsfleet catchment to the east of Dartford are, however, required to be included in the catchment model. Abstractions in the main Darent catchment may have affected the groundwater regimes in these adjacent catchments (and vice versa). In addition, extension of the model allows for the possibility of modelling engineering options which involve water resources in the extended model areas.

Field data collection during the investigation includes river gauging, establishing where possible groundwater level monitoring at existing private wells and river cross-sectional surveys. Data collected are for use in catchment modelling.

The investigation is programmed for completion in October 1992. This report describes the findings of Part 1, the pre-feasibility stage of the investigation.

1.4 Methodology

Many of the existing data required for the investigation have been collected and collated during Part 1. Hydrogeological data have been assessed to determine quality and completeness of records. For records such as those for abstraction, this assessment has indicated missing historical data which are required for modelling and might be obtainable from other, as yet untried, sources. Existing well testing data have been analysed and assessed to determine whether additional useful data could be obtained by testing at existing groundwater abstraction sources during further stages of the investigation.

Hydrometeorological and hydrological data have been used in the water balance assessment. A six year period from 1984 to 1990, which includes both dry and wet years, has been considered. The same methodology of surface water modelling has been used in the water balance assessment as will be incorporated in catchment modelling.

Study of the water-related infrastructure in Part 1 of the investigation has involved the assessment of water supply and wastewater networks for infrastructure zones within or connected with abstraction from the Darent catchment. Insight into low flow alleviation solutions previously proposed has been gained through review of existing reports. Engineering options have been assessed for impact in alleviating low flows and for broad technical feasibility. Unit rates from standard water industry and civil engineering pricing documents have been used in assessing costs of technically feasible options.

Public opinion as to the state of the river has been assessed mainly through contacts with members of the Darent River Preservation Society and a public meeting held by the society. A small exhibition was staffed at the meeting, giving rise to useful informal discussion with those attending. Answers to a questionnaire circulated at the meeting have provided a very useful insight into public concerns for the river.

For short-term low flow alleviation measures, consideration has been given to engineering options which might be implemented quickly at relatively low cost.

1.5 Acknowledgements

GDC gratefully acknowledges the co-operation and assistance received from various organisations and their staff during this first stage of the Darent catchment investigation. Hydrometeorological, hydrological, groundwater abstraction and much of the hydrogeological data have been assembled and provided by staff in the Resources Department of the NRA (Southern Region). Water companies operating in the Darent catchment namely, Thames Water Utilities, Mid-Kent Water Company, West Kent Water Company, Southern Water Services and East Surrey Water Company have provided useful information in discussion and spent considerable time and effort in assembling hydrogeological and catchment infrastructure data. The Wellcome Foundation has provided hydrogeological information relating to abstraction wells.

Thanks are due to the Darent River Preservation Society and to those people who completed a questionnaire at the meeting on 15 March 1991. The Marley company and Chipstead Sailing Club have assisted by taking part in discussions concerning the Longford Lakes.

CHAPTER 2

EXISTING INFORMATION

2.1 Introduction

An important aspect of the pre-feasibility stage of the investigation has been a rapid assessment of the widespread sources of data and information on catchment hydrology and water-related infrastructure. The catchment has been the subject of two previous studies intended to provide solutions to the problems of low flows. These were by Dossor (1978) and Halcrow (1987, 1988 and 1989). Both involved analysis of hydrological and water infrastructure data. Halcrow also compiled information on the state of the river from the nineteenth century onwards. WS Atkins (1991) carried out an investigation on behalf of NRA (Southern Region) to define an environmentally acceptable flow regime (EAFR) for the Darent.

A considerable amount of hydrological and hydrogeological data, collected mainly since the early 1960s, is already available to the NRA. The five water companies operating in the catchment hold information on various parts of the water-related infrastructure. Local people's personal recollections of the state of the river can also be useful, particularly if they stretch back to a time of a relatively low level of water resources development. Recollections of river and well water levels can form important benchmarks against which to judge the results of catchment modelling, especially when attempting to simulate pre-development conditions. Comments in historical guides, travel journals and periodicals can provide similarly useful, semi-quantitative data on the 'natural state' of the river and catchment.

2.2 Data Sources

Much of the existing hydrometeorlogical, hydrogeological and groundwater data have been provided from the NRA archives. These include:

- observation well monitoring;
- abstraction returns;
- daily rainfall and some autographic raingauge data;
- evaporation (MORECS);
- daily river flow gauging.

Responsibility for the catchment passed to NRA (Southern Region) in 1990. Prior to the Water Act of 1989 the Darent had been the responsibility of Thames Water Authority. As a result of these changes data formats vary. For example, some observation well data had already been transferred to computer, some were only available on paper copy. 1990 abstraction returns were available on computer but all previous data were in the form of microfiche. The NRA has also made available the existing reports on low flows in the catchment. Various other relevant documents and papers listed in Section 2.3.5, have also been obtained.

The water companies acknowledged in Section 1.5 have provided the following information:

- plans of water-related infrastructure;
- groundwater abstractions and flows within the infrastructure over the past five years;
- an indication of water supply zones and assessment of imports and exports of water for the catchment;
- sewage discharge (Thames Water Utilities only);
- some borehole lithology, geophysical logging and test pumping data.

Hydrogeological information is summarised on a published map covering the catchment (IGS, 1970). Other lithological data and limited test pumping information have been obtained from British Geological Survey archives at Wallingford. Ordnance Survey 1 : 25 000 scale topographical mapping has been used as the basis for fieldwork. Information on bench-marks has been obtained from Ordnance Survey for use in river cross-sectional topographic surveys.

2.3 Review of Reports

2.3.1 Introduction

Two studies which were concerned with the problem of low flows in the River Darent were commissioned by Thames Water Authority (TWA). John Dossor & Partners (in association with Associated Engineering Consultants) produced a report resulting from a water management desk study (Dossor, 1978). Between 1987 and 1989 Sir William Halcrow and Partners produced a series of reports on low flow alleviation, as part of a wider study of six catchments in the region. The study assessed the problems of low flows and recommended solutions, giving costings and outline designs. In the final report (Halcrow 1989), implementation of recommended solutions was set out in detail. A recent report for NRA (Southern Region) by WS Atkins (1991) defines an environmentally acceptable flow regime (EAFR) for the river. A Catchment Management Plan has also been prepared on behalf of the NRA by Atkins. Various other reports, periodicals and surveys contained limited information relevant to this investigation.

2.3.2 Water Management Study (Dossor)

The brief for this study was to review and put forward recommendations regarding possible future river basin management of the Darent. This related mainly to minimum desirable river flows but included consideration of water quality and also flood control.

The report includes a review of land use, hydrogeology, river flows and hydrochemistry. A mean annual water balance was developed. Land drainage, water supply and sewage disposal are discussed. As a separate issue (recognised as having no direct bearing on the problems of low flow) the report puts forward recommendations for improvements to the valley trunk sewer system.

The report contains the following useful hydrogeological data which have not been obtainable from other sources:

- Chalk groundwater level contouring for 1944 and 1966;
- Constant discharge well test data for Kemsing public water supply station.

After costing various options for alleviating low flows, Dossor favoured the following:

- sewage treatment at Sevenoaks with discharge of high quality effluent (after lagoon maturation) to the Darent;
- pumping of lagoon-matured, high quality effluent from the existing Long Reach sewage works at Dartford back into the Darent catchment for discharge to the river;
- utilisation of a possible 2.3 m drawdown in the main lake at Longford Lakes to provide river regulation.

The report also includes useful references to general research by the Water Research Centre into artificial recharge using surplus river flows. A requirement for a surface spreading area of 14 ha to recharge 40 Mld is quoted.

2.3.3 Low Flow Alleviation Study (Halcrow)

As indicated in Section 2.3.1 the study for TWA by Halcrow in the late 1980s was part of a larger study of six rivers or streams in the region considered to be seriously affected by groundwater abstraction. The Darent was considered as one of three of these catchments with more major problems of depleted river flows. The reporting sequence for the study was as follows:

May 1987	:	Interim Report comprising main report summary for the 6 catchments with details for each catchment in separate annexes.
April 1988	:	Final Report with Volume 1 a main report summary for the 6 catchments, with separate case study reports giving details for individual catchments.
February 1989	:	A single report on implementation of schemes.

The objectives of the study were to identify the areas where flows had been depleted by groundwater abstraction, to determine the extent to which improvement of river flows would be desirable, and to evaluate the technical feasibility, costs and environmental consequences of various options for improvement. For the Darent, the brief was to consider improvement to flows in the reach within the North Downs from Otford to Hawley. Proposed solutions, however, included schemes located outside this area, in particular in the subcatchment upstream of Otford.

The Interim Report provides a general assessment of river flows, hydrogeology and water balance. The ecology, landscape, historical setting and history of abstraction are described comprehensively in Annex A for the Darent catchment. An ecological database is presented as an appendix to Annex A.

The main report proposes water quality and flow objectives. A preliminary minimum flow target from Otford to Hawley is set as 10 Mld increasing downstream to 40 Mld. Various options for alleviation were costed. The following options were recommended for further consideration in later stages of the study:

- river regulation using the main Longford Lake, utilising a possible 3 m drawdown of lake levels;
- ceasing abstraction at Lullingstone and Eynsford with replacement by supplies brought in via a proposed London Ring Main;
- redistribution of abstraction within the catchment, away from the immediate vicinity of the river, in periods of low flow.

Augmentation of flows using Chalk groundwater was dismissed on the grounds that this would place further demands on an already highly developed aquifer. Furthermore it would represent poor resource management since the water would be lost downstream of Hawley. Aquifer recharge using surplus flows in winter and river support, with high quality effluent pumped into the catchment from Dartford, were dismissed on grounds of excessive cost. River water recirculation was shown not to be technically feasible as the river loses water progressively downstream below Lullingstone.

In the Final Report (April 1988), the Main Report (Volume 1) provides a general discussion of the types of solutions considered for all catchments included in the study. A brief summary is then provided for each catchment giving background, objectives, options considered and recommendations. The case study for the Darent (Volume 2 of the Final Report) follows a similar format. A considerable number of options are discussed, both those covered in the Interim Report and additional options resulting from further investigation. Four options are then costed.

The report redefines flow objectives, following an improved assessment, as being maintenance of a target flow of 30 Mld throughout the reach from Otford to Hawley, reducing to 20 Mld in severe drought conditions. It is argued that a target flow profile following a presumed natural pre-abstraction increase in flow in a downstream direction in this reach could only be achieved by cessation of groundwater abstraction. The report recognises as objectives a need to restore some of the previous wetland in the valley bottom where possible and the opportunity afforded by study implementation to engineer river cross-sections to suit flows, and to restore mill ponds.

In considering options there is reiteration of the arguments concerning schemes already discussed at the interim stage. The reliability of a surface water supply source with normal 7 day bankside storage located in the Dartford area is considered. The report concludes that reliability would be much lower in drought conditions than that of the groundwater sources within the catchment which it would be intended to replace. Reliability of supply could be increased by provision of a reservoir but this would increase the cost enormously. The option was not considered further.

Redistribution of abstraction away from the immediate vicinity of the river in the summer was considered favourably at the interim stage. However in the Final Report, the option is not considered for detailed costing owing to uncertainties in the consequent resurfacing of springs along the river. Halcrow also considered that the relocation of sources would have a greater benefit for the river in winter. This option however needs to be modelled in detail to assess the seasonality of benefits to flow.

Through comparison of recharge and abstraction for aquifers within the catchment, Halcrow concluded that the Folkestone Beds, part of the Lower Greensand aquifer (see Chapter 3) were little developed for public water supply abstraction. An additional option was therefore introduced with river augmentation using groundwater from the Folkestone Beds. The possibility of using river bed lining to prevent bed leakage between Lullingstone and Hawley was included in options for costing.

Options for which detailed costings are given include one or more of the following elements:

- flow preservation through river bed lining;
- augmentation using Folkestone Beds groundwater;
- river regulation using main Longford Lake storage;
- cessation of pumping at three major pumping stations above Hawley with replacement by water from the London Ring Main, necessitating development of links within the London water supply network.

It was assumed that any existing abstraction not subject to closure as part of the option, would be maintained at the rate of abstraction in 1986 ie at about 70% of full licensed rate. The cost of alternative means of making up supply to the full licensed rate (on the assumption of increase in demand) was included in all options. Costs attached to alternative sources of supply were found to be very expensive in relation to river regulation, augmentation and flow preservation. A scheme involving all three of these latter options was assessed as meeting target flows. It was preferred on the basis of lower cost to options involving cessation of pumping as cessation of pumping required provision of even larger alternative supplies at a very high cost.

The study involves a lengthy discussion of effects of implementation of options on the riparian environment, fisheries, landscape and amenity value. Opportunities for enhancement, with public accessibility, are included together with sketches of landscaping features. Preliminary designs for engineering components of the recommended scheme are also given.

The implementation report (February 1989) contains a useful review of river bed lining and materials used in other lining schemes which could have application for river bed lining. General implementation requirements for proposed schemes in all six catchments are discussed. These include trials with river bed lining materials and liaison with land owners, local authorities and local population. This section is followed by detailed discussion of approach for the schemes recommended in the Final Report. Each of the catchments, including the Darent, is discussed separately. Implementation programmes are then presented.

In the review of bed lining the report discusses in some detail the case of lining in the Gussage Brook, a tributary of the River Allen, in Dorset. The main objective in the case of the Gussage Brook was to ensure efficient conveyance of water from compensation boreholes to the River Allen. The brook was fenced to prevent lining damage by cattle and weed-cutting along the channel has therefore been necessary. This has maintained conveyance within a shallow depth of water and thus prevented overtopping of the lining and loss of compensation water. As a result, the report states that 'In places the stream has the appearance of a fast flowing canal rather than a natural watercourse; the management regime drastically curtails the diversity of plant and animal life in the Gussage Brook corridor'.

The report recognises that in the case of the River Darent 'bed lining is proposed as a means of partially restoring the ecological and landscape value' and that 'hydraulic design should allow for weed growth in the river bed and bank at low flows'. The section of the report concludes that the Gussage Brook project has shown that a stream bed can be sealed against leakage; lining work could be combined with vegetation and habitat diversity if taken into account during detailed design.

2.3.4 Environmentally Acceptable Flow Regime Study (Atkins)

The report defines the environmentally acceptable flow regime (EAFR) as 'flows that will maintain the biological and general environmental integrity of the river under other than natural discharge conditions'. An EAFR was derived using a methodology involving:

- a survey of macroinvertebrates, site characteristics, flow and water quality at nine sites between Westerham and Wilmington in October 1990;
- the River Invertebrate Prediction and Classification System (RIVPACS) to predict the type of invertebrate community which would be expected at the sites under natural flow conditions for comparison with survey results;

- statistical analysis of flows and broad assessment of sub-catchment areas contributing recharge to the Chalk groundwater system.

Following the field survey and RIVPACS analysis a survey site at Shoreham (Figure 1.1) was identified as being the most downstream location at which the macroinvertebrate community remained unaffected despite flow depletion. Further downstream communities were severely affected. The location at Shoreham was then used as an index site assuming that the flow regime was just managing to maintain biological and general environmental integrity at that site.

A flow duration curve was established for Shoreham based on flow characteristics at gauging stations up and downstream at Otford and Lullingstone and the flows measured on the day of the survey. Mean flow and the flow exceeded 95% of the time at Shoreham were determined from the flow duration curve. These flows were established as mean and minimum values for the EAFR at the site.

An assessment of river channel widths using field survey data indicated that, contrary to expectation for a natural river channel, widths decreased downstream of Shoreham. A possible explanation was considered to be that the channel has adjusted to accommodate substantially depleted flow. One approach to establishing an EAFR for the catchment using channel width characteristics was therefore rejected. It was considered that such an approach would produce an EAFR in part reflecting the abstraction pattern in the catchment.

The mean value of EAFR at the other survey sites was determined using mean effective rainfall at Shoreham and contributing surface water catchment area at each site. The effective rainfall, expressed as a depth over the contributing catchment at Shoreham, is the portion of rainfall which contributes to the defined mean EAFR through surface runoff, interflow and recharge after allowance for all losses, including abstraction.

With a mean environmentally acceptable flow defined at each site, ninety-fifth percentile flows were determined from Otford or Lullingstone type flow duration curves appropriate for each individual site. The catchment EAFR was hence defined by mean and ninety-fifth percentile (minimum) flows at the survey sites between Westerham and Wilmington.

The limited survey work carried out over a short period in 1990, did not provide data from which seasonality could be built into the catchment EAFR. Seasonality of flows is discussed however, with the comment that seasonal variation in EAFR should 'mimic' the pattern of seasonal variation in the natural flow regime. The report discusses the general difficulties of defining an EAFR and the early stage of development of this approach to catchment management. The need for further investigations is recognised.

2.3.5 Other Reports and Papers

Various additional reports and papers have been reviewed during this stage of the investigation. These include:

- 'The development of a lumped parameter model to simulate the leakage from rivers', by Allam (1983), which includes simulation of flows in the Darent;
- 'A Vale in Kent' by Rogers (1955), which contains useful historical background for the catchment;
- 'Water Supply of Kent' by Whittaker (1908) which has details of wells and springs;
- 'Kent Rivers Hydrological Survey' produced by the Ministry of Housing and Local Government (1964) has a list of abstractions for the early 1960s;
- 'Groundwater recharge of sewage effluents in the UK' by Montgomery, Beard and Baxter (1984) which provides details of existing sewage recharge schemes, the largest of which is at Winchester.

Allam (1983) refers to 19 tubewells constructed close to the Darent and includes a map and plans indicating the location of 14 of these at four sites between Lullingstone and Hawley. The report indicates monitoring in the late 1970s/early 1980s but no basic piezometry data are presented. However the report contains a further reference by Allam entitled 'Augmentation of the River Darent', a Thames Water Internal Report (Nr 64). It is recommended that this report be obtained, if still available, possibly through NRA (Thames Region). The site plans will be used in an attempt to locate the boreholes in the field. Allam also presents seven flow accretion profiles from Lullingstone to Hawley for the period 1981/82.

M Mansell-Moullin, who acts as adviser to the Darent River Preservation Society, has contributed many ideas and comments relating to river management, the options for alleviating low flows and the development of an EAFR which takes into account all aspects of river life and environment.

2.4 Historical Development

In the Interim Report, Annex A - River Darent Case Study, dated May 1987, Halcrow provides an excellent historical survey, mentioning known records of river flows, fishing, water mills, watercress farms and remains of water meadows, and then gives a general account of river ecology.

It is hard to improve on this survey, as Halcrow covered the whole of the river within the background study, partly because many quoted references to the river and its fisheries apply to the whole of the Darent. In addition, it specifically covers the eight miles upstream of Otford in the catalogue of water mills (starting at Westerham) and in its general description of the catchment.

For the reach of the Darent upstream of Otford, fed both from the Lower Greensand and the Chalk, there is plenty of literature to support its past importance as a stream and to validate the need to sustain this upstream reach as part of the overall strategy for the river.

Elizabeth I's archivist, William Lambarde, wrote in 1576 that the Darent 'rises from two fountains, the one appearing near the edge of our Shyre at Squyrreys in Westram ... the other at Tittesey in Surrey'. William Camden in his 'Britannia' of 1586 described the 'River Darent, which coming down from Surrey, flows gently not far from Sevenoak'. Hasted, in his history of Kent published in the late eighteenth century, describes the upper reach of the Darent in detail as follows:

> 'having crossed the high road at the end of Westerham Street, it runs north-east and east by Valence to Brasted, soon after which it separates into two streams which pass by Sundridge ... hence they run to Chipstead where the road crosses them on two bridges; soon after they unite again in one stream, which then passes on to Riverhead'

The old route of these split streams is now partly obscured by the gravel pits of the Longford Lakes.

The flows in these upper reaches were well attested in Hasted's time. The fine print of Westerham Mill published by G Samuel in 1818 shows an extensive mill stream, while there is also a contemporary print of the long pond at Westerham where children bathed and carters came to cool their horses. A century earlier, John Witney who lived at Coombe Bank between Brasted and Sundridge published a poem called 'The Genteel Recreation, or the Pleasure of Angling' (1700) in which he celebrated the trout fishing of his local stream. The fish pond he created survives below the present school. In addition, Witney has an interesting line:

> 'Down through the Moors to Otford gently go'.

Moors was the common expression for wetlands or marshes and it is reasonable to assume that the valley bottom now dominated by Longford Lakes were marshlands or at least very damp pasture 200 years ago. This was probably an extension upstream of the notoriously damp valley bottom at Otford where the palace rejected by Henry VIII as being 'lowe and ... rewmatike ... where I colde never be without syekness' and which was also considered unfit for Queen Elizabeth because 'it standeth in a very wett soyle, uppon springes and vantes of water contynually ronnynge under yt'.

Scraps of the old wetland habitat survive in the Darent valley and are vulnerable to low flows, both through direct drying up and through ploughing, which is encouraged as the land gets drier. In addition to the records mentioned in the Halcrow reports, the Kent Trust for Nature Conservation has records of a species-rich meadow near the source of the Darent, a meadow known as the Laundry Field at Lullingstone Castle which supports ragged robin, *Lychnis flos-cuculi*, a few scattered locations for meadow saxifrage, *Saxifrage granulata* in damp pasture and churchyards as at St Johns Jerusalem, and a location for marsh sow thistle, *Sonchus palustris* below Dartford.

The largest wetland habitats in the upper Darent are, however, the twentieth century gravel pits which have been developed in the valley close to Sevenoaks. The margins of these support thickets of willow which in some areas may be survivors from earlier osier beds. The lakes support heron, mallard, teal, widgeon and great crested grebe. The furthest downstream of this chain of lakes is the Sevenoaks gravel pit reserve. This is an example of pioneering habitat management in association with abandoned gravel working. It was the creation of Jeffery Harrison of the British Association for Shooting and Conservation, who started the reserve in 1956 in co-operation with Redland Ltd. It has been extensively studied and has attracted such spectacular rarities as osprey and avocet while supporting large populations of wildfowl and waders. The BASC publication 'The Sevenoaks Gravel Pit Reserve' (1974) is a good introduction to the site.

2.5 Public Perception

At this stage of the investigation public perception of the state of the river has been assessed mainly through contacts with members of the Darent River Preservation Society and a public meeting held by the society on 15 March 1991. A small exhibition was staffed at the meeting and formed a focus for useful informal discussion with members of the public and society members attending. The questionnaire indicated in Figure 2.1 was distributed and 87 completed copies returned. This has provided a very useful insight into public concerns for the river.

Certain obvious qualifications need to be made about the results of the questionnaire in terms of the particular occasion when the form was filled in. Inevitably, those who attended the meeting were not so much a random cross-section of the community as a selection of the more interested members of the public including active members of the Darent River Preservation Society. In addition, because the meeting was held at Eynsford it would have been expected to attract more people from that locality than from the uppermost reaches of the river.

The questionnaire set out in Figure 2.1 shows the number of responses to each option and the percentage of people who chose each option.

Additional information was as follows:

- under question 3, particular locations of concern were Kingfisher Bridge area, Eynsford, Shoreham, Otford to Shoreham, Lullington Lake, Hill House, Farningham, Otford, South Darent, Shoreham to Eynsford, Sevenoaks to Shoreham, West Minster Fields, Horton Kirby and Horton Kirby to South Darent;

- under question 4, specific concerns for the river, in addition to those items listed in the questionnaire, were 'to maintain character of valley', 'work in environmental studies', 'character of valley' and 'abstraction';

Questionnaire on Low Flows in the River Darent

To assist with our survey of public concerns for the river, please complete as much of this Questionnaire as you wish. Please tick more than one box per question if appropriate

1) Do you live

on the river	22	25%
within easy walking distance of the river	56	64%
within the Darent Valley	5	6%
elsewhere	4	5%

2) How long have you lived in the Darent valley

since 1980	40	46%
since 1960	9	10%
from before 1960	34	39%
not applicable	4	5%

3) Is your main concern for the area of the river from

Westerham to Sevenoaks	2	2%
Sevenoaks to Farningham	38	44%
Farningham to Dartford	27	31%
Whole river	59	68%
a particular location (please specify)		

4) Is your concern for the river connected with

your home	22	25%
your work	8	9%
a particular recreational interest	29	33%
an ecological interest	68	78%
the historical landscape	45	52%
pollution	29	33%
natural visual appearance of the river	70	80%
other, please specify		

5) Is your recreational interest in the river

walking	63	72%
fishing	15	17%
bird watching	41	47%
ecology	41	47%
sailing/boating	1	1%
picnicing	7	8%
enjoyment of Darent villages	52	60%
other, please state		

6) How often do you visit the river

daily	57	66%
weekly	26	30%
monthly	3	3%
quarterly		
less frequently	1	1%

If you wish to provide further information on long term changes to the river over the past 25 years or more, please give

Name: Tel. No:

- under question 5, recreational interests, other than those already itemised in the questionnaire were 'garden', 'beauty of our village', 'quality of life', 'farming hobby', 'beauty, bathing, boating', 'living beside Darent', 'children paddling'.

Out of the results some interesting trends and patterns emerge: 64% of people live within easy walking distance of the river. Those who had lived in the Darent Valley since 1980 comprised the largest category of residents with a score of 46%, while 39% had lived in the valley since before 1960. Among concerns for the river, 'natural visual appearance' interestingly received the highest number of ticks (70) followed closely by 'ecological interest' at 68. The 'historical landscape' was next in the order of concern with 45, while 'particular recreation' received a relatively low score of 29. Within the next section, this trend towards passive recreation was confirmed with the highest score (63) for walking, followed by 'enjoyment of Darent villages' at 52. Fishing only received a score of 15 and boating 1. The majority of people visited the river daily (57).

A picture then emerges of a general concern for the River Darent as something to be seen and often walked beside as a generally passive but important part of everyday life. While people were obviously concerned about their immediate local reach, the high score of 59, under question 3, shows that people value the whole river as an important feature of the Darent Valley.

Additional concerns and attitudes were usefully expressed during the meeting of 15 March. It was regretted that numerous small weirs had been removed in the past by drainage activities and their reinstatement, it was felt, would improve the fishing and help to make the most of the existing water. General support for water metering was expressed, together with concern that golf courses were using too much water.

CHAPTER 3

HYDROGEOLOGY

3.1 Data Availability

3.1.1 Geology

Sufficient geological data on the River Darent catchment are available to determine the regional geological structure of the study area. The hydrogeological map of the Chalk and the Lower Greensand of Kent (IGS, 1970) provides a useful source of information. It gives contours of surfaces such as the top of the Upper Chalk and of the Lower Chalk, and of the thickness of the Folkestone Beds and the Hythe Beds.

Information on the other geological formations can be found in the descriptions of about 30 deep boreholes in the region. The sources of these data are :

- Records Section of the British Geological Survey;
- Thames Water Utilities;
- Mid Kent Water Company;
- West Kent Water Company.

Although the lithological descriptions in the borehole logs are not very detailed, they provide an estimate of the otherwise unknown thicknesses of the following layers :

- Lower Chalk;
- Upper Greensand;
- Gault Clay;
- Sandgate Beds.

Descriptions for some old boreholes are given by Whitaker (1908).

3.1.2 Groundwater Levels

Data are available for 30 observation boreholes in the study area. The locations are shown in Figure 3.1. The boreholes have been monitored by various authorities and companies, and were functional during different periods in the past. Details of these boreholes are given in Table 3.1. Most are located in the central part of the River Darent catchment in the central area of the Chalk outcrop.

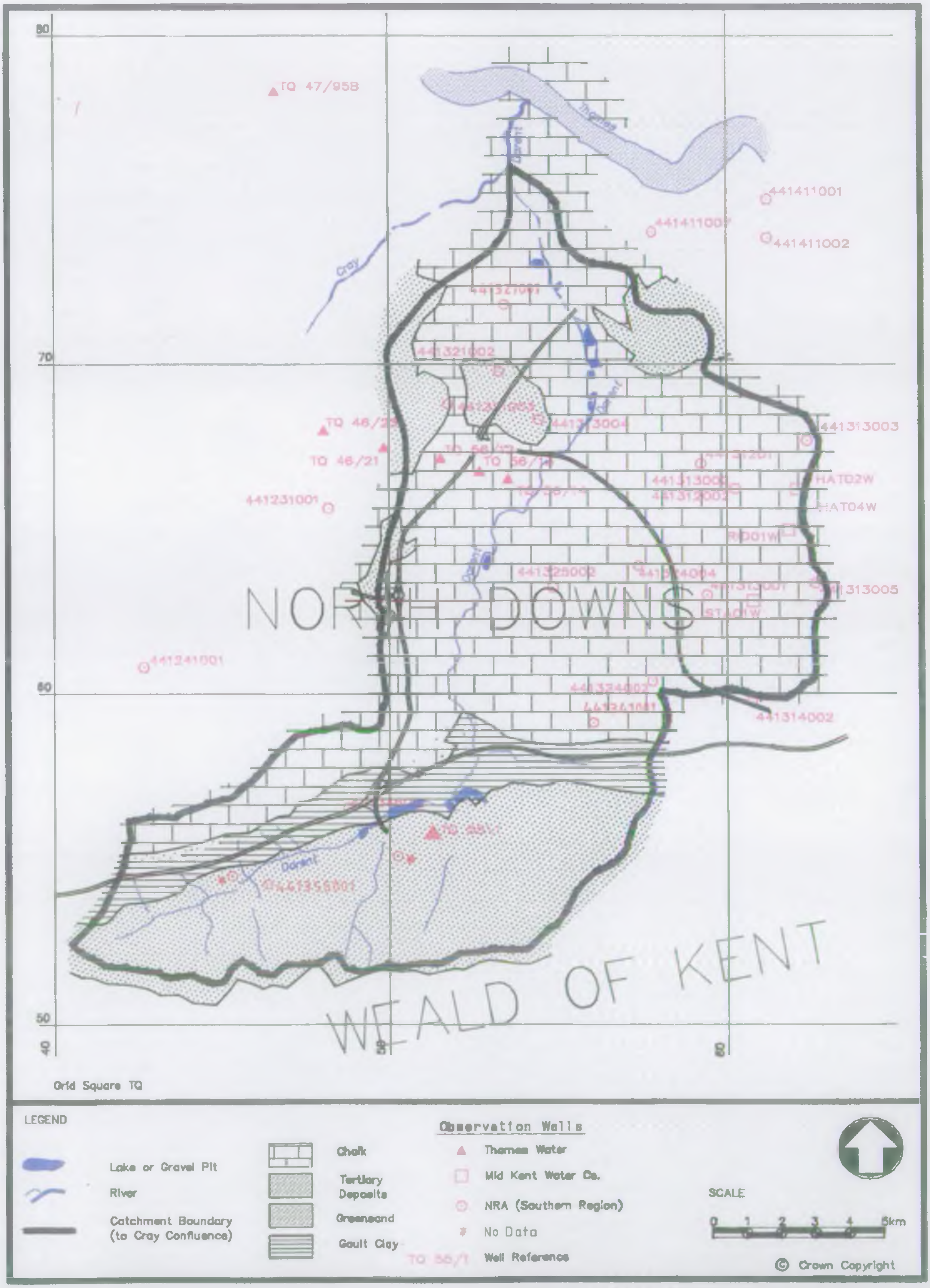
Table 3.1

Observation Borehole Details

WELL REFERENCE	LOCATION	GRID REFERENCE	AQUIFER	DATE	SOURCE
TQ46/23	Sweeps Lane, Kevington	TQ47606790	Chalk	1957-1989	Thames Water Authority
TQ55/1	Riverhead	TQ50655637	Hythe Beds	1962-1989	Thames Water Authority
TQ56/12	Crocken Hill No. 3	TQ50846724	Chalk	1955-1989	Thames Water Authority
TQ47/95B	East Wickham WX	TQ48467724	Basal Sands	1989-1990	Thames Water Authority
TQ46/21	Crouch Farm	TQ49396743	Chalk	1957-1989	Thames Water Authority
TQ56/14	Hulberry Eynsford	TQ52706658	Chalk	1961-1989	Thames Water Authority
TQ56/13	Wested Farm Crockenhill	TQ51866688	Chalk	1957-1989	Thames Water Authority
441325002	Eynsford Lower Austin Lodge	TQ53816377	Chalk	1963-1981	NRA (Southern Region)
441346001	Chevening Kitchen Garden	TQ48415774	Chalk	1972-1991	NRA (Southern Region)
441411002	Western Cross Quarry	TQ59367333	Chalk	1968-1970	NRA (Southern Region)
441411007	Salisbury Road, Dartford	TQ56367347	Chalk	1972-1991	NRA (Southern Region)
441411001	Empire Paper Mill	TQ59357437	Chalk	1973-1985	NRA (Southern Region)
441321002	Highlands Farm	TQ52366966	Chalk	1968-1991	NRA (Southern Region)
441321003	Swanley Secondary School	TQ51026872	Chalk	1968-1990	NRA (Southern Region)
441324002	Knotts Valley, West Kingsdown	TQ56486124	Chalk	1961-1991	NRA (Southern Region)
441324004	Maplescombe Farmhouse	TQ56006431	Chalk	1961-1991	NRA (Southern Region)
441231001	Alma Cottage	TQ47926592	Chalk	1968-1991	NRA (Southern Region)
441241001	Petleys Downe	TQ43036157	Chalk	1968-1989	NRA (Southern Region)
441312001	School Lane, Horton Kirby	TQ57716710	Chalk	1981-1991	NRA (Southern Region)
441313002	6 Acre Cottages, Fawkham	TQ58596641	Chalk	1968-1980	NRA (Southern Region)
441312002	6 Acre Cottages, Fawkham	TQ58596641	Chalk	1980-1990	NRA (Southern Region)
441313001	Church woods, West Kingsdown	TQ57886353	Chalk	1981-1991	NRA (Southern Region)
441313003	Hartley Cottage, Hartley	TQ60376780	Chalk	1962-1981	NRA (Southern Region)
441313004	Hop Pole Inn	TQ53406838	Chalk	1968-1991	NRA (Southern Region)
441313005	Pease Hill Cottage, Ash	TQ60666388	Chalk	1967-1991	NRA (Southern Region)
441314002	Terrys Lodge Farm	TQ59016064	Chalk	1968-1981	NRA (Southern Region)
441321001	Clement St Nurseries	TQ54107060	Chalk	1971-1991	NRA (Southern Region)
441341001	Walnut Tree Cottage	TQ57115876	Chalk	1990-1991	NRA (Southern Region)
441355001	Foxwold Brasted	TQ466556	Lower Greensand	1972-1991	NRA (Southern Region)
Not known	Hosey Hill (approx)	TQ456559	Lower Greensand	No data	NRA (Southern Region)
Not Known	Manor Farm (approx)	TQ503511	Lower Greensand	No data	NRA (Southern Region)
STA01W	Stansted	TQ606629	Chalk	1988-1991	Mid Kent Water Company
RID01W	Ridley	TQ614649	Chalk	1988-1991	Mid Kent Water Company
HAT04W	Hartley	TQ616664	Chalk	1988-1991	Mid Kent Water Company
HAT02W	Hartley	TQ616664	Lower Greensand	1990-1991	Mid Kent Water Company

Figure 3.1

Observation Well Locations



Coverage of the north-western part of the region where Thanet Beds outcrop, the southern part of the Chalk and the Lower Greensand outcrop, is poor. It is also evident that very few of the boreholes are located in the Darent valley itself. Although a number of observation boreholes have been constructed in the valley (Allam, 1983), no data are available.

Figure 3.2 shows the availability of the piezometric data from the different observation boreholes in the catchment. For the Lower Greensand, only two hydrographs, one covering the period 1962 to 1989 and the other covering the period 1989 to 1991, are available. The following piezometric maps are also available:

- estimated minimum groundwater levels in the Chalk (IGS, 1970);
- estimated minimum groundwater levels in the Folkestone Beds (IGS, 1970);
- estimated minimum groundwater levels in the Hythe Beds (IGS, 1970);
- low Chalk groundwater levels, summer 1984 (TWA);
- high Chalk groundwater levels, winter 1984-1985 (TWA);
- Chalk groundwater levels, January 1966 (TWA);
- Chalk groundwater levels, autumn 1944 (TWA).

3.1.3 Test Pumping

Data on four recent pumping tests in the Chalk aquifer, carried out by the Mid Kent Water Company, are available. Details of these tests are given in Table 3.2.

TABLE 3.2

Test Pumping Data

Well	Test type	Date	Aquifer
Hartley Pump Station	Constant rate	07/07/89	Chalk
Hartley Nr 6B	Constant rate	22/01/91	Chalk
Hartley Nr 5	Step test	08/05/90	Chalk
Hartley Nr 6	Step test	19/01/91	Chalk

In the archives of the British Geological Survey, data were found for an old step test in the Chalk at Mardyke Meadows, Aveley (July 1955), carried out by the Thames Board Mill Ltd. Some other yield/drawdown data for wells in the River Darent catchment are available in these archives. Data for a pumping test in the Lower Greensand aquifer are available in a report for the TWA (Dossor, 1978). No other pumping test data have been found.

3.1.4 Groundwater Abstraction

Details of licensed abstraction returns have been obtained from the NRA. Pre-1989 records are in the form of approximately 500 microfiche files compiled originally by TWA. Recent records are held in computer files. The records include licence numbers, location, purpose and use, licensed quantities and returns. The location of the licensed groundwater abstractions greater than 50 Ml/year are shown in Figure 3.3.

Information on non-licensed, small scale abstractions, which are mainly for domestic use, have been obtained from Dartford Borough and Sevenoaks District Councils. The abstractions are not significant in terms of catchment water balance. However the abstraction locations are being investigated as potential groundwater monitoring points.

3.2 Geology

The outcrop of the Chalk in the central part of the Darent catchment forms the main geological feature in the study area, as shown in Figure 3.4. It forms a well defined escarpment in the southern part of the catchment, from which the Chalk dips gently to the north. South of the Chalk escarpment, the Gault Clay and the Lower Greensand outcrop in succession. The northern part of the catchment is characterised by the outcrop of Tertiary formations, mainly the Thanet Beds with minor local occurrence of Blackheath Beds and Woolwich Beds. Two geological cross-sections through the study area, in a NE-SW and a NW-SE direction, are shown in Figure 3.5.

The stratigraphic succession, which is summarised in the legend in Figure 3.5, is described below.

Superficial deposits include gravels and alluvium. Gravels in the study area flank the river valleys and cap the high ground, while the alluvium of varying extent, is deposited in the main river valleys.

In the catchment, the Tertiary formations comprise :

- The Blackheath Beds, consisting mainly of fine sand with a pebble bed, and varying in thickness from 0 to 25 m;

- The Woolwich Beds, consisting of loam and clay, and forming an aquitard which isolates the minor aquifer of the Blackheath Beds from the Thanet Beds and the Chalk aquifer. Its thickness is small, ranging from 0 to 10 m;

- The Thanet Beds, consisting of poorly cemented sands becoming silty downward, with a band of flint rubble at the base, and resting unconformably upon the Chalk. In the Darent catchment, the Thanet Beds are in direct hydraulic contact with the underlying Chalk. The thickness varies from 13 m to 45 m.

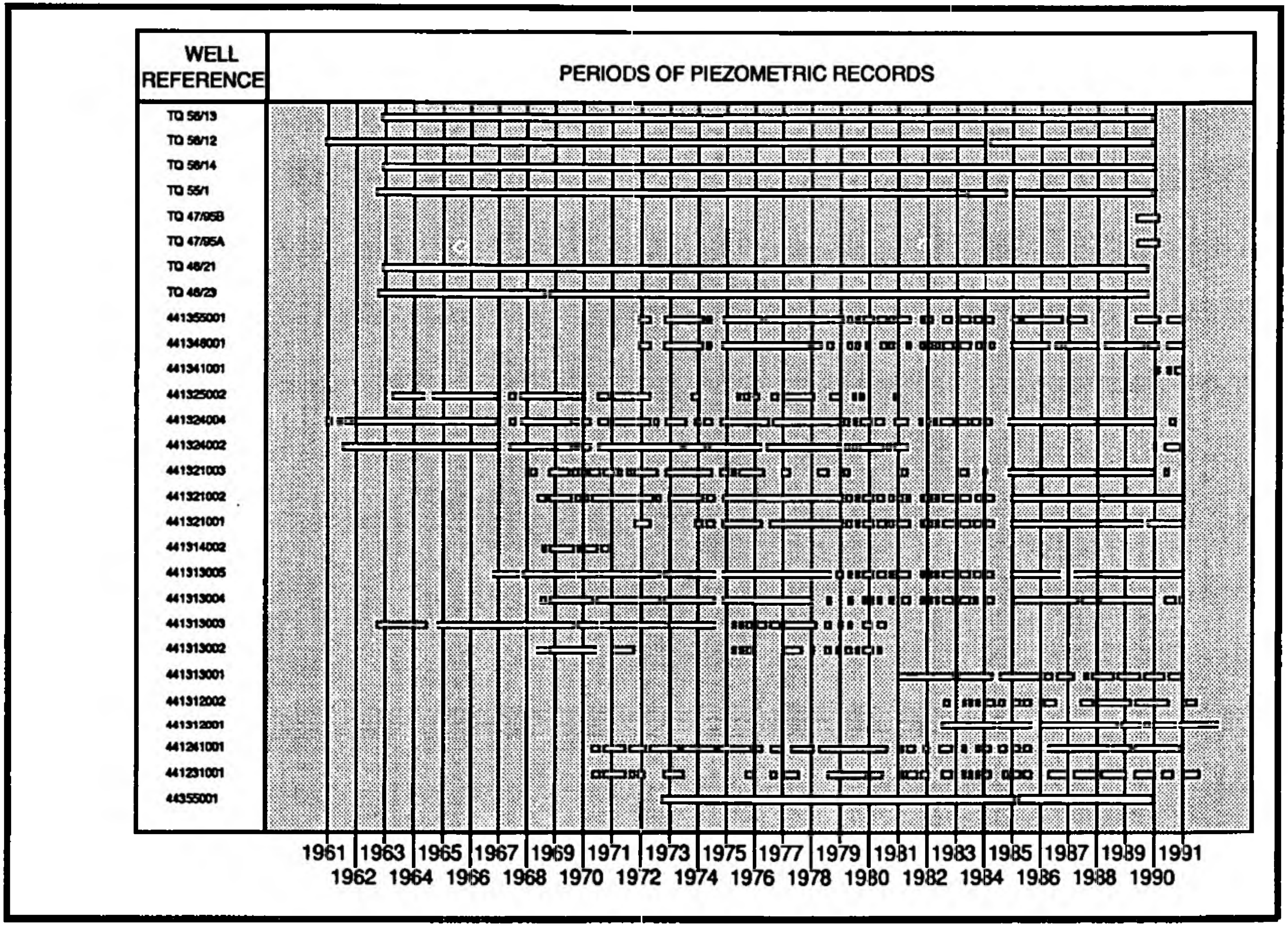


Figure 3.2

Availability of Observation Borehole Data

Figure 3.3
Abstraction Sources

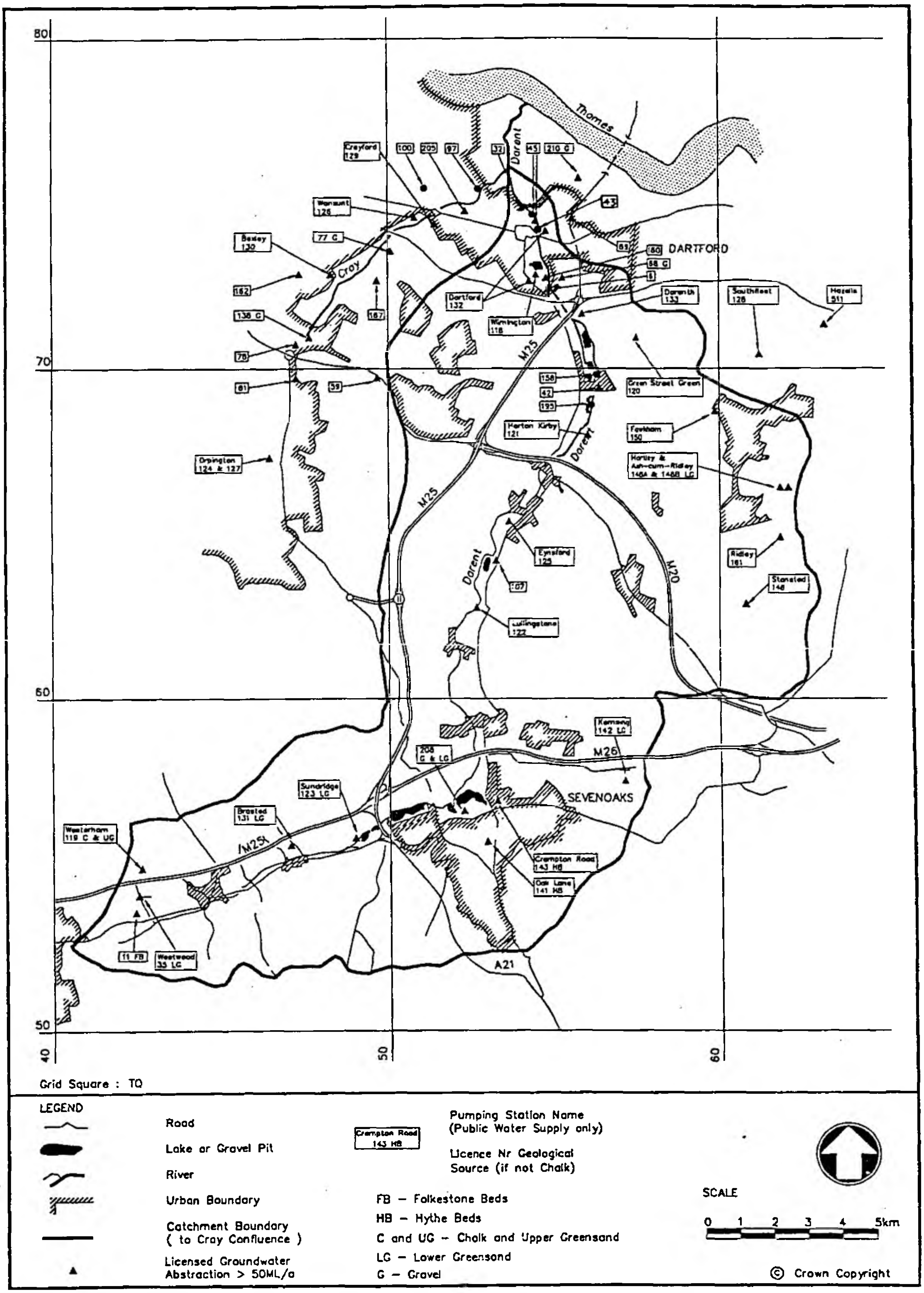


Figure 3.4
Location of Geological Sections

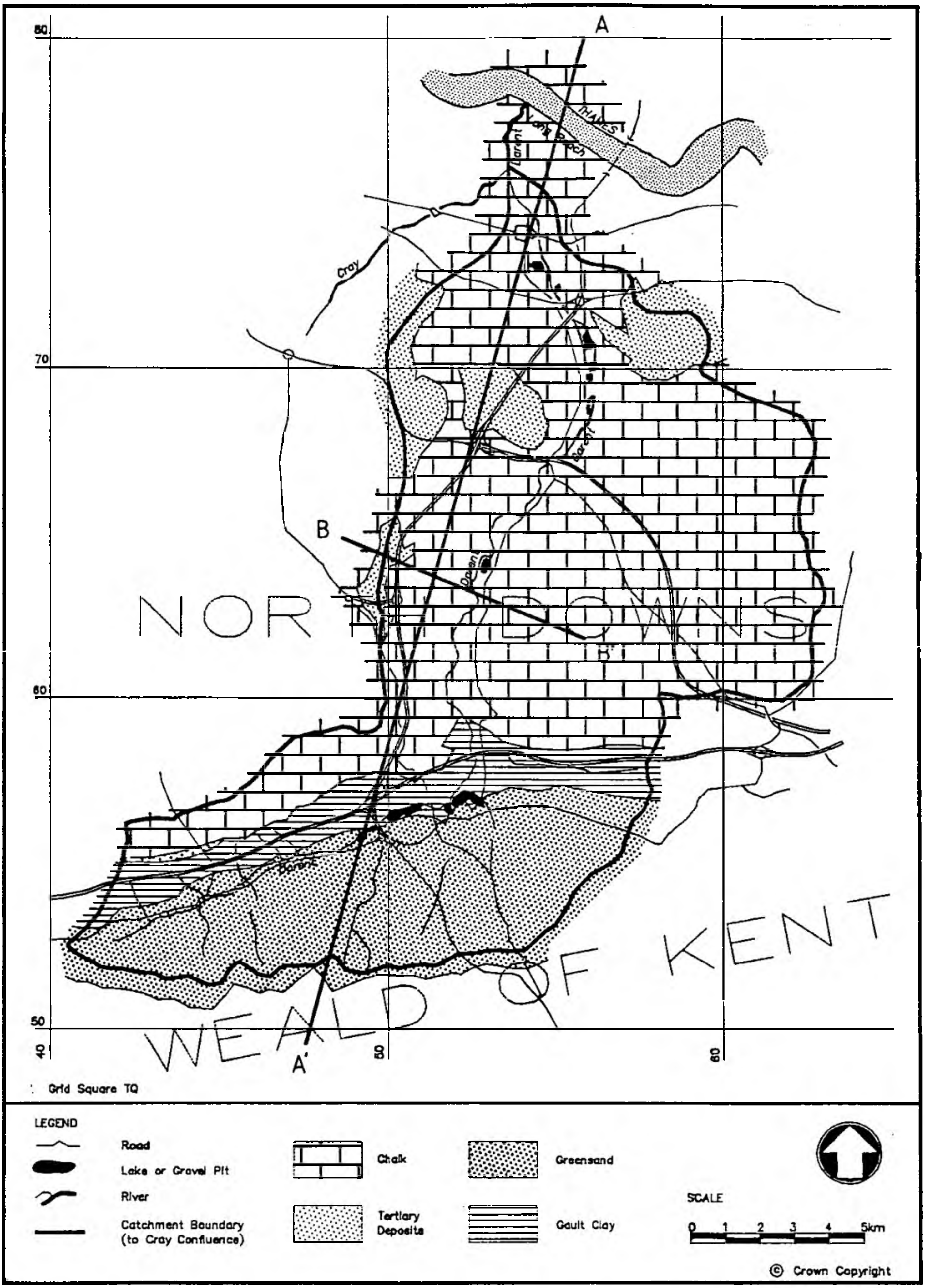
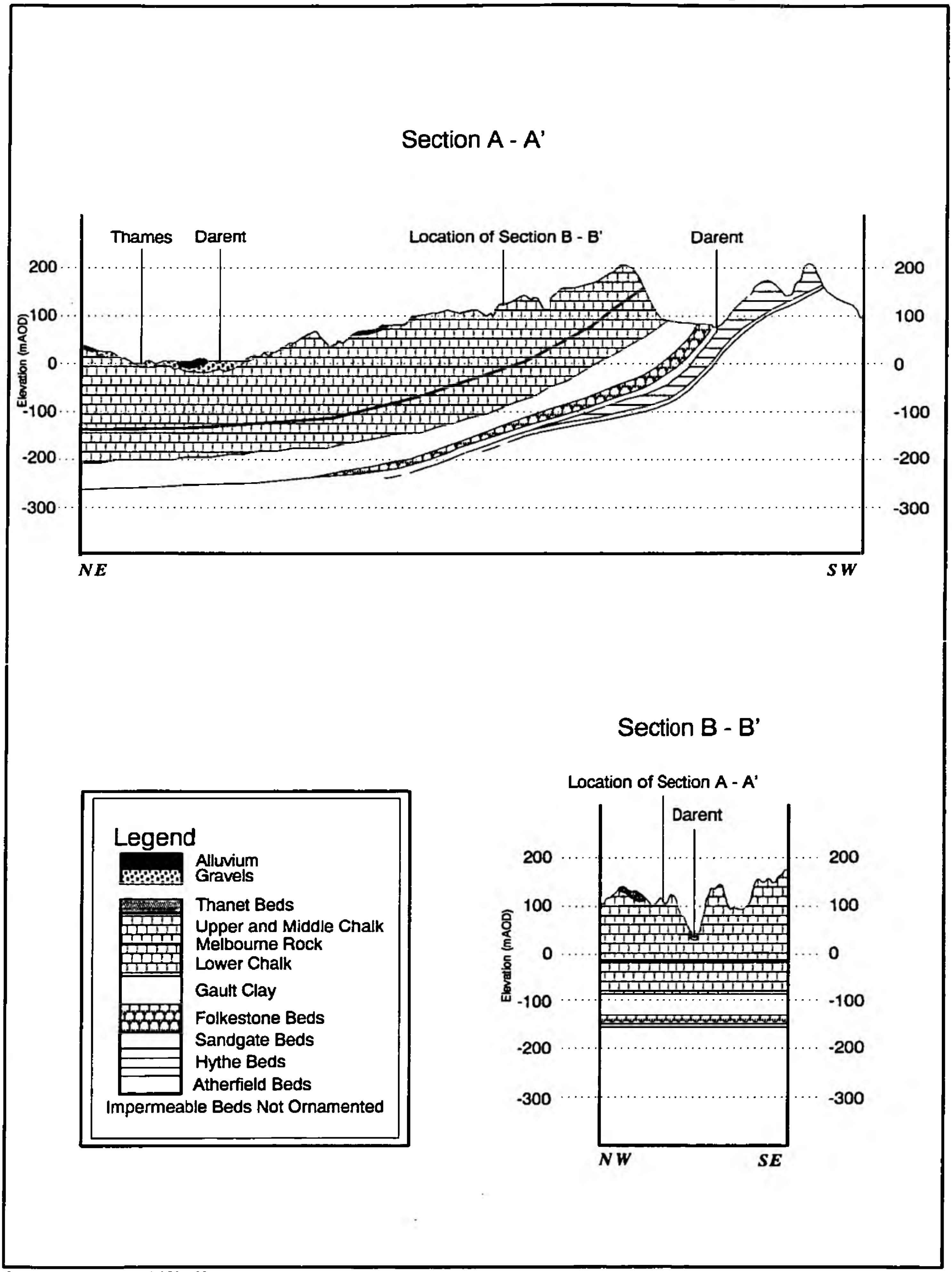


Figure 3.5
Geological Cross Sections



River Darent F:\HYD-TEC\DEC\GEOAASB1.GEM 26/06/91 By D. Cavaliere

The Chalk forms the most important aquifer in the study area. It is characterised by three distinct layers :

- Upper Chalk, varying in thickness from 80 m to 130 m, comprising a soft whitish microporous limestone with nodular and tabular flints. The base is marked by a hard nodular chalk bed;

- Middle Chalk, 60 to 80 m thick, resembling the Upper Chalk, but containing more marl and less flint. At its base, a hard nodular chalk bed, the Melbourn Rock, occurs. Both units are well fissured;

- Lower Chalk, 40 to 80 m thick, more marly than the Middle Chalk, and may be of low permeability near its base.

The Upper Greensand, a minor sandstone, underlies the Chalk. It is only present at the western edge of the catchment and has a thickness of a few metres.

The Gault Clay, a thick (40 to 110 m) and impermeable clay formation, forms an important aquitard between the Chalk aquifers and the underlying Lower Greensand aquifer.

The Lower Greensand consists of several distinct units:

- Folkestone Beds (0 to 70 m thick), comprising coarse to fine sands and sandstones with occasional clayey sands and sandy clays, forms a porous, non-fissured aquifer;

- Sandgate Beds (0 to 40 m thick), comprising silty clays and clays with subordinate fine sands and sandstones in some areas. This layer acts as an aquitard between the Folkestone Beds and the underlying Hythe Beds aquifer;

- Hythe Beds, between 0 and 60 m thick, comprising calcareous sand, sandstones and sandy limestones;

- Atherfield Clay (0 to 20 m thick) consisting of clays, locally silty and sandy, forms an impermeable base to the aquifer system in the study area.

3.3 Piezometry

Groundwater level hydrographs for two observation boreholes in the Chalk, one close to the river and the other located in the upper part of the catchment, are given in Figure 3.6. The hydrographs show the expected pattern of seasonal piezometric fluctuations, in response to the variation in rainfall and infiltration. The fluctuations are generally greater beneath the higher ground, remote from spring outflows along the river.

The Chalk aquifer is unconfined throughout most of the catchment. Where overlying Thanet Beds and underlying Upper Greensand are present, they are in good hydraulic contact with the Chalk aquifer.

The hydrogeological map of the Chalk and Lower Greensand in Kent (IGS, 1970) shows the regional piezometry of both the Folkestone Beds and the Hythe Beds in the winter of 1968. It is evident from this map that the two layers are hydraulically isolated from each other by the Sandgate Beds, and from the Chalk aquifer by the Gault Clay.

3.4 Aquifer Properties

3.4.1 Data Quality

Given the number of observation boreholes and abstraction wells in the study area, the scarcity of test pumping data, and therefore of aquifer parameter values, is surprising. The very few data available, mentioned in Section 3.1.3, do not allow a regional assessment of the parameters. The four pumping tests from the Mid Kent Water Company only allow the estimation of the aquifer properties at the Hartley site. The results of the step test from the Thames Board Mill Ltd are not easy to interpret since the pump discharge was not kept constant during each step. The specific capacity tests give only an approximate idea of transmissivity at a few locations because of the assumptions implicit in the analysis (using the Logan equilibrium approximation method).

3.4.2 Data Analysis

The available data were analysed using standard interpretation methods. The results are given in Table 3.3 and 3.4. None of the test data can be analysed to provide values of storage coefficients.

TABLE 3.3

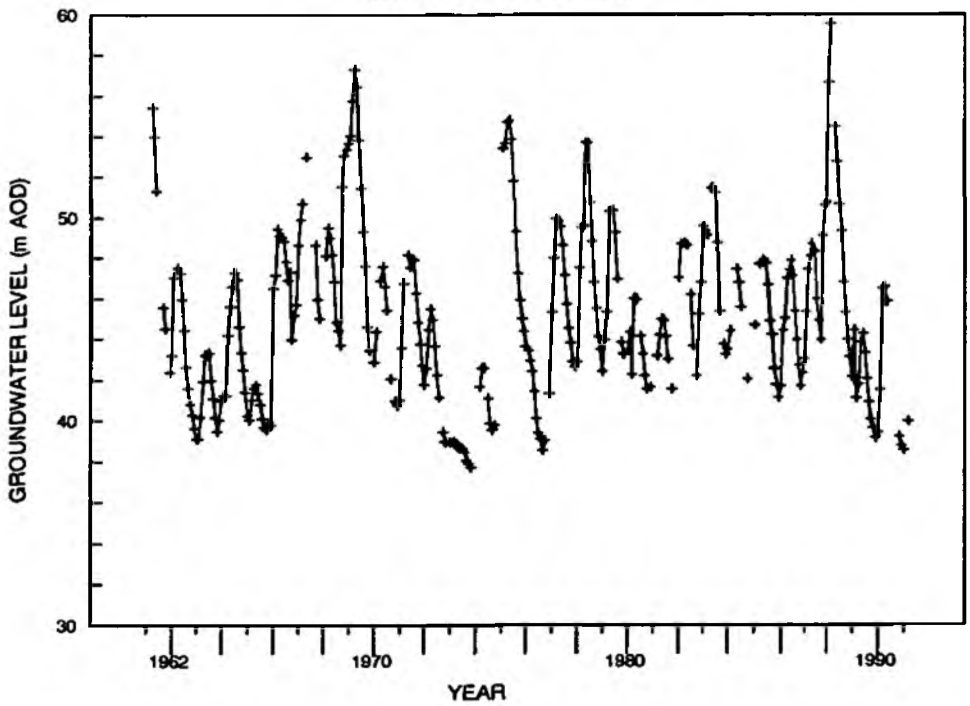
Analysis of Constant Rate Tests

Location	Aquifer	Borehole	Discharge (l/s)	Transmissivity (m^2/d)
Hartley PS	Chalk	Production well Observation well	10.7	104 171
Hartley Nr 6B	Chalk	Production well Observation well	11.4	140 142
Kemsing PS	Lower Greensand	Production well	24.4	493

Figure 3.6

Chalk Groundwater Level Hydrographs

Maplescombe Farmhouse
(441324004 - North Downs)



Eynsford Lower Austin Lodge
(441325002 - River Valley)

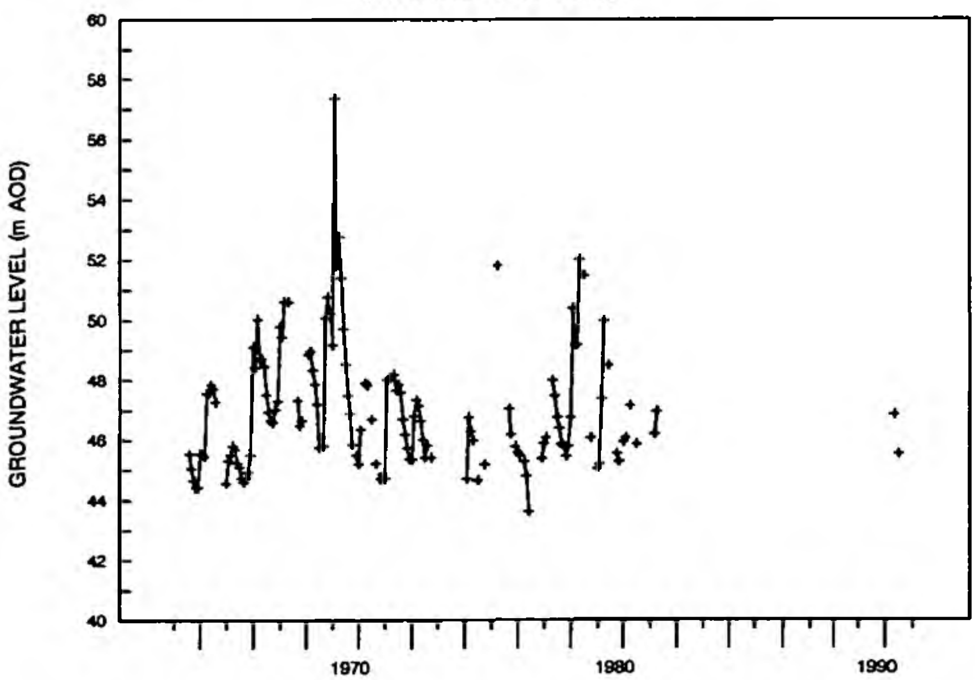


TABLE 3.4

Analysis of Step Tests

Location	Aquifer	Step	Discharge (l/s)	Transmissivity (m^2/d)
Hartley Nr 5	Chalk	1	3.8	97
		2	7.6	157
		3	12.0	69
		4	15.2	20
Hartley Nr 6	Chalk	1	6.3	56
		2	12.6	80
Averley	Chalk	1	17.7	1 403
		2	42.3	478
		3	64.3	219

It is evident that the calculated transmissivity values for the Chalk aquifer, with the exception of the Averley test, are very low. There could be several reasons for this eg, fissure flow is the main flow mechanism in the Chalk aquifer and Hartley is located in the upper part of the catchment, where the Chalk may be much less fissured and therefore less transmissive than in the river valleys.

Well performance tests on the Hartley Nr 5 borehole showed anomalous results, possibly because the well was still developing during the test and its efficiency was increasing.

3.5 Groundwater Abstractions

Details of the licensed abstractions for public and private water supply are given in Table 3.5. Their locations are shown in Figure 3.3.

Figure 3.7 gives more information on the availability of data on groundwater abstraction. It shows clearly that the abstraction records are reasonably complete from 1974 onwards, although there are gaps in some licence returns particularly for non-public water supply licenses after 1986. Few data are available for the pre-1974 period.

3.6 Water Quality

Chalk groundwaters are generally of good chemical quality and hard to very hard. Some saline intrusion has occurred within the aquifer along the Thames and in the vicinity of north Dartford.

Groundwater in the outcrop areas of the Folkestone and Hythe Beds is also of good quality. Problems of high iron content are fairly frequently encountered in Lower Greensand aquifers.

Table 3.5

Licensed Groundwater Abstraction Details

LICENCE NUMBER	NAME	GRID REFERENCE	SOURCE	LOCATION	USE	LICENCED ANNUAL TOTAL (CUBIC METRES)
1/0003/GR	R KLINGER	TQ477704	CHALK		IO	545520
1/0011/GR	TITSEY ESTATE CO.	TQ424537	FOLKESTONE BEDS		IGW	70918
1/0032/GR	WIGGINS TEAPE PAPERS LTD	TQ535752 TQ539748	CHALK		I	2000240
1/0035/GR	EAST SURREY WATER CO.	TQ424541 TQ425542	LOWER GREENSAND	WESTWOOD P.S.	PWS	2045700
1/0042/B/GR	HORTON KIRBY PAPER MILLS	TQ562694 TQ563694	CHALK		I	300036
1/0045/B/GR	WELLCOME FOUNDATION LTD	TQ543744 TQ546745 TQ545746	CHALK		I/IC	2273000
1/0059/GR	A VINSON LTD	TQ496697	CHALK		A	55565
1/0065/GR	COATES LORILLEUX	TQ468680	CHALK		IGW	65917
1/0068/GR	CLUBBS WASHED GRAVEL CO. LTD	TQ551727	GRAVEL		IGW	152609
1/0069/B/GR	WELLCOME FOUNDATION LTD	TQ544745 TQ554746	CHALK		I	1513818
1/0077/B/GR	BEXLEY SAND & BALLAST CO. LTD	TQ500735	GRAVEL		IGW	295490
1/0078/GR	SCHWEPPES (HOME) LTD	TQ472707	CHALK		I/IC	412786
1/0081/GR	WILLIAM NASH LTD	TQ472697	CHALK		I/D	120014
1/0107/GR	LULLINGSTONE WATER LTD	TQ531642	CHALK		PWU	
1/0118/GR	THAMES WATER UTILITIES	TQ543728	CHALK	POWERMILL LANE, WILMINGTON P.S.	PWS	6969018
1/0119/GR	THAMES WATER UTILITIES	TQ429558	CHALK & UPPER GREENSAND	PILGRIMS WAY, WESTERHAM P.S.	PWS	354588
1/0120/GR	THAMES WATER UTILITIES	TQ573709	CHALK	GREEN STREET GREEN, DARENTH	PWS	1659290
1/0121/GR	THAMES WATER UTILITIES	TQ558680	CHALK	HORTON KIRBY P.S.	PWS	4977870
1/0122/GR	THAMES WATER UTILITIES	TQ525628	CHALK	LULLINGSTONE P.S.	PWS	3318580
1/0123/GR	THAMES WATER UTILITIES	TQ490557	LOWER GREENSAND	SUNDRIDGE P.S.	PWS	4977870
1/0124/GR	THAMES WATER UTILITIES	TQ464673	LOWER GREENSAND	ORPINGTON	PWS	4977870
1/0125/GR	THAMES WATER UTILITIES	TQ535655	CHALK	EYNSFORD P.S.	PWS	6139373
1/0126/GR	THAMES WATER UTILITIES	TQ501741 TQ507745	CHALK	WANSUNT,BEXLEY	PWS	4977870
1/0127/GR	THAMES WATER UTILITIES	TQ464673 TQ459653	CHALK	ORPINGTON	PWS	4045940
1/0128/GR	THAMES WATER UTILITIES	TQ610704	CHALK		PWS	829645

PURPOSE	D=DOMESTIC	A=AGRICULTURE	PWU=PRIVATE WATER UNDERTAKING	H=HORTICULTURE
	SI=SPRAY IRRIGATION	I=INDUSTRIAL	IGW=AGGREGATE WASHING	IC=COOLING
	IO=OTHER USE	FF=FISH FARM	PWS=PUBLIC WATER SUPPLY	WC=WATERCRESS

Table 3.5 (continued)

Licensed Groundwater Abstraction Details

LICENCE NUMBER	NAME	GRID REFERENCE	SOURCE	LOCATION	USE	LICENCED ANNUAL TOTAL CUBIC METRES)
1/0129/GR	THAMES WATER UTILITIES	TQ513743 TQ515748	CHALK	CRAYFORD	PWS	4977670
1/0130/GR	THAMES WATER UTILITIES	TQ482728	CHALK	BEXLEY	PWS	19896208
1/0131/GR	THAMES WATER UTILITIES	TQ470557	LOWER GREENSAND	BRASTED P.S.	PWS	1663836
1/0132/GR	THAMES WATER UTILITIES	TQ546741 TQ541726	CHALK	OVERY ST.MARY, DARTFORD P.S.	PWS	1327432
1/0133/GR	THAMES WATER UTILITIES	TQ556719	CHALK	HAWLEY ROAD, DARENTH P.S.	PWS	7632734
1/0141/GR	WEST KENT WATER	TQ528558	HYTHE BEDS	OAK LANE P.S.	PWS	331858
1/0142/GR	WEST KENT WATER	TQ569576	LOWER GREENSAND	KEMSING P.S.	PWS	1659290
1/0143/GR	WEST KENT WATER	TQ531570	HYTHE BEDS	CRAMPTONS RD P.S.	PWS	6444682
1/0146/GR	MID KENT WATER CO.	TQ606629	CHALK	STANSTED	PWS	3739539
1/0148/A/GR	MID KENT WATER CO.	TQ616664	CHALK	HARTLEY	PWS	3739539
1/0148/B/GR	MID KENT WATER CO.	TQ616664	LOWER GREENSAND	HARTLEY & ASH-CUM-RIDLEY P.S.	PWS	827372
1/0150/GR	SOUTHERN WATER	TQ597687	CHALK	FAWKHAM P.S.	PWS	2491208
1/0160/GR	SAMAS VICKERS LTD	TQ546727	CHALK	FAWKHAM P.S.	I	98193
1/0161/ /G	MID KENT WATER CO.	TQ614649	CHALK	RIDLEY	PWS	3739540
1/0162/ /G	THE NATIONAL GRID CO. LTD	TQ473728	CHALK	FOOTSCRAY LANE COOLING STATION	IC	958370
1/0167/ /G	THE NATIONAL GRID CO. LTD	TQ496726	CHALK	VICARAGE ROAD, BEXLEY COOL STN	IC	958370
1/0182/ /G	THE NATIONAL GRID CO. LTD	TQ442724	CHALK	GREENWICH COOLING STATION	IC	399321
1/0205/ /	VICKERS FURNITURE LTD	TQ522747	CHALK	MAIDEN LANE	I	227300
1/0208/ /	REDLAND AGGREGATES LTD	TQ521567	GRAVEL & LOWER GREENSAND	BRADBOURNE GRAVEL PIT	I	3559512
1/0210/ /	NATIONAL POWER PLC	TQ556757	GRAVEL	LITTLEBROOK	I	297036
1/0219/ /	THE NATIONAL GRID CO. LTD	TQ438731	CHALK	BLANMERLE ROAD, NEW ELTHAM , COOLING STATION	IC	798641
1/0221/ /	CROSSWAYS PARK DARTFORD	TQ564752	GRAVELS	CROSSWAYS PARK, DARTFORD TRADE PARK	SI	59998
1/0511/ /G	SOUTHERN WATER	TQ629713	CHALK	HAZELLS P.S.		177221264

PURPOSE	D=DOMESTIC	A=AGRICULTURE	PWU=PRIVATE WATER UNDERTAKING	H=HORTICULTURE
	SI=SPRAY IRRIGATION	I=INDUSTRIAL	IGW=AGGREGATE WASHING	IC=COOLING
	IO=OTHER USE	FF=FISH FARM	PWS=PUBLIC WATER SUPPLY	WC=WATERCRESS

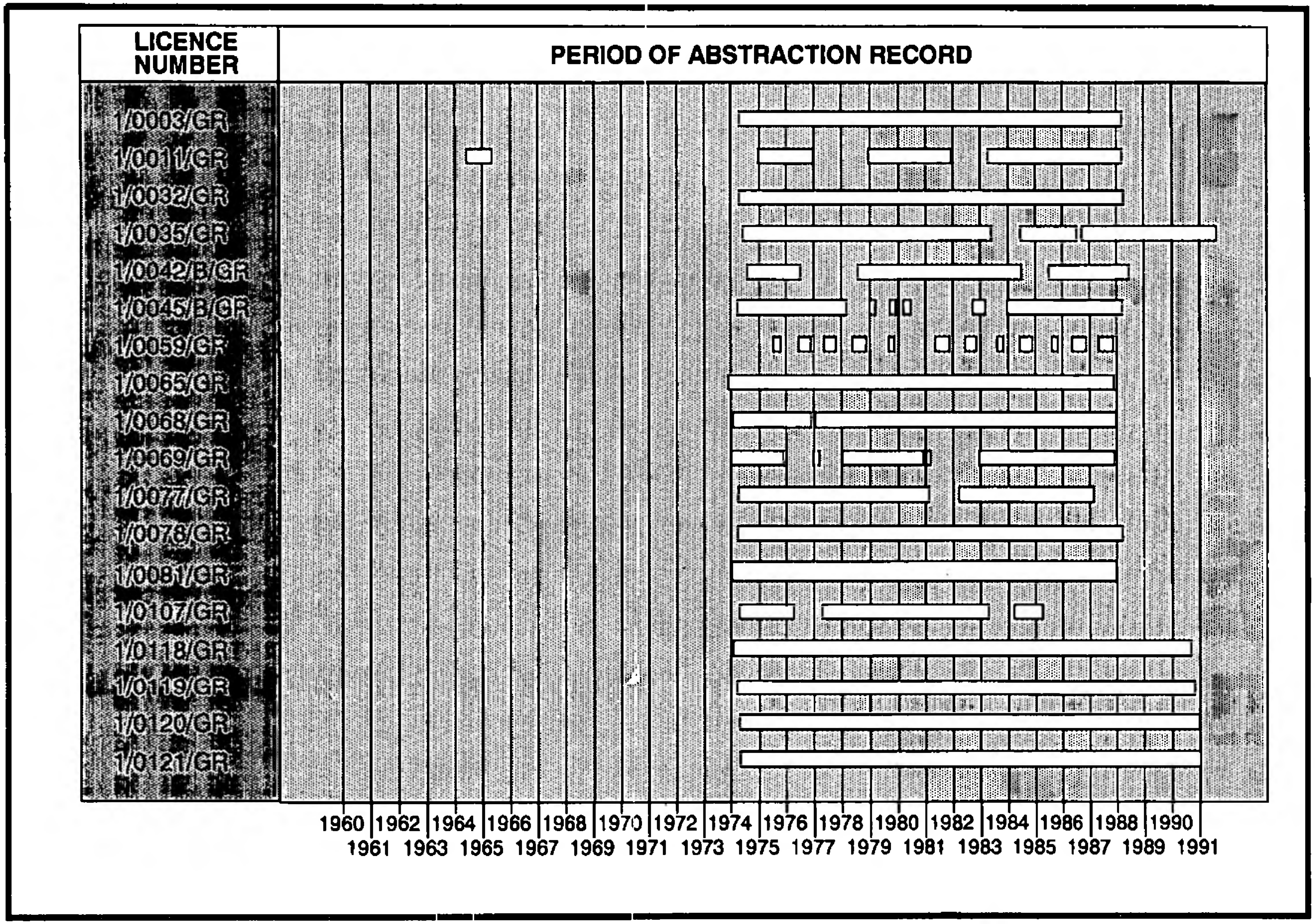


Figure 3.7

Availability of Groundwater Abstraction Data

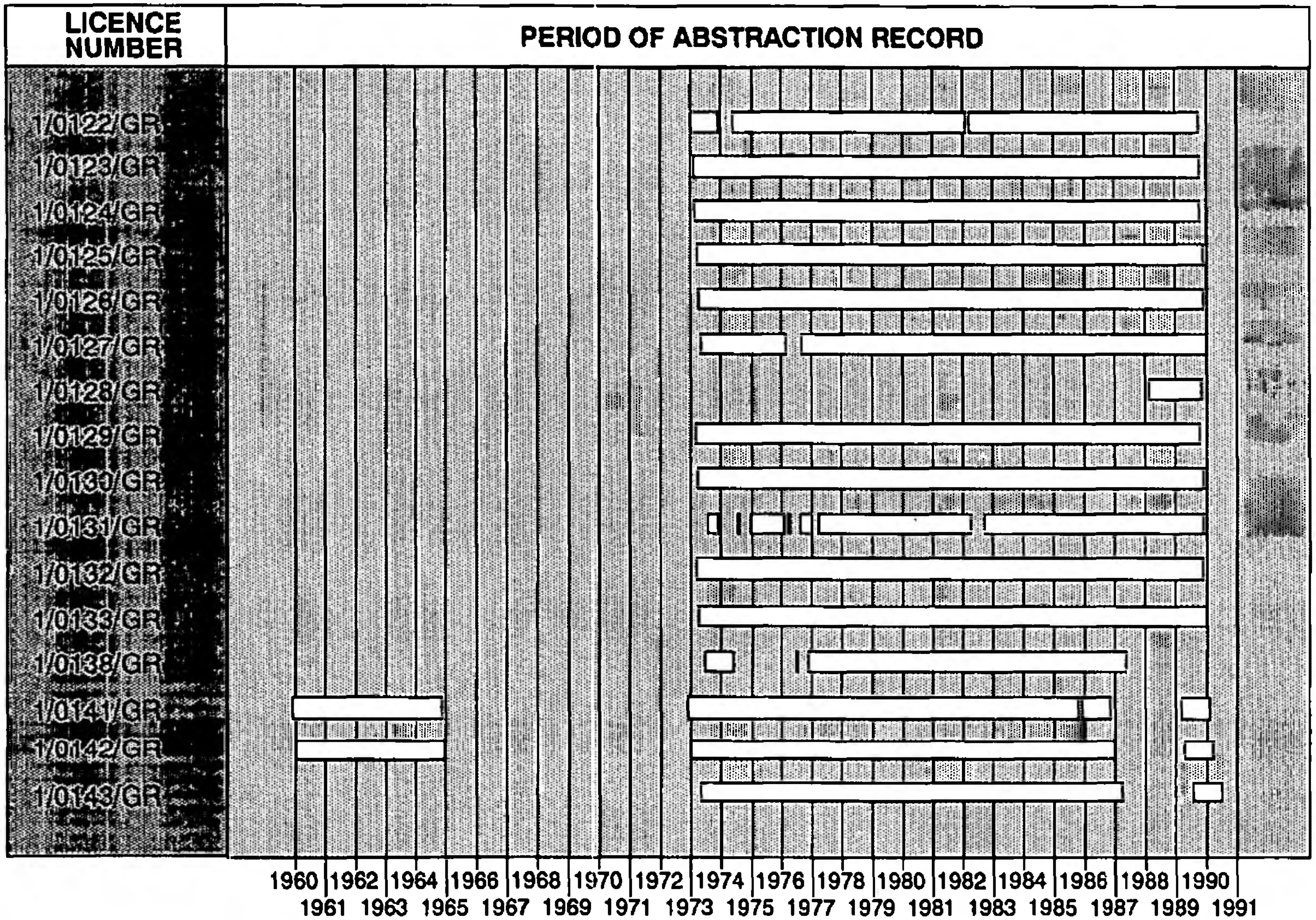
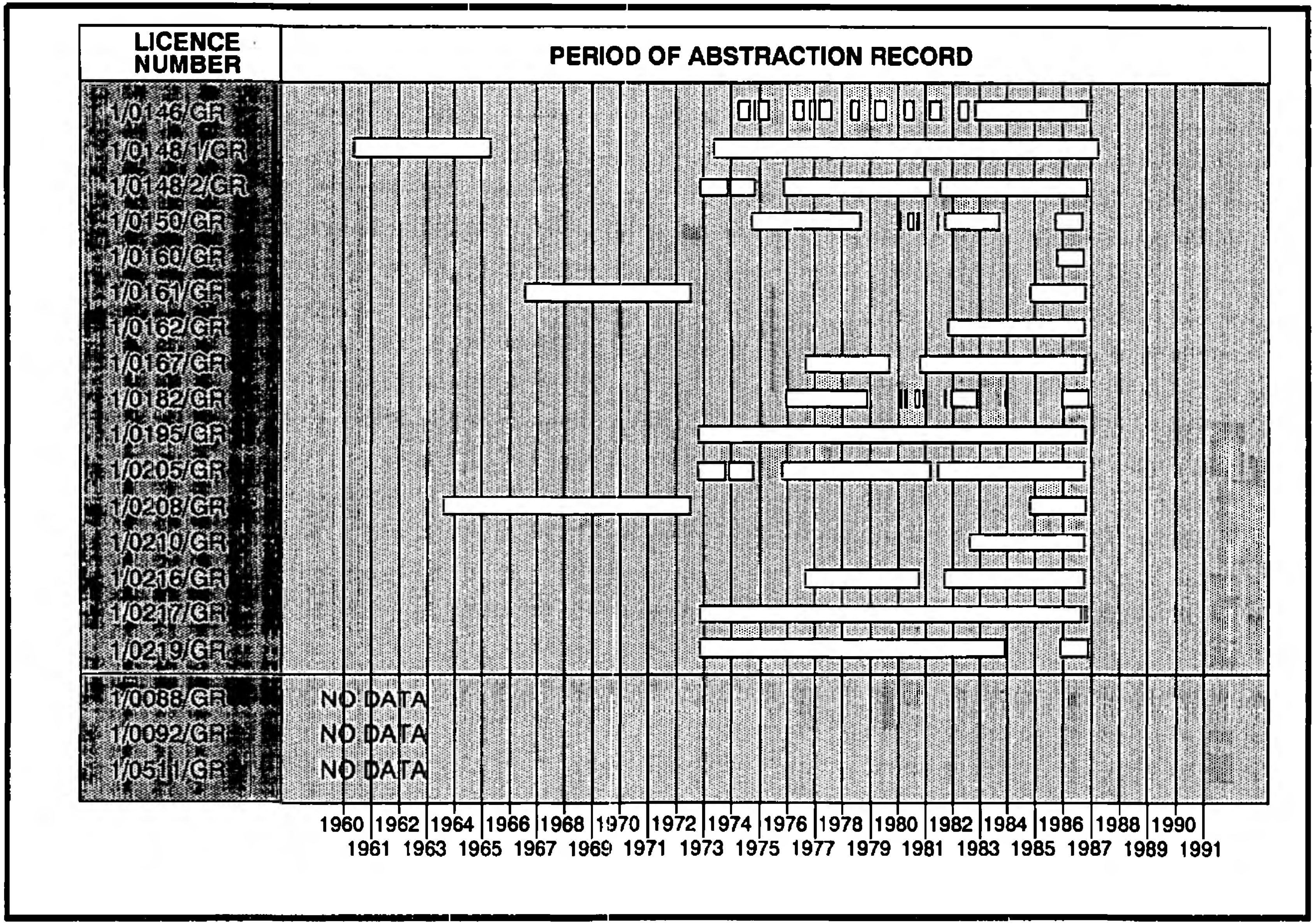


Figure 3.7 (continued)
Availability of Groundwater Abstraction Data



Availability of Groundwater Abstraction Data

Figure 3.7 (continued)

CHAPTER 4

SURFACE WATER HYDROLOGY AND WATER BALANCE

4.1 Introduction

The objectives of the hydrological studies have been to evaluate the hydrological data and calibrate a surface water model to obtain recharge and water balance estimates for subcatchments within the main Darent catchment. The work has been carried out using data for the period October 1984 to September 1990. Recharge has also been obtained for an extended period using the rainfall records for 1960 to 1990.

4.2 Hydrological Data Evaluation

4.2.1 Rainfall

Daily rainfall and autographic rainfall data were required for the surface water aspects of catchment modelling. The distribution and number of gauges of these types are good. Stations relevant to the calculation of catchment rainfall are shown in Figure 4.1 and are listed in Figure 4.2. Reference numbers (RO1, RO2 etc) have been assigned to each station to make identification easier.

The length of daily rainfall record is extensive with eight of the stations dating back to 1931. Within each record length, periods of missing data are relatively short. In selecting data for this study some stations with relatively long periods of missing data were discarded in favour of other stations nearby with a more complete record. Where months of missing data existed in records for selected stations, the record was infilled using the normal ratio method based on the record at two or more nearby stations.

The length of autographic data readily available on computer diskette is poor, with records for most stations within or close to the catchment being less than one year. Other data are available in chart form although the usefulness of these data is still being investigated. In the present study autographic data for Eynsford (Station R19) were used in view of the station's central location within the catchment. The data record on computer is from September 1990 to April 1991.

For further work a longer record should be used, if available. It was anticipated that any problems with data quality would be highlighted when calibrating the surface water model. However, in cases where the rainfall records were examined during modelling, records were found to be consistent with data from nearby stations.

4.2.2 Evaporation

There are no meteorological stations located within the catchment measuring evaporation or soil moisture. MORECS monthly potential evapotranspiration (PE) data were available for a 40 km grid square (reference number 162) which covers the catchment area. Previous modelling work in other areas of Southern England has indicated that these data provide adequate estimates of the catchment potential evapotranspiration. MORECS data generally date back to 1961. Data have been received for the period from January 1985 to April 1991.

4.2.3 River Flow

The flow is recorded at three gauging stations, namely: Otford, Lullingstone and Hawley (Figure 4.3) with records dating back to 1963 at Hawley. For the record length up to September 1989 the mean daily flow and the annual runoff have been computed (Table 4.1). These show that between Hawley and Lullingstone the river loses water, and an inspection of the record at Otford and Lullingstone shows that there are frequent occasions when the Otford mean daily flow is higher than that at Lullingstone. These losses are thought to be due to groundwater abstractions from the catchment although no flow data are available prior to abstractions to show how the river would gain or lose water in its natural state.

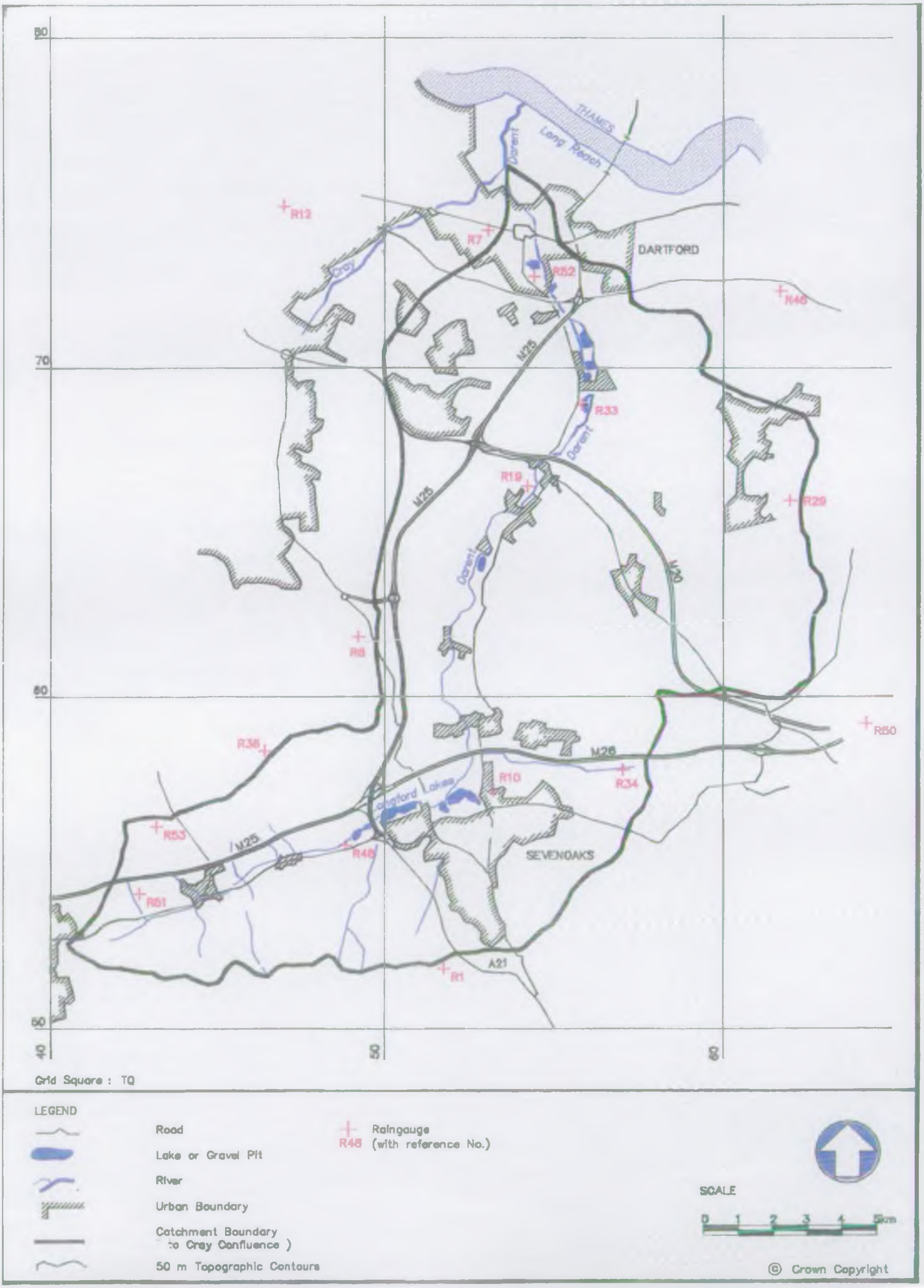
The quality of flow data was considered at the time of calibrating the surface water model (Section 4.3.3). Overall the flow record appears to be good at Otford, but shows some periods of suspect flows at Lullingstone and Hawley. These are looked at in more detail in Section 4.3.3.

TABLE 4.1

Gauging Stations and Flow Statistics

Station name	Grid reference	Catchment area (km^2)	Weir type	Start year	Mean flow (m^3/s)	Mean annual runoff (mm)
Otford	525 584	100.5	Compounded crump	1969	0.548	172
Lullingstone	530 643	118.4	Broad crested	1968	0.654	174
Hawley	551 718	191.4	Crump	1963	0.572	94

Figure 4.1
Location of Rain Gauges



Ref Nr	Station Name	NRA Gauge Nr	Grid Reference
R01	Bayleys Hill	3410001	519521
R07	Christch Road	1211001	531740
R08	Colgates Farm	1243001	495617
R10	Crnptons RDPS	1343001	530570
R12	Danson Park	1221001	468754
R19	Eynsford PS	1320002	535655
R29	Hartley	1314001	617664
R33	Horton Kirby	1320003	561685
R34	Kemsing PS	1341002	569576
R36	Knockholt WW	1351001	466583
R46	Southfleet WW	1413001	610724
R48	Sundridge PS	1350001	489556
R50	Trtsclff PS	2111001	640594
R51	Westwood PS	1354003	425541
R52	Wilmington WW	1310001	543728
R53	Westerham PS	1354001	429558

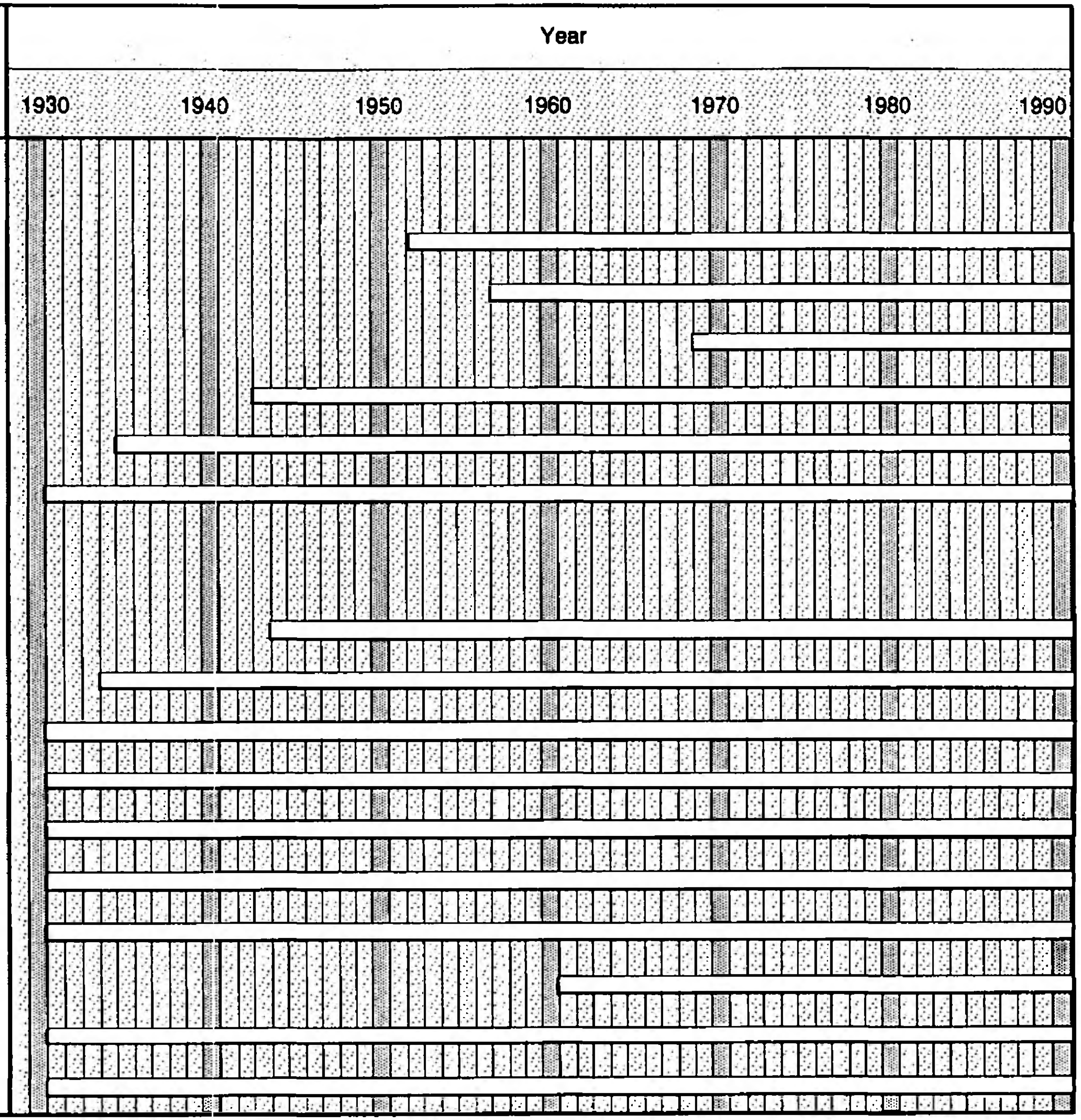
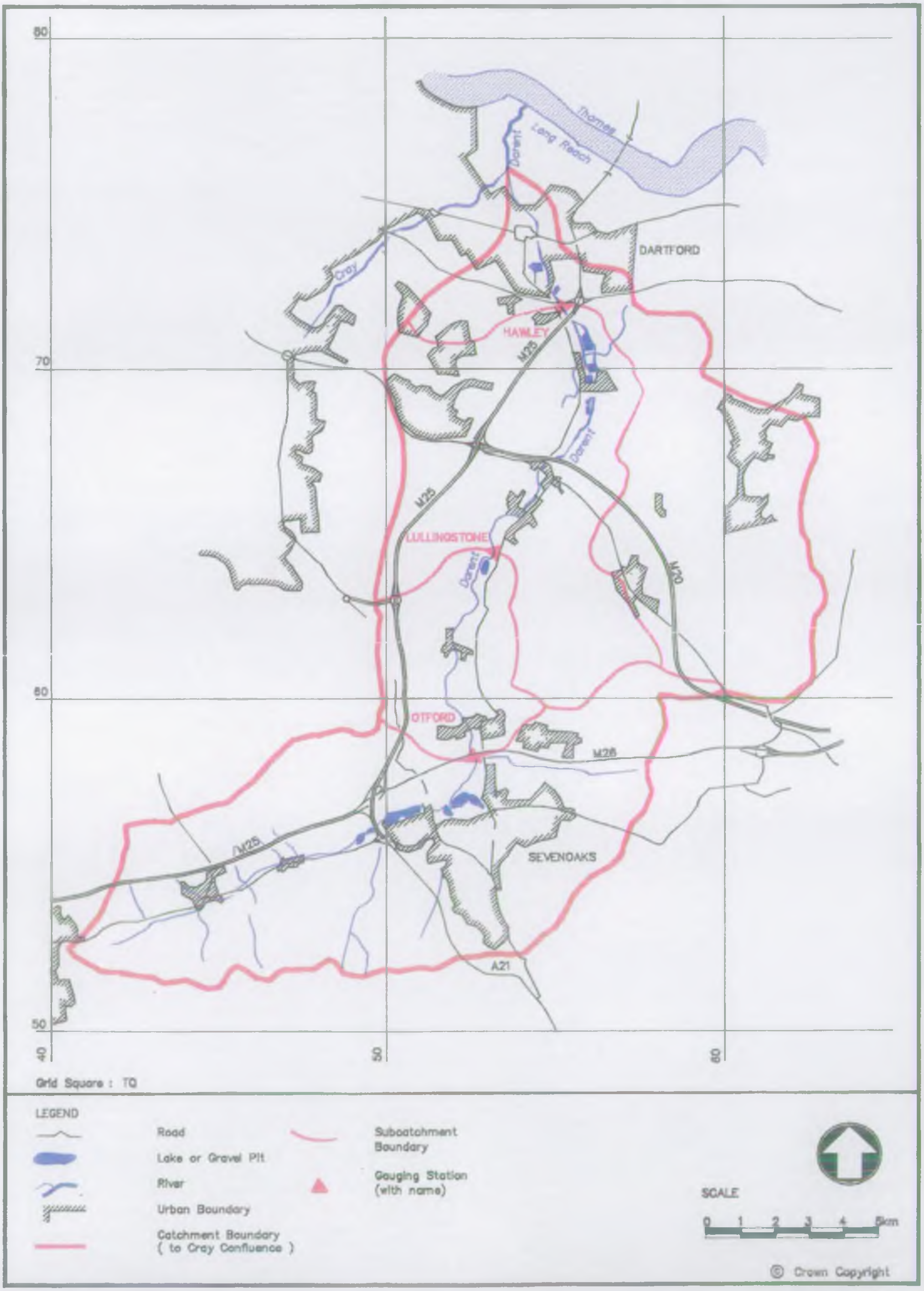


Figure 4.2
Availability of Daily Rainfall Data

Figure 4.3

Subdivision of Catchments



4.3 Recharge Assessment

4.3.1 Approach

Recharge has been computed using the Stanford Watershed Model which is recognised as one of the most conceptually complete representations of the hydrological cycle. Modifications have recently been made to the model to allow for groundwater abstraction and return flows to the river.

The Stanford Model (Figure 4.4) is effectively driven by the hydrometeorological inputs, principally precipitation and evapotranspiration. Incoming precipitation first fills the interception storage in vegetation before any moisture reaches the soil surface.

Soil infiltration is the key process in determining catchment response to rainfall. It is principally dependent on the amount and distribution of soil moisture storage, soil permeability and precipitation rate and quantity. Two soil horizons are modelled: an upper zone representing the top few centimetres of the soil which controls runoff overland flow and interflow, and is depleted by both evaporation and interflow; a lower zone, controlling the infiltration function, which is depleted by evapotranspiration and recharge to groundwater storage.

The groundwater storage zone is depleted by groundwater abstraction and by baseflow to the river which follows a Horton type recession. Variable rates of recession can be modelled and also gains and losses from groundwater across catchment boundaries.

The Stanford Model output provides a summary of the water balance of which recharge is one component. The model is calibrated by comparison of simulated river flows output by the model with observed river flows.

The Stanford Model is a lumped parameter model, in which the catchment is considered as a single unit upstream of the defined catchment outflow point. Spatial representation of certain processes can be incorporated through catchment subdivision and segmentation, although adjustment of calibration parameters can only be effectively achieved upstream of a flow gauging station.

The flow data for the River Darent have allowed calibration and verification of the Stanford Model for the catchment upstream of Hawley. Recharge estimates between Hawley and the confluence with the River Cray have been obtained by extrapolating the results of the recharge estimates upstream of Hawley to the area downstream of Hawley.

4.3.2 Data Preparation

Data preparation for the Stanford Model includes the preparation of physically based catchment parameters and the preparation of hydrometeorological data and abstraction data. Most of the physically based parameters were determined from 1 : 25 000 scale topographical maps and survey of land use carried out in May 1991. For the purpose of this water balance study, data were prepared for the period October 1984 to September 1990.

For the purpose of modelling, four subcatchments were defined by the location of flow gauging stations (at Otford, Lullingstone and Hawley) and at the downstream end of the catchment by the confluence with the River Cray (Figure 4.3). Appropriate model parameters were defined and data prepared for each of the subcatchments.

Ideally the Stanford Model requires hourly rainfall data. In the absence of these data, daily rainfall data were used from which hourly rainfall data were stochastically generated within the model using a set of parameters derived from the autographic rainfall record at Eynsford.

Estimates of daily catchment rainfall have been computed based on Theissen polygon weightings; these were computed taking into account the availability of station data. Rainfall was computed for the subcatchments upstream of Otford, upstream of Hawley and upstream of the confluence with the River Cray.

Groundwater and surface water abstraction data were available on a monthly basis and converted to mean daily abstractions. In general, records of public water supply abstractions were complete for the period 1984 to 1990, but significant gaps exist in records of groundwater abstraction for other uses. Abstractions for public water supply do, however, constitute 80 to 90% of the groundwater abstractions in the Darent catchment. Where any data were missing these were infilled based on data from the years for which licence returns were available.

4.3.3 Surface Water Modelling

Ideally calibration should be carried out for each of the three subcatchments with gauged flow data. Although this was attempted, it was found that the subcatchment between Otford and Lullingstone was difficult to calibrate owing to its small size and the magnitude of abstractions relative to the recharge. For this reason the two subcatchments between Otford and Hawley were combined to form one subcatchment. Calibration was thus carried out on the subcatchments upstream of the Otford gauge and between the Otford and Hawley gauges.

Calibration was carried out using data for the hydrological years 1985/86 and 1986/87 and verified on the years 1987/88 and 1988/89. In water balance calculations, data for 1984/85 and 1989/90 were also included.

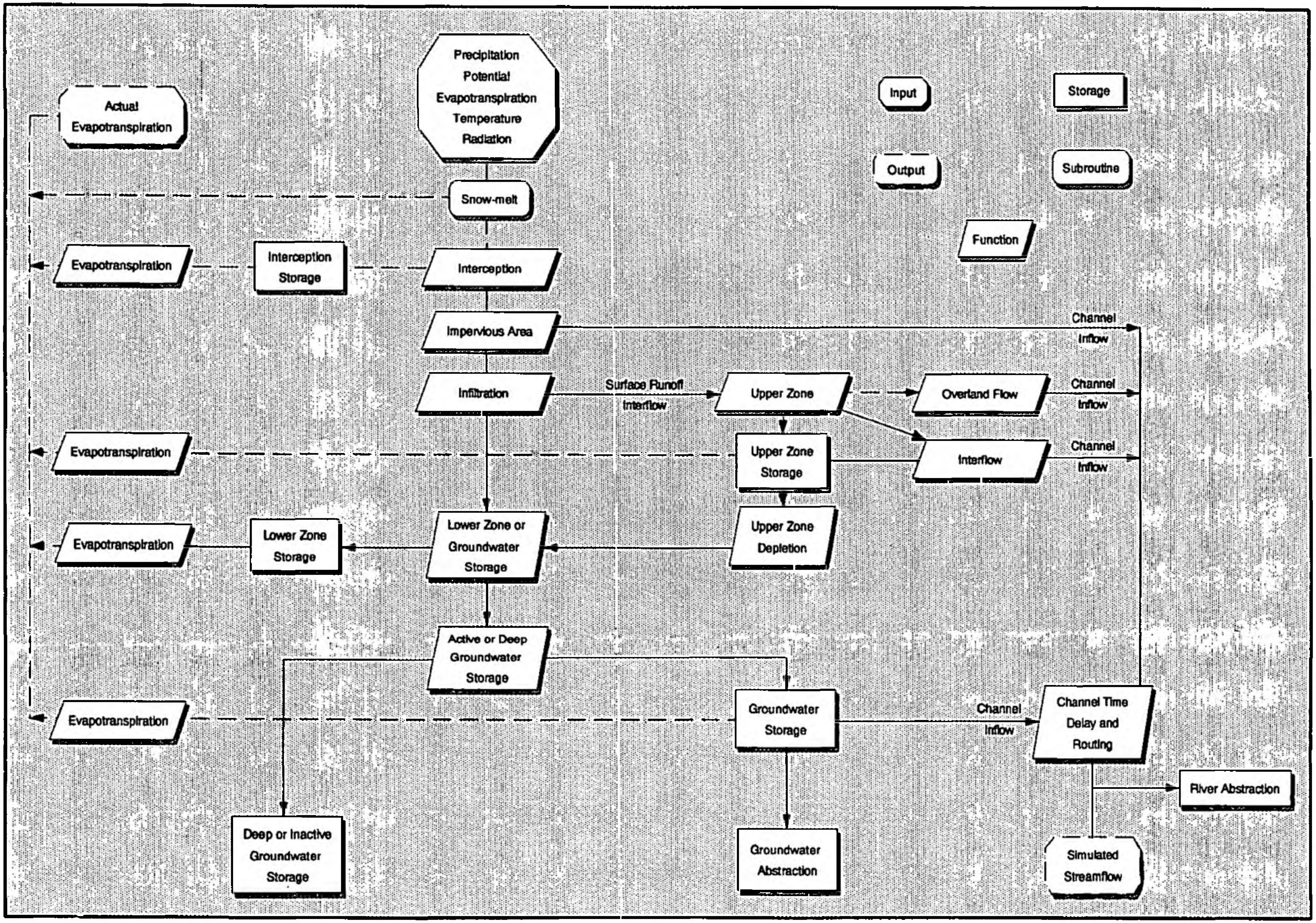


Figure 4.4

Flowchart of the Stanford Watershed Model

The calibration and verification of the model at Otford is shown in Figure 4.5; overall the simulation is very good. In presenting the results in Figure 4.5 flows above 6 m^3/s are not shown so as to highlight the low flows. The peaks, interflow recession characteristics and the timing of the hydrographs are all modelled effectively. Groundwater recession characteristics have been harder to model. The variable recession parameter for the wet and dry months was adjusted to optimise the fit. Overall the volume simulation is good with simulated runoff being 97% of the observed runoff. Calibration parameters are given in Table 4.2.

During the initial stages of calibration it was found that surface runoff in the summer was much higher than the observed hydrograph. It was felt that lake storage in the Sevenoaks area could account for the peakedness of surface runoff being attenuated by the time the flow reaches Otford and also some of the impervious runoff not reaching the river directly. By reducing the proportion of the impervious area from the initial estimated value, much improvement to the peaks was subsequently achieved, especially in the cases of summer runoff. Winter peak flows have been simulated well in most years and exceptions to this are thought to be due to the difference between the synthetic hourly rainfall used and actual hourly rainfall data.

TABLE 4.2

Calibration Parameters

Parameter	Unit	Subcatchment upstream of Otford	Subcatchment between Otford and Hawley
Upper zone storage	mm	5	7
Lower zone storage	mm	35	95
Infiltration	mm/h	10	40

The calibration and the verification of the model at Hawley is shown in Figure 4.6. The simulated flows for the Otford and Hawley subcatchments have been combined and compared against the observed flows at Hawley. The scale of the plot has again been chosen to highlight the low flows. The plot illustrates the problem of calibrating the Stanford Model when groundwater abstractions are of the same order of magnitude as recharge. In addition, the peakedness of the flow at Otford has not been adequately attenuated in the model resulting in an oversimulation of the peaks at Hawley. In volume terms the observed runoff was 92% of the simulated runoff in the period from October 1984 to September 1988, with most of the oversimulation occurring in January to March 1985. In that year and the subsequent year when the localised streamflow was negative, the abstraction rates exceeded the recharge. It was concluded that good simulation could not be achieved under these circumstances.

To further verify the calibration parameter values for the subcatchment between Hawley and Otford the model was run using data for the total catchment upstream of Hawley. A good fit was obtained (Figure 4.7).

4.3.4 Discussion

The modelling studies have highlighted the difficulty of applying the Stanford Model to catchments where groundwater abstraction is higher than recharge within certain subcatchments. However, good simulations have been achieved for the subcatchment at Otford and the total catchment upstream of Hawley. A comparison of the calibration parameters for each of these areas indicates the different characteristics of the subcatchments upstream and downstream of Otford. Upstream of Otford the geology of the area is Lower Greensand with some Chalk whilst between Otford and Hawley the geology is predominantly Chalk. In the upper part of the catchment modelling indicates that the soil moisture storage capacities and the infiltration rate are low and slopes are steeper; this results in greater peakedness of runoff and a higher surface runoff to baseflow ratio.

4.4 Catchment Water Balance

4.4.1 Introduction

Water balances have been prepared for the following three subcatchments:

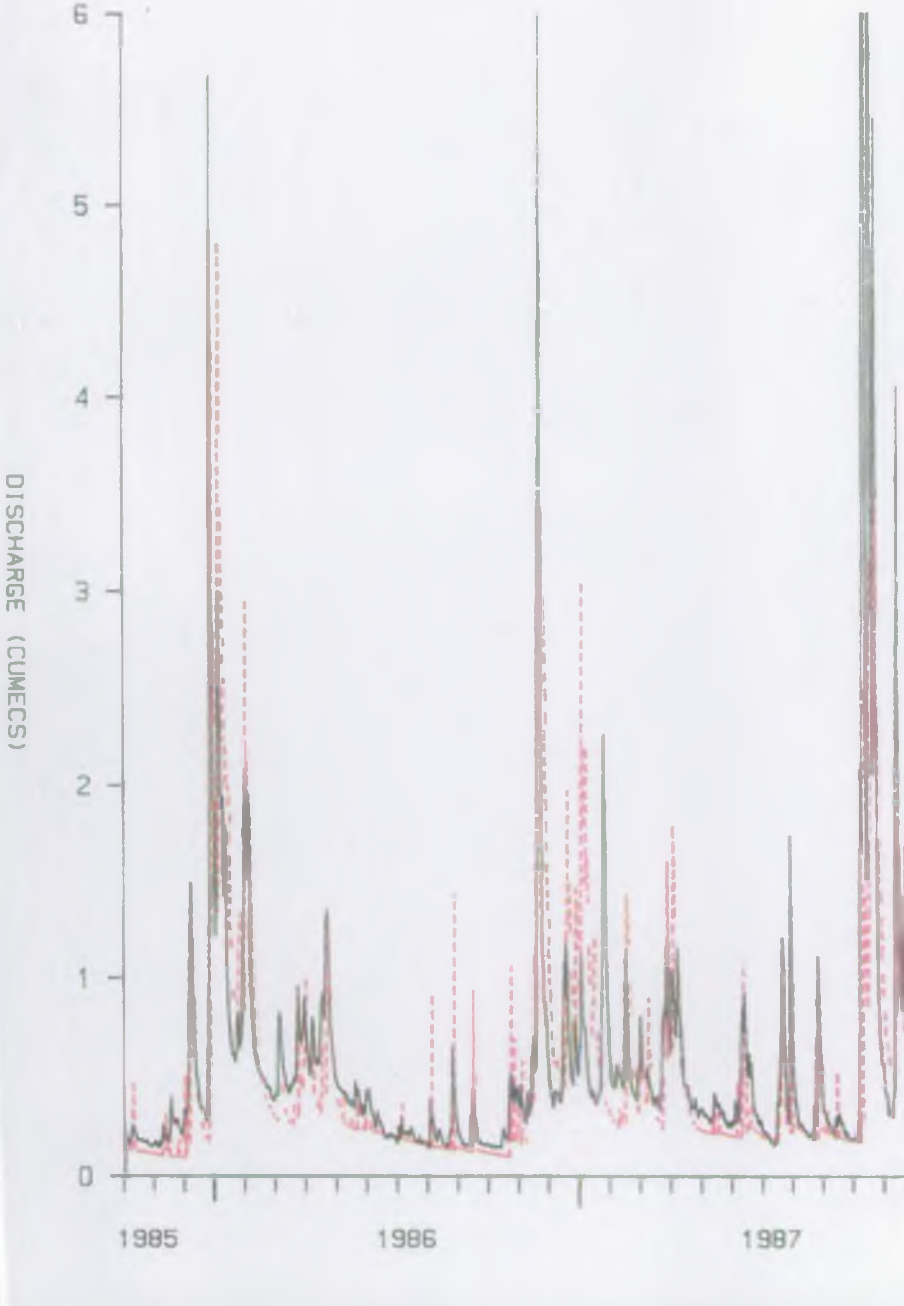
- Otford;
- Otford to Hawley;
- Hawley to the Darent/Cray confluence.

Balances have been produced using results from the Stanford Watershed Model for six water years from October 1984 to September 1990. Tables giving the balance on a three-monthly basis are presented in the Appendix. Annual water balances for the three subcatchments are presented in Table 4.3. The following equations govern the water balance presented in the tables:

(i) Rainfall = Evaporation + Surface Runoff + Recharge ± Change in Soil Moisture Storage

(ii) Recharge = Baseflow + Abstraction ± Change in Groundwater Storage

Mean rainfall and recharge data expressed in mm depth are given in Table 4.4.


DISCHARGE (CUMECS)
0
1
2
3
4
5
6
1985
1986
1987

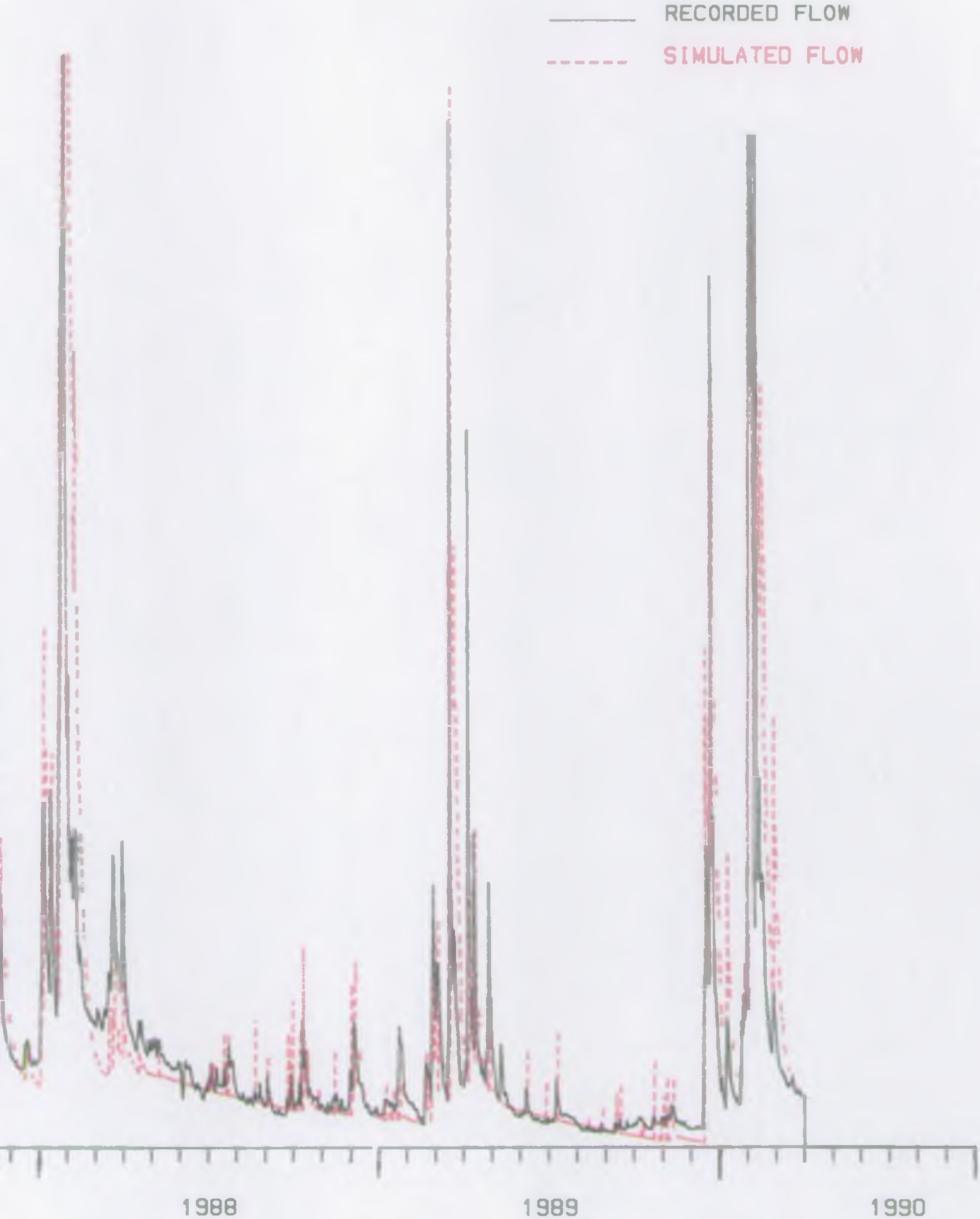


FIGURE 4.5

SIMULATION AT OTFORD

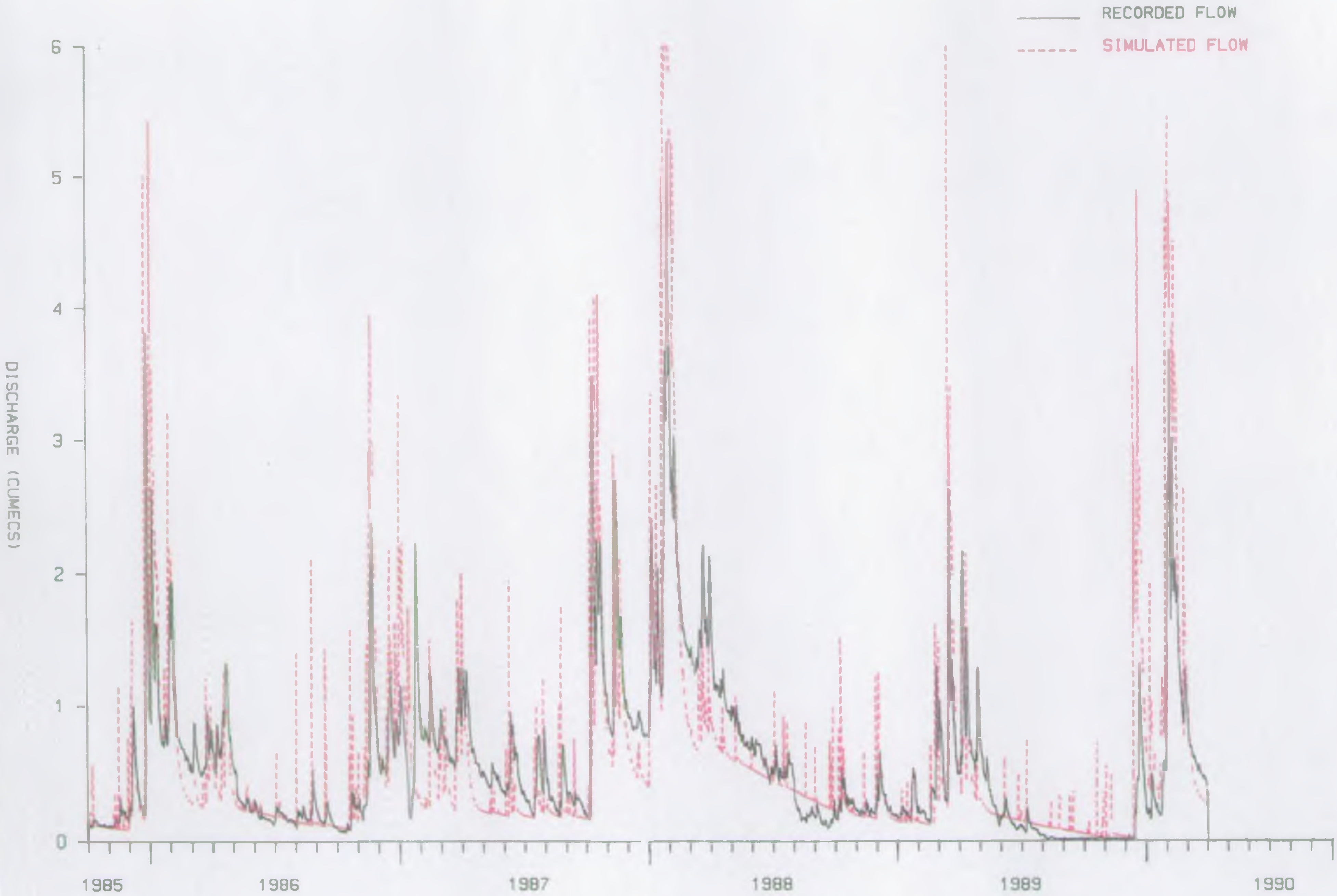


FIGURE 4.6

SIMULATION AT HAWLEY (with catchment subdivision)

FIGURE 4.7

SIMULATION AT HAWLEY (without catchment subdivision)

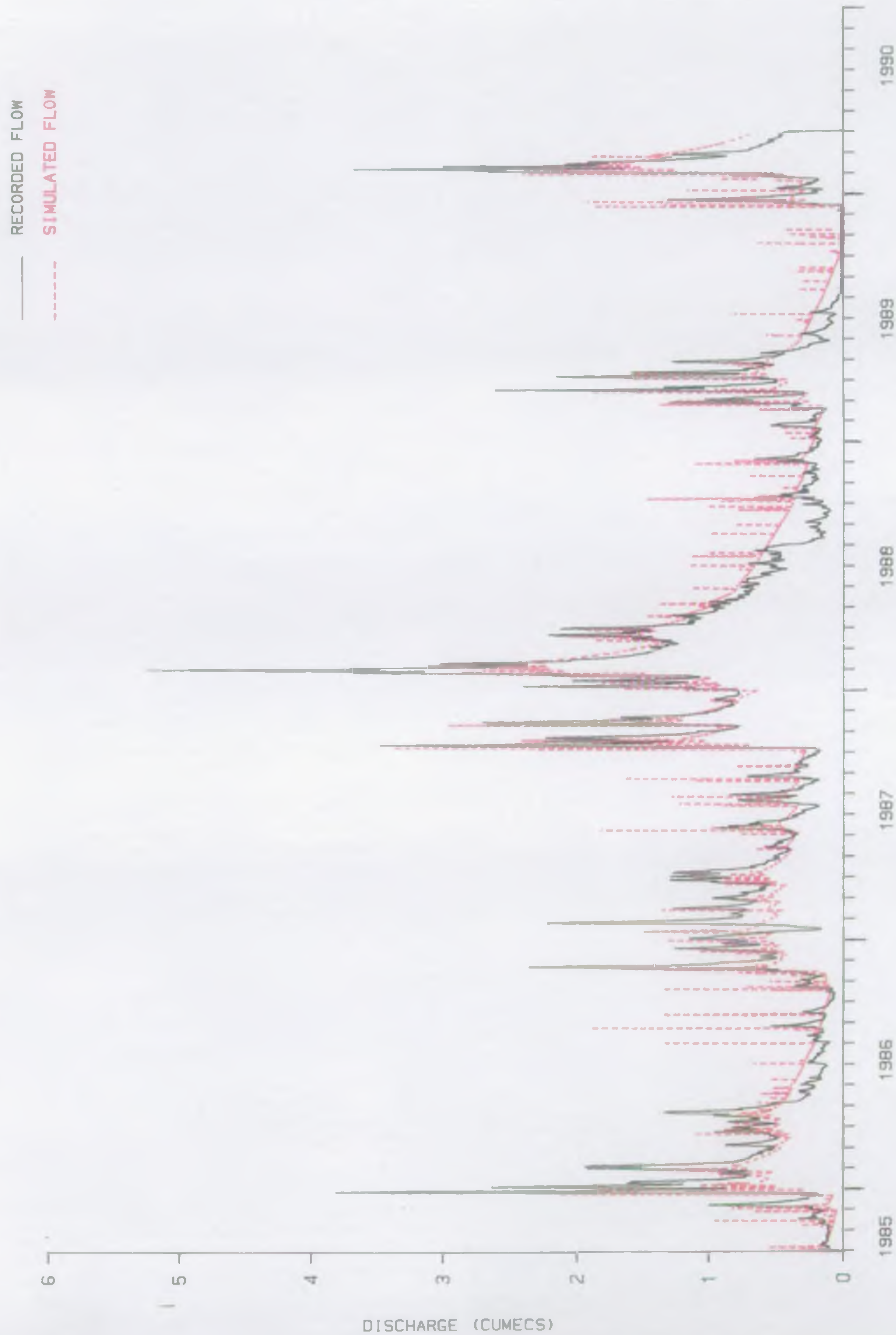


Table 4.3
Annual Water Balance

a) Otford Subcatchment

WATER YEARS	RAINFALL	EVAPOTRAN-SPIRATION	SURFACE RUNOFF	SOIL MOISTURE STORAGE CHANGE	RECHARGE		BASEFLOW	ABSTRACTION			GROUNDWATER STORAGE CHANGE
					GREEN-SAND	CHALK		GREEN-SAND	CHALK	RIVER	
1984/1985	231.0	145.5	23.3	-6.1	45.6	22.7	19.7	32.7	0.9	0.0	15.0
1985/1986	204.7	126.6	22.3	4.5	34.3	17.1	19.2	35.0	0.9	0.0	-3.8
1986/1987	227.8	142.0	24.0	0.2	41.1	20.5	20.2	34.5	0.9	0.0	5.9
1987/1988	243.0	128.4	41.1	2.3	47.6	23.6	34.4	34.7	0.9	0.0	1.3
1988/1989	150.3	109.0	12.1	-6.7	24.0	11.9	15.6	36.4	1.0	0.0	-17.0
1989/1990	193.2	103.4	28.5	3.6	38.5	19.1	18.9	35.6	1.0	0.0	2.1
Annual Average	208.3	125.8	25.2		38.5	19.2	21.3	34.8	0.9	0.0	

b) For catchment between Otford and Hawley

WATER YEARS	RAINFALL	EVAPOTRAN-SPIRATION	SURFACE RUNOFF	SOIL MOISTURE STORAGE CHANGE	RECHARGE	BASEFLOW	ABSTRACTION		GROUNDWATER STORAGE CHANGE
							CHALK	RIVER	
1984/1985	169.5	129.4	6.3	-1.7	38.8	3.2	44.8	0.1	-9.2
1985/1986	165.0	121.2	2.9	7.2	33.7	0.0	44.6	0.1	-10.9
1986/1987	185.6	127.9	3.5	3.7	50.6	0.0	42.9	0.1	7.7
1987/1988	189.7	121.1	19.9	-8.7	73.5	16.0	47.2	0.1	10.3
1988/1989	118.6	103.0	2.0	-3.6	17.3	0.1	49.2	0.1	-32.0
1989/1990	161.1	108.8	3.4	2.0	46.9	0.0	50.2	0.1	-3.3
Annual Average	164.9	118.6	6.3		43.5	3.2	46.5	0.1	

c) For catchment between Hawley and the River Cray confluence

WATER YEARS	RAINFALL	EVAPOTRAN-SPIRATION	SURFACE RUNOFF	SOIL MOISTURE STORAGE CHANGE	RECHARGE	BASEFLOW	ABSTRACTION		GROUNDWATER STORAGE CHANGE
							CHALK	RIVER	
1984/1985	123.6	95.5	5.2	-2.0	25.1	0.2	43.2	0.1	-18.3
1985/1986	120.5	89.8	4.8	5.0	20.9	0.0	41.8	0.1	-20.9
1986/1987	139.6	96.4	6.0	2.7	34.4	0.0	39.3	0.1	-4.9
1987/1988	142.2	92.0	6.6	-5.3	48.9	0.0	41.2	0.1	7.7
1988/1989	91.7	77.7	3.4	-0.8	11.4	0.0	32.6	0.1	-21.2
1989/1990	117.2	81.5	5.4	-0.2	30.5	0.0	36.6	0.1	-6.1
Annual Average	122.5	88.8	5.2		28.5	0.0	39.1	0.1	

All units: Mld

TABLE 4.4

Mean Rainfall and Recharge 1984 to 1990

Subcatchment	Rainfall	Recharge
Otford	757	270
Otford to Hawley	662	175
Hawley to Cray confluence	635	148

All units: mm depth.

The table indicates the marked decrease in rainfall and resultant recharge between the upper and lower Darent catchment.

Recharge was also calculated for the period 1960 to 1990 in order to determine a longer term mean and approximate one in five year and one in ten year recharge values (below mean) for the Lower Greensand aquifer and Chalk aquifer as a whole. The results are summarised and compared with mean recharge and abstraction for 1984 to 1990 in Table 4.5.

TABLE 4.5

Long Term Recharge

Aquifer	Recharge				Mean groundwater abstraction 1984-1990
	Long Term Mean	1 in 5 year	1 in 10 year	Mean 1984 to 1990	
Chalk	101	71	54	91	86
Lower Greensand	43	35	30	39	35

All units: Mld.

MORECS potential evaporation data were not available for the Darent area for the period 1960 to 1984. Evaporation for this period was calculated using a record for the entire period 1960 to 1990 for the River Test catchment in Hampshire. Corresponding periods of record for the Darent and Test (1984 to 1990) were first compared and then an extended synthetic record derived for the Darent from the Test record using multipliers derived from the comparison.

Monthly potential evaporation varies from year to year by much less than rainfall and the regional variation across south and south-east England is also generally fairly small. Reasonable confidence can therefore be placed in the evaporation values derived and the resulting recharge. Once the full 30 year record of potential evaporation values are available for the Darent catchment then recharge can be recalculated. Resulting values would not be expected to vary greatly from those already obtained however.

The Otford subcatchment receives baseflow contributions from the Chalk and Lower Greensand aquifers. For the water balance assessment the subcatchment has not been segmented according to geological outcrop. It has been assumed that soil moisture and other model parameters controlling recharge have the same values throughout the subcatchment. Variation in these parameters will be considered in the catchment modelling. Total recharge has therefore been distributed between the Chalk and Lower Greensand aquifers in proportion to aquifer outcrop areas and assuming that no recharge takes place over the 23% of the subcatchment area underlain by impermeable Gault Clay. The methodology applied and the results obtained to date are considered reasonable as the basis for a broad water balance assessment.

Results presented in Table 4.5 indicate that mean annual recharge over the period 1984 to 1990 was significantly lower than for the period extending over the last 30 years. This is mainly as a result of very low rainfall and resultant recharge throughout the catchment in 1988/89 (recharge 41 Mld for Chalk, 24 Mld for Lower Greensand), which serves to reduce the mean values for 1984 to 1990 by about 10%.

4.4.2 Comparison of Recharge and Groundwater Abstraction

Lower Greensand

The results in Tables 4.3a and 4.5 indicate a very high level of development for the Lower Greensand aquifer as a whole. Recent annual abstraction averages about 80% of long term mean recharge and 90% of recharge over the past six years. Annual abstraction is also at a similar level to the one in five year recharge.

As groundwater storage within the Greensand is probably high, this storage would enable abstraction to continue through low recharge years largely unaffected. Abstraction would be expected to deplete storage in these years and storage would be replenished with a return to normal recharge conditions. The ability of storage in the Lower Greensand aquifer to buffer the effects of low recharge periods needs to be established by catchment modelling. The high level of existing development of the aquifer does however throw into doubt the feasibility of any river support scheme or other engineering options which require further development of the Lower Greensand aquifer.

Chalk

Table 4.5 indicates an even higher level of development of the Chalk aquifer overall than for the Lower Greensand. Recent annual abstraction is about 85% of long term mean recharge and nearly 95% of average recharge over the past six years. Abstraction exceeds the one in five year recharge by 30%. These statistics and the baseflow values shown in Table 4.3 indicate that Chalk abstractions in the subcatchments below Otford are highly dependent on river baseflow contributions from the subcatchment above Otford.

As indicated in Table 4.3, however, abstraction is not evenly spread throughout the Chalk aquifer. Along the north side of the Otford subcatchment between Westerham and Sevenoaks the Chalk aquifer is little developed. Annual abstraction averages only 5% of calculated recharge. There may therefore be potential for developing groundwater augmentation schemes or summer abstraction sources as substitutes for pumping stations close to the river. Development could also depend on the extent of development in the adjoining Cray subcatchment lying further to the north, however.

In contrast, downstream of Otford abstraction exceeded mean recharge by nearly 20% in the period 1984 to 1990. Much of this abstraction is concentrated close to the river. Within the subcatchment contributing between Hawley and the Darent/Cray confluence (Figure 4.3) groundwater usage in the vicinity of Dartford accounts for 60% of total abstraction. To the southeast of Hawley, within this subcatchment, annual abstraction reduces to about 70% of mean recharge. It may be possible, though perhaps unlikely, that groundwater schemes to benefit the river could be developed in the area of this subcatchment southeast of Hawley. In other areas downstream of Otford it seems very unlikely that there could be any long term benefits to the river from schemes which either maintain abstraction at current levels or required increased abstraction, unless the schemes have a component of artificial recharge.

4.4.3 Conclusions

From the water balance assessment it can be concluded that both the Lower Greensand and much of the Chalk aquifer in the catchment have been developed to the point where abstraction at the current level is close to long term mean recharge. An area of Chalk outcrop exists within the Otford subcatchment which might be developed, possibly with groundwater augmentation schemes or summer abstraction sources. However, taken overall, total mean recharge to the Chalk (101 Mld) only exceeds abstraction (86 Mld) by about 15%. Chalk abstraction exceeds the one in five year recharge by 30%. For the Lower Greensand, long term mean recharge exceeds abstraction by about 20%. In these circumstances it seems unlikely that major low flow alleviation options could be developed which either allow for maintenance of abstraction at current levels or for increased abstraction, unless the options involve artificial recharge.

4.5 Environmentally Acceptable Flows

4.5.1 Introduction

Atkins (1991) derived discharge values for the EAFR at the three gauging sites on the Darent as indicated in Table 4.6.

TABLE 4.6

Environmentally Acceptable Flow Regime

Gauging Station	$EAFR_{95}$		$EAFR_{mean}$	
	m^3/s	Mld	m^3/s	Mld
Otford	0.12	10.4	0.59	51.0
Lullingstone	0.16	13.8	0.69	59.6
Hawley	0.26	22.5	1.12	96.8

The $EAFR_{95}$ is assumed to be the lowest flow required to maintain the abundance and diversity of macroinvertebrates expected in a theoretically pristine Chalk stream at the location. The $EAFR_{mean}$ is the mean flow desirable from an environmental viewpoint at the location.

In the EAFR report it is suggested that the seasonal variation in EAFR should follow the seasonal variation in gauging station discharge data. Monthly environmentally acceptable flows would be in proportion to the mean monthly gauged flows. Whilst invertebrate sampling and the RIVPACS analysis provide an initial measure of the EAFR further studies would seem essential both to refine the values for the EAFR and to establish an appropriate seasonal variation in EAFR. It would be appropriate to use additional environmental factors such as the seasonal flow requirements of plant and all animal communities in, or dependent on, the river to determine a suitable flow regime with seasonal variation.

Environmental studies relating to EAFR need to consider the requirements of flora and fauna, principally invertebrates, fish and birds, water quality and sediment transport, the need to maintain or improve adjacent damp habitats and the visual and amenity value of the river. River margins need to be kept moist at all times to maintain plant species such as bur reed, yellow iris, water forget-me-not and brooklime. Aquatic plants, such as water crowfoot, *Ranunculus aquatilis*, should flourish throughout the summer in all sections of the river where previously occurring. This would require not only adequate flow for growth of the plant but also sufficient flow to prevent build up of nutrients and deposition of silt. Adjacent damp grassland is also important, especially in winter and spring. For example, damp grazing pasture at Lullingstone supports feeding snipe and lapwing. Restoration of fisheries is a very important further consideration.

In addition the watercourse should be seen to be flowing vigorously at all times in such popular places as Eynsford village centre and opposite the pub in Farningham. Visually attractive water levels should be retained at all times in those areas where the Darent is an amenity for private landowners as along the mill leat in Farningham and beside back gardens in Shoreham.

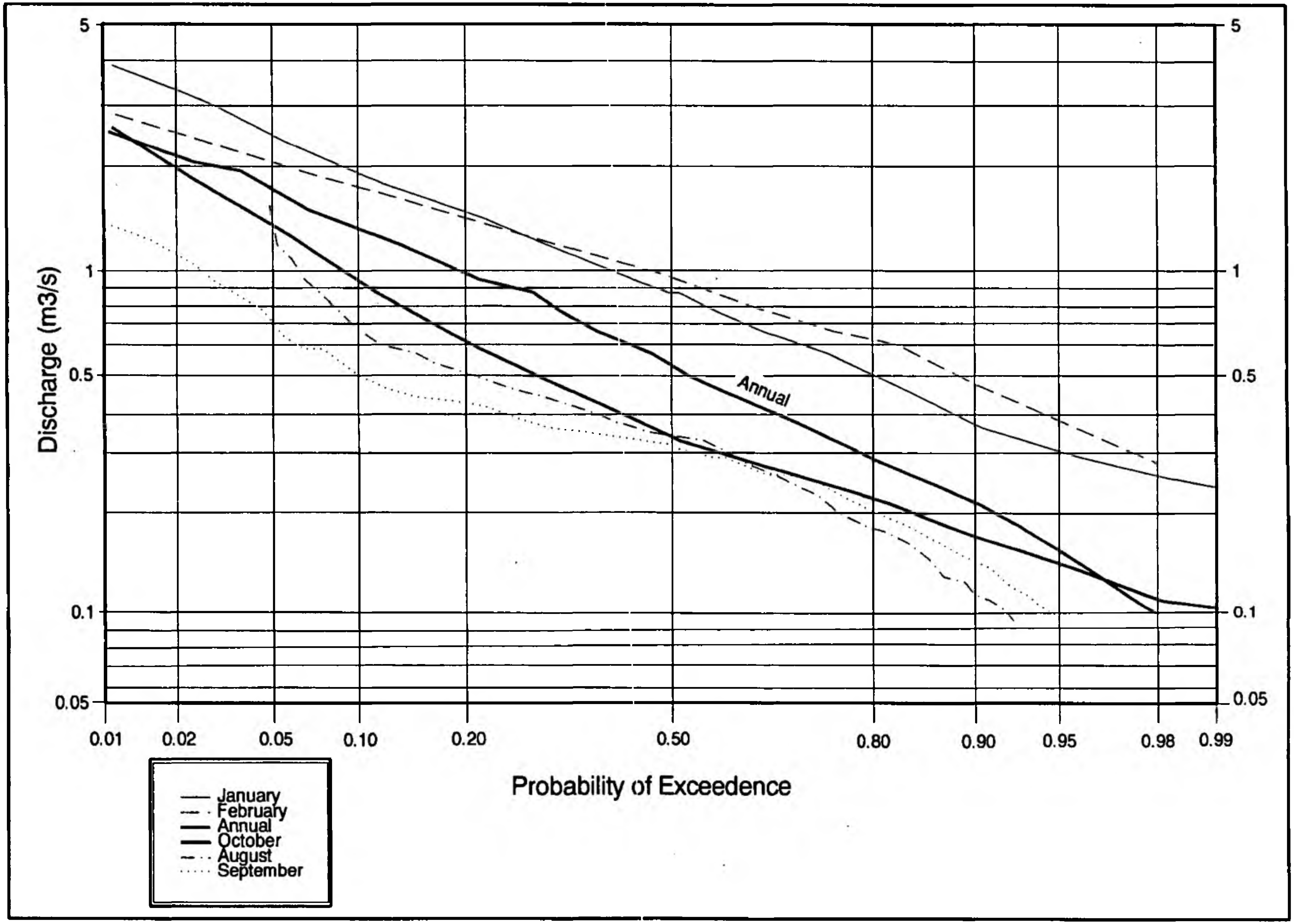
In Figure 4.8 flow duration curves for Lullingstone gauging station, derived using data for specific months, are compared with the flow duration curve using all year data. Months of lowest flow (August and September) and highest flow (January and February) are included to indicate the range in monthly flow duration curves. October is included as it was the month in which the macroinvertebrate survey, used to determine EAFR, was carried out.

A reasonably similar discharge value obtains at the ninety-fifth percentile (Q95) for the annual flow duration curve and the curve derived using October data. Since the survey on which EAFR values were based was carried out in October, it seems reasonable for this stage of assessment of engineering options to apply the Q95 values derived by Atkins as a fixed value throughout the year. In assessing engineering options at this pre-feasibility level, flow deficits (or in some cases surpluses) are generally only considered on an annual basis.

4.5.2 Flow Deficits

The $EAFR_{95}$ values indicated in Table 4.6 have been used to derive annual deficits in river discharge as shown in Figure 4.9. The annual totals are the summation of deficits in days when the mean daily flow was below the threshold of the $EAFR_{95}$ for the gauging site, ie below the minimum flow acceptable from an environmental viewpoint.

Figure 4.9 indicates that deficits at Otford and Lullingstone are of a limited order. At Hawley, however, deficits are of an order of magnitude higher. A similar pattern is seen in Figure 4.10 which shows the number of days on which a deficit occurred in each year. At Otford and Lullingstone deficits are restricted to a sequence of low rainfall years in the early to mid 1970s and to 1989 (assessment for 1990 not complete). In contrast, at Hawley, deficits occur in every year from 1969 to 1989. Years with 100 or more days of deficit occur regularly. In 1973, deficits existed at Hawley over a period of eleven months out of twelve.



River Darent F:\HYD-TEC\DEC\FLOWDUR.GEM 27/06/91 By D. Cavaliere

Figure 4.8
Flow Duration (Lullingstone)

Figure 4.9

Annual Flow Deficits

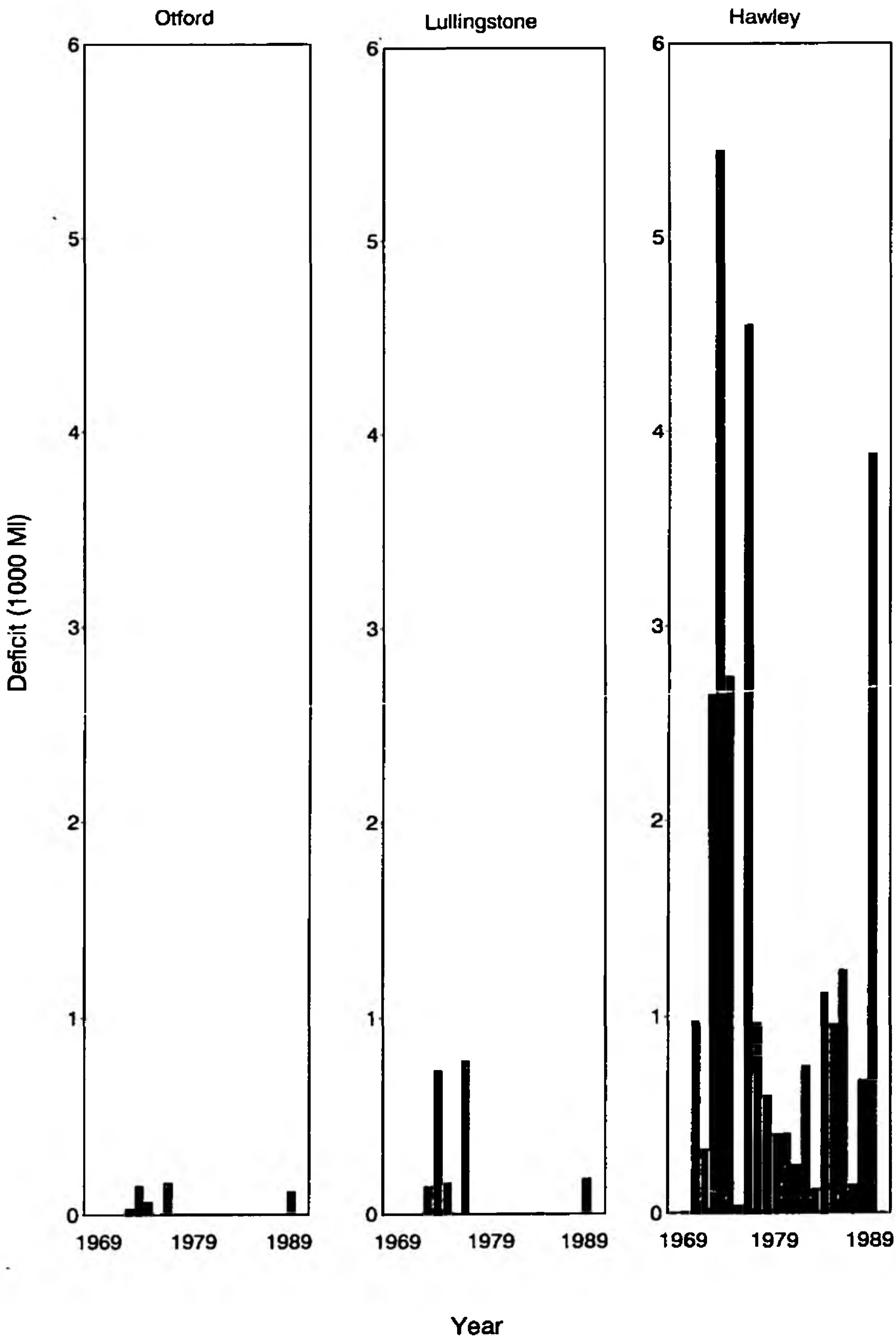
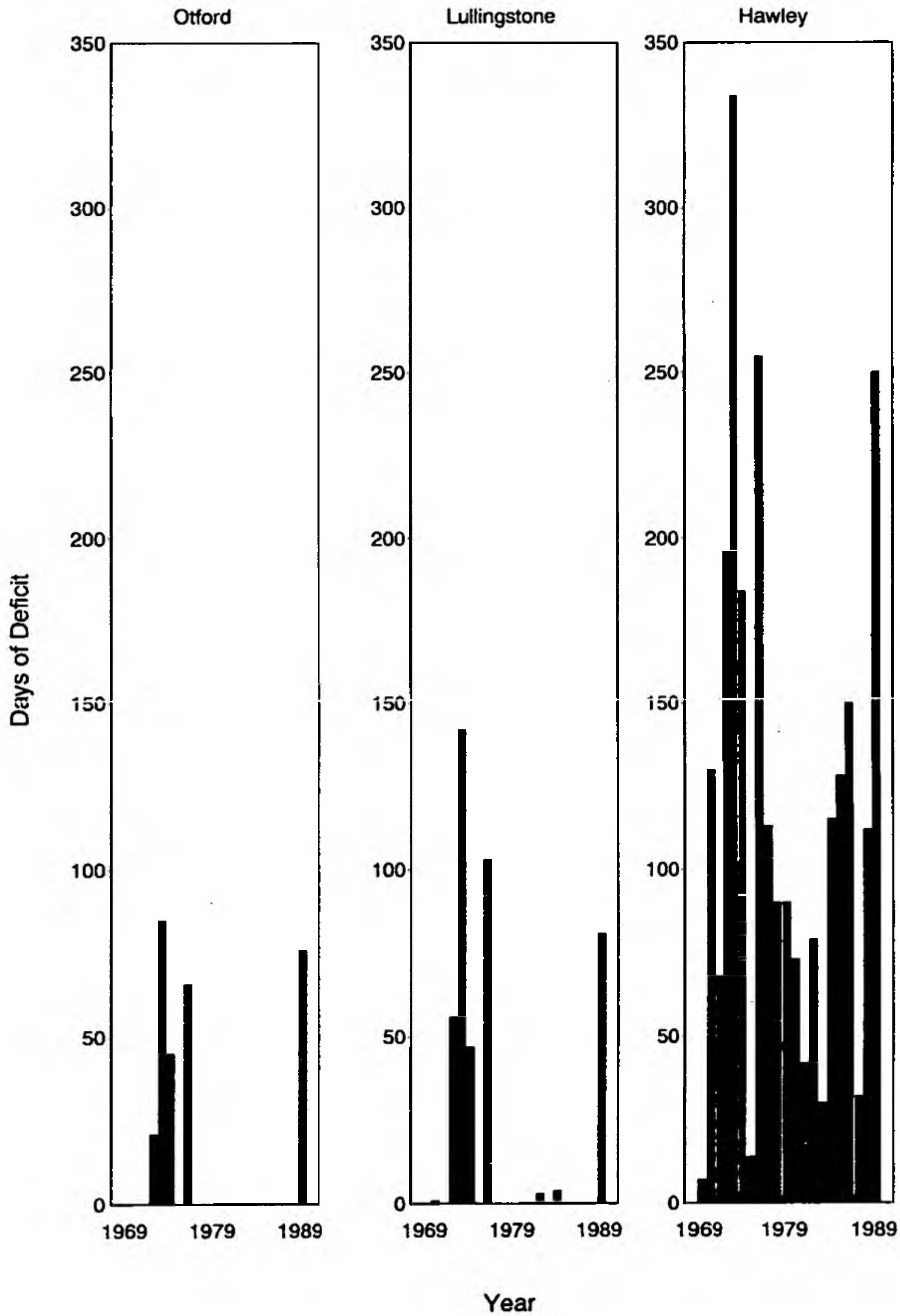


Figure 4.10

Days of Deficit



CHAPTER 5

ENGINEERING STUDIES

5.1 Introduction

The main objective of the engineering studies is to identify practical means of alleviating the low flow problems in the Darent. A wide range of options have been suggested in this respect, and the principal aim at this stage of the study is to screen these options, and identify those which appear to have the most promise for further evaluation, using the catchment model where appropriate.

The strategies for alleviating low river flows can be broadly categorised as abstraction reduction/relocation, flow augmentation, flow conservation, recirculation, demand management or some combination of these. Options within these strategies may involve changes in the management of existing groundwater and surface water resources, development of new groundwater sources, use of storages within the catchment, artificial recharge, use of sewage effluent, control of demand, etc. Any options which involve a reduction in current abstractions will involve some assessment of the practicality of finding replacement supplies.

This chapter discusses:

- the size of the problem, and hence the necessary scale of the engineering options;
- the current infrastructure, and how this affects the options;
- the options considered, including their advantages, disadvantages and costs.

The last section of the chapter summarises the options considered and compares them in terms of unit cost.

5.2 Augmentation Flow Required

Relating flows at the three gauging stations (Otford, Lullingstone and Hawley), to the environmentally acceptable flows (as defined in the WS Atkins study, 1991) provides an indication of the size of problem to be tackled. At this stage only fixed values of EAFR which do not allow for seasonal variation are available for each gauging station. The analysis using these fixed values indicates that the deficits recorded at the Otford and Lullingstone gauges relative to the minimum flows required from an environmental viewpoint are relatively infrequent and small, and that the principal problem is between Lullingstone and Hawley. Charts summarising average monthly deficits at the three gauging sites over the respective periods of record are given in Figure 5.1.

Although only fixed annual values of EAFR are available the seasonal nature of the problem is reasonably illustrated by Figure 5.2. This shows the distribution of deficit days for the three sites, and indicates that while the problem principally arises from mid-summer to late autumn, it can extend through to mid-winter, particularly at Hawley. It is thus likely that any augmentation flow needs to be sustained for periods of several months. Sustained deficit periods (defined as periods when deficits occur on the majority of days in the month for successive months) are indicated in Table 5.1, which also indicates deficit volumes.

TABLE 5.1

Sustained Deficit Periods

Station	Period	Duration (months)	Deficit volume (Ml)
Otford	8/73 to 11/73	4	140
	7/76 to 9/76	2.5	140
	8/89 to 9/89	2	90
Lullingstone	7/73 to 12/73	5.5	680
	6/76 to 9/76	4	780
	8/89 to 10/89	2.5	170
Hawley	5/65 to 11/65	7	700
	6/70 to 10/70	5	930
	6/72 to 1/74	20	8 300
	4/74 to 9/74	6	2 500
	3/76 to 11/76	9	4 550
	7/77 to 10/77	4	950
	9/78 to 11/78	3	550
	9/79 to 11/79	3	360
	8/80 to 9/80	2	270
	8/81 to 9/81	2	240
	8/82 to 9/82	2	650
	7/84 to 10/84	4	1 100
	8/85 to 12/85	4	710
	5/86 to 10/86	5.5	1 200
	8/88 to 2/89	6	900
	5/89 to 12/89	7	3 600

The record at Hawley indicates regular deficits of 2 to 4 months duration over the July to October period, with typical deficit volumes in the range 250 to 1 000 Ml, and longer deficit periods and volumes in the dry years which typically extend from May through to December with volumes in the range 1 000 to 5 000 Mld. The 20 month deficit period in 1972/73, with a deficit volume of over 8 000 Mld would appear to be exceptional, perhaps matched by the current deficit period for which analysis is not yet available.

Figure 5.1

Monthly Deficit Records

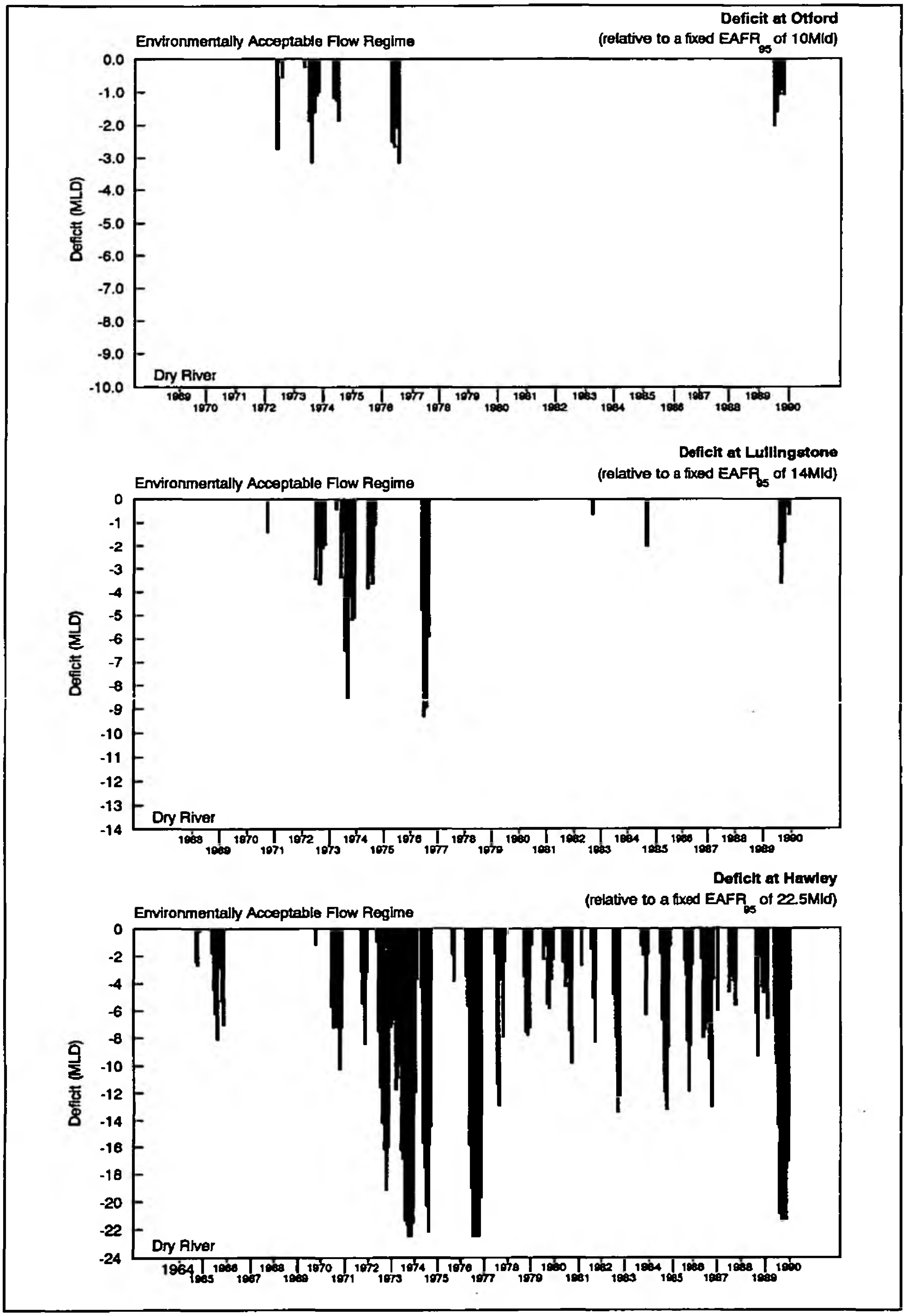
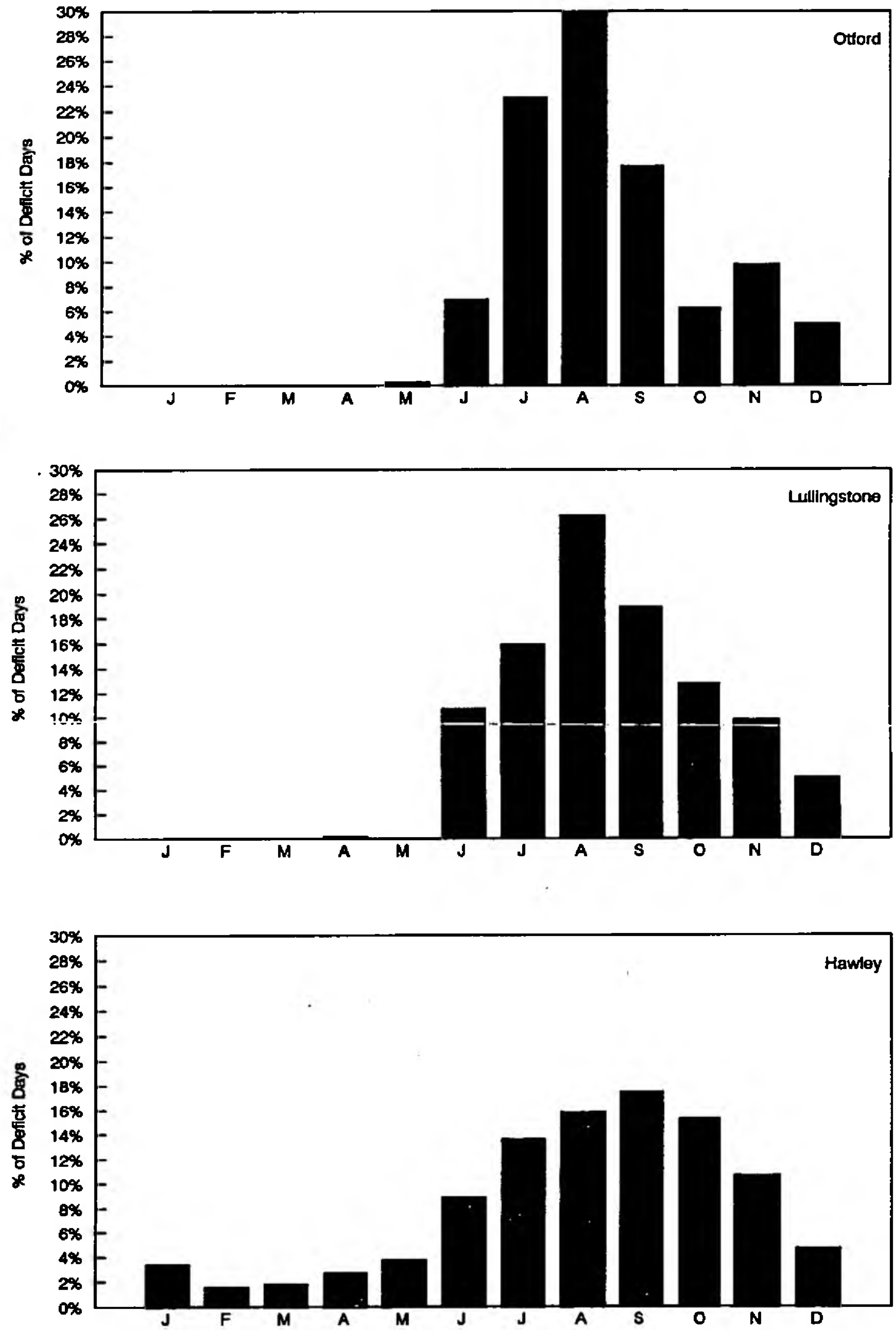


Figure 5.2
Seasonal Distribution of Deficit Days



Note :- based on fixed values of $EAFR_{95}$ for each station

The conclusion drawn from the table is that the deficits at Otford and Lullingstone are relatively infrequent, occurring only in the very dry years, and of moderate duration (2 to 5 months) and volume (up to 150 Ml at Otford, and 800 Ml at Lullingstone). The problem at Hawley is clearly of a different order of magnitude and is likely to require a strategic solution. The problems in the river reaches in the vicinity of Otford and Lullingstone may, however, be amenable to 'local' solutions.

It is thus evident that any augmentation solution proposed needs to be able to provide flows for lengthy periods and deliver large volumes of water, particularly at Hawley.

Further analysis of the gauging records has been carried out with a view to assessing the capacity required of augmentation options considered. This analysis is summarised in Table 5.2, which provides an indication of augmentation flows against percentage of time the $EAFR_{95}$ is achieved.

TABLE 5.2

Augmentation Flows Required (Mld)

Station	$EAFR_{95}$	% Time $EAFR_{95}$ met at present	Augmentation flow (AF)		
			AF (95%)	AF (98%)	AF (100%)
Otford	10.4	96	0.0	1.7	4.3
Lullingstone	13.8	94	1.0	5.0	10.0
Hawley	22.5	73	20.0	22.0	22.5

Note: AF (n%) Augmentation flow to ensure that $EAFR_{95}$ met n% of the time on a monthly average basis.

From the table, if it is accepted that the $EAFR_{95}$ is only met for 95% or 98% of the time, there would be a substantially smaller augmentation capacity requirement at Otford and Lullingstone. At Hawley, there is little difference between the values.

Suggested design requirements for augmentation required to attain minimum environmental flows at the three gauging stations are summarised in Table 5.3.

TABLE 5.3

Design Augmentation Requirements at Gauging Sites

Station	Maximum capacity (Mld)	Duration (months)	Volume (Ml)
Otford	2	3	150
Lullingstone	5	5	700
Hawley	22	9	5 000

Clearly, since these figures represent requirements at the gauging sites, allowances need to be made for seepage losses in the reach between Lullingstone and Hawley where losses are known to be very high and have been measured as 15 Mld at relatively low river flows. For this reach, it is thus likely that an augmentation flow of 35 to 40 Mld would be required, with a corresponding increase in volume of about 3 500 Ml.

5.3 Water Related Infrastructure

5.3.1 General

The major water supply infrastructure and operational zones in and adjacent to the Darent catchment are illustrated in Figure 5.3a, which shows public supply wells and reservoirs, their ownership and the areas served by the relevant supply companies. The area is served by four water companies, namely, Thames Water Utilities and West Kent, Mid Kent and East Surrey Water Companies. In addition to groundwater abstraction and supply operations by these four companies, groundwater is also abstracted from the catchment by Southern Water Services. Substantial quantities of groundwater abstracted from the Darent catchment by the water companies are exported to supply other areas in the region.

About 30% of the water supplied to south-east London by TWU is derived from surface water sources in the Thames Valley and is transferred via the south-west trunk main system to the Honor Oak complex, from where it is distributed. The remainder is derived from 22 groundwater sources, 10 of which are located in the Darent catchment. Many wells (eg Southfleet, Green Street Green, Horton Kirby, Eynsford) service local demands, but in some cases water is transferred some distance within the south-east London area. An indication of the links between wells, reservoirs and supply zones and the associated distribution of abstracted water is provided in Figure 5.3b.

About half of the water abstracted by the West Kent Water Company in the Darent catchment is transferred to the Tunbridge area, with the remainder supplying Sevenoaks and environs. Water abstracted in the catchment by the Mid Kent Water Company meets local needs and is supplemented by imports from Trosley. Water from the wells operated by the East Surrey Water Company and by Southern Water is transferred to adjacent catchments.

The size of groundwater abstractions for public water supply are indicated in Table 5.4. Some additional abstractions for other uses take place within the catchment. These amount in total to a licensed quantity of about 17 Mld with an estimated actual total abstraction of about 8 Mld in the period 1985 to 1989. The major part of this additional abstraction is for industrial use in the Dartford area where licences for uses other than public water supply total about 14 Mld. Abstraction in Dartford should not, however, affect river flows in the reaches which are of most concern, ie as far downstream as Hawley.

Figure 5.3a

Water Supply Operational Areas

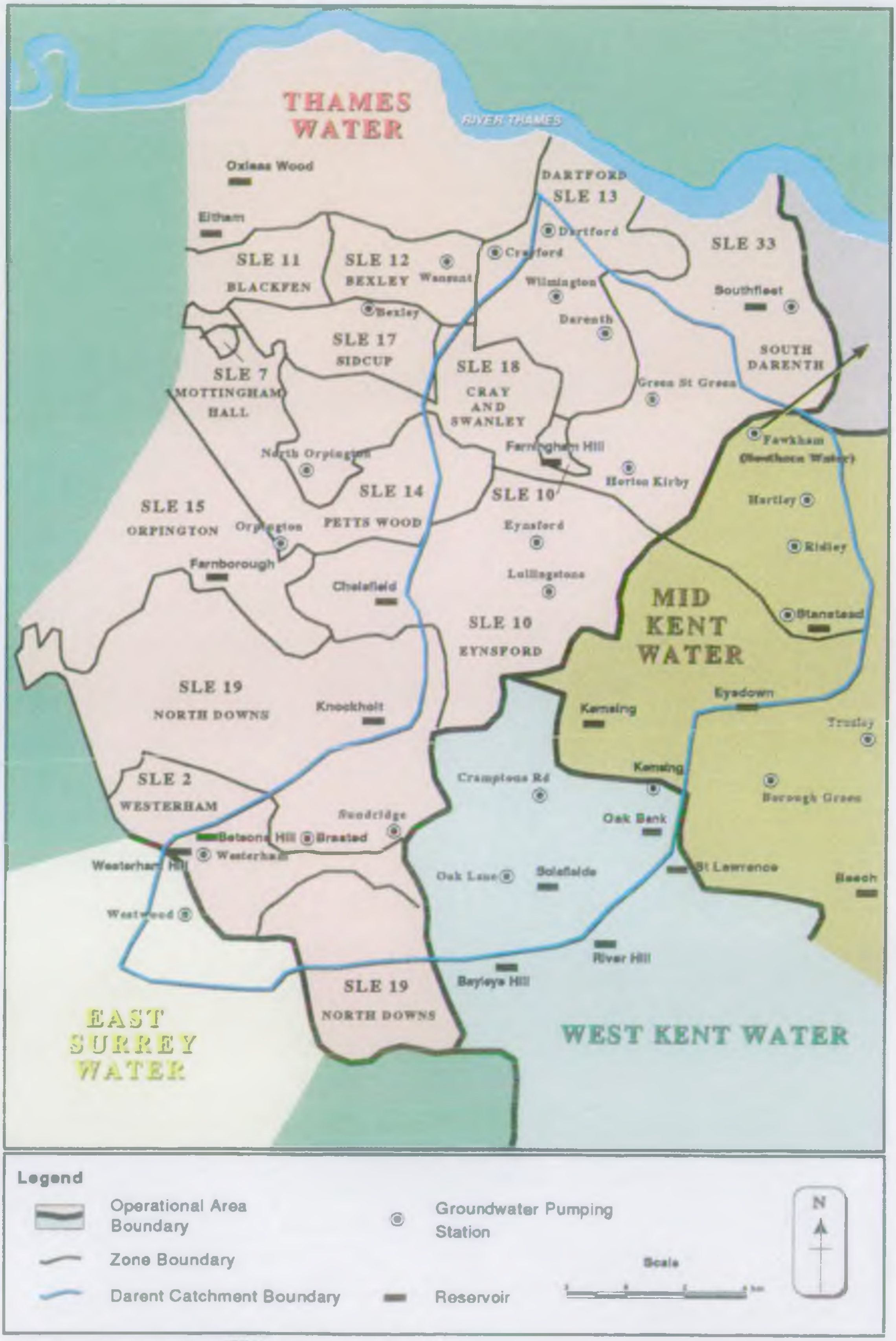


Figure 5.3b

Indicative Water Distribution

TABLE 5.4

Abstractions for Public Water Supply

Abstractor	Number of sources	Licensed average abstractions (Mld)	Average abstractions for 1985 to 1989 (Mld)
Thames Water	10	106.9	81.0
West Kent Water	3	23.1	18.8
Mid Kent Water	3	12.5	5.4
Southern Water	1	6.8	6.1
East Surrey Water	1	5.6	1.9
Total	18	154.9	113.2

Notes: (1) Licensed average abstraction is the licensed annual abstraction divided by 365 days.

(2) Source: TWU Database and water companies' data.

It is clear that the focus of any assessment should be with the first two abstractors shown in Table 5.4 which account for 80% to 90% of abstractions. The distribution of public water supply abstractions within the catchment is indicated in Figure 5.4. An approximate assessment of the exports from and imports to the catchment is given in Table 5.5. The table provides some indication of how abstractions from the catchment are distributed. Although there is little data on flows across the catchment boundaries, it is estimated from the data provided that about 50 Mld (40% to 50%) of the water abstracted in the catchment is exported to adjacent supply zones, compared to imports of about 3 Mld.

The major sewerage infrastructure of interest is the Darent Valley trunk sewer, the location of which is shown on Figure 5.5. This serves the main population centres in the Darent catchment and discharges to the Long Reach sewage works in Dartford, which also serves other parts of SE London, including Bexley, Bromley and some of Croydon.

The trunk sewer was originally constructed during the last century, and comprised a 24 inch stoneware pipe running from Westerham to Dartford. A parallel sewer of 36 inch diameter was added between Farningham and Wilmington to provide additional capacity, and at some point the section from Wilmington to Dartford was uprated to a 54 inch diameter pipe. In the 1980s, additional work was carried out, with a 900 mm diameter pipe being added between Sevenoaks and Farningham. There are a number of branch sewers.

The effluent in the sewer is a potential resource currently lost to the catchment. The potential for using this resource depends on the quantity and quality of effluent. Information on quantity and quality is very limited, comprising data at the Long Reach sewage works, which includes effluent from other parts of south-east London, and spot flow measurements made on the Darent Valley Trunk

TABLE 5.5

Catchment Imports and Exports

Supply zone(s)	Darent source(s)	Average daily flow at source (Mld)	Status in relation to Darent catchment
Thames Water			
Westerham (SLE2)	Westerham Hill	0.9	35% exported
Eynsford (SLE10)	Lullingstone	5.5	20% exported
Blackfen/Bexley/Dartford[1] (SLE 11/12/13)	Darenth/Dartford/Wilmington	35.0	30% exported
Sidcup/Cray/Swanley (SLE 17/18)	Eynsford/Horton Kirby	21.6	60% exported
North Downs (SLE19)	Brasted/Sundridge	13.8	70% exported
South Darenth[2] (SLE33)	Green St Green	4.3	10% exported
	Total	81.1	
West Kent Water Co			
Sevenoaks/ Tonbridge/Tunbridge Wells	Cramptons Road/Kemsing/ Oak Lane	18.8	45% exported
Mid Kent Water Co			
Stansted	Hartley/Ridley/Stansted	5.4	Internal
Exedown (part)[3]	None	3.0	Imported
East Surrey Water Co			
Kent Hatch/Crockham Hill	Westwood	1.9	Exported
Southern Water			
Medway Area	Fawkham	6.1	Exported

Notes:
1. These zones partly supplied from Bexley and Wansunt sources.
2. This zone partly supplied by Southfleet source.
3. The Exedown zone is supplied by sources in the Medway catchment. It is assumed that half the supply provided to Exedown zone is used in the Darent catchment.
4. Estimates based on flow data where available or an assessment of service areas.
5. Note that water used within the catchment leaves via the Darent trunk sewer and is not recirculated.

Sources: Thames Water Utilities, Mid Kent Water Co, West Kent Water Co, Southern Water, East Surrey Water Co.

Sewer at Farningham in April 1991. The latter suggested average flows of 13 to 14 Mld, which are broadly consistent with other indicators, such as population and water supply information. With regard to quality, informal discussions with the area trade effluent officer for the Sevenoaks area have indicated that there are no undesirable substances in the effluent. Further down the catchment in the more urban and industrial areas, the quality of the effluent is likely to deteriorate. Dossor (1978) suggests that the dry weather flow at the confluence of the sewer with the Long Reach Trunk Sewer is of the order of 65 Mld, rising to about 140 Mld in a storm.

The flow at Long Reach sewage works averages around 150 to 200 Mld. The sewage receives secondary treatment by means of an activated sludge process and produces an effluent of 20 BOD.

Figure 5.4

Public Water Supply Abstractions

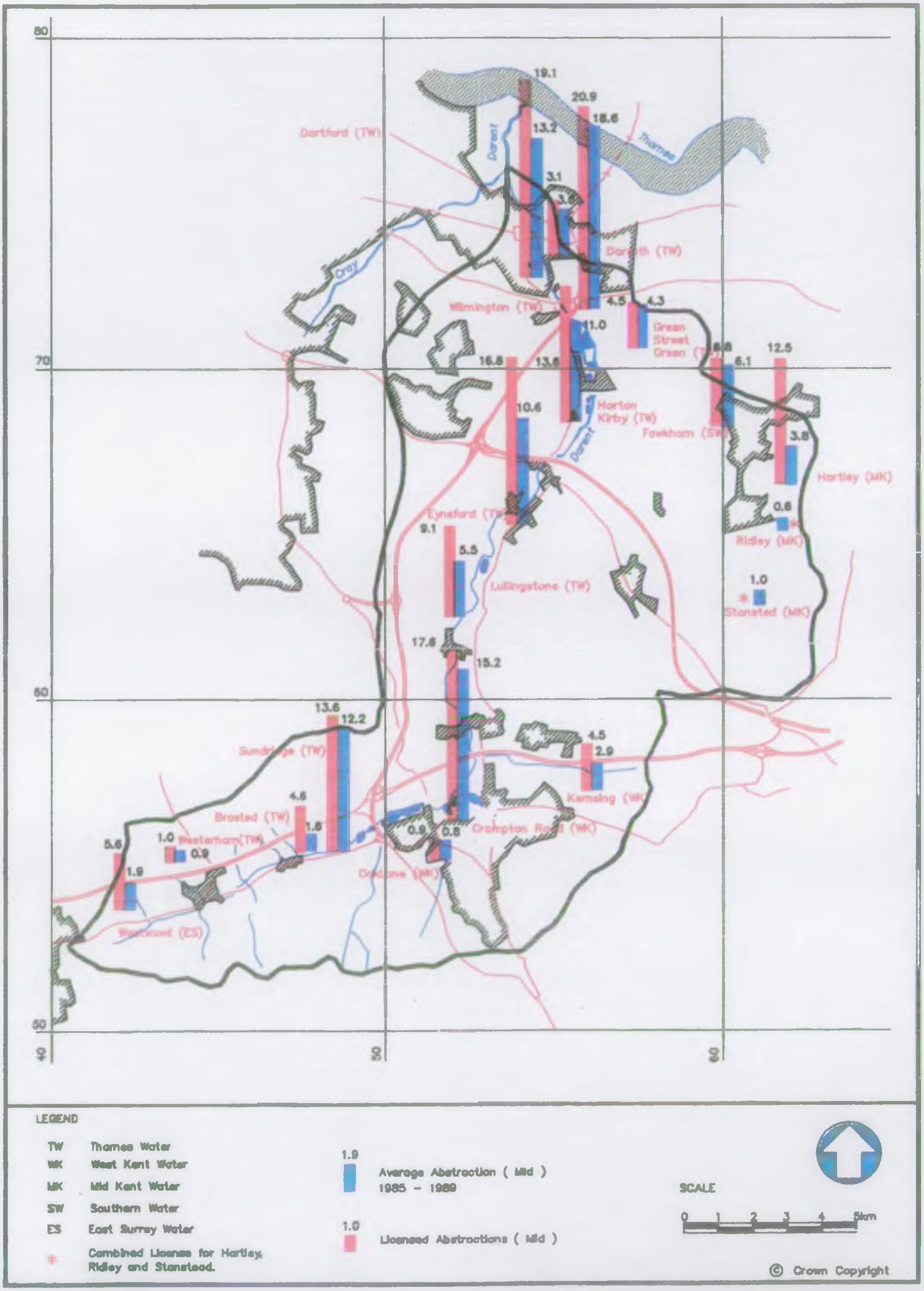
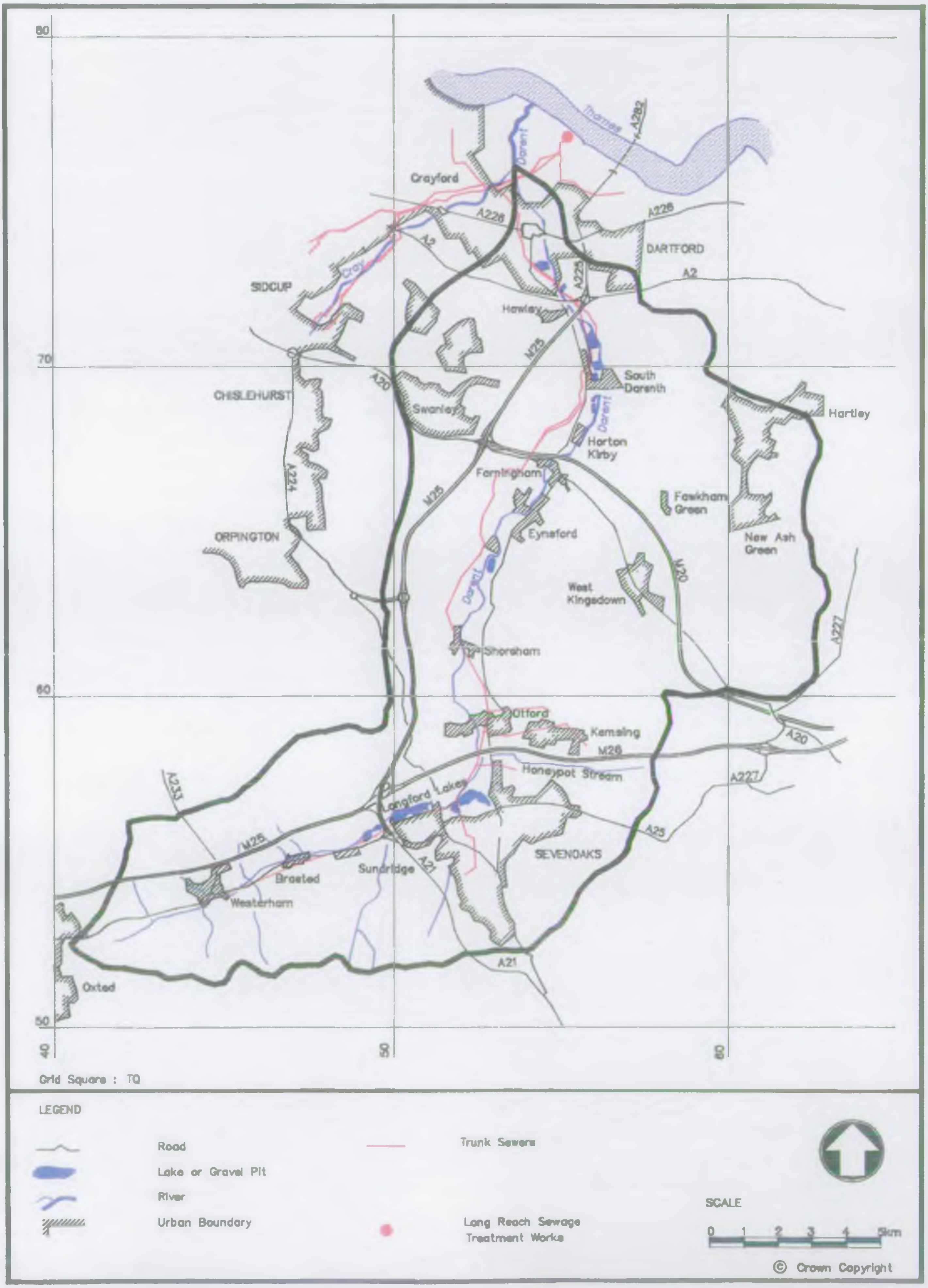


Figure 5.5

Darent Valley Trunk Sewer



This compares with the consent standard for discharges to the Thames tideway of 50 BOD. There are thus no plans to improve this standard, although capacity enhancements are planned.

5.3.2 Demand Growth

Estimates of demand growth have been provided by Thames Water and Mid Kent Water directly, and by the NRA for West Kent Water and for the Kent Medway Division of Southern Water.

The planning area used by Thames Water for demand forecasting purposes is the Kent Wells Conservation Area, indicated in Figure 5.6. This area does not fully correspond with the operational supply zones indicated on Figure 5.3a. Mid Kent Water use the operational supply zones as the planning unit.

For Thames Water, the data are presented in Figure 5.7, and represent a growth in population of 0.25%, and a demand growth of 0.79% pa to 1997, rising to 1.03% pa thereafter. Planning by Mid Kent Water is based on three demand growth scenarios (low, medium and high), ranging from 0.78% to 3.0%. The figures provided by NRA for the West Kent Water Company suggest average growth over a 20 year horizon of about 0.75% pa assuming no uptake of domestic metering. For the Kent Medway Division of Southern Water, the comparable figure is 0.7% pa. With effective leakage control, zero growth in demand is projected for Kent Medway.

Total demands and implied gross per capita consumption figures (where available) are compared in Table 5.6 for four planning horizons.

TABLE 5.6

Demand Projections

		1991/2	1996/7	2001/2	2011/12
Thames Water Kent Wells Zone	Mld lcd	212 344	217 346	228 360	251 387
West Kent (1)	Mld lcd	36.8 276	38.3 286	39.8 297	42.8 320
Southern Water (1,2) Kent Medway Division	Mld lcd	168.6 400	175.8 411	184.2 422	194.6 455
Southern Water (1,3) Kent Medway Division	Mld lcd	168.1 399	146.3 342	154.1 353	165.1 386
Mid Kent low Stanstead medium Zone high	Mld Mld Mld	5.6 5.7 6.0	5.9 6.1 6.8	6.2 6.5 7.6	- - -
Mid Kent low Exedown medium Zone high	Mld Mld Mld	5.1 5.3 5.6	5.3 5.7 7.1	5.5 6.0 7.8	- - -

Notes:
1 Assuming no increase in domestic metering uptake
2 Assuming no improvement in leakage control
3 Assuming improved leakage control

The higher gross per capita figures for Southern Water and Thames Water compared to West Kent probably reflect higher proportions of commercial and industrial consumers within those areas. In 1988 commercial/industrial demand was about 25% of total in West Kent and about 43% in the Kent Medway zone of Southern Water.

If it is assumed that the growth in demand in the Darent catchment and adjacent areas averages 1% per year, then demands currently met from the Darent catchment would increase to the levels indicated in Table 5.7.

TABLE 5.7

Demand Projections for Darent Catchment (Mld)

Year	1990	1995	2000	2010
Exported	51	53	56	62
Internal use	62	65	68	76
Total	113	119	125	138

Clearly, while framing solutions to the current problems, the above projections need to be considered. It is evident that these long term requirements could not be met from the Darent catchment, and there is thus a need to consider how this growth can be met from sources outside the catchment. It would be feasible to divert some of the current exports to meet internal demands, but wider solutions are required for the adjacent supply zones in any event. If catchment abstractions are sustained at current levels, additional resources of about 25 Mld would need to be found elsewhere by the end of the above planning horizon. If catchment abstractions are reduced to ensure minimum river flow criteria are met, resources of 50 to 60 Mld would need to be found from outside the catchment by 2010.

5.4 Review of Engineering Options

5.4.1 General

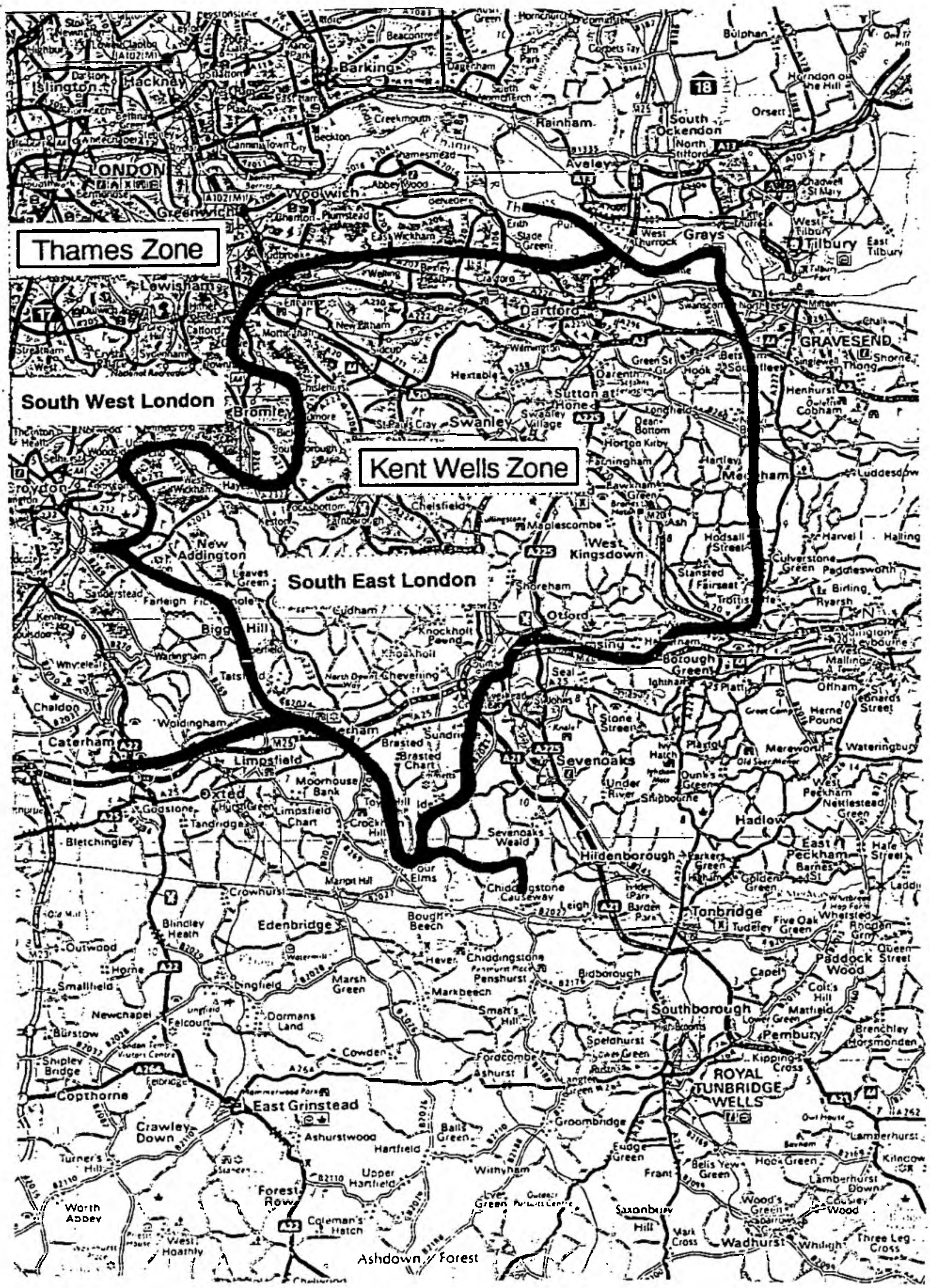
Solutions to the low river flow problem may involve groundwater or surface water management or new development options, or some combination of these. It is thus not easy to categorise solutions to the problems, although this has been done in a broad manner, recognising that some options could be included under alternative categories. Options considered as part of this review are:

Groundwater Management

- revoke licences or reduce licensed abstractions by agreement, importing water to the catchment to replace these supplies;

- develop additional wells away from the river for use as summer sources or for direct river augmentation;

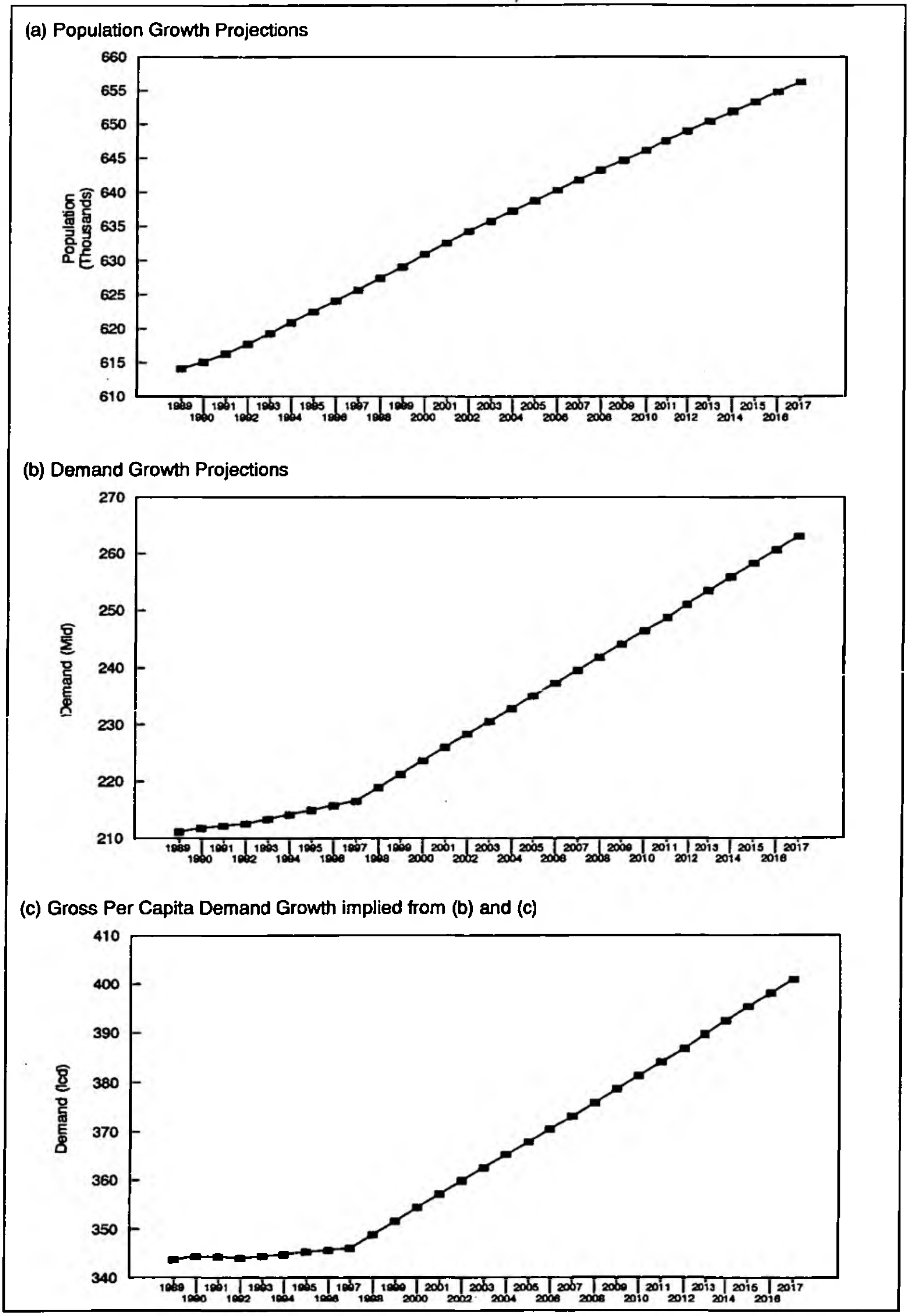
Kent Wells Conservation Area



Source : TWU

Figure 5.7

TWU Demand Growth Projections for Kent Wells Zone



- bankside wells (artificial springs).

Surface Water Management

- groundwater recharge using surplus (winter) surface flows;
- seasonal storage of flows in existing lakes;
- bed lining of critical channel sections to limit seepage losses;
- recirculation of river flows from downstream;
- river intake, bankside storage and treatment works at Dartford (to replace existing groundwater abstractions);
- use of sewage effluent to augment natural river flows.

Demand Management

- limiting demand through quotas, domestic metering and associated tariff setting pricing strategies;
- differential pricing of water from different sources;
- leakage control.

These options are discussed in the next sections.

5.4.2 Groundwater Management

Changes in Licensing Arrangements/Importation

The options included under this heading involve full or partial revocation of selected abstraction licences and reduction in abstraction through mutual agreement with the abstractor. In practical terms, there would be little advantage in full revocation of licences if sources remain viable in wet periods, since these sources are likely to give low cost, good quality supplies. For this reason, partial revocation or reduction by mutual agreement is preferred. Determining how many and which wells should be controlled in this way to ensure the required river flows are met will need to be tested using the catchment model.

The principal (and related) issues with respect to changes in licensing arrangements are the level of compensation which would be sought by the licensees, and finding alternative resources to compensate for the reduction in abstraction, either on a seasonal or permanent basis. One of the problems of seasonal management of the existing resources is that at times when water is short in the Darent, it is also likely to be short elsewhere in the region. The issue is thus one of regional water resources.

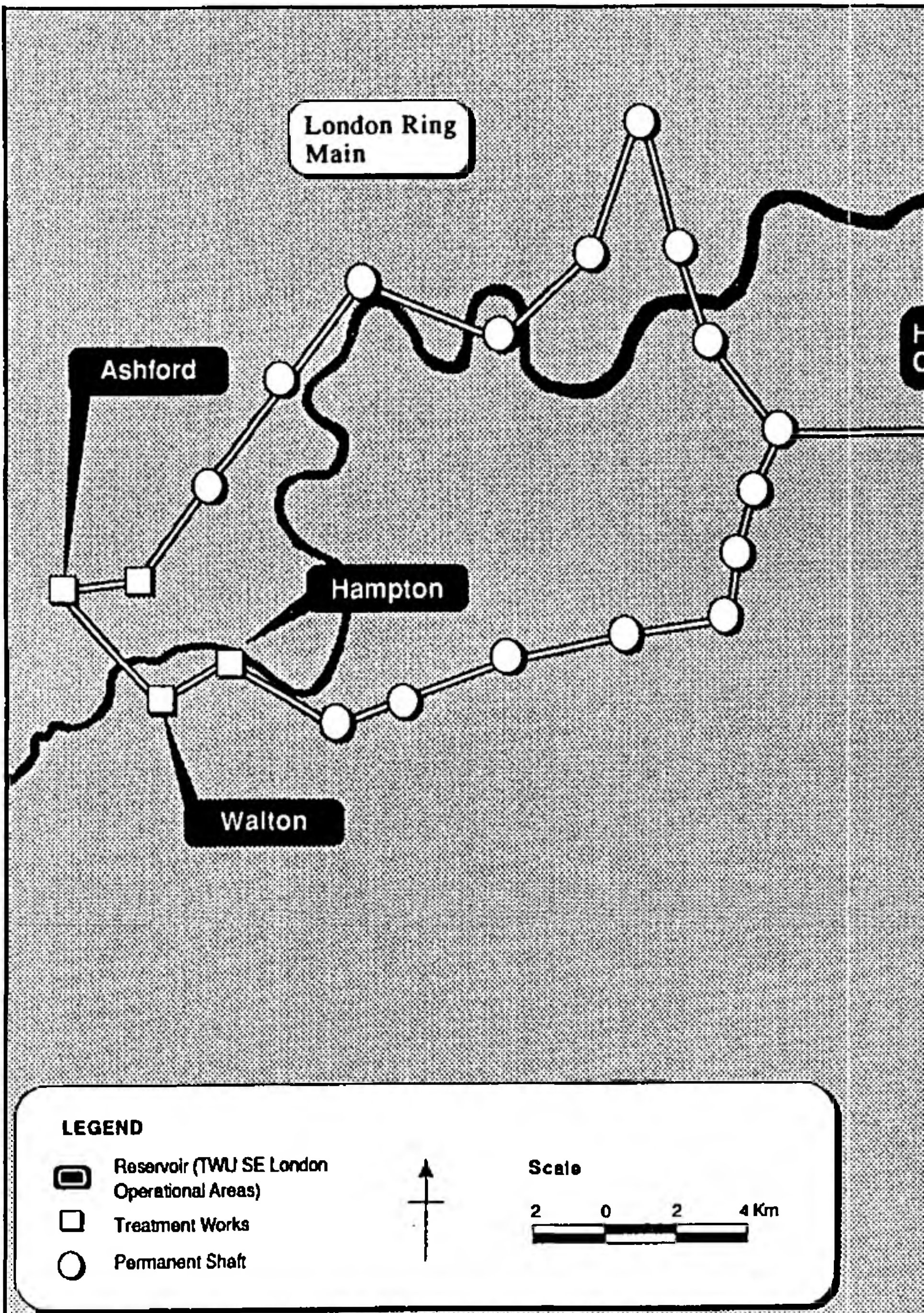
Given the demand growth projections outlined in Section 5.3.2, it would seem that sources from outside the catchment may need to be found in the future, regardless of current problems. It may thus be appropriate in some cases to provide capacity at the present time to deal with current problems and meet future needs.

Discussions have been held with Thames Water Utilities (TWU) regarding the possibility of making use of the flexibility afforded by the London Ring Main (LRM) in meeting local deficits in the Darent catchment through conjunctive use of surface and groundwater supplies. The location of the ring main in relation to the Darent catchment is shown in Figure 5.8. The link to the zones currently fed from the Darent catchment would be via the Honor Oak complex. TWU are currently carrying out model studies of the water supply systems within the south-east London area. Zonal boundaries proposed for the studies are indicated in Figure 5.9. These appear to be similar but not identical to the operational zones shown on Figure 5.3a.

About 30% of water supplied to Thames' SE London area is currently derived from surface sources at Hampton, Walton, Ashford Common and Surbiton. Transfer from the Thames Valley is via the south-west trunk main system to the Honor Oak complex. From Honor Oak, water is transferred to eight of the SE London supply zones (Oxleas Wood, Bromley, Bickley, Plumstead, Northumberland East, Farnborough, Castlewood and Shooters Hill) and is repumped from these zones to feed other areas. Some zones (eg Farnborough) are served by both surface water and groundwater. New Cross zone is fed directly from the Hampton main.

The remainder of the supply to the SE London area is drawn from 22 groundwater sources, which tend to feed local zones, with little transfer of supplies between zones. However, there is a degree of flexibility within the supply systems, and the boundary between areas supplied from the Thames Valley and areas fed from groundwater changes on a day to day basis in response to changes in source production and demands.

To replace groundwater supplies directly with surface water would involve development of additional surface water resource works (eg reservoirs, basin transfer schemes). This is likely to be an expensive option although it may be necessary to meet general demand growth. Examination of such options is beyond the scope of the current study, although it is understood that studies to address the general resource development and use issues within the Thames area will be commenced shortly by NRA (Thames). However, it may be feasible to make use of 'off-peak' capacity in the current system and this has been discussed with TWU.



London Ring Main
Ashford
Hampton
Walton
LEGEND
Reservoir (TWU SE London Operational Areas)
Treatment Works
Permanent Shaft
Scale
2 0 2 4 Km

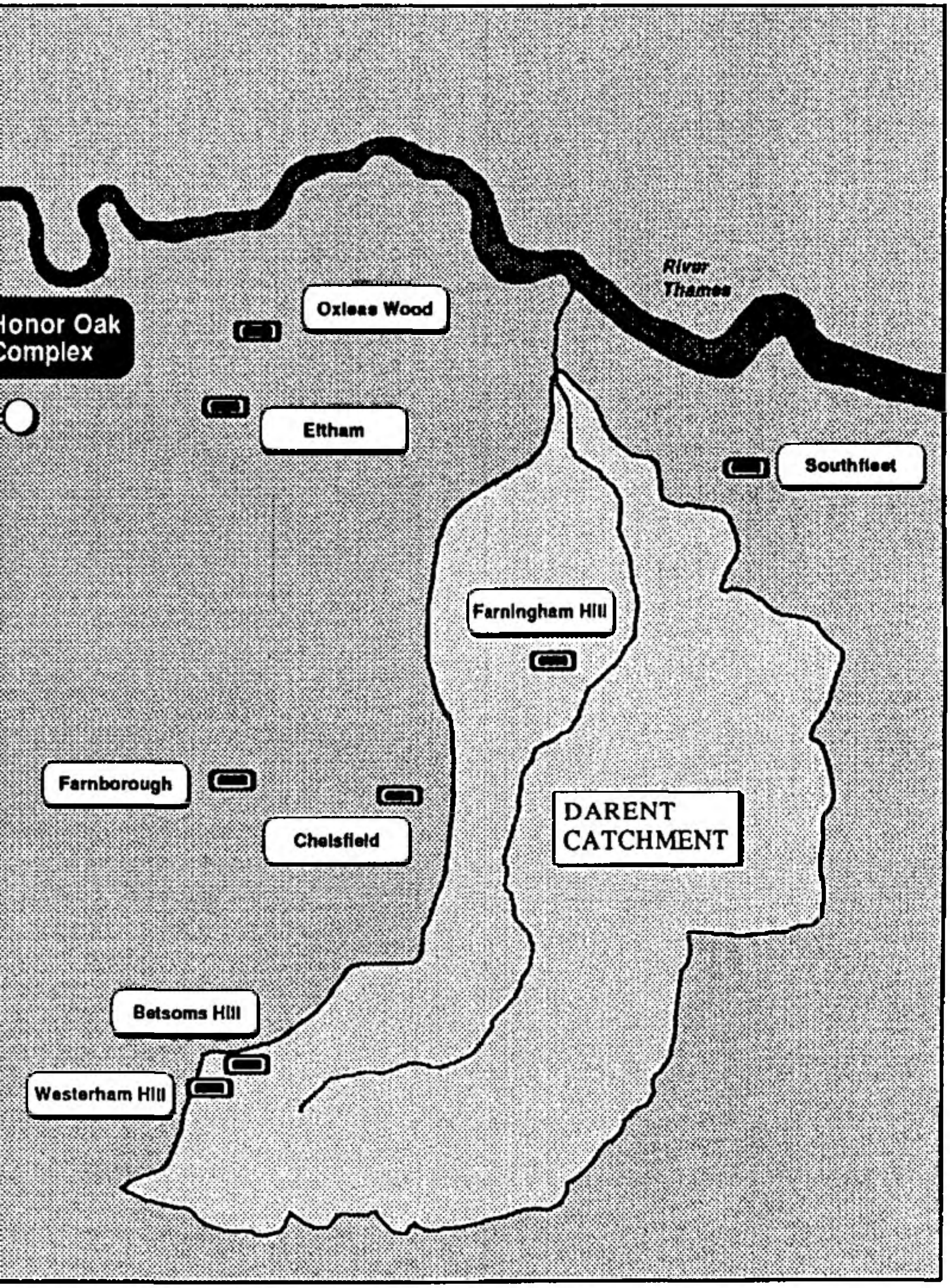


Figure 5.8

Location of London Ring Main

Figure 5.9

Thames Water Supply Zones - SE London

Schemes in the USA and the Enfield-Haringey scheme have shown that conjunctive use of surface and groundwater is a cost effective approach to additional resource development and public supply management. In that type of scheme, surplus capacity in the surface water abstraction, treatment and trunk main systems at off-peak times (eg winter) are used to transfer surface water resources to groundwater storage through recharge. This stored water can then be used at peak times. A similar approach to water management would appear possible for the south-east London area. Given that 70% of the supply is currently abstracted from the ground, one approach would be to 'rest' selected wells during the winter to allow groundwater levels to recover, rather than, (or in addition to), recharging the aquifer using surface water.

It is understood from the discussions with TWU that there is currently surplus off-peak capacity at the Honor Oak complex of about 30 Mld. The link to the LRM, currently scheduled for the year 2000, will increase the capability to transfer water from the Thames Valley further (capacity yet to be confirmed). Conjunctive use of surface and groundwater could thus be instrumental in meeting future demands and addressing the problems of over-abstraction. It is stressed that, while the capability to transfer off-peak supplies may be in place, the resource itself is limited in terms of peak capacity.

In order to make use of off-peak surface water to recharge the aquifer or 'rest' wells, changes will need to be made to the water transfer systems. TWU's recently commissioned study to develop network models for the whole of the south-east London supply area will allow an examination of how transfer of surface water surpluses from west to east can be best managed in relation to the management of groundwater in the Darent catchment. The study will also examine the means of meeting general demand growth, as well as that in specific high growth areas. High growth areas include the Greenwich peninsula and those associated with the M25 such as the Dartford/Northfleet development area, a part of the south-east Thames corridor under review by SERPLAN. Clearly, in terms of studying west-east transfers, there is a degree of inter-dependence with the groundwater model being developed in this study, which will help to determine which wells have the greatest impact on river flows, and whether use of off-peak surplus capacity will be of benefit during drought periods.

Figures 5.10a and 5.10b present simplified schematic diagrams of the SE London supply system operated by Thames showing the wells, reservoirs and supply zones. From these, it appears that the supply zones fed by the Darent wells are generally independent of the supply systems carrying surface water from Honor Oak, which feed the western part of the area.

It is not proven at this stage of the study which of the Darent wells are the primary contributors to the low flow problems or whether conjunctive use can be of real benefit under drought conditions. The Halcrow (1988) report speculated that the Lullingstone, Eynsford and Horton Kirby wells were the prime factors in creating low flow problems in the river. If this is so, then surface water supplies to replace these abstractions would need to be delivered to the Farningham Hill, Chelsfield and Southfleet reservoirs (see Figure 5.3). It is also possible that the Darenth, Dartford and Wilmington wells, which feed the Eltham reservoir, have an impact on river flows.

There are several ways in which transfers of surface water could be achieved, and potential solutions will need to be evaluated using the proposed network model. However, from a preliminary examination of the schematics and the physical layout, possibilities have been identified. These are indicated on Figure 5.11 and comprise the following:

(i) A link between the Oxleas Wood and Eltham Reservoirs (or a direct link from the trunk main feeding Oxleas Wood) would allow transfer of surface water from Honor Oak to the Eltham system, thus allowing supplies from the Darenth, Dartford and Wilmington wells to be reduced, or switched to other supply zones (eg those fed by Lullingstone, Eynsford and Horton Kirby).

The link would involve about 2 km of 0.6 m dia pipeline of 35 Mld capacity. The Oxleas Reservoir water level is about 12 m higher than that at Eltham, and gravity flow is feasible. On the schematics provided by TWU, a reverse link (ie, from Eltham to Oxleas Wood) via a booster pumping station is shown, which could be used if it has adequate capacity. A link from the Darenth well to the Farningham Reservoir would involve about 6 km of 0.60 m dia pipeline of 27.5 Mld capacity.

(ii) A link from the Farnborough reservoir to the Chelsfield reservoir and on to the Farningham Hill reservoir could provide a similar function, allowing supplies from the Lullingstone, Eynsford and Horton Kirby wells to be reduced (assuming there is off-peak capacity in the delivery mains and at the booster pumping station at Shortlands).

The link from Farnborough to Chelsfield would involve 7 km of 0.60 m dia pipeline of 27.5 Mld capacity, and a static lift of about 40 m. The head difference from Chelsfield to Farningham Hill is about 70 m, and the gravity link would involve about 7 km of 0.50 m dia pipeline of 22.5 Mld capacity.

(iii) A link between the Darenth, Dartford and Wilmington wells and the South Fleet reservoir, depending on (i) above, which would allow substitution of abstractions from these wells for those currently obtained from Horton Kirby. This would involve about 5 km of 0.35 m dia pipeline of nominal 10 Mld capacity.

The types of links described would introduce flexibility into the supply system. The actual links to be developed would depend on the outcome of network modelling and the phasing of capacity provision to meet growth. Costs of the links, based on providing equivalent capacity to the wells which they would supplement would be as indicated below, assuming that, for conjunctive use, they would operate for about 30% of the time (based on number of deficit days at Hawley).

Capital Cost	£6.5 million
Operating Cost	£0.2 million per annum

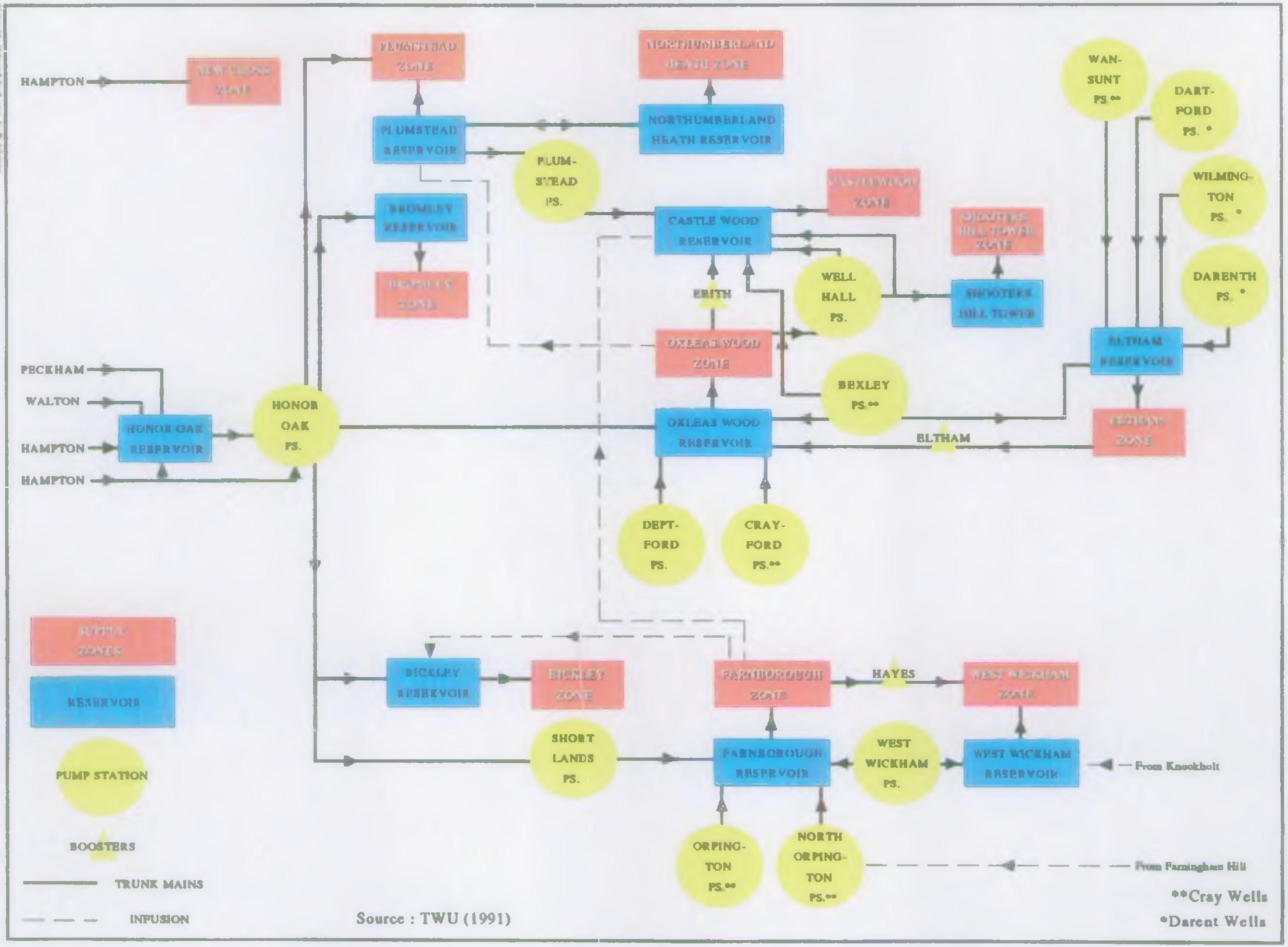
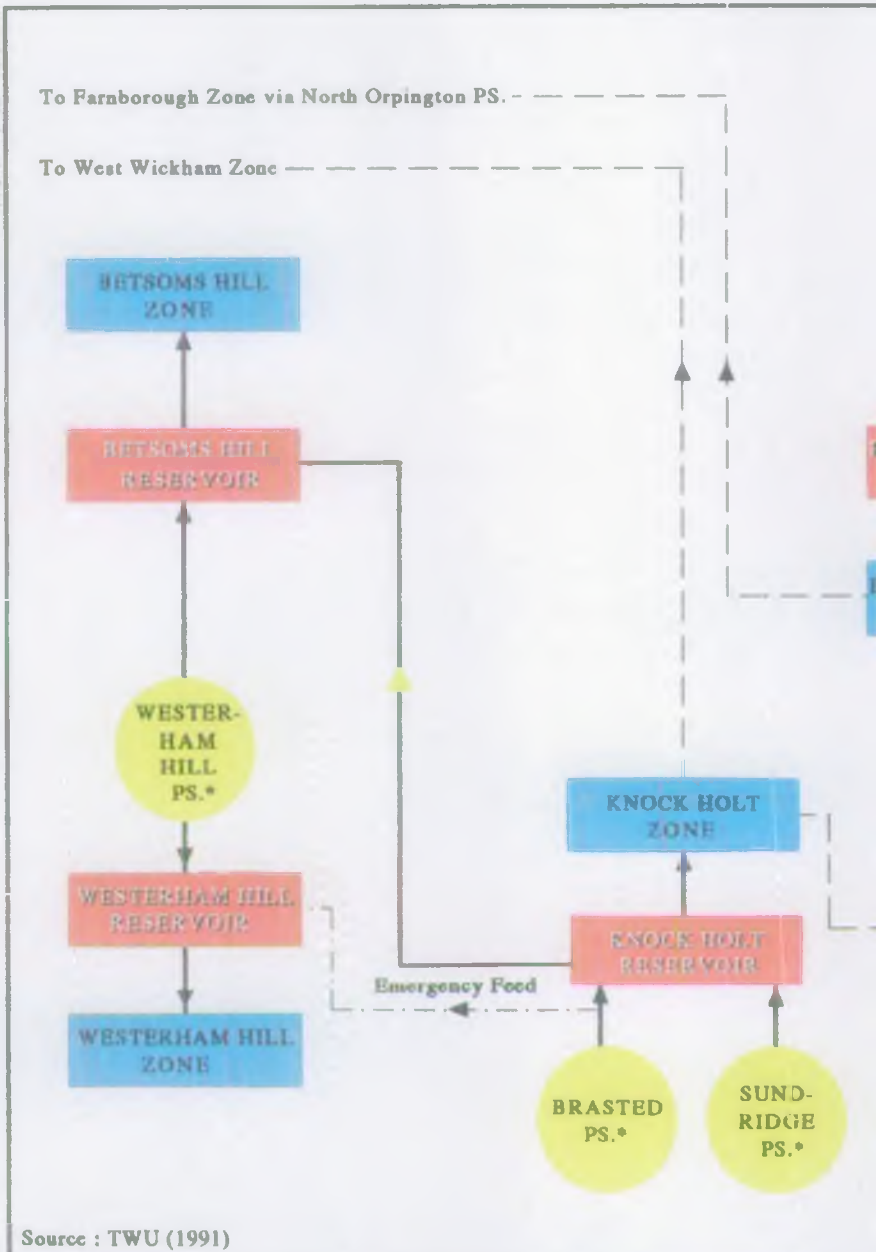


Figure 5.10a
TWU SE London Schematic 1



Source : TWU (1991)

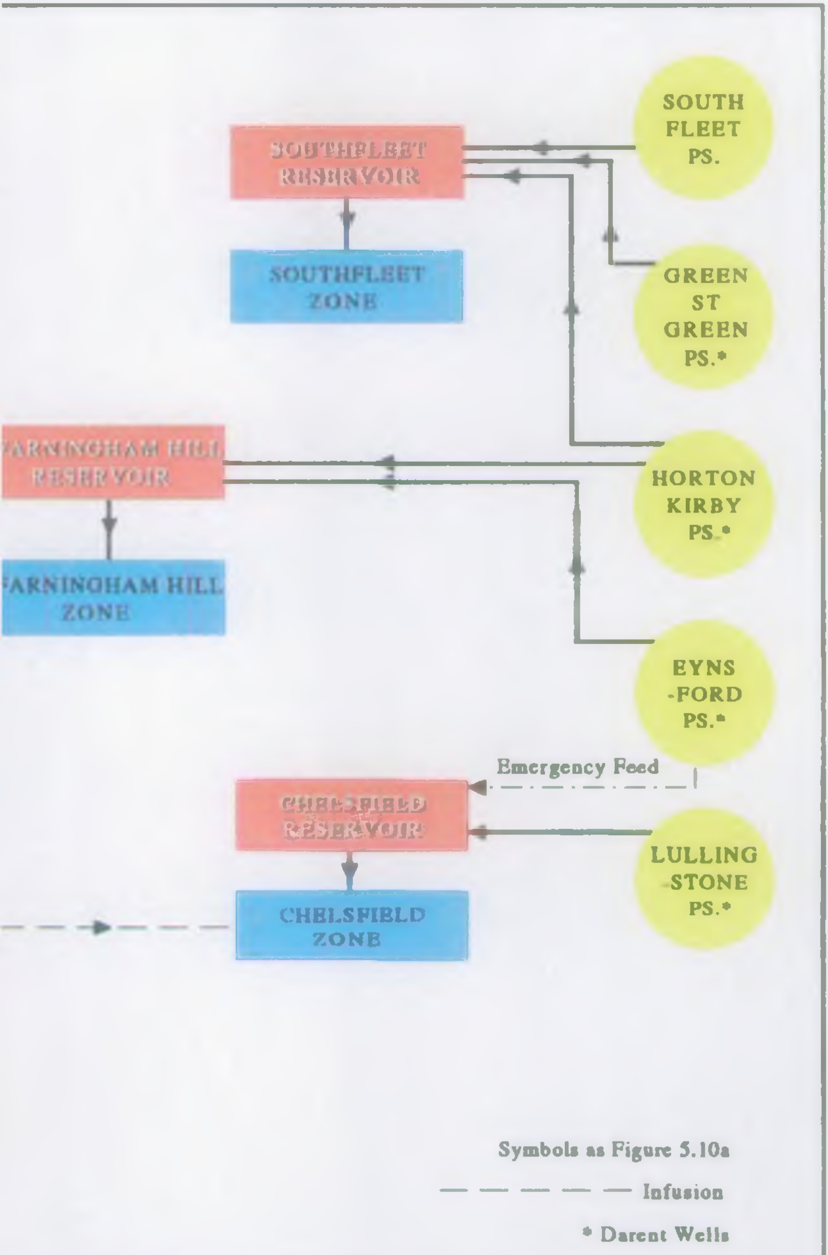
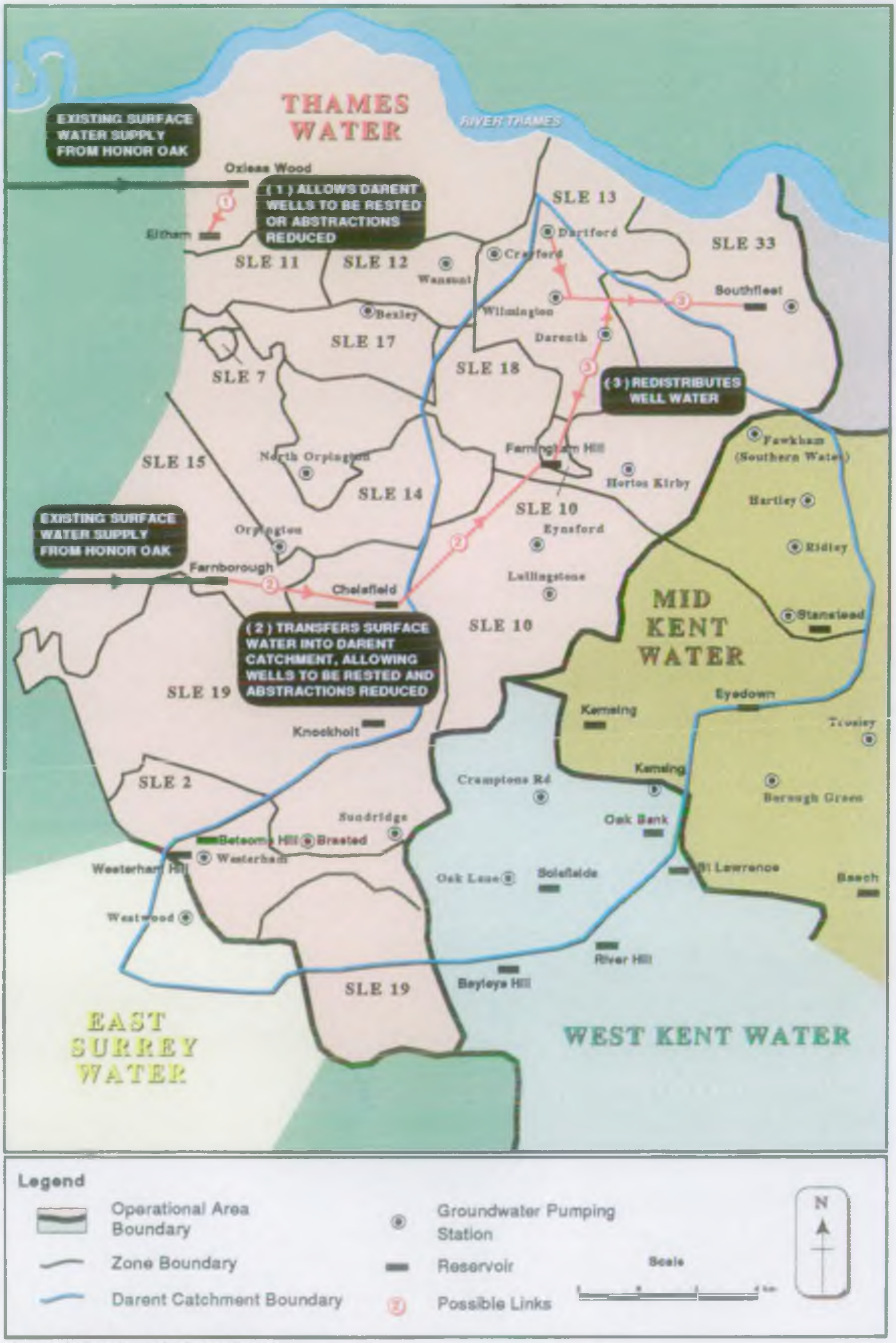


Figure 5.10b

TWU SE London Schematic 2

Figure 5.11

Potential Links in Trunk Main System



The prospect for increased use of surface water from the Thames Valley via the Honor Oak complex in conjunction with the existing groundwater sources appears promising, particularly when future demand growth is considered. The approach would involve "resting" wells in the Darent catchment to allow aquifer levels to recover whenever off-peak surface water is available, and whenever the aquifer level is below a threshold level to be set in relation to the river bed. Depending on performance of this option, direct recharge might also be considered under some circumstances. The impact of these actions at times of peak demands would need to be evaluated using the catchment model. The option may also have scope for meeting growth in other parts of SE London.

The possibility of importing water from adjacent catchments has not been investigated, and would require a wider water resources study. However, from informal discussions with the water utilities, it would appear that prospects for further resource development are limited, with the resources available needed to deal with local deficits.

Additional Wells Development

Given the investment in the current infrastructure, and also that, in wet periods, the existing wells can be operated without major impacts on the river system, there would appear to be little merit in replacing wells completely. Additional wells might be developed either as summer sources or for direct augmentation of river flows on an as-needed basis. It should be noted, however, that results of the water balance assessment presented in Chapter 4 casts considerable doubt on the validity of any such scheme in meeting flow objectives, unless combined with artificial recharge. Schemes of this type cannot be rejected outright at this stage and need to be costed for comparison with other options.

The rationale behind these wells is that they make use of groundwater storage in undeveloped parts of the catchment. The effect is that groundwater flows to the river system are modified with the result that there is a seasonal redistribution of baseflow between summer and winter.

Direct augmentation of river flows avoids the costs associated with treatment for public supply and would involve lower pumping costs. However, use of wells as summer sources has the advantage that water does not need to be pumped twice (ie for river augmentation and for public supply).

A decision as to well location could only be made once the model has been constructed and calibrated. For costing purposes, it has been assumed that wells would be located on a line running approximately mid-way between the reach of river from Lullingstone to Horton Kirby and a line joining the pumping stations at Stansted, Ridley, Hartley and Fawkham. The wells would be about 3 km from the river. The area is also not too distant in terms of delivering to the Farningham Hill or Chelsfield public supply reservoirs.

The assumptions used in costing this sub-option are:

- 24 Mld would be extractable over the design deficit period (capacity assumption has no impact on unit costs);

- for summer sources, delivery is to the Eynsford and Horton Kirby well sites, where they link to exiting pipework;

- for augmentation, delivery is to Lullingstone.

Other possible well sources include the Lower Greensand aquifer along Honeypot stream between Otford and Kemsing, suggested by Halcrow, and the Chalk to the north of the upper Darent between Westerham and Sevenoaks. The water balance assessment has cast doubt on the feasibility of further development of the Lower Greensand. In contrast, the Chalk appears little developed in the upper Darent catchment.

A further potential problem with the Lower Greensand aquifer is the iron content of the water. In costing, it has been assumed that aeration would be required to reduce this.

Given the location of these wells in relation to the area of need, the prospects for use as a public supply appear limited, and it is assumed they would be used for direct river augmentation. The supplies are likely to be limited in capacity (an output of 8 Mld has been assumed), but have potential as a solution for the Sevenoaks to Lullingstone reach.

Costs are estimated to be as follows:

Sub-option	Capital. cost (£m)	Operating cost (£m)
Lower catchment		
Chalk wells, 24 Mld, summer source	2.1	0.07 pa
Chalk wells, 24 Mld, augmentation	2.2	0.08 pa
Upper catchment		
Lower Greensand wells, 8 Mld augmentation	1.0	0.03 pa
Chalk Wells, 8 Mld augmentation	0.6	0.02 pa

Bankside Wells (Artificial Springs)

The general approach would be to construct wells adjacent to the river at several locations along its length, effectively creating artificial springs, which would be operated on an as-needed basis. The approach would not stand alone, but would need to be considered in conjunction with other augmentation schemes as a means of minimising losses along the river length, in a similar manner to bed lining. At times of drought, it is likely that the aquifer becomes disconnected from the river system, and the wells would thus draw from the general reservoir which would be recharged from seepage through the river bed.

The concept would need to be evaluated using the model and subjected to site trials, but would typically involve wells of 4 Mld capacity drilled to a depth of about 40 m. It is estimated that about ten such wells would be required.

A bankside wells scheme would provide a relatively low cost option, in that infrastructure development is limited and operating costs low, since it would only be used on an as-needed basis. It has the benefit that wells could be installed incrementally, thus minimising financial risk. A pilot scheme could be developed relatively quickly.

Costs for a ten wells scheme are estimated to be:

Capital	£0.80 million
Operating	£0.08 million per annum

5.4.3 Surface Water Management

Recharge of Groundwater using Surplus River Flows

This option would aim to provide augmentation flows in the Lullingstone to Hawley reach or to provide a summer source for public abstraction.

The option would involve diversion of high (winter) flows in the Darent and use of these to recharge the Chalk aquifer. During periods of low flow, the local storage created by the recharge would be drawn down to augment river flows or for public supply. The term 'surplus' in this context has been taken to mean any flow in excess of the $EAFR_{mean}$ values derived by Atkins (1991), which are 0.69 m^3/s at Lullingstone and 1.12 m^3/s at Hawley. For the purposes of analysis, it has been assumed that 0.30 m^3/s would be used to recharge the aquifer whenever flows in the river exceed 0.99 m^3/s at Lullingstone and 1.42 m^3/s at Hawley. Better performance (in terms of volume abstracted for different capacities) may be feasible. The recharge options include direct injection and land spreading.

The siting for recharge would need to be some way away from the river, to prevent rapid return to the system and pumping would be involved in either case, given the topography. For direct injection, removal of suspended matter would be required and while the use of natural lakes such as that at Lullingstone would provide some settlement, it is likely that more sophisticated removal facilities will be required. Direct land spreading would overcome this problem, but requires definition of suitable sites for lagoons.

Recovery for river augmentation could be by natural leakage back to the river (which will occur anyway) or by abstraction from the recharged aquifer and direct delivery to the river via the pipeline. For the purposes of this review, it has been assumed that these would be equally effective. However, it is likely that there would be advantages in terms of efficiency and timing if water is pumped from the storage when required, rather than relying on the uncertainties of natural seepage, and pumping has been assumed in the costing. Recovery for public supply would be by abstraction.

A possible disadvantage of this option is that the storage created during times of surplus will dissipate over the year, and it is unlikely that over-year storage could be created. Surpluses would thus need to be pumped to storage each winter, in anticipation of a dry summer. However, the record at Hawley indicates that augmentation flows would be required in most summers, and for this reason the option is not as inefficient as it might at first appear.

An examination of the monthly flow record indicates that, while surplus flows are available for most years, the volume is limited, and in very dry years such as 1973, when winter flows tend to be low, there is no surplus. In terms of augmentation flow required at Lullingstone, the estimated deficit at Hawley needs to be increased to cater for seepage losses. It is thus desirable that about 0.4 m^3/s is provided at Lullingstone when Hawley is dry.

A comparison of annual surplus and deficit volumes is shown in Figure 5.12 for assumptions of 0% and 50% loss rate and 0.15 m^3/s steady seepage loss between Lullingstone and Hawley. The figure indicates that the surplus flows would, on average, meet only 10% of the deficits for these assumptions. However, as noted above, in very dry years such as 1972/3 there is no surplus at all. The solution is, at best, a partial one, and unit costs of water recovered are high. It may have some merit if used in conjunction with a scheme to conserve water in the Lullingstone to Hawley reach (ie bed lining or artificial springs).

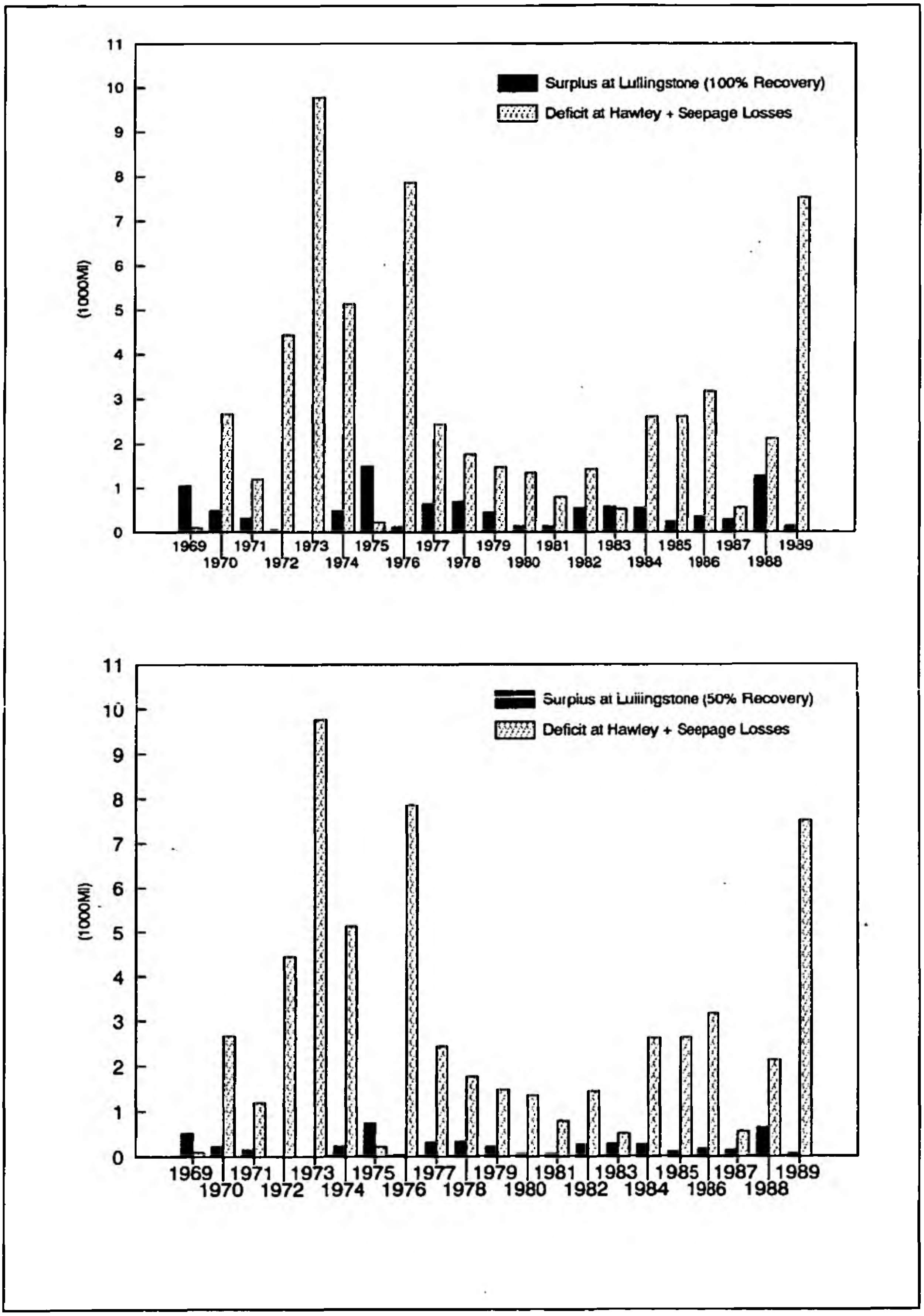
The possibility of pumping surplus water from downstream of Hawley has been examined, on the assumption that as much water could be pumped as is required (assuming no minimum flow requirements, once into the bottom of the catchment). The volumes are available, although costs are quite high.

Given the limitations of diversion of surplus flows at Lullingstone, costs are estimated on the assumption that diversion at the bottom of the catchment is acceptable. The estimated costs are as follows:

Sub-option	Capital cost (£m)	Operating cost (£m)
Summer source, land spreading	5.9	0.26 pa
Summer source, injection	8.6	0.30 pa
Augmentation, land spreading	5.2	0.26 pa
Augmentation, injection	8.0	0.29 pa

The assumption of pretreatment for direct injection makes land spreading appear more attractive. However, the need for such treatment would have to be investigated.

Figure 5.12
Recharge with Surplus Flows



Another approach to using winter surpluses would be to make maximum use of bed leakage to recharge the aquifer. This would be achieved by building weirs in the river to pond winter flows. A notch would need to be created in each weir to allow low flows to pass during dry periods, to prevent total loss of flow. This would be stoplogged during wet periods to create the ponded conditions. There are potentially adverse impacts of such weirs on flood defence which would need to be evaluated separately. It is unlikely that these weirs would have a great impact on recharge, and while they could be evaluated using the catchment models, this is unlikely to be worthwhile, and the approach has been given a relatively low priority for further investigation.

Seasonal Storage in Existing Lakes

The use of the storage provided in the existing lakes (formerly mineral workings) near Sevenoaks has previously been suggested as a partial augmentation solution to the problems of low flows. The principal water bodies are the two lakes managed as a wildfowl reserve by the Harrison Trust, and the (main) Longford Lake at Chipstead, owned by the Marley Group. There are two smaller lakes just upstream of this. The river flows through one of these smaller lakes, through Longford Lake and through one of the wildfowl lakes, and is connected to the other, as indicated in Figure 5.13.

The use of Longford Lake was suggested in the Halcrow report of 1988, when a cost of £400 000 was attached to this option, principally to modify the control system at the lake outlet and provide accommodation works for current lake users (Chipstead Sailing Club and anglers). The Halcrow proposal involved a drawdown of 1.4 m from normal lake levels, which represents the maximum drawdown available between normal lake and downstream river levels. Given the lake area of 0.25 km^2, the volume available with this drawdown would be 350 Ml.

Compared to the deficit volumes identified in Table 5.1 and the suggested 'design' requirements in Table 5.3, this volume would satisfy the deficit at Otford (150 Ml) and about half of the deficit at Lullingstone (700 Ml), but would do little to meet the deficit at Hawley (5 000 Ml), particularly when seepage losses in the lower part of the river system between Lullingstone and Hawley are considered. To the problem at Hawley, this option can, at best, provide only a very limited solution. It would be feasible to draw the lake down further by pumping, although this is likely to be unpopular with the interest groups, and would probably have to be moderated because of these. If 3 m of drawdown was accepted, the volume generated would be 750 Ml.

Discussions concerning these proposals have been held with the interest groups involved. As far as the owners (Marley) are concerned, they sympathise with the general problems of low flows in the river, but would not want to take any action which would be against the interests of their tenants (the sailing and angling clubs). In addition, they have obtained planning permission to develop the former industrial site to provide 35 000 m^2 of office accommodation, and see the lake as providing an important amenity in this regard. They would thus be reluctant to see lake levels drawn down substantially, particularly if mud banks or other unsightly features were to be exposed.

With regard to the leisure interest groups, as far as the sailing club is concerned, it would seek to retain the current sailing area through dredging, and to provide suitable launching facilities to accommodate the expected range of water levels. The angling club's main concern is the impact of varying lake levels during the fish breeding season.

An assessment of costs for reprofiling and other accommodation works was made in the Halcrow report. It was also suggested in the report that the lake may stratify, thus reducing dissolved oxygen levels, and that a water quality monitoring programme be implemented to confirm the feasibility of using the lake water for augmentation. Since this programme has not been pursued, the suitability of the source has yet to be proven.

The possibility of retaining higher lake levels to increase the storage volume has been considered, but has limited potential and would cause further difficulties. Firstly, the Marley site is low-lying, only about 0.5 to 0.8 m above normal water levels of 69.5 m. This limits the scope for retaining increased volume, even if flood defences along the south eastern shore, and/or spillway capacity are provided to ensure that the site is not unduly threatened by flooding. Given the low-lying and urban nature of the land to the south and east of the Marley site, it would not be prudent to raise levels in the lake more than about 0.5 m, (implying an additional volume of 125 Ml) even if defences are provided. There could also be local problems with 'backing up' in the River Darent along the southern shore of the lake, and this could affect properties such as the sailing club and the Cheshire Home. For these reasons, the possibility of retaining higher lake levels has been discounted.

It is debatable whether the benefits obtained from the regulation of Longford Lake are worthwhile, given the interest group pressures and the fact that it only provides a partial solution to the problems at Hawley. The current cost of the previously proposed works is estimated to be about £450 000. However, it is not clear from the previous study why a new outlet control structure was needed, and there would appear to be no reason why the current practice of stoplog control should not continue (with the owners' agreement). This would limit the cost of the option to the accommodation works required to satisfy the angling and sailing interests, which at current prices would be of the order of £250 000. If pumping were to be adopted, the cost of a small pump station would be of a similar order, although it would probably be more economic to have a temporary pump which could be used elsewhere when required.

The lakes developed by the Harrison Trust as a wildfowl reserve (0.28 km^2) have potential for providing a similar (or even greater) volume for river regulation to Longford Lake, but would require pumping. However, the lakes are recognised as being of ecological importance, and it is thus unlikely that this would be acceptable. For this reason, the use of these lakes has not been considered further.

The lakes upstream of Longford Lake (<0.1 km^2) would appear to have limited potential for providing storage volume, although without hydrographic survey, it is only possible to speculate about the amount of drawdown (and hence volume) which would be achievable. Given that these were formerly mineral workings, it is possible that they are quite deep, and the local angling club has suggested

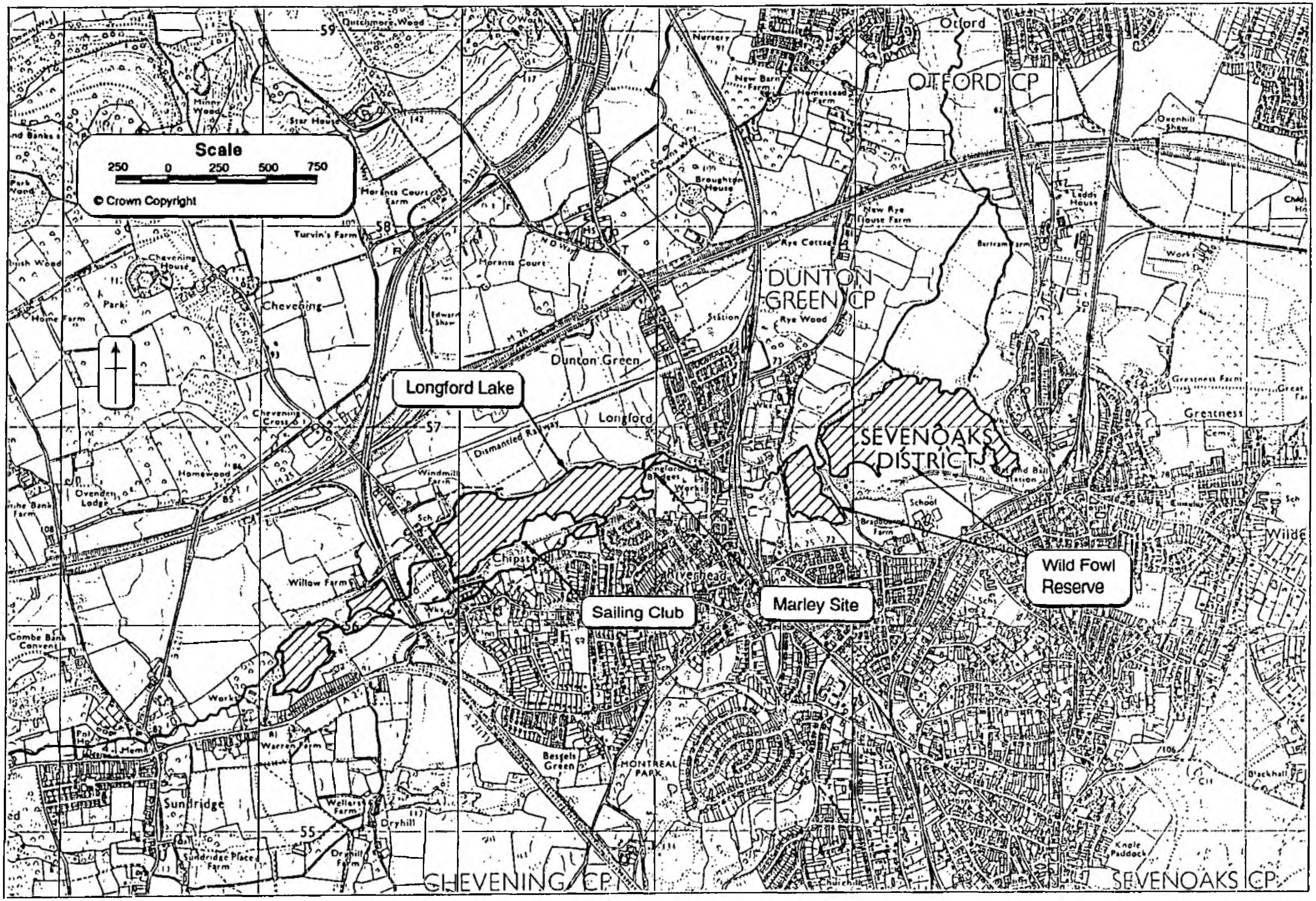


Figure 5.13
Existing Lakes

8 to 10 m. The lakes are used by the angling club for carp fishing. A similar volume to the (gravity) proposals for Longford Lake could be produced with a 3.5 m drawdown. The quality of the water at depth would need to sampled before undertaking this and it is also possible that significant lowering of the water level could have an adverse impact on the Sundridge borehole.

The aggregate volume assuming drawdown of about 3 m in the Longford and two upstream lakes would be around 1 000 Ml, or a sustainable average flow of about 4 Mld over the 'design' deficit period. It is thus unlikely that the use of these lakes as storage would have much impact on the problem at Hawley, although they could be considered as a partial solution or as a means of augmenting flows for the reach from Sevenoaks to Otford. Given the conflicting user interests, it is suggested that they are used infrequently for the latter purpose, rather than as a means of tackling the regular problems further down the system.

Bed Lining of Critical Channel Sections

Bed lining of the river section between Lullingstone and Hawley (6 km) has been suggested in the Halcrow (1988) report as a means of conserving flows in that section. The lining would be carried out in conjunction with upstream augmentation measures. Actual losses in this reach are high (measurements in May 1991 indicating about 13 Mld), and a solution of this type, if fully effective and in conjunction with other augmentation options, could have a significant impact on flows at Hawley.

The principal disadvantages of this option relate to pragmatic factors, such as:

- the potential ecological problems due to the disruption created by placing a lining;
- the problems of implementation in respect of land ownership and general disruption;
- lack of technical experience of linings in this application, most previous experience being related to lagoons, canals or small ditches, rather than natural rivers;
- technical problems in dealing adequately with back pressures on the lining induced by spring flows, which do appear to occur in wet years;
- uncertainty regarding long term durability and maintenance requirements of different lining types, in view of problems with physical damage caused by, for example, rodents, cattle, tree roots, etc;
- uncertainty regarding impact on existing abstractions along the reach.

In terms of the environmental difficulties, these relate principally to:

- building the liner into the section without the removal of the many mature trees along the river bank;

- impacts of excavation of the banks and bed on the general flora and fauna of the river;

- impacts of the liner on the spring-fed nature of the river;

- joining the liner to existing structures such as the ornamental crossing at Farningham without causing damage, if such joining is necessary to sustain watertightness.

Apart from the likely ecological and general implementational problems, there is a degree of technical uncertainty in this solution which requires that trials are conducted. While this may help to determine the feasibility of construction, it would not indicate the long term performance characteristics and maintenance needs. The impact on abstractions could be examined using the model.

Lining types previously considered include puddled clay and chalk and various artificial membranes. In all cases, the approach would be to remove the existing bed and banks, place the lining and associated underdrainage system and replace the bed and bank materials.

The cost of bed lining, estimated at £2.8 to £3.0 million depending on type, is moderate given the achievable impact on river flows. However, from the pragmatic point of view there are clearly major obstacles and uncertainties to be faced in adopting this solution. Thus while the solution has economic merit, it is not highly favoured for further study.

Recirculation of River Flows

Recirculation of river water would entail abstracting water from a point on the river where adequate flows are available and pumping this back upstream to locations where flow support is required in dry periods. The flow records and accretion profiles for the river indicate that the problem of flow reduction in the downstream direction is such that the option would not be practical and is not considered further as a separate solution. However, in conjunction with other augmentation options it could have potential.

The possibility of diverting winter flows at Dartford to storage and recirculating these also exists. The average winter surplus at Hawley is adequate (of the order of 4 000 Ml) to meet typical deficits, although the problem of dry winters, as described for the recharge option using winter surplus, occasionally occurs. The main argument against this option would be the cost of providing an effective storage lagoon near Dartford, since it has been assumed that this would need to be lined to keep losses to an acceptable level.

Costs are estimated to be as follows:

Sub-option	Capital cost (£m)	Operating cost (£m)
Recirculation (say 20 Mld) Recirculation with storage	1.4 13.1	0.03 pa 0.13 pa

River Intake, Bankside Storage and Treatment Works at Dartford

This option would involve the cessation or reduction of abstraction from selected wells in critical parts of the catchment, and construction of a river intake, bankside storage and treatment works in the vicinity of Dartford to replace the well abstractions. The premise behind the option is that a reduction in abstraction will result in enhanced river flows in the sensitive reaches, which could then be abstracted using a surface water intake further downstream.

It is not clear at this stage of the study which wells should be shut down nor what impact such shutdowns would have on the river flows, although the model will help to clarify this. However, it is probable that shutdown of the Lullingstone, Eynsford and Horton Kirby wells would have the greatest impact on the Lullingstone to Hawley reach. The combined average abstraction of these wells is about 27 Mld, and if the river were to recover by the same amount, then this would be adequate to meet the $EAFR_{95}$. However, it is possible that other wells (eg Darenth) would also need to be shutdown in order for the river to recover the required flow. If the Darenth well were also closed, the abstraction deficit would be 45 Mld.

Since the impact of reduced abstractions on the river flows is uncertain, costs have been developed for surface water abstraction schemes ranging in capacity from 20 to 50 Mld. The options include a bankside storage provision of 7 days, although it is possible that a lower standard might be acceptable if the current infrastructure were kept in place as a standby facility, or for use when flows in the river are high enough to sustain the use of both facilities. It is also possible that, with a reduction in abstractions, the river would be subject to greater seasonal fluctuations and some form of regulation (eg augmentation) would be required.

The costs of these options are as follows:

Sub-option	Capital cost (£m)	Operating cost (£m)
20 Mld 35 Mld 50 Mld	10.6 14.2 19.4	0.45 pa 0.62 pa 0.80 pa

As a means of enhancing resource availability, the possibility of diverting surplus winter flows to storage has been considered. The additional costs are largely associated with the cost of a purpose built lagoon, which it is assumed would need to be lined to minimise losses. The costs are estimated as:

Sub-option	Capital cost (£m)	Operating cost (£m)
20 Mld	21.9	0.50 pa
35 Mld	32.5	0.67 pa
50 Mld	44.3	0.85 pa

Use of Sewage Effluent

At present, all sewage from the Sevenoaks area is conveyed out of the catchment via the Darent Valley Trunk Sewer to the Long Reach Sewage Treatment works in Dartford, where it is treated to secondary standard (along with sewage from other parts of SE London) and discharged to the Thames tideway. The effluent is a resource currently lost to the catchment which, suitably treated, could be used to supplement river flows or recharge the aquifer. The options for achieving this would be:

(i) Install a treatment works in the Otford/Lullingstone area which would take sewage from the Darent Valley trunk sewer, treat this to a high standard, and return the flow to the river. Flows in the sewer have recently (April 1991) been measured at Farningham. These measurements indicate an average flow of about 13 Mld which is broadly consistent with population data and water demands in the associated area. A design capacity of 12 Mld has been assumed and flows in excess of this (eg during storms) would be taken by the existing trunk sewer. A high standard of treatment would be required since the available dilution flows in the river can be as low as 6 Mld for significant periods of time.

(ii) Install a treatment works of similar capacity and in a similar location to that outlined above, but treating to a primary standard only. The effluent would then be pumped to a suitable location for land treatment (as at Winchester). The effluent would then recharge the aquifer and enhance the baseflow of the river.

(iii) Provide tertiary treatment for part (say 40 Mld) of the secondary effluent at Long Reach, and pump this back up to Lullingstone for augmentation purposes.

(iv) Pump secondary effluent from Long Reach back into the catchment for land treatment, as indicated in (ii).

The costs of these options are as follows:

Sub-option	Capital cost (£m)	Operating cost (£m)
Tertiary STW at Otford	12.4	0.34 pa
Otford STW and Land Treatment	4.9	0.26 pa
Tertiary STW at Long Reach	13.3	0.07 pa
Land Treatment of Long Reach effluent	6.0	0.14 pa

Options (i) and (ii) provide only a partial solution to the problem, whereas (iii) and (iv) provide a full solution, and have potential for flows being increased further, if required. One disadvantage of these options is that they would have to be continuously operated. Operating costs would thus be high, relative to options which are used on an as-needed basis. Option (iii) could be used on an as-needed basis, and has been costed as such. Option (iv) could also be used on an as-needed basis but would require deficit periods to be anticipated ahead to allow for travel time through the aquifer. In the costing, this mode of operation has been assumed.

Land treatment sites would need to be a safe distance from any public supplies and pumping costs would be high. Careful geological investigation would be required to identify or confirm a suitable site, and about 50 ha of land will be needed. Research into the potential effects of such a scheme on groundwater quality would be required. This would include an assessment of the effects of the unsaturated zone in removing nitrates and other potential pollutants.

A possible variation of this option would be to make use of aquatic macrophyte beds as a means of tertiary treatment. Secondary effluent from Long Reach (BOD 20 Mgd) would be passed through the beds and the treated effluent collected and pumped for recharge or flow augmentation, depending on quality. Loading rates of 5 to 10 l/d per m^2 of bed area have been reported to reduce BOD, nitrogen and phosphorus by 50% to 80% respectively. Thus to treat a flow of, say, 40 Mld would require an area of 200 to 400 ha (installations of this type are typically of the order of 5 to 10 ha). Some of this flow would infiltrate into the substrate and the amount recoverable is not certain.

This possibility has not been costed at this point, since cost would depend on identification of a suitable area and the cost of land in that area. A pilot scheme would be needed to confirm the quality and quantity of the treated effluent.

5.4.4 Short Term Options

River support pumping from wells at Brasted pumping station and Horton Kirby paper mill were arranged by NRA (Southern Region) during the summer and autumn of 1990. Amenity value was also improved at certain locations when flow was available by use of temporary sandbag weirs which increased the depth of water.

There is considered to be limited scope for use of weirs however. By increasing depth of water at times of low groundwater levels weirs also act as recharge dams tending to increase the rate of depletion of river flow, further depleting flows to downstream reaches. Any extensive use of more permanent weirs could also have an adverse impact on flood defence and land drainage in wetter periods.

In addition to measures implemented in 1990 further schemes which could be implemented at relatively low cost and in the short-term include:

- additional flow augmentation schemes utilising Chalk groundwater;
- utilising drawdown in Longford Lake;
- bankside wells (artificial springs).

In view of the conclusions of the water balance assessment presented in Chapter 4, there would seem limited opportunities for implementation of flow augmentation schemes. It might be possible to construct wells in the Chalk in the upper Darent (Otford subcatchment) with pumping which could benefit the river perhaps as far downstream as Shoreham. Benefits might be extended further downstream if combined with a scheme of bankside wells. A water balance assessment of the adjoining Cray catchment to the north of Westerham would have to be carried out before proceeding with an augmentation scheme.

Use of the Longford Lake could be strongly opposed and be very unpopular with users of this amenity. Benefits to the river would also be very limited, although these might be extended by combination with bankside wells.

Bankside wells could provide the means to maintain limited amenity and ecological value of the river both upstream and downstream of Lullingstone, on a reduced scale in drought conditions. There is little risk that recirculation of water by this means could deplete the Chalk groundwater system further to a significant degree and risk failure of existing abstractions. Schemes could be implemented piecemeal in either of the following ways:

- construction of new wells, close to the river with pipelines and outfalls, with the schemes implemented and operated by temporary generators under contract;

- utilise any surplus licence capacity at existing abstractions close to the river, and divert for river support through construction of pipeline and outfall.

Improvements to the river valley environment starting in the short term might also be achieved through government supported projects such as the Countryside Stewardship pilot scheme. The objective of this pilot scheme is to recreate traditional landscapes such as water meadows and Chalk grassland and provide public access for 'quiet enjoyment' through annual payments to landowners.

5.5 Demand Management

Demand management includes a variety of physical and financial measures which could be used to curb demand for water in an area of known deficit. In the extreme, this could include actions such as relocating industries which are heavy water users, prohibiting use of water for agriculture, limiting developments which may result in heavy water use. In the context of the Darent, possible measures include:

- limiting demand through quotas or pricing strategies;

- leakage control;

- differential pricing of water from different sources.

Reducing transmission and distribution losses is often cited as an example of demand management which can help to limit abstractions and thus preserve the resource. In the context of the Darent, it is probable that much of the loss associated with distribution serves to recharge the aquifers anyway, and the resource implications may not be that great. However, given that 40% to 50% of the abstracted water is exported, it may be that some saving is achievable (say 10% of 50 Mld), which suggests that this is unlikely to be of the order of magnitude required. Nonetheless there are cost as well as resource implications associated with excessive leakage which suggests that leakage control deserves attention, even if its contribution to the overall problem is small.

Limiting consumer demand through quotas (eg hose pipe bans) is the current response to the deficit and will clearly need to be maintained while the drought conditions persist. Adoption of pricing strategies such as increasing block tariffs for consumers implies metering of supplies. While this is suitable for bulk consumers, it is not expected that supplies to the general public will be metered in the immediate future although it is possible that this could happen within the strategic planning horizon being considered (20 years). In this instance, it would be feasible to introduce pricing strategies which would serve to curtail demand. Recent trials have indicated that water savings of the order of 10% are achievable through metering.

Pricing water from different sources at prices which reflect environmental externalities could prove a powerful incentive to the public water companies to reduce abstractions from environmentally sensitive areas. At the moment, aquifers such as those in the Darent are seen as a low cost source of supply, and it is thus in the water companies' interest to make maximum use of these. While the current dry spell has cast doubts over reliability, and may in itself encourage abstractors to seek or use other sources, there is little other incentive for abstractors to seek alternative supplies. There appears to be little doubt that abstractions from the Darent are underpriced, given the impacts that are having on the local environment. If the price of abstraction were to be increased absolutely or on a seasonal basis, this may provide sufficient incentive for abstractors to prefer other sources and adopt broader supply strategies, such as interbasin transfers or conjunctive use.

5.6 Summary of Options

A number of options have been reviewed, some of which provide only partial solutions. The options are summarised briefly in Table 5.8. Some options are only capable of addressing the problems between Otford and Lullingstone, and will have little impact on flows in the reach between Lullingstone and Hawley. Others have potential for providing longer term solutions, while also addressing current problems. It is thus difficult to compare options directly in terms of performance.

Figure 5.14 shows options and sub-options within the structural categories of river augmentation, revocation/relocation/variation of existing licences, recirculation and flow conservation and the non-structural category of demand management. In terms of comparing the structural options, some benchmark of performance needs to be established. Some of the options are only used on an as-needed basis, whereas others depend on full time operation. Similarly, some provide a full solution to the problem, whereas others provide a partial solution. Furthermore, some solutions would be able to accommodate demand growth.

Two benchmarks have been used to evaluate the options and the evaluation is summarised in Table 5.9.

The first benchmark is the ability of the solution to meet the design deficit period (9 months) at Hawley. In cases where the available volume is limited, performance is expressed in terms of average sustainable flow over the design deficit period. Where volume is not limited, the nominal capacity of the scheme is used.

The second benchmark is the unit cost of the solution, expressed in £/m^3. Evaluation of this is complicated by the fact that some solutions have to be run full time, whereas others would only be used on an as-needed basis. In order to allow for this, the average annual deficit period for Hawley, calculated as 100 days per annum over the period of record, has been used. Thus if an option provides a 'full time' solution, this is only considered to be effective in dealing with the low flow problems in the river over 100 days each year. This means that 'full-time' solutions appear expensive.

The results presented in Table 5.9 are based on assumptions which would need to be validated using the catchment model. However they do indicate that options such as construction of a water treatment works at Dartford or a sewage treatment works at Otford would be expensive.

In terms of unit cost, the use of the Longford Lakes appears attractive but provides a very limited solution in terms of meeting the deficit in the Lullingstone to Hawley reach. The problems likely to arise given the user interests makes this option unattractive, except as a means of dealing with the problems in the river down to Lullingstone. Augmentation using groundwater has a low relative cost, but from the catchment water balance appears to have little potential unless linked to artificial recharge. Recharge of winter surplus would only be technically feasible with pumping from downstream of Hawley, which makes it fairly expensive. Bankside wells would appear to be more attractive than bed lining for conserving river flows in the Lullingstone to Hawley reach, and some combination of augmentation, recharge and conservation might have potential.

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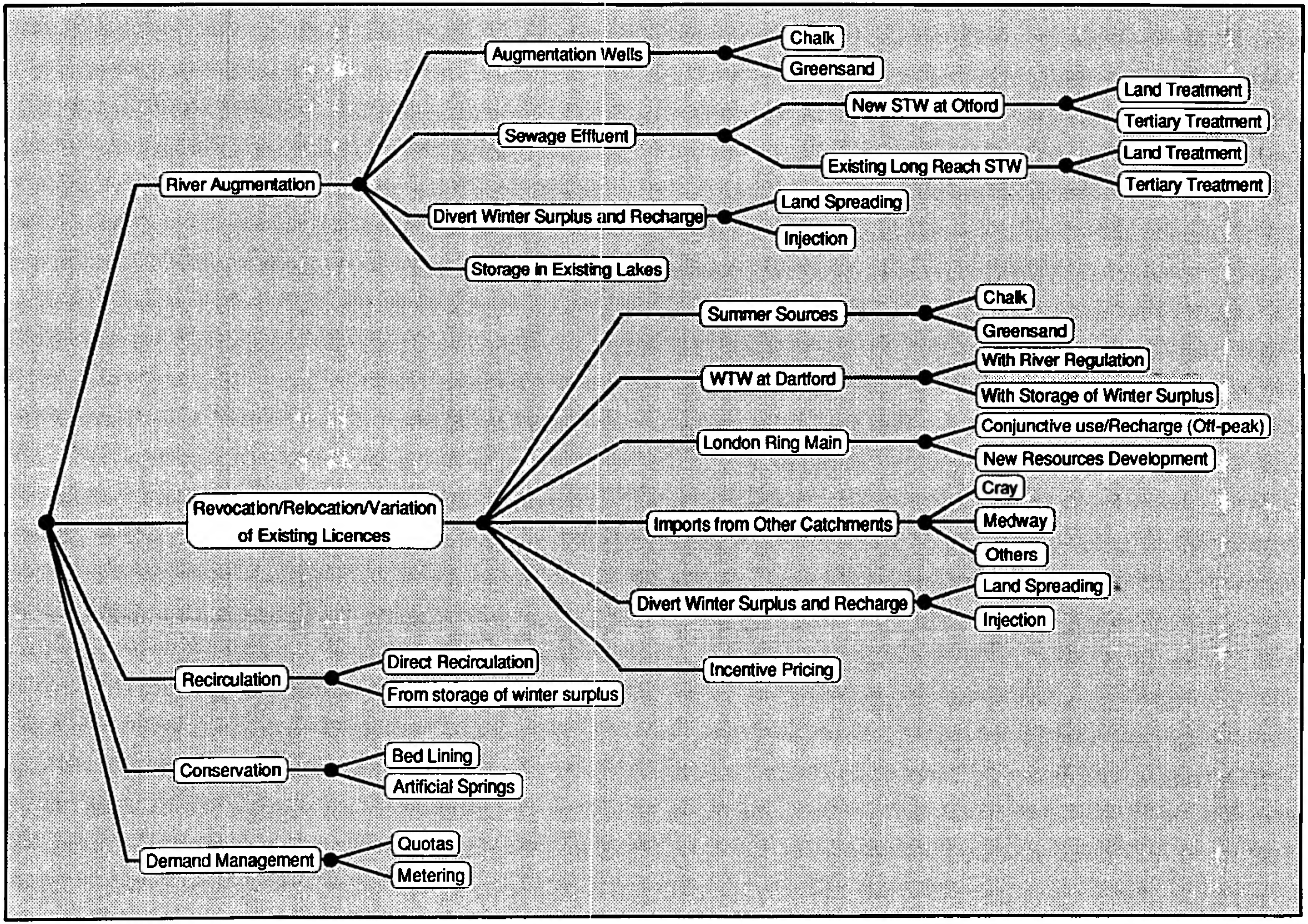


Figure 5.14
Summary of Options

With a view to demand growth, the preferred options which provide additional resources available (rather than seasonal redistribution) are the use of sewage effluent from Long Reach (although doubts over quality would need to be satisfied if land treatment is to be adopted) and conjunctive use of off-peak water from the Thames Valley surface water system.

TABLE 5.8

Summary of Options Considered

Option	Comment
Construction of additional wells for direct river augmentation or for groundwater use as summer water supply sources	Relies on utilising groundwater storage in undeveloped parts of the catchment, altering the seasonal pattern of groundwater flow. Water is drawn from storage in dry periods, reducing potential groundwater flow to river at other times. With direct river augmentation has the advantage that it only needs to be used when required, thus keeping operating costs low. Effectiveness in doubt on the basis of the water balance assessment and needs to be tested using the catchment model.
Use of sewage effluent	Makes use of resource currently lost to the catchment. Resource options considered include use of sewage arising within the catchment (partial solution to the low flow problems) and pumping of effluent from the Long Reach treatment works (full solution feasible). Treatment options considered for both resources include tertiary standard for direct return to river or land treatment for indirect return via aquifer. Latter appears most cost effective.
Recharge of aquifer using surplus (winter) flows	Pumps surplus water from river to recharge aquifer, relying on natural seepage and/or subsequent abstraction to augment river flows or provide a summer source. Diversion at Lullingstone provides only a partial (10%) solution in average years, and would fail in extreme years such as 1972/73. Pumping from downstream of Hawley would be a possibility but is expensive. Would need to be used each winter in anticipation of a dry summer and is thus somewhat inefficient.
Seasonal storage in existing lakes	Provides only a partial (5 to 10%) solution to the problems at Hawley, but would overcome the lesser problems at Otford. Interest-group pressures would make implementation difficult.
Surface water abstraction and treatment at Dartford	Relies on closure of selected wells on the assumption that river flow will recover sufficiently to allow surface water abstraction at Dartford. Uncertain how many wells will need to be closed without modelling and reliability of river flows in dry periods may be a drawback. Expensive.
Increased conjunctive use of surface water from Thames Valley and local groundwater	Has long term potential for meeting growth, as well as providing solution to current problems. Links between surface water supplied and groundwater supplied reservoirs would allow over-stretched wells to be rested, allowing aquifer to recover. Impacts of reducing abstractions at selected locations need to be determined using the catchment model. Effectiveness of links in transferring water from west to east can be examined in the network model being developed by TWU.
Recirculation	No potential alone but may have potential in combination with other options.
Bed lining of critical channel sections	Would be effective in conjunction with another augmentation option, but difficult to implement. Problems with ecological disruption and land ownership, plus the technical uncertainty over long term performance and the need to carry out trials to establish technical feasibility weigh against this solution. Bankside wells provide a direct alternative.
Development of bankside wells	Recirculates flows lost to ground in reaches of river where losses are high. Cheap to implement and run. Requires site trials, but risk low. Impact of wells can be tested using the model. Will probably need to be used in conjunction with other augmentation options. Alternative to bed lining.
Demand management	Involves use of financial incentives to encourage abstractors to prefer alternative sources and for consumers to be more economical in their use. May not be implementable immediately, but should be pursued as a matter of policy to deal with long term resource problems.

Table 5.9 - Comparison of Structural Options

Option Category	Option	Sub-option	Nominal Capacity	Effective Capacity	Capital Cost	Disc. Cost	Unit Cost	Comment
River Augmentation	Augmentation Wells	Chalk (Lower Darent)	24	24	2.1	3.2	0.09	Water balance doubts
		Chalk (Upper Darent)	8	8	0.6	0.9	0.08	Little impact beyond Lullingstone
		Greensand with Iron Removal	8	8	1.0	1.4	0.12	Little impact beyond Lullingstone
	Reuse of Sewage Effluent	Primary STW at Otford + Land Treatment	12	12	4.9	8.1	0.48	Limited by available flow
		Tertiary STW at Otford	12	12	12.4	16.2	0.95	Limited by available flow
		Ex. STW at Longreach + Land Treatment	40	40	6.0	7.4	0.13	Possible quality problems
		Ex. STW at Longreach + Tertiary Treatment	40	40	13.3	13.2	0.23	
	Use Winter Surplus & Recharge (pumped from Dartford area)	Land Spreading	40	30	5.2	8.5	0.20	Pumping from d/s Hawley
		Direct Injection	40	30	8.0	11.5	0.27	Pretreatment assumed required
	Use Storage in Existing Lakes	Longford Gravity Scheme	N/A	1	0.3	0.4	0.07	Limited Solution - user interests
		Pumped Longford plus Upstream Lakes	N/A	4	0.5	0.7	0.05	Limited Solution - user interests
Revocation/Relocation/ Variation of Existing Licenses	Summer Sources	Chalk	24	24	2.1	3.0	0.09	Water balance doubts
		Greensand with Iron Removal	8	8	-	-	-	Too far from delivery point
	Dartford Treatment Works	With river regulation	35	35	14.2	21.8	0.41	Capacity required uncertain, depending
			50	50	19.4	29.2	0.38	on impact of reduced abstraction.
		With storage of winter surplus at Dartford	35	35	32.5	39.2	0.76	Assumes storage lagoon would need
			50	50	44.3	52.8	0.72	to be lined. Probably limited by surplus
	Use Existing Off peak Capacity	Conjunctive Use/Recharge	30	30	6.5	8.6	0.18	Price is for links in trunk main system
	London Ring Main	Conjunctive Use/Recharge (inc off-peak)	60	60	-	-	-	Depends on network analysis
		New Resource Development	60	60	-	-	-	Requires wider resources study
	Other Catchments	Cray	?	?	-	-	-	Included in modelling
		Medway	?	?	-	-	-	Requires wider resources study
		Swanscombe area	?	?	-	-	-	Included in modelling
	Use Winter Surplus & Recharge as Summer Source (pumped from Dartford area)	Land Spreading	40	30	5.9	9.2	0.22	Pumping from d/s Hawley
		Direct Injection	40	30	8.6	12.2	0.29	Pretreatment assumed required
Recirculation	Direct recirculation		-	-	-	-	-	Not feasible alone
	Using Stored Winter Surplus		40	40	14.2	14.9	0.26	Assumes lined lagoon
Conservation	Bed Lining	Lullingstone to Hawley	16	16	2.8	3.4	0.15	Implementational problems
	Artificial Springs	Lullingstone to Hawley	40	16	0.8	1.9	0.08	Similar function to bed lining

Notes:

1/ Nominal capacity = Installed capacity of solution

2/ Effective capacity = Average sustainable flow over design deficit period (9 months)

3/ Costs in £million, Unit costs in £/m3, Capacities in Mld

4/ Discounting based on real rate of 6% and 30 years

5/ Unit costs based on average annual number of deficit days (100) at Hawley

Options proposed for further detailed assessment using the catchment model (or otherwise) are:

Short/Medium Term Options

- use of bankside wells (artificial springs) as a means of conserving flows in the Lullingstone to Hawley reach;

- seasonal redistribution of flows using new Chalk wells as summer sources to replace abstractions from existing wells;

Long Term Strategic Options

- artificial recharge using surplus winter flows from downstream of Hawley, with subsequent abstraction for public supply as a means of reducing abstractions from existing wells in the river valley on a seasonal basis, or for river augmentation;

- pumping of secondary effluent from Long Reach STW for land treatment within the catchment as a means of augmenting river flows (although possible effluent quality problems and public perception may be against this);

- conjunctive use of off-peak surface water from the Thames Valley via the existing trunk main system through the creation of links between reservoirs and, in the longer term, through use of the London Ring Main and reinforcement of the trunk main system;

- replacement of abstractions through use of the London Ring Main.

These four options have potential in terms of meeting longer term demand growth.

If a solution is needed **for the Sevenoaks to Lullingstone reach,** then the favoured options for further investigation are:

- augmentation wells in the Chalk aquifer to the north of the valley between Westerham and Sevenoaks;

- use of storage in Longford and upstream lakes.

Given that the lake storage option would be required infrequently, it may be best considered as a temporary measure, relying on use of the existing structure for gravity drawdown and hired plant for pumping. The biggest difficulty is likely to be in obtaining owner and tenant consent to this.

The possibility of recirculation in conjunction with augmentation should not be overlooked as a means of further increasing the efficiency of the solution.

CHAPTER 6

CATCHMENT MODELLING

6.1 Model Specification

Use of an integrated catchment model which simulates flows in the aquifers and in the river and the interaction between surface and groundwater components is proposed for the Darent Catchment Investigation. The integrated model was developed and tested during low flow studies for several Chalk catchments and proved to be an excellent technique for this type of investigation. As the model is applicable in its present form to the more complex Darent catchment, no further development is required. The program will, however, be modified to improve the efficiency of the solution and reduce run times, by incorporating the calculations of river flow as an integral part of the matrix routine for simultaneous solution of heads in all layers. Some modifications to the representation of lakes may also be necessary.

The model is based on the fundamental concepts of Darcy's law and the principle of continuity with resolution of flow into horizontal components in the aquifers and vertical flow through the intervening aquitards or leakance interfaces. The model uses the integrated finite difference method (IFDM) and incorporates an iterative solution technique based on a backward difference approximation.

Owing to the varied geology of the Darent catchment and differences in piezometry between the main aquifers, a six layered model may be required, although none of the layers is present over the whole catchment. The layers and their functions are shown schematically in Figure 6.1.

The top layer is used to represent alluvium, river gravels or the Tertiary deposits depending on location. The Chalk layer includes both the normally shallow permeable zone and underlying less productive section. Variation in permeability with depth will be modelled if there are sufficient data to define the distribution.

The IFDM technique requires the subdivision of both time and space into small elements. The model network is based on the systematic and repeated subdivision of a regular mesh of squares. This method allows accurate modelling of the river system, with the river represented by a line of polygon faces. It is envisaged that the network for the Darent model will be generated from a basic grid of 2 km squares, with fourth order subdivision to produce 500 m squares for maximum detail. These small nodes will be used along the river and for other areas requiring accurate representation, eg the spring zones in the Chalk and Lower Greensand outcrops and the major abstraction points. Boundary nodes can also be subdivided or deleted to match the boundary accurately.

As indicated in Section 1.4 the Cray catchment and also the area around the Ebbsfleet catchment to the east of Dartford are required to be included in the catchment model. Extension of the model allows for simulation of the effects of abstraction from the Darent on adjacent catchments (and vice versa). It is also then possible to model engineering options which involve water resources in the extended model areas. The area of the proposed catchment model is shown in Figure 6.2.

The model boundaries will be chosen as follows:

- southern boundary, along the southern limit of the outcrop of Hythe Beds. This can be readily defined from published geological mapping. The model will generate discharge across the boundary simulating springs on the scarp slope of the Lower Greensand. This discharge would not be included in the Darent catchment balance;

- eastern boundary along the groundwater divide in the Chalk between dry valleys of the Darent and Medway catchments. From published hydrogeological mapping (IGS 1970) this appears to coincide approximately with divides in the Folkestone and Hythe beds;

- western boundary along the groundwater divide coinciding in places with the western boundary of the Cray surface water catchment and located to the west of the surface water boundary in the vicinity of Bromley. This groundwater divide has also been identified from published hydrogeological mapping;

- northern boundary, with a fixed head aligned along the River Thames. The area downstream of the Cray/Darent confluence would not need to be modelled in detail.

A major feature of the model is the interface between the river and aquifers. The river and its tributaries will be represented by a series of specially defined polygon faces, where flows between the aquifers and river are calculated. As the river is only in contact with the superficial alluvium or the top of an aquifer, flow between the aquifer and river includes a vertical component which is simulated as a leakage flow through the river bed, controlled by the difference between the water level in the river and head in the underlying aquifer. Springflows are also calculated by the model, when water levels in outcrop nodes reach ground level.

Flow in the river is routed downstream, with the addition of contributions from tributaries, springs, river augmentation wells (if applicable) and runoff calculated by the Stanford Model. Six flow conditions are incorporated:

- dry river;

- no inflow from upstream but initialisation of baseflow, thus representing seasonal springs and the movement of the bourne head in the river system;

- flow from upstream augmented by baseflow from the aquifer;

Figure 6.1

Modelled Aquifer System

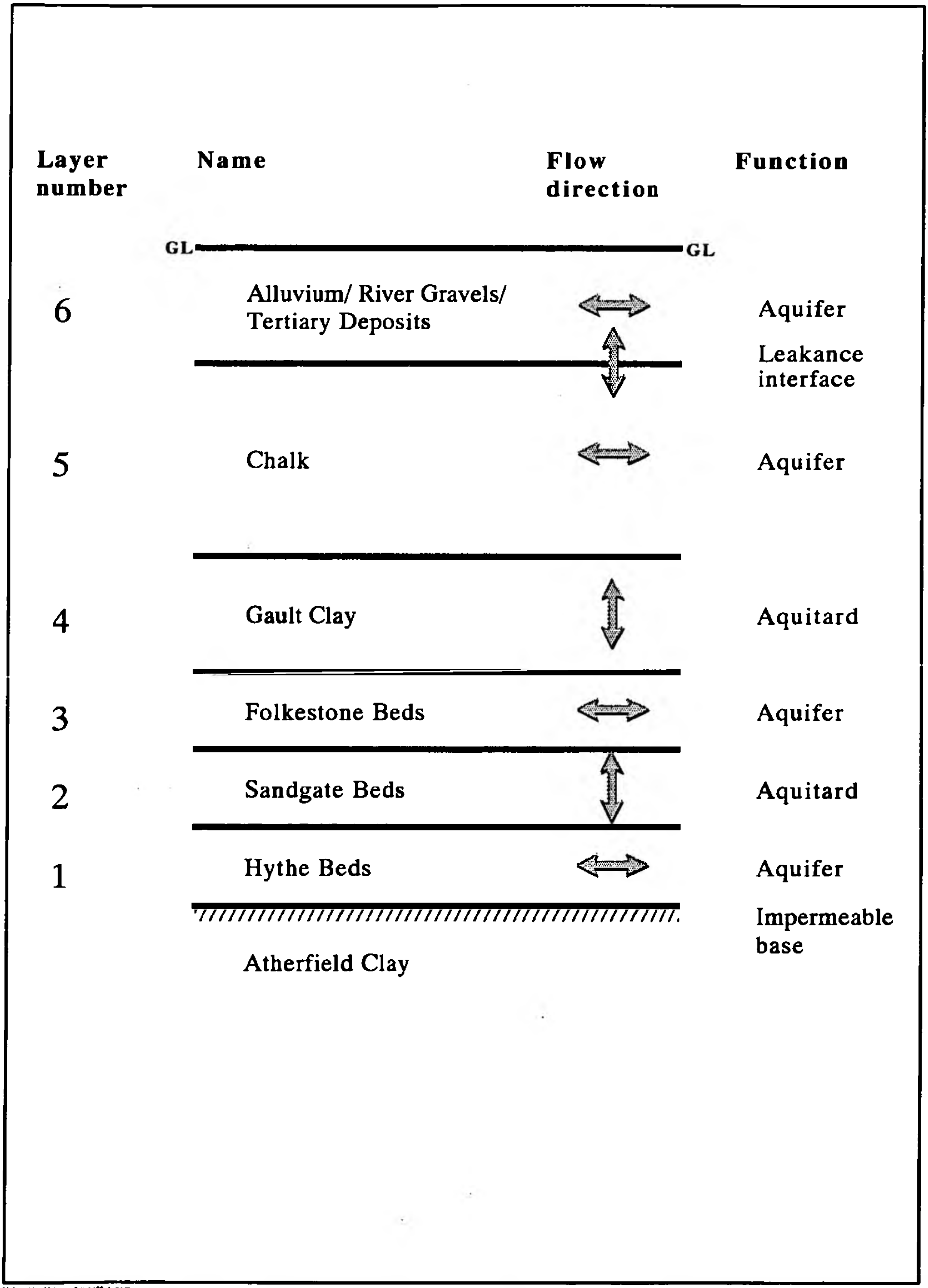
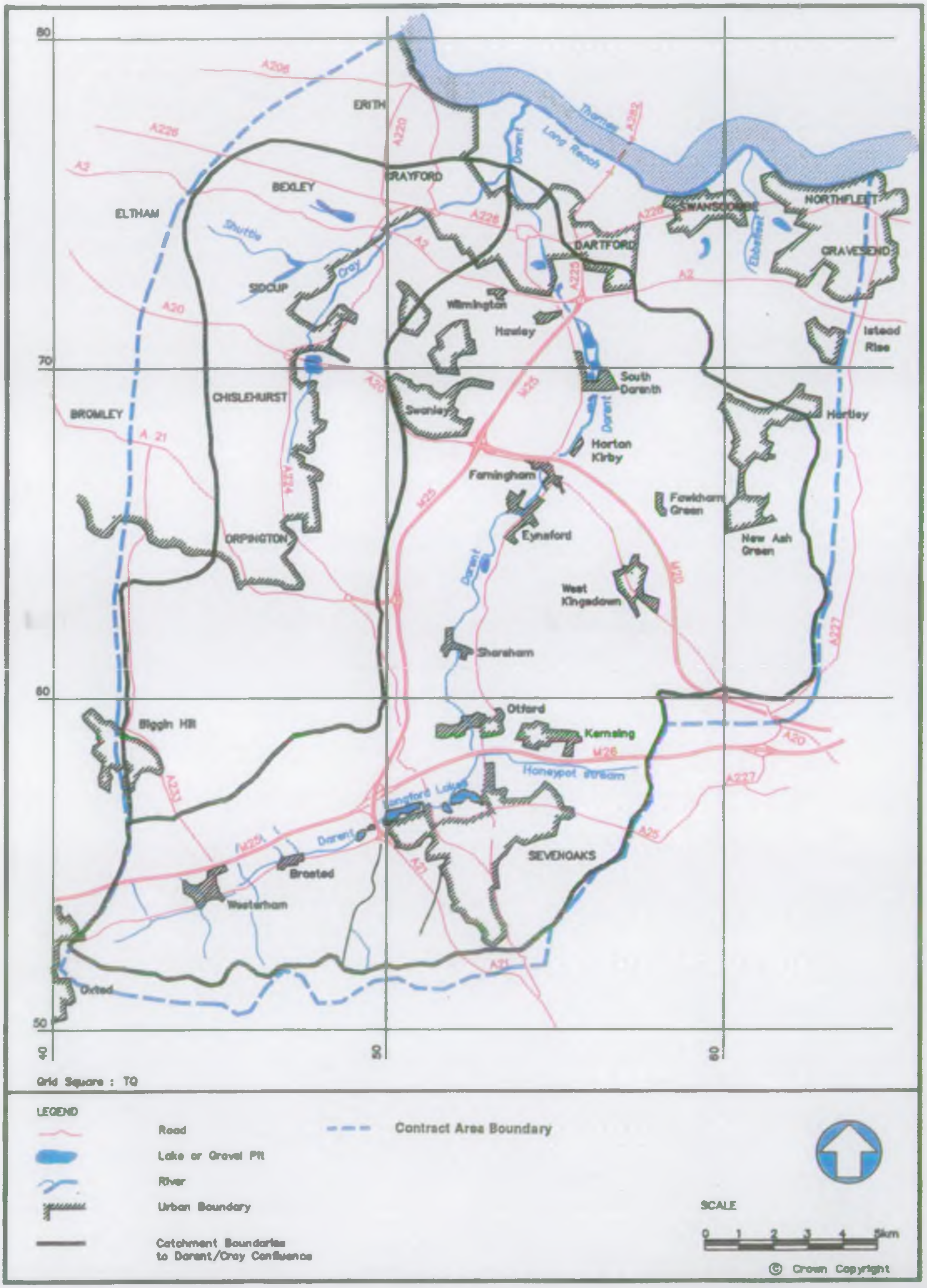


Figure 6.2

Catchment Model Area



- flow from upstream reduced by leakage to the aquifer;

- flow from upstream isolated from groundwater, eg where the river crosses the Gault Clay outcrop;

- lakes, where surface storage is represented.

The data input to the model will be based on the existing information and results of field measurements and hydrological studies, described in Chapters 3 and 4. As interpolation between measured points and estimation of poorly defined data are inevitable, careful calibration of each component of the integrated model is essential.

For the groundwater component, preliminary calibration will consist of running the model for steady state conditions using a line of fixed head nodes to approximate the river, and average values of recharge and abstraction. The main objective of this stage will be the assessment of the leakage coefficients of the aquitards and the degree of vertical interconnection between the aquifers.

The integrated catchment model will be used for final steady state and transient calibration. Transient calibration will use monthly time steps and concentrate on the period with the best data, 1984 to 1991. The calibration obtained for this period will then be verified by running the entire sequence from the start of the period of availability of detailed abstraction returns. To date, detailed returns have been obtained for 1974 onwards. The results of both calibration periods will be compared with:

- hydrographs of gauged river flows at Otford, Lullingstone, Hawley and Crayford;
- flow profiles defining gaining and losing reaches;
- measured spring flows;
- groundwater hydrographs and contouring of piezometry.

6.2 Data Assessment and Further Requirements

6.2.1 Surface Water and Recharge

Calibration and verification of the Stanford Model has been achieved using the data received for the period from October 1984 to September 1990, although the data record was not as complete as might have been hoped for. The main limitations were incomplete abstraction records, which required infilling and the scarcity of autographic rainfall data.

For subsequent surface water, recharge and hydraulic modelling work additional data are required as follows:

- monthly MORECS potential and actual evapotranspiration data for grassland from 1961 to 1984 for grid square 162;

- autographic rainfall data for any stations within the catchment or within 10 km of the catchment boundary;

- information on the dimensions of river gauging structures in order to determine stage discharge relationships used in modelling the river/aquifer interface.

Some additional hydrological data may be required for recharge assessment for the Cray catchment and Ebbsfleet area. An assessment of water supply distribution losses and the effects of urbanisation on rainfall recharge will also be required, particularly for the Cray catchment.

6.2.2 Geology

The geology of the Darent catchment is well established and sufficient information is available to define the extent, lithology and thickness of all the major formations in the study area. For modelling the interaction between river and aquifers, data are required on the geometry and hydraulic properties of the valley alluvium. Although its extent has been mapped, observations on the lithology and thickness of the alluvium from existing or new boreholes are needed to complete the assessment. Some lithological information has been made available for observation boreholes recently constructed by Thames Water Utilities close to the river.

6.2.3 Piezometry and Aquifer Properties

The existing information on aquifer parameters and piezometry is very variable and does not provide a complete regional picture of all layers and the interaction between the different aquifers.

For the Chalk aquifer, there are adequate monitoring data to define the piezometry and changes with time in the central part of the catchment on Chalk outcrop away from the river, and at the western and eastern boundaries. There are however large areas in the northern and southern parts of the Chalk for which no recent measurements are available. Additional monitoring points are required to define piezometry, gradients and groundwater flows in these parts of the catchment. Data are also required for observation wells in surrounding catchments to improve definition of groundwater boundaries particularly in the northern and southern Chalk areas. Observation wells are also required to define piezometry close to the river between Otford and the Thames. An observation borehole and test well construction and testing contract proposed by the NRA and discussed during Part 1 of the investigation should provide much of the data for the Darent catchment.

The reliable estimates of transmissivity in the Chalk are unfortunately limited to one set of values from pumping tests at Hartley. No estimates of storage coefficients were possible using these data. In the Chalk, a marked contrast between transmissivity in the main valleys and interfluve areas is normally found, thus pumping tests should be carried out on existing wells at a number of sites located close to the river, in seasonal/dry valleys and in the higher parts of the outcrop to establish the distribution of transmissivity in the Darent catchment. For some of these tests, nearby boreholes should be used as observation wells to allow calculation of specific yield/storage coefficients.

The location of the main aquifer zone and fissure horizons and associated variation in permeability with depth are also unknown. This information is relevant to the modelling and should be obtained by geophysical logging, especially flow and downhole TV, of existing large diameter wells during testing.

The role of the two main clay formations, the Gault Clay and Sandgate Beds, in restricting vertical flow also requires further investigation. As measurement of regional values of vertical permeability is not practicable, the best information will come from measurements of vertical head differences between the adjacent aquifers.

The IGS hydrogeological mapping indicates piezometry for the Lower Greensand in areas where it is confined by the Chalk. Piezometry is defined only to the east of the Darent by water level observation at Hartley and three other Lower Greensand abstraction sources to the east of the catchment. Although piezometry will be influenced by abstraction, in the absence of other observation well data, groundwater hydrographs should be obtained for these stations and Chalk piezometry determined for the area in order to define head differences across the Gault Clay.

Information from hydrogeological mapping by IGS also shows that measurable head differences exist between the Hythe and Folkestone Beds, implying that the Sandgate Beds form an effective aquitard. Little recent information on the piezometry of either formation is available, thus additional observation wells are required to supplement the existing data. These wells should be designed carefully to allow sampling of both Hythe and Folkestone Beds and measurement of the changes in head with depth. Test pumping of existing boreholes is also required to supplement the single estimate of transmissivity derived from test data for Kemsing, although as these aquifers are expected to be more uniform than the Chalk, a wider spacing of data points than in the Chalk is acceptable.

6.2.4 Groundwater Abstraction

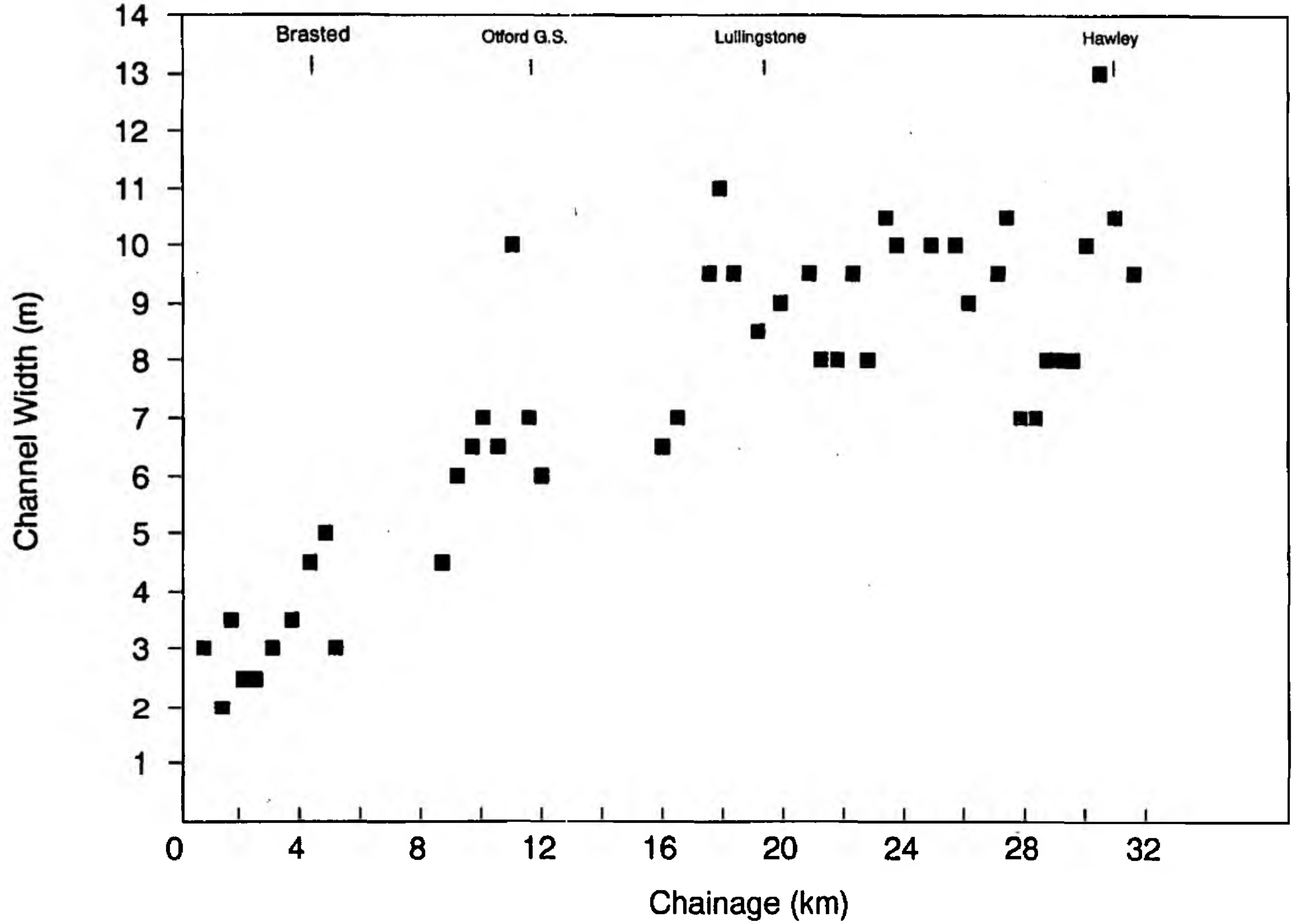
The records of groundwater abstraction from 1974 onwards are, in general, sufficiently detailed to be used as input to the catchment model. Some post-1986 non-public water supply abstraction records are still required. The calibration period could be extended if additional data or reliable estimates of abstraction before 1974 were obtained. An extended calibration period could usefully include the sequence of dry years in the early 1970s, notably 1973 when the Darent was particularly severely affected.

6.3 Channel Survey

In order to establish stage discharge relationships at various locations along the River Darent, it is proposed that the computational hydraulic model HYDRO be run for steady state conditions. The model requires river cross-section data and values of Mannings 'n' in conjunction with information on the structures measuring or controlling the flow in the river.

A cross-sectional survey was carried throughout the entire length of the main channel and part of the Kemsing tributary (Honeypot Stream) in March 1991. Cross-sections were taken approximately every 0.5 km and were tied in to bench-mark levels. Sixty-five cross-sections were measured on the main river between Westerham and Dartford. A comparison was made between the results of this survey and the work carried out by Atkins (1991). The widths of the channel at bank level were plotted against the distance downstream from Westerham. The results (Figure 6.3) show that the small sample of cross-sections taken by Atkins are not fully representative. The more extensive survey shows that channel width generally increased downstream from Westerham to Lullingstone. Downstream of Lullingstone channel width fluctuates considerably over short distances but on average remains constant at about ten metres. The results of the survey contrast with the discontinuity in channel width identified by Atkins between Shoreham and Lullingstone. The appearance of a discontinuity seems to have resulted mainly from measurement of a particularly wide channel section at Shoreham.

Cross-sectional surveys of the Cray and Ebbsfleet will be carried out prior to model calibration.



River Darent Channel Characteristics

Figure 6.3

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following conclusions have been drawn from the various aspects of Part 1 of the investigation:

(a) Public Perception

There is general public concern for the River Darent as something to be seen and often walked beside, as a generally passive but important part of everyday life. Whilst there are concerns for specific reaches, results of the questionnaire circulated at the public meeting in March 1990 indicate that people value the whole river as an important feature of the Darent Valley.

(b) Hydrogeological Evaluation

(i) Geological data are generally sufficient for catchment modelling.

(ii) Chalk piezometry is well defined in the central North Downs area but is poorly defined to the north and in the south of the outcrop area and within the Darent valley.

(iii) Lower Greensand piezometry is poorly defined at present with very few observation wells currently monitored.

(iv) Very few data are available to determine aquifer properties. Nothing is known of the depth of fissuring and changes in permeability with depth within the Chalk.

(v) Abstraction licence returns date back generally to 1974 and are generally reasonably complete. Some post-1986 non-public water supply abstraction records are not available.

(c) Hydrological Catchment Water Balance

(i) The Stanford Watershed Model has been used for catchment water balance assessment. Hydrometeorological data coverage required for the model is good, except in the case of autographic raingauge records. More complete records of abstraction returns would also have been desirable.

(ii) A reasonable calibration has been obtained for the model using data for water years from 1984/85 to 1989/90.

(iii) Water balance calculations indicate that much of the Chalk aquifer has been developed to the point where abstraction at the current level is close to or exceeds long term mean recharge. The Lower Greensand aquifer is also highly developed. Taken over the whole catchment, mean annual recharge exceeds recent abstraction by only:

- 15% for the Chalk aquifer;
- 20% for the Lower Greensand.

For the Chalk aquifer abstraction exceeds the one in five year recharge by 20% whilst for the Lower Greensand abstraction is at the same level as the one in five year recharge.

(iv) An area of Chalk outcrop exists within the Otford subcatchment which, depending on abstraction within the adjacent Cray subcatchment, might be developed with groundwater augmentation schemes or summer abstraction sources. It seems unlikely however that major low flow alleviation options could be developed in either aquifer which allow for maintenance of abstraction at current levels or allow for increased abstraction, unless the options involved a component of artificial recharge.

(d) Engineering Options for Low Flow Alleviation

(i) A broad assessment of engineering options, both full and partial solutions, has been made. A methodology for comparing cost and effectiveness of options has been developed. Options are summarised and compared in Tables 5.8 and 5.9.

(ii) None of the options considered at this stage can be dismissed outright. However it was concluded that the following options merit detailed assessment during catchment modelling, in some cases in combination with other options:

Short/medium term options:

- use of bankside wells (artificial springs) as a means of conserving flows in the Lullingstone to Hawley reach;
- seasonal redistribution of flows using new Chalk wells as summer sources.

Long term strategic options:

- artificial recharge using surplus winter flows from downstream of Hawley, with subsequent abstraction for public supply as a means of reducing abstractions from existing wells on a seasonal basis or for river augmentation;

- pumping of secondary effluent from Long Reach STW for land treatment within the catchment as a means of augmenting river flows;

- conjunctive use of off-peak surface water from the Thames Valley via the existing trunk main system through the creation of links between reservoirs and, in the longer term, through use of the London Ring Main and reinforcement of the trunk main system;

- replacement of current abstractions from the Darent catchment with supplies from elsewhere, for example through use of the London Ring Main.

The last four options have potential in terms of meeting longer term demand growth. Effluent quality and public perception could effect the feasibility of the secondary effluent recharge option however.

(iii) Options just for the river upstream of Lullingstone worth further consideration are:

- augmentation wells in the Chalk aquifer to the north of the valley between Westerham and Sevenoaks;
- use of storage in the Longford Lakes.

7.2 Recommendations

Recommendations are given for additional fieldwork to provide data for catchment modelling:

(a) An observation borehole and test well construction and testing contract proposed by the NRA and discussed during Part 1 of the investigation, should provide piezometric data and some of the test pumping data indicated in Section 6.2. It is recommended that wells in the Lower Greensand should be designed to permit sampling of both the Hythe and Folkestone Beds and measurement of the changes in piezometric head with depth.

(b) Additional valuable aquifer property data could be obtained from a programme of test pumping of existing public water supply wells at all the public water supply sites in the catchment. The winter of 1991/92 would be a suitable time, when demands are low and there may be spare capacity at the sites. The programme should consist of step-discharge tests on at least one well per site with some additional three-day constant discharge tests.

(c) During the testing programme, downhole flow and TV logging are recommended in large diameter wells where access to the aquifer zone is available past pumps, rising main etc. Locations of fissures and the main aquifer zone and variation in permeability with depth could then be assessed.

Other requirements for additional data for catchment modelling are given in Section 6.2. To obtain further information on observation wells in the Darent valley which were monitored around 1980, NRA (Thames Region) should be requested to provide a TWA Internal Report (Nr 64) by J Allam entitled 'Augmentation of the River Darent'.

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APPENDIX

APPENDIX

STANFORD MODEL 3-MONTHLY

SIMULATED WATER BALANCES

Table A.1 3-monthly Water Balance For Otford Subcatchment

YEAR	MONTHS	RAIN FALL	EVAPOT RANSPI RATION	SURFACE RUNOFF	SOIL MOISTURE STORAGE CHANGE	RECHARGE	BASE FLOW	ABSTRACTION GROUND	ABSTRACTION RIVER	GROUND WATER STORAGE CHANGE
1984	OCT-DEC	335.6	68.7	62.2	60	144.7	16.1	29.1	0	99.6
1985	JAN-MAR	170.3	100.6	22.9	-30.3	77.1	26.9	36.2	0	14
1985	APR-JUN	216.2	217.1	4	-35.3	30.5	21.2	36.1	0	-26.8
1985	JUL-SEP	200.2	195.3	3.8	-19.4	20.5	14.9	32.9	0	-27.2
1985	OCT-DEC	242.1	64.1	23.3	76.5	78.2	12.2	31.9	0	34.1
1986	JAN-MAR	224.9	79.8	52.1	7.4	85.5	31.5	36.7	0	17.3
1986	APR-JUN	162.5	204.5	10.3	-83.6	31.3	20.8	39.8	0	-29.3
1986	JUL-SEP	189.5	157.6	4	16.7	11.1	12.8	35.5	0	-37.1
1986	OCT-DEC	310.6	76.9	48.6	70.2	114.8	19.6	35.8	0	59.4
1987	JAN-MAR	145.7	65.4	31.5	-6.9	55.7	23.5	36.7	0	-4.5
1987	APR-JUN	212.7	220.9	10.6	-53.6	34.8	20.1	35.1	0	-20.4
1987	JUL-SEP	240.1	203.8	5.2	-9.5	40.5	17.8	34	0	-11.3
1987	OCT-DEC	312.8	74.1	39.2	59.9	139.6	39.7	33.5	0	66.4
1988	JAN-MAR	344.8	95	120.5	0	129.3	44.1	36.6	0	48.7
1988	APR-JUN	102.4	171.2	1	-79.4	9.6	32.4	35	0	-57.8
1988	JUL-SEP	211.7	173.5	4.2	27.7	6.3	21.4	37.4	0	-52.4
1988	OCT-DEC	130.3	69.5	6.8	22.8	31.2	16.6	35	0	-20.3
1989	JAN-MAR	208.3	88.8	31.6	14.6	73.3	16.4	38.3	0	18.5
1989	APR-JUN	160.7	174.5	9.4	-63	39.8	20.2	39.2	0	-19.7
1989	JUL-SEP	103.3	103.4	1	-1.4	0.3	9.3	36.9	0	-45.9
1989	OCT-DEC	260.6	66.6	32.2	71.6	90.2	7.2	37.8	0	45.2
1990	JAN-MAR	277.6	104.3	78.7	-27.8	122.4	36.2	37	0	49.2
1990	APR-JUN	144.3	159.7	2.3	-35.9	18.2	21	35.9	0	-38.7
1990	JUL-SEP	91.3	83.8	1.5	5.4	0.7	11.8	35.6	0	-46.8

All units: Mld

Table A.2 3-monthly Water Balance For Catchment Between Otford And Hawley

YEAR	MONTHS	RAIN FALL	EVAPOT RANSPI RATION	SURFACE RUNOFF	SOIL MOISTURE STORAGE CHANGE	RECHARGE	BASE FLOW	ABSTRACTION GROUND	ABSTRACTION RIVER	GROUND WATER STORAGE CHANGE
1984	OCT-DEC	245.1	61.6	7.5	108.3	69.6	1.8	43.2	0	24.6
1985	JAN-MAR	131.4	91	9.4	-14.8	52.7	6.9	44.6	0	1.2
1985	APR-JUN	174.2	194.3	6.7	-52.1	29.5	4.1	41.8	0	-16.4
1985	JUL-SEP	126.7	170.5	1.8	-49.1	3.8	0.3	49.6	0.3	-46.1
1985	OCT-DEC	166.2	57	3.8	80.8	24.6	0	41	0	-16.4
1986	JAN-MAR	188.5	71.8	3.9	31.7	81	0	44.1	0	36.9
1986	APR-JUN	140.4	201.3	1	-84.2	22.4	0	47.5	0.2	-25.2
1986	JUL-SEP	165.3	154.4	2.9	0.2	7.8	0	45.8	0.2	-38
1986	OCT-DEC	233.7	70.9	5.2	81.7	75.8	0	40.5	0	35.3
1987	JAN-MAR	123.6	59.2	2.4	6.8	55.2	0	41	0	14.2
1987	APR-JUN	187.5	195.1	2.8	-52	41.7	0	43.5	0.2	-1.8
1987	JUL-SEP	196.3	185.6	3.4	-22.3	29.7	0	46.7	0.2	-17
1987	OCT-DEC	266.3	66.8	15.5	69.8	123.2	9	46	0	68.2
1988	JAN-MAR	270.1	85.6	35.4	20.2	157.7	28.8	48.1	0	80.8
1988	APR-JUN	87.5	185.5	19.6	-110.4	11.5	18.7	46.1	0.2	-53.3
1988	JUL-SEP	134.9	146.8	9.2	-15.3	1.9	7.7	48.4	0.2	-54.2
1988	OCT-DEC	96.3	60	2.2	30.5	4.1	0.5	48.8	0	-45.2
1989	JAN-MAR	152.1	78.6	2.8	38.4	32.3	0	44.4	0	-12.1
1989	APR-JUN	135	168.3	2.1	-68.4	33	0	51.1	0.2	-18.2
1989	JUL-SEP	91.9	105.4	0.8	-14.7	0.4	0	52.5	0.2	-52.1
1989	OCT-DEC	212.9	59.7	4.9	101.5	46.8	0	48.6	0	-1.8
1990	JAN-MAR	228.1	93.8	5.7	3.9	124.6	0	49.8	0	74.8
1990	APR-JUN	130.5	189.6	2.1	-78.6	17.4	0	52.1	0.2	-34.8
1990	JUL-SEP	74.1	92.6	0.9	-19.6	0.2	0	50.2	0.2	-50

All units: Mld

Table A.3 3-monthly Water Balance For Catchment Between Hawley and the River Cray Confluence

YEAR	MONTHS	RAIN FALL	EVAPOT RANSPI RATION	SURFACE RUNOFF	SOIL MOISTURE STORAGE CHANGE	RECHARGE	BASE FLOW	ABSTRACTION GROUND	ABSTRACTION RIVER	GROUND WATER STORAGE CHANGE
1984	OCT-DEC	171.9	46.9	9.3	71.9	43.9	0.2	42.8	0	1
1985	JAN-MAR	96.1	68	4.5	-12.9	37.1	0.6	45	0	-8.5
1985	APR-JUN	140.6	145.9	4.8	-27.8	17.7	0	42.3	0.1	-24.6
1985	JUL-SEP	85.5	121.1	2.1	-39.7	2	0	42.8	0.2	-40.8
1985	OCT-DEC	128.3	43.1	6.7	61.6	16.9	0	42.1	0	-25.2
1986	JAN-MAR	125.9	54.8	5.7	17	48.3	0	41.9	0	6.4
1986	APR-JUN	102.9	147.1	1.9	-61	14.9	0	42.5	0.2	-27.6
1986	JUL-SEP	124.8	113.9	4.7	2.1	4.1	0	40.6	0.2	-36.6
1986	OCT-DEC	170.3	54.2	8.7	60.3	47.1	0	36.7	0	10.3
1987	JAN-MAR	89.3	45.2	3.8	3.3	37	0	42	0	-5
1987	APR-JUN	148.8	145.7	5.5	-34.7	32.3	0	38.1	0.2	-5.9
1987	JUL-SEP	148.9	140	6	-18.4	21.3	0	40.6	0.2	-19.2
1987	OCT-DEC	185.2	51.3	10.2	53.5	70.2	0	38.7	0	31.5
1988	JAN-MAR	206.2	65.6	11.6	15.5	113.6	0	43.3	0	70.2
1988	APR-JUN	72.2	139.9	1.6	-79.8	10.4	0	39.8	0.2	-29.5
1988	JUL-SEP	105.1	111.3	3	-10.9	1.7	0	42.8	0.2	-41.1
1988	OCT-DEC	75.4	45.4	3.2	23	3.7	0	41.8	0	-38
1989	JAN-MAR	107.2	60.2	4.5	24.5	18.1	0	26.8	0	-8.8
1989	APR-JUN	101.7	127.2	3.3	-52.5	23.6	0	27.2	0.2	-3.6
1989	JUL-SEP	82.9	78.1	2.4	1.8	0.5	0	34.5	0.2	-34
1989	OCT-DEC	151.9	49.4	8.1	66.3	28	0	32.7	0	-4.7
1990	JAN-MAR	163.3	70.9	9	-0.3	83.8	0	33.2	0	50.6
1990	APR-JUN	92.4	135.8	2.9	-57.2	11	0	40.2	0.2	-29.2
1990	JUL-SEP	61.7	70.2	1.7	-10.3	0.2	0	40.3	0.2	-40.1

All units: Mld