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Assessing the water resource sustainability of Trinity Broads, Norfolk: initial appraisal of the water flux, storage and groundwater data for use in a conceptual daily water balance model

Groundwater Systems and Water Quality Programme

Commissioned Report CR/03/068N

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Assessing the water resource sustainability of Trinity Broads, Norfolk: initial appraisal of the water flux, storage and groundwater data for use in a conceptual daily water balance model

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Key words

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Executive Summary

Data are required to inform and calibrate a conceptual water balance of the Trinity Broad system including the internal fluxes feeding the water supply taken from Ormesby Broad. The water balance will enable Essex and Suffolk Water Company to use the resource in full knowledge of the environmental impacts.

Since the inception study during the winter of 2001/02 Starflow® gauges have been installed beneath the main causeways and in the Muck Fleet channel to observe inter-broad flow and overall outflow from the system. In addition, five observation boreholes have been drilled and water level and groundwater chemistry data collected. Meteorological data continues to be gathered for the area.

The flow data have been problematical, as periodic erratic records, or apparent peak flows equating with torrents flowing beneath the causeways, have had to be identified and filtered out of the data set. The cause of these erratic data are not known, but running mean filtering and picking minimum flows from the means has enabled some consistency to be gained, and a 'worst case' scenario for environmental compensation flows identified.

An outline water balance for the system suggests that the Trinity Broads can sustain current abstraction with some margin. Confirmation of this is the constant measured outflow in the Muck Fleet channel, other than immediately after the sluices have been opened.

It is recommended that flow data collection continues for at least two and preferably three years, and to include one dry summer if possible. Modelling of the system should be enhanced by parameterisation of a groundwater model to allow checks of various future climate, management and operational scenarios to be carried out. Development of an hourly model to supplement the daily information would also be useful in assessing within-day stresses on the resource.

1 Introduction

The initial report on the proposal for development of a hydrogeological model of the Trinity Broad catchments (Hudson et al., 2001) recommended the augmentation of the network of hydrometric equipment within the catchment to measure flows and groundwater levels. These data were required to inform and calibrate a conceptual model of the water balance of the whole Trinity Broad system while also investigating the internal fluxes feeding the water supply taken from Ormesby Broad. The development of the model is aimed at improving understanding of the system and to enable Essex and Suffolk Water Company (E&SWC) to plan their future utilisation of the resource taking full regard of its sustainability, its demand on the various inputs to the Broad and the environmental impacts of abstraction on this area of high nature conservation value.

As recommended in the report, E&SWC arranged installation of the flow measurement equipment, water level monitors for the Broads and observation boreholes constructed around the Broad. Over one year's data have now been collected since installation in September 2001. However, it is the nature of water balances that they only start to make sense when viewed in the longer term. There are problems associated with carry over of storage deficits from year to year, especially when these are large in relation to the fluxes being measured, and there is always a need to allow for natural inter-year hydrological variability, which is a fundamental issue in sustainable water resource assessment.

An initial attempt to populate the water balance model with the data collected has also been carried out, but only as a pointer to future work and to assess its potential rather than as an end in itself. It is unfortunate that although most of the data required to populate a model going back at least to the beginning of the 1990s are available, estimates of the surface flows from the Broad system down the Muck Fleet were until recently missing. Ultimately the sustainability of the system will be dependent on the inputs of water from the whole of the Trinity Broad catchment, rather than just the Broads themselves. The development of the model will allow quantification of the way groundwater movement and surface flow into the Broad replenishes the water abstracted and is lost by natural means, and will allow calibration of a groundwater model to investigate what stresses the abstractions are putting on the hydrological system. This should enable future planning of the resource over a period when both water resource and ecological demands, and also the climate, are likely to change.

Although a single year's data are not sufficient to either fully develop a model or draw any meaningful conclusions from the results, this milestone nevertheless provides an opportune moment to assess the data recovered so far from the Trinity Broads. It is important to determine how well the equipment has operated, to recommend any changes or improvements that could be made and to assess the quality and representativeness of the data collected.

2 Data Collection and Collation

A daily time step has been chosen for analysis. This is a compromise between the time step of data already available and data newly collected for the project. Some existing data (e.g. evaporation) are only available as monthly totals, whereas the data available from the new networks and logged automatically is available sub-daily (15-minute). The daily time step will eventually be a convenient period for planning of water resource utilisation, and because it is sufficiently long for the system to have reacted and re-equilibrated to rainfall inputs there are, therefore, no worries about having to consider lag times and flow routing in the modelling.

The daily time step may suffer from the fact that the rainfall totals are read from 9 am to 9 am while for convenient manipulation within a spreadsheet the flow data are bulked in midnight to midnight periods. It is possible this may be conveniently and simply justified and dealt with by using the Meteorological Office practice of throwing back the rainfall reading to the previous day, so that flow logically follows rainfall with an inbuilt lag of 15 hours.

2.1 RAINFALL DATA

Daily rainfall data have been provided from the raingauge at the Ormesby Treatment Works (Figure 1).

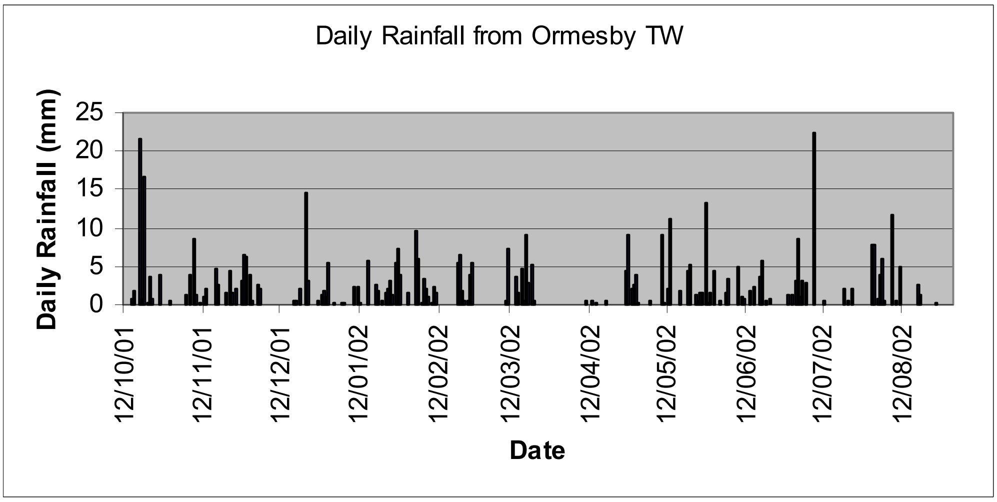


Figure 1 Daily rainfall total from the Ormesby Treatment Works

This covers the whole period that the new hydrometric networks, i.e. Starflow flow meters and borehole monitors, have been in operation. Ideally, and for the sake of the ultimate accuracy of the water resource assessment of Trinity Broad, this record should not be used as it stands, but for the distribution into daily figures of period rainfall from other gauges within the Trinity catchment, thereby improving the estimates of catchment rainfall. These monthly data are available at the National Water Archive or from MORECS. However, in these early stages of development of the catchment water resource model, it is probably an unnecessary refinement, and it is unlikely in any case that the spatial variability in rainfall is large in this topographically-smooth area.

2.2 EVAPORATION DATA

The original Trinity Broad report (Hudson et al., 2001) used MORECS evaporation data for the monthly balance produced for Ormesby Broad. MORECS (Hough and Jones, 1998) is quoted as monthly totals and is not available as daily data except at some cost, even though the monthly estimates must have been obtained as a summation of daily data from met sites within the MORECS 131 grid square. The Meteorological Office (MO) has recently developed a new model, MOSES, which is currently under evaluation, and which potentially gives a more realistic estimate of evaporation in mixed land use catchments, particularly at time of soil moisture stress. This is not on-line at present, although it could be considered for future work.

In the absence of these daily data it is necessary to disaggregate the monthly MORECS data in a sensible way. Ideally this technique could use any surrogate daily analogue data for evaporation that might be available in the vicinity, for instance air temperature or wind speed, which are both important driving variables in the Penman equation. The nearest station at Hemsby is MO owned and run and is actually in the catchment. However the data are not available, except at excessive cost. An opportunity could be taken to use the Climate Observers Link, which co-ordinates data collection and provides summaries from sites run by amateur observers all over the UK. There is no COL station very close, but ones at Lowestoft and Beccles look promising candidates. As the data are only to be used for disaggregation of MORECS, then accuracy and precision is not of the highest priority, though it should be said that many of these sites are run to MO standards and some even contribute data to the MO.

Currently we do not have these data, and so for the initial run of the model a simple within-month distribution has been carried out assuming a sinusoidal annual distribution of potential evaporation (Finch and Hall, 2001). The results are shown in Figure 2.

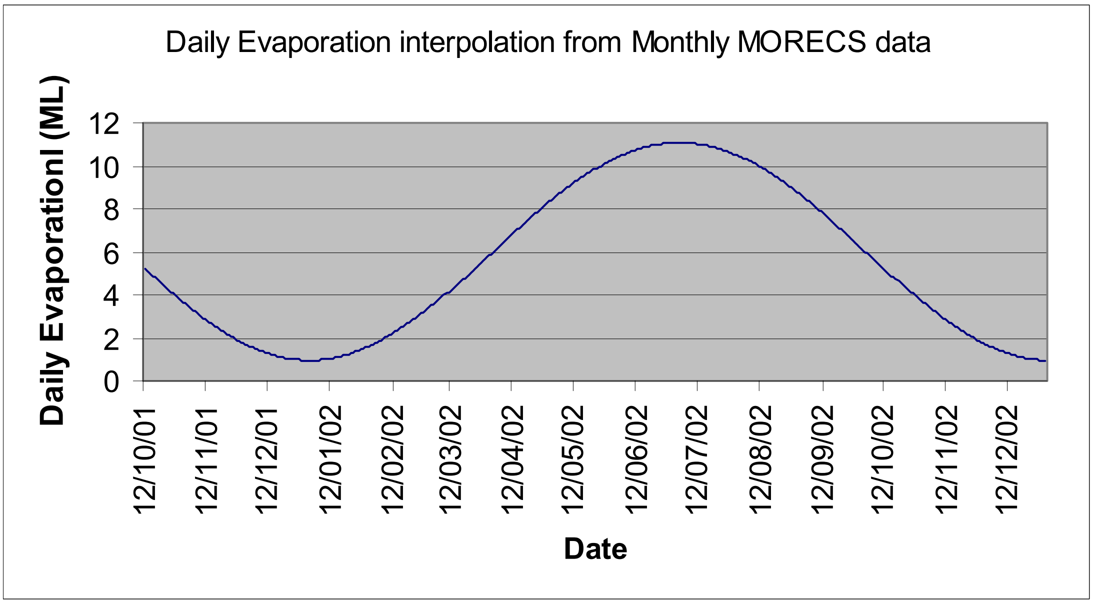


Figure 2 Daily evaporation rates fitted as a cosine interpolation from monthly MORECS data

It should be pointed out that the current version of the model only requires evaporation from the Broad surfaces themselves; catchment evaporation is dealt with implicitly by the reaction of the groundwater system to recharge over the whole catchment. Therefore, it is really open water evaporation that is required, which will differ from evaporation from vegetation, and will be slightly different from the mixed land use potential values given by MORECS. However, as the Broad areas are small relative to the feeder catchment area, any errors introduced are not likely to be significant at this stage of model development.

2.3 RESOURCE UTILISATION

Daily abstraction data for Ormesby Broad Treatment Works (TW) have been provided by E&SWC and are shown in Figure 3. The levels indicate a distinct peak in summer and autumn, presumably coinciding with the holiday season.

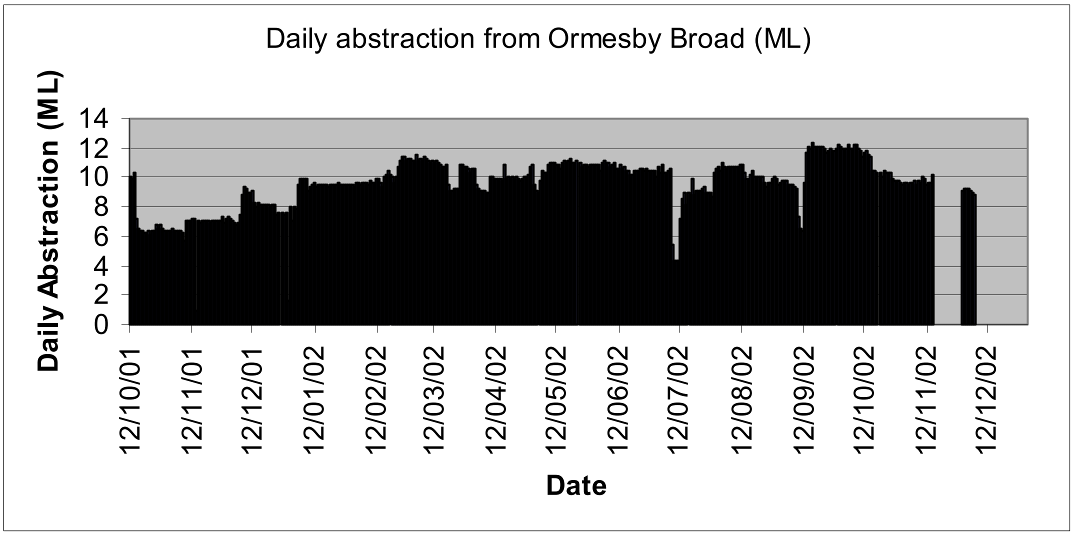


Figure 3 Daily abstraction data for Ormesby Broad TW from E&SWC.

2.4 BROAD STORAGE

In practice there is only a small variability in levels within the Broad system. These levels are now monitored every 15 minutes by the pressure transducers of the Starflow® velocity meters installed in the channels between the Broad. However, for some time they have also been monitored manually, perhaps accurately and at more appropriate locations, at approximately weekly intervals. These data are more useful simply because they are quoted as a deficit from a control level in the Broad, to match the relationship between these levels and Broad storage provided by E&SWC. The fact they are not daily values has been allowed for in this initial model run by a linear interpolation of levels between reading dates.

For future reference, the flow between Broads, and the resultant water surface drawdown in the connecting channels, means that the 15-minute logged levels are generally lower than the real Broad levels in any case. This is illustrated by the comparison of the manual water levels in Ormesby Broad and manual levels taken at the Starflow meters for the study period (Figure 4) which indicates a drawdown of around 2-3 cms, and sometimes more. Abstractions from Ormesby Broad will also tend to depress levels in Ormesby Broad itself, but this is rapidly compensated by inflow from Rollesby and Filby Broad and groundwater inflow.

Levels in the Broads overall are controlled by the Muck Fleet sluice which is operated manually on occasions to allow for passage of floods, for fisheries operations or for maintenance. In theory this sluice is self-regulating, and, therefore, maintains a fairly constant level within the system providing there is an excess of rainfall and groundwater input over evaporation and abstraction that allows water to continue to flow through the system. The Muck Fleet flow data, for all their current inadequacies, indicate that flow never ceases out of the system, averaging 0.3 m^3s^{-1} and rarely dropping below 0.17 m^3s^{-1}, which bodes well for sustainability of the resource.

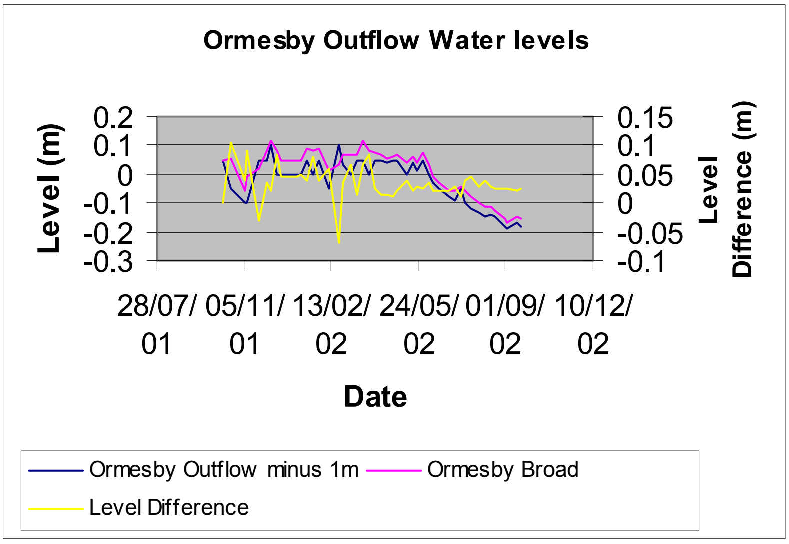


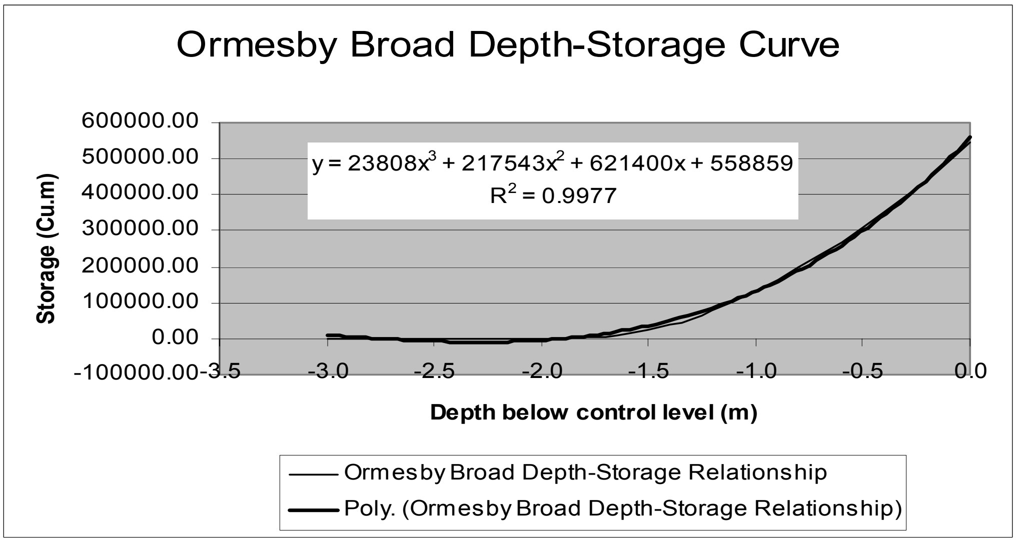
Figure 4 The relationship between water level at Ormesby Broad TW and the drawndown level in the channel between Ormesby and Rollesby, adjacent to the Starflow meter.

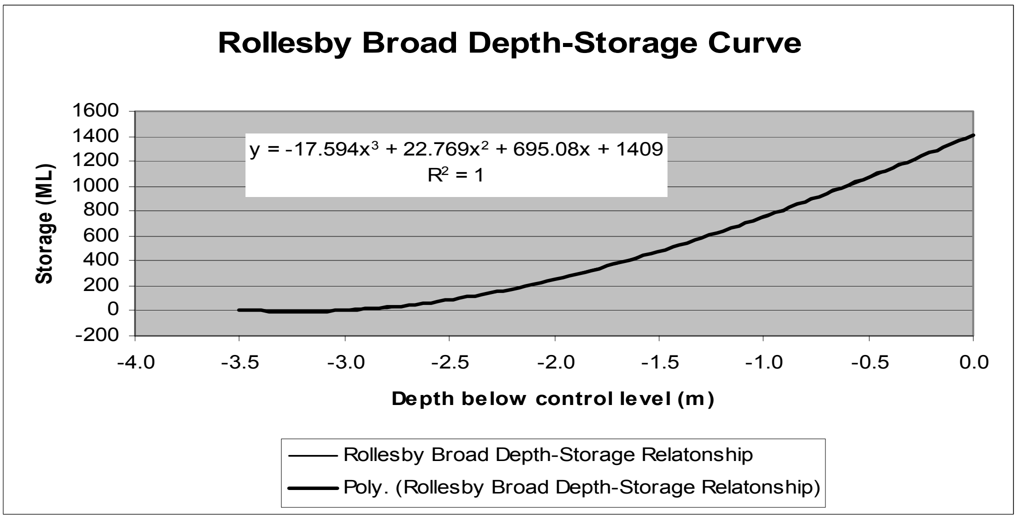
Allowance for changes in storage in the Broads, therefore, becomes important for the model in the summer months and is crucial to the daily water balance assessment over this period. Surveys of the Broads (Robinson, *pers. comm.*) have given a series of Depth (d)-Storage (S) curves for the individual water bodies. These are shown in Figures 5a-5c.

Ormesby	$S = (23808d^3 + 217543d^2 + 621400d + 558859)/1000$ ML	$R^2 = 0.9977$
Rollesby	$S = (-17594d^3 + 22769d^2 + 695076d + 1.409*10^3)/1000$ ML	$R^2 = 1$
Filby	$S = (-12547d^3 + 1469.2d^2 + 377374d + 780173)/1000$ ML	$R^2 = 1$

For each water balance accounting period the monitored level can be equated to total storage and the change in storage from the previous level calculated. For this purpose polynomial curves have been fitted to the cumulative storage estimates at various depths below a control level for each Broad. The fits are excellent for Filby and Rollesby, but less so for Ormesby, especially when the Broad levels are low. However, as Ormesby Broad rarely approaches a level of 1m below control level, the fit in the important upper region is perfectly adequate.

The main problem for modelling in future, using the Starflow transducer levels, will arise in equating the datum level for the curve (control level) with the measured daily average depths over the Starflow transducers, i.e. knowing from where on the fitted curve the change in storage needs to be taken. In practice this depth only needs to be known approximately, as for segments of the curve the relationship is approximately linear, giving an accurate change in storage (slope) for a given change in level, even if the absolute amounts of both are in error. As a reasonable approximation, the level in Ormesby Broad, for instance, can be taken as the level at the Rollesby Bridge transducer, plus 3 cm to allow for the drawdown.





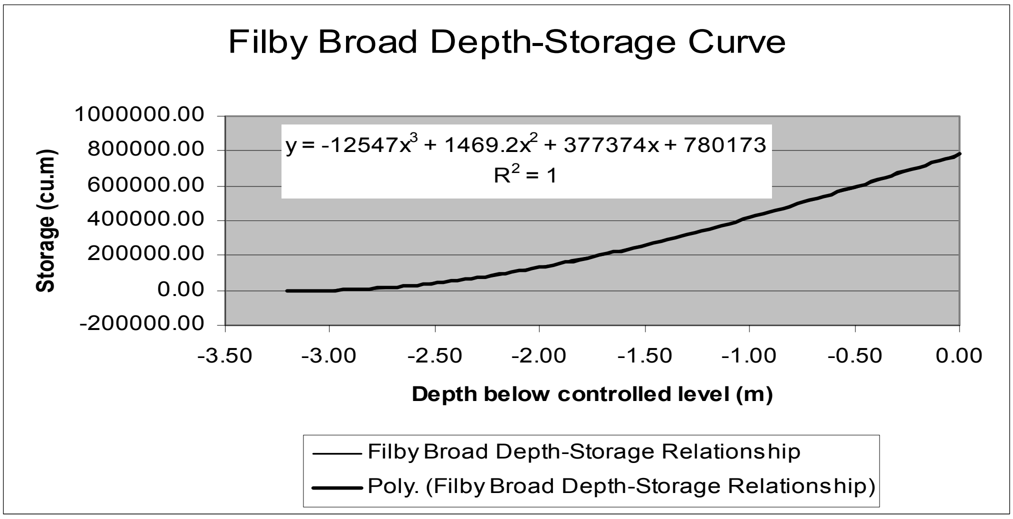


Figure 5 Relationships between depth below control levels and total Broad storage for (a) Ormesby, (b) Rollesby and (c) Filby Broads.

2.5 FLOW DATA

On the recommendation of the first Trinity report (Hudson et al., 2001), which recognised the lack of information on surface flows within and out of the system, flow data have now been collected for over a year using Starflow® ultrasonic units installed at 4 points within the Broad system. At Rollesby Bridge the outflow from Ormesby Broad and the input to Rollesby is measured, at Filby Bridge the outflow from Rollesby Broad and the input to Filby is measured and at Charity Farm the outflow from Filby Broad is measured.

Within the Muck Fleet, which drains the whole system and is, therefore, the key site for assessing the water resources of the system, the water levels are controlled by a pair of sluices in series. The lower and most recently-built of these is the one currently operational. Although it was designed as a self adjusting sluice, problems with the float mechanism means that it has mainly been used as a variable but fixed weir that is used operationally to allow fish movements. This means it may stay fixed for long periods but when altered does not necessarily return to the same level. A hydraulic approach would, therefore, have proved very difficult in the absence of accurate information on changing sluice invert levels.

A fourth Starflow was, therefore, installed upstream of this sluice to measure flows out of the system into the River Bure. It was particularly important at this site that a Starflow was used, as direct measurements of velocity at any given depth are essential above this variable height control.

2.5.1 Assessment of the flow gauging stations

The four flow gauging stations are based on the Acoustic Doppler technique, in the guise of the Starflow meter. Of particular relevance to the measurements at Trinity Broad, and the reason the technique was recommended, is that the following advantages accrue:

- Bi-directional flow can be catered for, and it can be installed in either direction in the channel to minimise the effects of sediment deposition on the lenses.
- As the Starflow measures velocity directly, rather than relying on a stage-discharge relationship that will be variable in natural channels, it can cope with variable head differences between water bodies upstream and downstream of the measuring section, i.e. when broad levels are different. It was always going to be difficult to define flows between Broads from head differences alone, as these are invariably small and often within measurement error.
- It can cope with variable resistance due to weed growth etc., as unlike a hydraulic approach it does not rely on known channel hydraulic characteristics along a reach.
- It is relatively cost effective and easy to install with only minor civil works required.

These advantages make it the only technique available at reasonable cost that could be used in such circumstances. However, it has certain disadvantages against which the accuracy and reliability of the results from the units need to be interpreted.

- It relies on a good survey of the cross sectional area, which is difficult in deep channels with soft and uneven banks and bed.
- The unit can periodically become covered with deposited silt and other sediments, thus blocking or reducing the signal.
- The cone of measurement depends on the suspended material density which affects the weighting of the return signal from different depths in the vertical column

- The technique needs an independent calibration, preferably by velocity-area methods, to assess the representativeness of the single velocity measurement.
- There is a great deal of interpretation required to allow filtering out of false readings. These are often obvious, but at the same time can be very frequent and time consuming to deal with. It is also difficult to find a single filter analogue to deal with all circumstances.

In each case a single meter was installed, giving a measurement of depth and velocity as an average of one-minute measurements over each 15-minute period. The meter was not necessarily placed in the centre of the channel. This single velocity measurement represents an average of the distribution of velocities in a cone of water above and at an angle to the sensor, which is installed on the bed with its pressure transducer orifice at effectively zero water depth. In the absence of calibration information to suggest the contrary, it has to be assumed that this velocity is representative of the average velocity across the whole channel. This is rarely a reasonable assumption, and more often than not it results in a biased (generally high) estimate of velocity, with the amount of bias varying from reading to reading depending on flow conditions and water properties, especially turbidity.

To obtain flow estimates from the velocity measurements, an accurate initial survey of the channel is required to give a relationship between depth of flow and cross-sectional area, which the installer can then program into the Starflow processor. The depth measured by a pressure transducer in the Starflow head is then entered to this relationship and the resultant area multiplied by the 'average' velocity to calculate flow. Clearly the technique is very dependent on the accuracy of the depth measured by the vented transducer. In theory this gives the weight of the column of water above the transducer relative to atmospheric pressure, but in practice the values obtained may need a zero correction to ensure that zero depth really means a dry bed under the Starflow transducer.

Alternatively, flow can be calculated from raw velocity and depth data at a later date, which gives an opportunity to introduce further calibration velocity data and improved depth-cross sectional area relationships once the raw velocity data have been corrected.

INDEPENDENT CALIBRATION

To improve the future estimates of flow at the Trinity Broad Starflow sites, and to correct existing data, an independent current metering calibration was carried out at three sites - Rollesby Bridge (Ormesby Broad outflow), Filby Bridge (Rollesby Broad outflow) and the Muck Fleet sluice (whole Broad system outflow). At each, a comprehensive channel survey was carried out, relating the bed cross-section and water levels at the time to the level and position of the Starflow transducer and local Ordnance data. As a hydraulic approach to rating the channel has been ruled out, it was not necessary to measure the relative levels of the adjoining Broads.

The current metering was carried out using a Valeport 801 electromagnetic meter, which like the Starflow is capable of performing in low and even negative flow. On this occasion, it was only possible to carry out the survey at one flow level, but it is hoped that this can eventually be repeated at a different time of year and with a different water/flow level to improve the calibration across the flow range. The collection of these data makes it possible to relate the manually-collected data to the contemporary depth and velocity data from the Starflows and to propose corrections to the Starflow flow and level data to provide improved estimates.

Table 1 Details of the current meter gaugings and the relationship with Starflow® outputs

Detail	**Ormesby Outflow**	**Rollesby Outflow**	**Muck Fleet sluice**	
			Starflow X-section	**Current meter X-section**
Date	3/12/02	4/12/02	4/12/02	4/12/02
GMT -start	13:40	11:20	10:40	09:35
GMT -finish	14:40	11:35	10:50	10:30
Level survey				
Datum -position	On top corner of RB pier of car park bridge and AOD gauge board	On top corner of LB pier of walkway bridge	On top of nut on upper sluice mechanism and lower sluice gauge board	
Datum –level AOD	101.138	Not measured	Not measured	
Datum –local level reduced	Not needed	9.909	9.295	
Starflow zero level	99.375 (AOD)[1]	9.116 (AALD)[2]	7.055	Not applicable
Current Metering				
X-section area (m^2)	3.355	1.58	Not applicable	3.218
Flow (ls^{-1})	74.74	211.85	Not applicable	258.1377
Mean velocity (ms^{-1})	0.0223	0.1341	Not applicable	0.080217
Reduced water level (m)	100.04 (AOD)[1]	9.502 (AALD)[2]	7.936 (AALD)[2]	7.952 (AALD)[2]
Starflow data				
Depth at Starflow –survey (m)	0.66	0.38	0.903	Not applicable
Depth at Starflow –meter transducer (m)	Not working	0.32	0.878	Not applicable
X-sectional area from survey (m^2)	3.355	1.58	8.302	Not applicable
X-sectional area in memory (m^2)	Not calculable	0.988	6.889	Not applicable
Velocity (ms^{-1})	0.005 (0-0.015)	0.089 (0.080-0.098)	0.069	Not applicable
Flow ($l\ s^{-1}$)	16.70	140.6	572.8	Not applicable

[1]Above ordnance datum
[2]Above arbitrary local datum

The fourth site at Filby Broad outflow was not visited. This was partly due to the difficulties and danger of performing current metering at this deep-water site, but also due to the fact that the Starflow was not working at this site at the time, making a comparison impossible.

At the Muck Fleet sluice site the water depth also made it difficult to carry out current meter gauging at the actual Starflow position. In this case an approximate bed survey was carried out adjacent to the Starflow, but the current metering to give discharge and average velocity for the reach was carried out at a more convenient and safe location immediately above the upstream fixed sluice.

A summary of the results from the 3 sites is given in Table 1.

ORMESBY OUTFLOW

The comparison for the Ormesby outflow at Rollesby Bridge (Table 1) indicates that under the particular conditions encountered the Starflow data for the same period as the manual gauging gives four times lower velocities than current metering. However, the gaugings were done at an awkward period when flow had virtually ceased but increased again soon after; the discrepancy could be one of synchronicity as much as a real difference. Neither will the relationship necessarily hold true at all depths and under all conditions of water 'cloudiness'. It was also apparent that the consecutive 15-minute Starflow velocity values showed huge variability, far more than the consistent results given by the electromagnetic meters over the same period of the gauging (Figure 6). This may be partly due to the fact that the Starflow points downstream and is, therefore, not so efficient when measuring what it sees as a negative velocity when water is flowing out of Ormesby Broad.

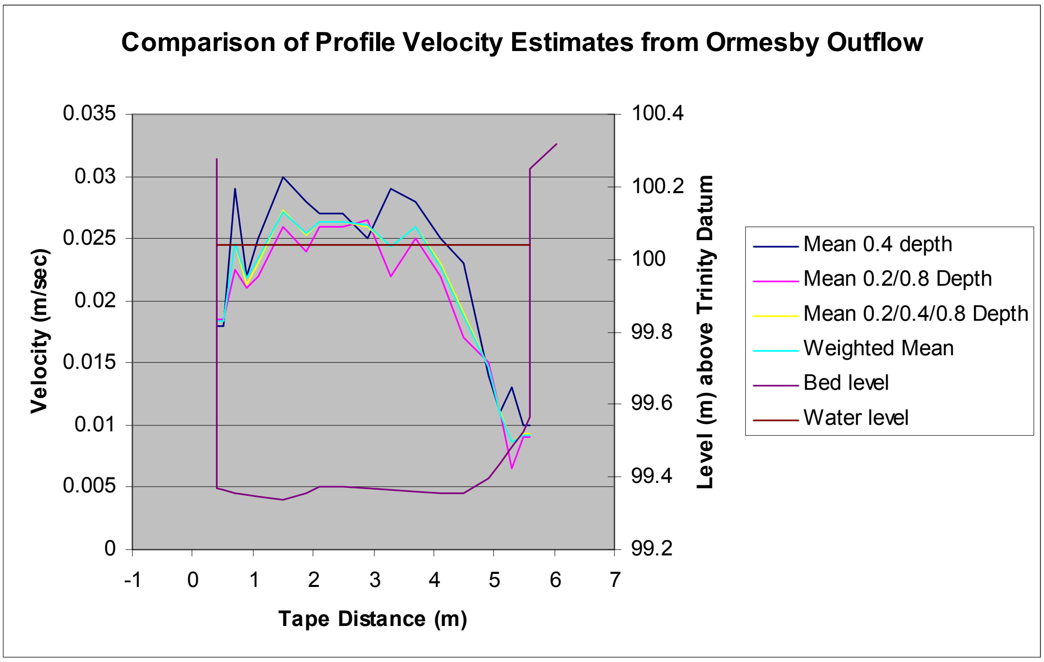


Figure 6 Cross section of the Ormesby outflow gauging site and the distribution of mean column velocities across the stream, calculated by various means

In the absence of further gaugings it will have to be assumed that the Starflow data gives a good approximation of the profile velocity throughout the flow range. This is provided a correction (proportional offset) is applied to allow for the difference between profile velocity and actual mean velocity across the section from the current metering. As the flow range has been relatively small over the last year, then it would seem this may be a reasonable assumption, however, the data as they stand must be treated with caution until further calibration checks are carried out and the erroneous data filtered out.

A further problem at Ormesby is that, unfortunately, the depth as measured by the Starflow transducer was reading some 2 m too high at the time of the current metering, a problem that started after suspected vandalism on the unit on 16 August 2002. It is difficult to say from the record exactly when the damage occurred, or to explain why there was a gradual increase in measured depth followed by a more rapid jump. It would seem that if the unit had come loose and was moving about in the water, then the depth could tend to decrease not increase. Furthermore, if the unit were immersed so that the transducer vent became full of water, this would also serve to reduce the measured depth rather than increase it.

In spite of the jump, the transducer has continued to respond in such a way that if a correction to allow for the apparent jump is made to the Starflow depth data it remains in line with manual depth measurements (Figure 7). This suggests that post-processing of the depth data should allow reasonable confidence in the cross sectional areas estimated at Rollesby Bridge. In the meantime enquiries are being made from the manufacturers as to the cause of the jump, as there is an indication that a change of range may have occurred. Repair of the unit is a priority, otherwise the integrity of future data will be in jeopardy.

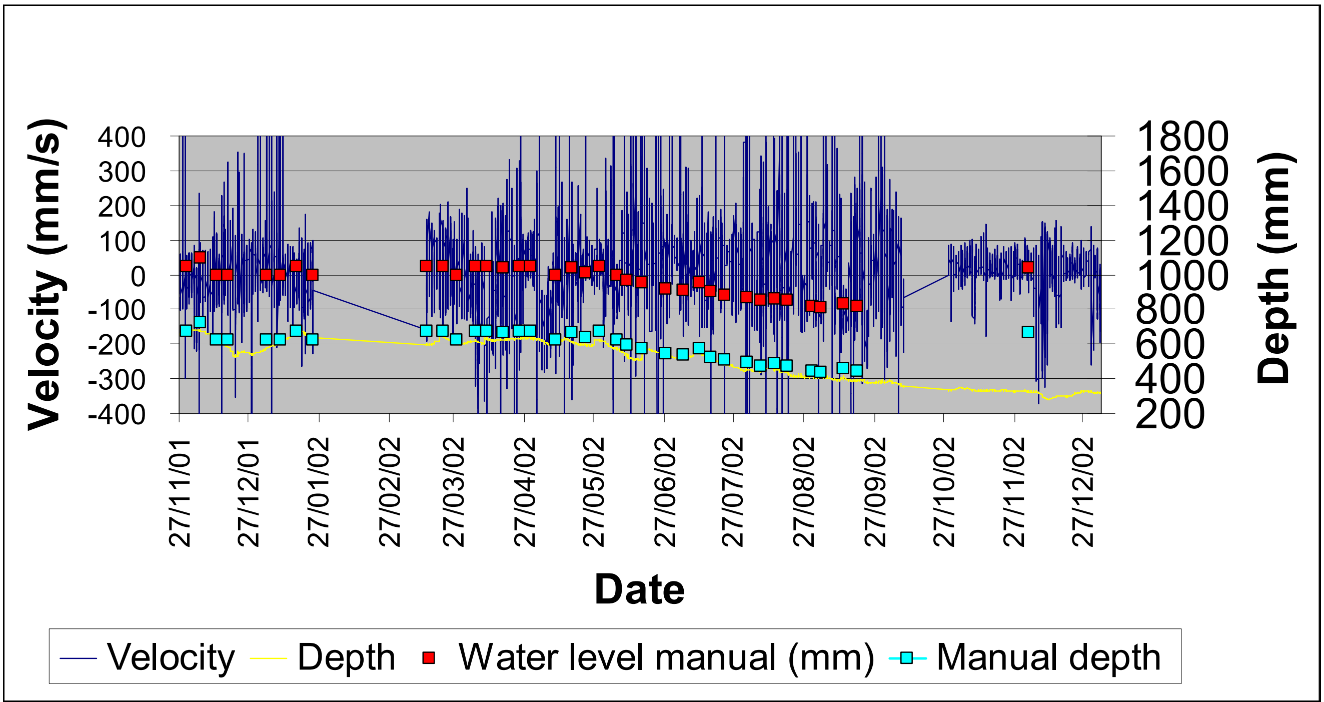


Figure 7 Fifteen minute flow and transducer levels, compared to corrected manual water levels and depths at the Ormesby outflow.

One further doubt surrounding the Starflow estimates concerns the cross sectional area input to the device to allow calculation of flow. Cross-sectional area obviously varies with water depth, and so the calculation in the logger requires an equation relating it to water depth over the Starflow transducer. A survey was carried out to obtain this new information (Figure 8) and to allow a future comparison with the equation within the Starflow. This comparison was not carried out on this occasion because of the poor state of the flow data, which makes it difficult to back-calculate the cross-section for each flow estimate. The post-processing made necessary by the shift in the depth measurement, described above, and the need to filter the velocity data, can be seen as opportune. When this is done, it will also allow incorporation of a more accurate depth-area relationship.

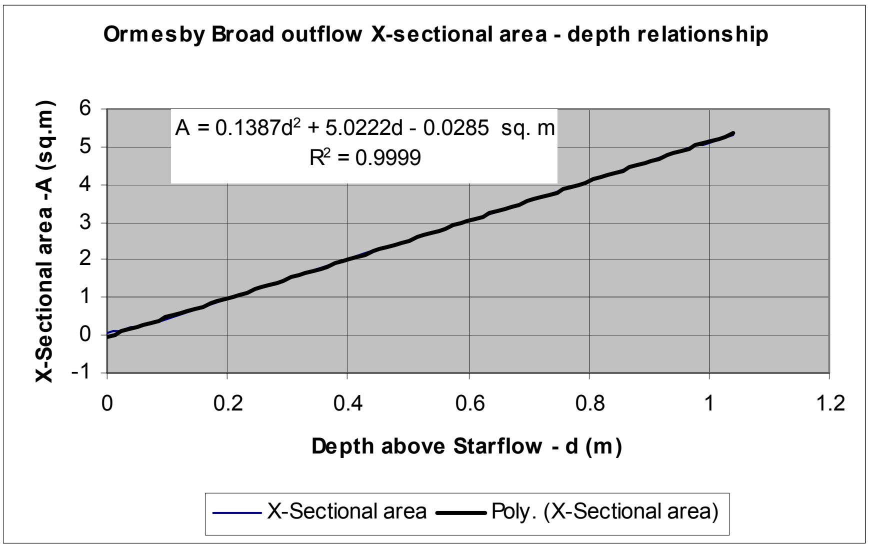


Figure 8 A check of the relationship between channel cross-sectional area and water depth at Ormesby Broad outflow, used to calculate flow in the Starflow logger.

ROLLESBY AND FILBY OUTFLOWS

The analysis of internal flows has been restricted in this interim report to the two most important sites at Rollesby Bridge (Ormesby outflow) and Muck Fleet sluice (whole system outflow). Neither the Rollesby nor Filby outflows have been considered at this stage.

MUCK FLEET SLUICE (WHOLE SYSTEM) OUTFLOW

The flow data collected at the sluice form probably the most important record as far as the operation of the whole Trinity Broad water resource system is concerned. The Starflow records here are the most reliable of the four sites, because flows are greatest here, they are always unidirectional and the water is always turbid to some extent, minimising the shadowing of returning ultrasonic signals and making data interpretation easier. However, this is also a deepwater site so the velocities tend to be low.

The comparison shown in Table 1, between the Starflow data and the manual gauging carried out on 4 December, is made more difficult by the fact that the two sets of measurement could not be taken in the same place. Nevertheless, the indication is that the flow estimates do not correspond particularly well. The average uncorrected flow over the manual gauging period at the Starflow site of 572 ls^{-1} is some 122% higher than the 258 ls^{-1} measured at the current metering site. This difference is unlikely to result from the Starflow being placed at a non-representative site, and applying a correction simply by using a ratio of the Starflow and current meter velocity estimates may not be appropriate.

The variability of the Starflow data as indicated by the quoted range is also somewhat worrying. There was no visual evidence of variable velocity at the site when the gauging was being carried out, so this is a clear indication that the Starflow sampling regime may not be appropriate. With the benefit of hindsight, a programme of current meterings should have been conducted from the time the Starflows were installed, to ensure that these were giving sensible results from the beginning. With this information, early adjustment of the velocity sampling programme could have been made to ensure the correct use of other parameters such as cross sectional area and depth.

Table 2 Results of a manual flow gauging and channel survey carried out on 4/12/02 upstream of the Muck Fleet sluice Starflow site

Date 04/12/02
Datum (top of sluice mechanism nut) (m) 0.705
Datum - Reduced level (m) 9.295
Valeport unit 18572 **Meter** 17892

Time	Pos-ition	Tape	Water depth	Survey – levels reduced to datum		Velocity (proportionate depth)					Column area	Mean column velocity			Mean column discharge		
				Bed	Water level	0.2	0.4	0.8	Mean .2/.8	Mean .2/.4/.8		0.4	.2/.8	.2/.4/.8	.4	.2/.8	.2/.4/.8
		m	m	m		m/s					sq. m		m/s			l/s	
09:25	RB	0.9	0.10	7.852	7.952		0.048		0.048	0.048							
		1.0	0.10	7.852	7.952		0.048		0.048	0.048	0.010	0.048	0.048	0.048	0.480	0.480	0.480
		1.2	0.28	7.672	7.952		0.006		0.006	0.006	0.038	0.027	0.027	0.027	1.026	1.026	1.026
		1.4	0.28	7.672	7.952		0.063		0.063	0.063	0.056	0.035	0.035	0.035	1.932	1.932	1.932
		1.6	0.50	7.452	7.952		0.027		0.027	0.027	0.078	0.045	0.045	0.045	3.510	3.510	3.510
		1.8	0.55	7.402	7.952	0.022	0.091	0.103	0.063	0.072	0.105	0.059	0.045	0.050	6.195	4.699	5.198
		2.0	0.58	7.372	7.953	0.099	0.117	0.106	0.103	0.107	0.730	0.104	0.083	0.090	11.752	9.323	10.132
		2.2	0.65	7.302	7.953	0.129	0.125	0.111	0.120	0.122	0.123	0.121	0.111	0.115	14.883	13.684	14.084
		2.4	0.85	7.102	7.953	0.126	0.122	0.127	0.126	0.125	0.150	0.124	0.123	0.123	18.525	18.488	18.500
		2.6	0.94	7.012	7.953	0.124	0.118	0.127	0.126	0.123	0.179	0.120	0.126	0.124	21.480	22.554	22.196
09:50		2.8	0.95	7.002	7.953	0.109	0.120	0.124	0.117	0.118	0.189	0.119	0.121	0.120	22.491	22.869	22.743
		3.0	1.00	6.952	7.953	0.107	0.104	0.120	0.114	0.110	0.195	0.112	0.115	0.114	21.840	22.425	22.230
		3.2	1.07	6.882	7.953	0.099	0.096	0.104	0.102	0.100	0.207	0.100	0.108	0.105	20.700	22.253	21.735
10:03		3.4	1.09	6.862	7.953	0.100	0.099	0.093	0.097	0.097	0.216	0.098	0.099	0.099	21.060	21.384	21.276
		3.6	1.06	6.892	7.953	0.084	0.088	0.083	0.084	0.085	0.215	0.094	0.090	0.091	20.103	19.350	19.601
		3.8	1.00	6.952	7.953		0.088		0.088	0.088	0.206	0.088	0.086	0.087	18.128	17.665	17.819
		4.0	0.94	7.012	7.953		0.080		0.080	0.080	0.194	0.084	0.084	0.084	16.296	16.296	16.296
10:12		4.2	0.75	7.202	7.953		0.069		0.069	0.069	0.169	0.075	0.075	0.075	12.591	12.591	12.591
		4.4	0.70	7.252	7.954		0.057		0.057	0.057	0.145	0.063	0.063	0.063	9.135	9.135	9.135
		4.6	0.67	7.282	7.954		0.047		0.047	0.047	0.137	0.052	0.052	0.052	7.124	7.124	7.124
		5.0	0.56	7.392	7.954		0.024		0.024	0.024	0.246	0.036	0.036	0.036	8.733	8.733	8.733
		5.2	0.50	7.452	7.954		0.010		0.010	0.010	0.106	0.017	0.017	0.017	1.802	1.802	1.802
		5.4	0.30	7.652	7.954		-0.004		-0.004	-0.004	0.080	0.003	0.003	0.003	0.240	0.240	0.240
		5.6	0.20	7.752	7.954		-0.004		-0.004	-0.004	0.050	-0.004	-0.004	-0.004	-0.200	-0.200	-0.200
10:30	LB	5.7	0.02	7.932	7.954		-0.004		-0.004	-0.004	0.011	-0.004	-0.004	-0.004	-0.044	-0.044	-0.044
										x-s area	3.218 m^2			Flow	259.781	257.316	258.138
														Velocity	0.081	0.080	0.080

2.5.2 Raw flow gauging data

In the first instance no attempt was made to filter the Starflow data for erroneous signals. Flow estimates for the Muck Fleet site have, therefore, been used in their raw state to calculate an initial overall water balance of the Trinity system. It is clear from the balance that flow is being vastly overestimated, particularly at certain times of year, and that further work needs to be done on these data. This also applies to the other Starflow site data. The collection of additional data will clearly help, but work also needs to be done on interpreting the existing data.

The Ormesby Broad output is presented for illustrative purposes in Figure 7, but as can be seen it is extremely noisy, to the extent that it is sometimes difficult even to work out which way the water is flowing. The output from the Starflow at Muck Fleet Sluice is cleaner, but clearly has episodes of erroneous data giving flows of up to 8 m^3s^{-1} during the summer months. This is an order of magnitude greater than reality. Flows of this level would empty the Broad system, which is estimated to hold 2.74 x 10^6 m^3 of water in about 4 days. The cause of these problems needs to be investigated prior to cleaning up of the data. There is also a substantial gap in the data during September and October 2002, for which period it is not clear whether data are available.

2.5.3 Flow data filtering and correction

A discussion with the Starflow installers regarding the way the Starflows have been set up to record, average and store data has highlighted areas of potential error that need to be addressed when filtering the data. Within the samples taken that gives each one-minute reading, the ultrasonic unit sometimes incorrectly 'sees' very high values that can bias the one-minute value and, therefore, also the stored 15-minute average velocity. To correct this it is, therefore, necessary to define what are real data and what is a biased (overestimate) of velocity.

For this reason it is not adequate to take a running mean of the values, as some or all of these will be overestimates and will, therefore, still result in an overestimate of 15-minute velocities. A spreadsheet algorithm has, therefore, been set up to determine the minimum value for a given period, on the assumption that, unless this represents a zero for missing data, this is most likely not to contain any biased values. During periods when a reasonable number of 'good' (i.e. minimum) values occur then a 3-hour running mean (13 values) is sufficient to filter the data. However in times of poorer quality data a longer running mean period may be necessary, up to 24 hours or longer.

2.5.4 Filtered flow data assessment

After filtering periods with remnant 'bad' flow data have been removed and a linear interpolation used between adjacent 'good' data points. This may have introduced bias because of the implicit assumption of 'no change' over each of these periods, but is on balance a better approach than allowing grossly overestimated data to remain. The lightly filtered data confirms and even highlights the presence of diurnal variability in flow, which may be the result of abstractions and variable evaporation over the day. This suggests that the system is able to compensate for these losses during the day by increasing the groundwater flow to the Broad during the night. The main problem with the heavily filtered data (e.g. 24 hour or longer) is that this diurnal variability is lost by the heavy smoothing effect of the correction.

The most important conclusion from this data set is that, at least for the short period of record so far collected, the pressure on the system caused by abstraction from Ormesby Broad is rarely if ever sufficient to prevent compensation flow from the Broad through the Muck Fleet sluice. If anything, the use of the 'minimum flow' filtering technique illustrates the worst-case scenario for compensation flow, and yet even under these circumstances the resource and the environmental conditions appear to be sustainable. There are a couple of short periods when velocity is reduced to zero, usually following periods of higher than average flows. It is assumed that these were due to sluice movements designed to let water out, followed by a period where the system re-filled.

2.6 GROUNDWATER

Five observation boreholes have now been drilled, one at Rollesby village (Ob1) three in line perpendicular and to the west of Rollesby Broad (Ob 2, 3 and 4)and one at Filby (Ob5).

The strata penetrated in the boreholes is largely in line with the geological sections presented as part of the Year 1 study. Likely stratigraphic interpretation of the drillers logs is given in Table 3

Table 3 Likely statigraphic interpretation of the drillers logs.

Borehole	Corton Formation to (m)	Crag proven to (m)
Ob 1	3.1	20.5
Ob 2	7.6	20.5
Ob 3	3.2	21.5
Ob 4	2.5	18.2
Ob 5	4.8	23.5

All the boreholes and existing piezometers have been levelled in allowing piezometric surfaces to be drawn for the available hydrograph data which spans the period November 2001 to September 2002. A piezometric level map (Figure 9) has been prepared; it represents the late winter period. The piezometric level indicates that groundwater is flowing towards the Broads except at the Muckfleet end of the system throughout the year. Some surface water may be lost to the Crag at the lower end of Filby Broad as Piezometric levels are less than the broad water level at Burgh Common. Hydraulic contact between groundwater and surface water may be poor, however, as ingress of surface water through bottom muds will tend to clog up pore throats whereas groundwater flowing upwards into the Broads will have the opposite effect and maintain good hydraulic contact. Observation boreholes 2, 3 and 4 along Court Road show a hydraulic gradient towards the broads (Figure 10). This illustrates the roll of bankside storage that the near-field unconfined Crag aquifer offers. The water levels in Ob 1 at Rollesby and Ob 5 at Filby indicate that groundwater will flow from the Crag towards the broads from these points, there being a positive head difference between groundwater and Broad water level. Note that the lowest astronomically caused tides at Lowestoft are 1.50m below OD; groundwater levels below this elevation are unlikely, unless influenced by local pumping.

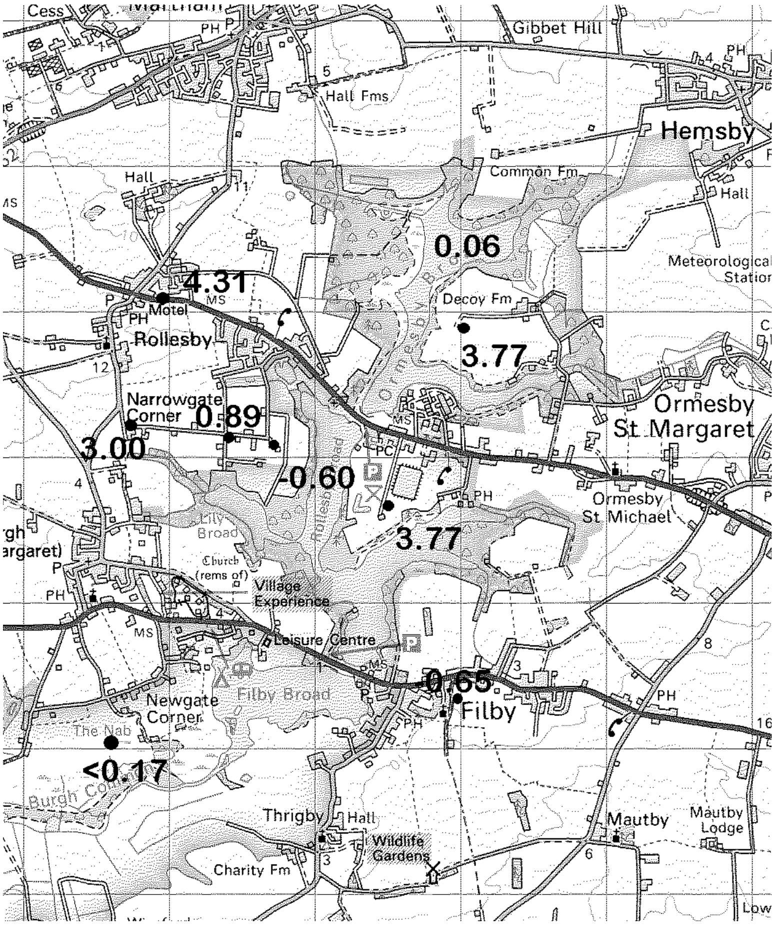


Figure 9 Piezometric levels (metres relative to OD)

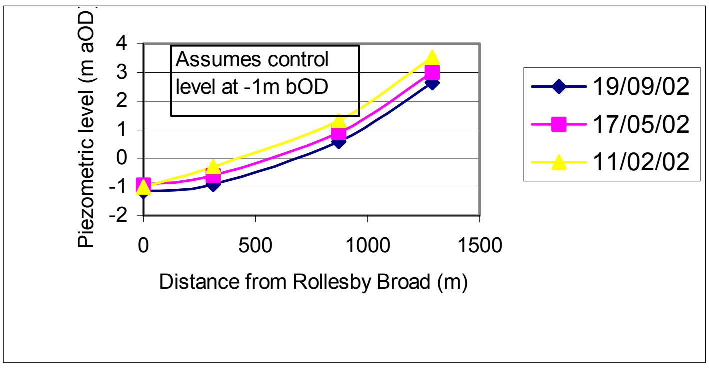


Figure 10 Piezometric level along Court Road to Rollesby Broad

Data from the piezometers indicates a high piezometric level at Decoy Farm, possibly of perched water over clay in the Corton Formation. The Day Reservoir is also higher than the level in the Broads indicating that there is a groundwater flux westwards towards the broads. However, at Burgh Common at the bottom end of Filby Broad the piezometric level is lower than the broad level indicating the potential for surface water to drain into the Crag from Filby Broad in this area.

The hydrochemical data from the observation boreholes indicate that the groundwater in the Crag is calcium-bicarbonate type water typical of a calcite rich arenaceous deposit. The pH is about neutral. Nitrate attains over 100 mg/l in the groundwater samples whereas it is generally below 5 mg/l in the surface water. Sulphate, manganese and iron are also generally less in the surface water samples than in the groundwater samples, reflecting anerobic conditions in the partially confined Crag aquifer.

There are some variations in chemistry between boreholes and in each borehole with time. Disregarding determinands such as iron and manganese, which require a sample uncontaminated with air to be realistic, the groundwater chemistry is consistent with time regardless of time of year. This suggests a relatively large groundwater system recharged at sufficient distance for incoming infiltration to have little diluting effect on the existing groundwater. This is in keeping with the confined nature of the aquifer in the vicinity of the Trinity Broads. Differences in chemistry between boreholes, all of which draw on the confined Crag aquifer, probably reflect dominant flow horizons within the Crag intersected by each borehole. It is noteworthy that calcium, bicarbonate, nitrate and sulphate concentrations all increase in Ormesby Broad water during the winter months reflecting a greater contribution from groundwater then whilst the piezometric levels in the aquifer are highest and the hydraulic gradient towards the broads is greatest.

Recharge to the Crag appears at first unlikely where it is overlain by clays of the Corton or Lowestoft Till formations. However, for piezometric heads observed in Ob 2 and Ob 5 plus Decoy Farm to occur in the Crag then recharge must be occurring through these formations. Besides, standing water after heavy rainfall pools in hollows and slowly percolates underground assisting the recharge process. Recession of groundwater levels is typified by the hydrograph for Ob 2 (Figure 11).

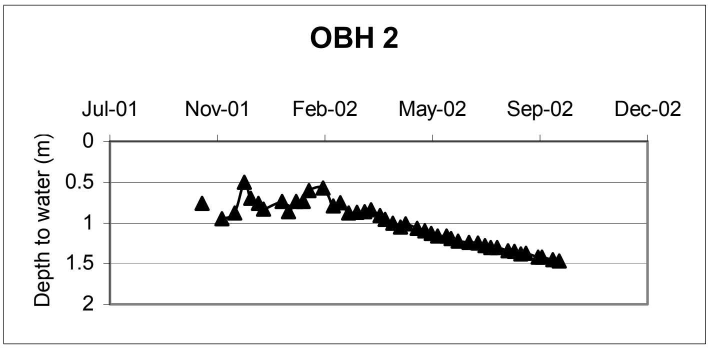


Figure 11 Hydrograph for Ob 2 at the top of Court Road

The groundwater flows in and around the Broad system are largely unknown and probably complex. However, it is believed that inputs to the Broad system, although partially driven by shallow regional hydraulic gradients in the Crag, are mainly due to storage-discharge mechanisms operating in the near bank areas. Inputs and/or outputs depend on the relative levels in groundwater and in open water, and on hydraulic conductivities in the near bank areas. Groundwater inputs to the Broad system are important for sustaining the Trinity resource, especially in the summer months when advantage is taken of recharge to the aquifer underlying the groundwater catchment area surrounding the Broad that occurred during the previous winter. These inputs are very difficult to quantify without recourse to a numerical groundwater flow model. However, there is a lack of data on hydraulic conductivities and an imprecise knowledge of the shape of the groundwater surface in the immediate vicinity of the Broads.

On the other hand, the internal water balance of the individual Broads and the system as a whole can be used to infer what the contribution from groundwater (and any surface inputs – assumed to be minor) might be. It ought to be possible to use the residual of the water balance to help calibrate (or optimise) a simple conceptual model of groundwater to open water interaction. This would need to be formulated in terms of length of bank contact, variable optimised hydraulic conductivities and the driving potential heads between groundwater levels measured in the observation borehole network and the Broad water levels. A useful start would be the development of a simple strip model for the bank segment intersected by groundwater flow past the boreholes along Court Road.

3 Water Balance Model

The water balance model to be used for assessment of the resource sustainability in Ormesby Broad can be carried out on two levels.

1. The behaviour of Ormesby Broad itself can be assessed in terms of the total amount of water used for evaporation, abstraction from the Broad itself and environmental flows allowed down the outlet channels. For a sustainable resource, this needs to be counterbalanced by rainfall on the Ormesby catchment and inputs from storage in the lower two Broads and their surrounding surface and groundwater catchments to replenish water used.

   The daily water balance equation equating the water resource with the use of water for the open water part of the Broad system (this is the operational unit as opposed to the catchment area) would therefore be of the form:

$$\mathbf{P + R + \Delta S + G \quad = \quad Q + A + E}$$

   Where:

   P is direct rainfall on the open water area

   R is direct runoff from the surrounding catchment area

   ΔS is a negative change in storage within the Broad

   G is the input to the Broad from groundwater

   Q is the surface (channel) flow from the Broad

   A is the abstraction for water supply

   E is the open water evaporation from the Broad

   Of these all variables except R and G are known to varying degrees of accuracy. In the case of both Ormesby and Trinity as a whole, R can probably be ignored for the most part as there are no obvious channels contributing flow to the Broad. After heavy rainfall there has been evidence of water ponding on the surface of agricultural land in the catchment and of lateral surface runoff occurring between temporary surface water bodies, but there is no evidence of even temporary channel networks evolving to deliver surface water to the Broad. It appears that except in the most extreme conditions (during which periods the abstraction system is unlikely to be under stress in any case) most laterally-moving surface water eventually finds a vertical route through the soil surface in areas of increased infiltration capacity. It then becomes recharge and part of the groundwater system and is implicitly incorporated in the G component of the equation. These factors effectively take care of the net contribution to the resource from the surrounding catchment area.

   The geological maps presented in the original report (Hudson et al., 2001) suggest that there may not be much hydraulic contact between the regional groundwater and Ormesby Broad. This may serve to simplify considerably the quantification of fluxes in the model for Ormesby alone, and once the flow data are corrected, a form of parity in the measured inputs and outputs could be expected. Any deviation from this might suggest an unknown input or at least help to quantify remnant errors in the data sets.

2. The same model can be run for the whole system, which actually gives a better picture of the way the abstraction at Ormesby utilises the whole storage of water in the Broads and in groundwater in the surrounding catchment. It is thought that it does this by inducing reverse flow into Ormesby and causing recharge of the two lower Broads by groundwater moving under steeper hydraulic gradients as the open-water levels drop.

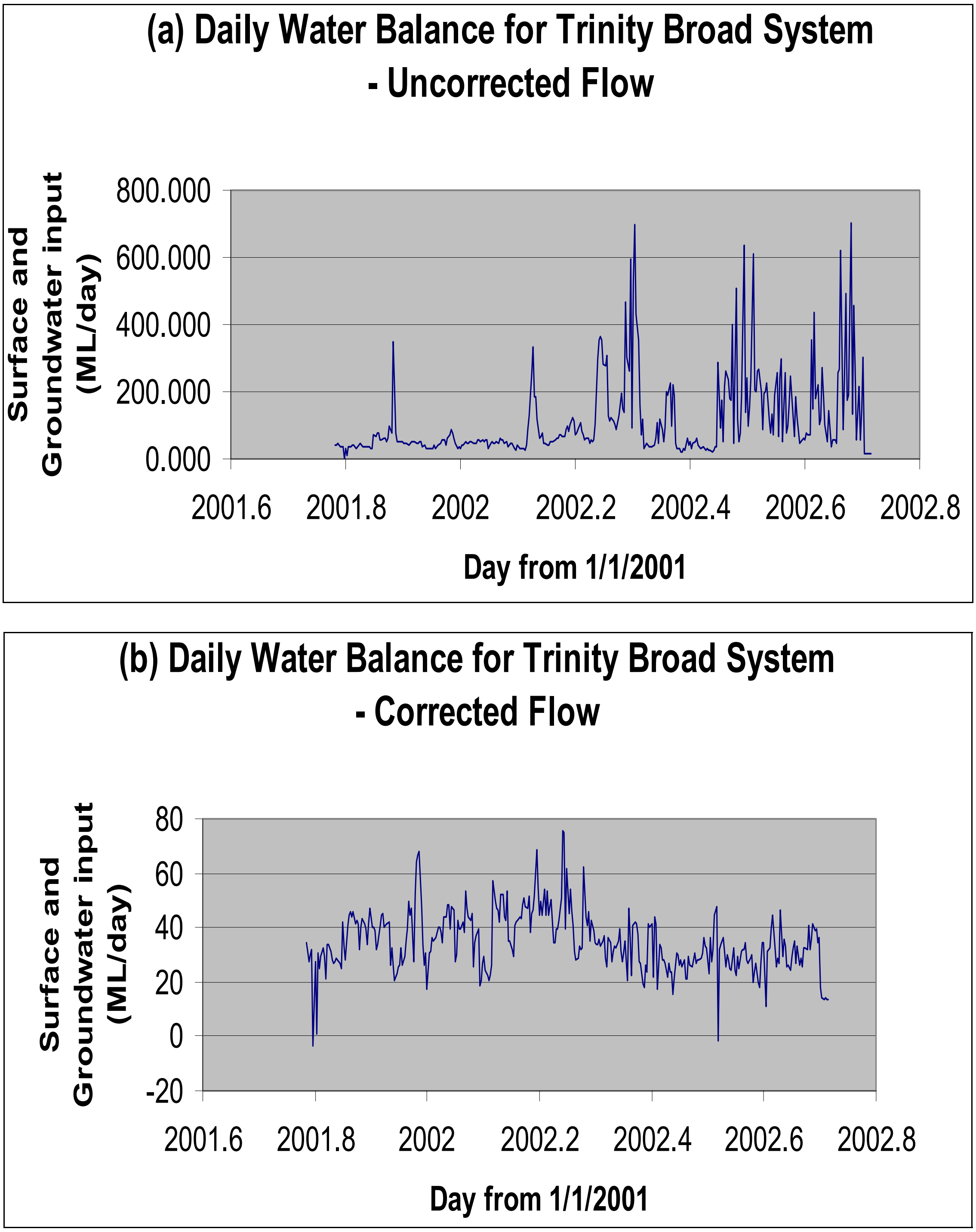


Figure 12 Combined surface and groundwater inputs to the Trinity Broads water resource system inferred from a daily water balance using (a) raw flow data from the Muck Fleet sluice, and (b) corrected flow data.

The estimates of groundwater discharge (which include a small amount of surface water) into (and out of) the whole Broad system are shown in Figures 12a and 12b. From the initial analysis it is clear there are major problems to be overcome with many of the data streams, and particularly flow, before the model will become useable in terms of water resource assessment.

The analysis using corrected flow data (Figure 12b) appears to be realistic (the average fluxes are of the correct order of magnitude, the flows are logical in terms of accretion along the Broad system and the seasonal pattern reflects the influence of winter groundwater recharge to suggest that the corrections adopted are probably appropriate). The estimates of groundwater and surface water inputs are orders of magnitude lower than the uncorrected flow data. Furthermore, allowing for some noise caused by remaining problems with the flow data, the groundwater inputs are relatively consistent from day to day, as might be expected from flows driven by relatively invariant hydraulic gradients. The existence of a seasonally high groundwater flow during February to March 2002 is also consistent with the normal recharge processes which tend to give highest groundwater levels and., therefore, highest hydraulic gradients at that time of year. Further evidence is given by the chemistry variations in the Broads in which concentrations of calcium, bicarbonate, nitrate and sulphate increase in the winter months reflecting the greater input of groundwater into the Broads during these months.

4 Interim Conclusions and Recommendations

An initial attempt at populating the conceptual water balance model for the Trinity Broad system has proved useful, but so far mainly in highlighting the shortcomings in the data and indicating where improvements could be made. The available datasets on rainfall, open water evaporation and changes in storage in the Broads are not perfect, and should also be improved, but are unlikely to be the source of large errors. On the other hand, the surface flows from the Broads are totally reliant on the Starflow data. It is these errors that are the major cause for concern as a reason for the poor estimation of groundwater flows into, and (as can be seen from Figure 12) occasionally out of the Broads.

The flow data are clearly inadequate in their present form. It is recommended that the following courses of action are taken over the coming years to improve the situation.

- Data collection from the Starflows should be continued to give at least two and preferably three years data
- The Starflow at Rollesby Bridge should be reset to compensate for the 2 m jump in recorded water depth (Streamline Measurements Ltd. have now replaced this unit).
- Further discussions should be held with Streamline to investigate the settings of the Starflow equipment and define how velocity and flow are measured or calculated. It is particularly important to define how the units are currently sampling, averaging and recording velocities and, therefore, to assess whether the post-collection correction methods adopted here are valid. It may be necessary to re-program the loggers at sites where erroneous values and/or excess variability in velocity are being recorded, and if so this should be done as soon as possible to prevent further data loss.
- Further manual gaugings should be carried out using current meters to determine how well the Starflow represents mean velocity and flow at each of the sites over a wide range of flow and turbidity conditions
- Assessment of manual level data and water depths given by the Starflow transducers should be undertaken and corrections defined where necessary.
- Post-processing of the velocity data should be undertaken to incorporate a better cross-sectional area depth relationship in the flow calculation.

Once these objectives have been achieved and at least a further year’s data collected, the daily model should be run again with the aim of estimating the contribution to the Trinity resource of groundwater inputs to all three Broads, but especially Rollesby and Filby, which are believed to be in more obvious hydraulic contact with the groundwater system than Ormesby. At the same time there should be further investigation of the surface water inputs to the Broads. These are not currently believed to be important, but there is currently little evidence to back up this assertion. If any significant inputs are found, flow gaugings should be carried out to determine their volumetric importance.

Using filtered flow data the daily model is now in a position to give estimates of groundwater discharge (and occasionally bank recharge) to the open-water system. Along with the evidence that flow rarely, if ever, ceases along the Muck Fleet, this indicates that the groundwater resources in the Trinity catchment are capable of replenishing the system to compensate for abstraction while ensuring a good environmental flow through the system. At present however this can only be stated for the recent period over which flow data are available, and there has been no recent experience of drought conditions.

The exact source of this groundwater is postulated as bank discharge in Rollesby and Filby Broad where it is in better hydraulic contact with the Crag. However, this can only be ascertained with any degree of certainty by establishing the water balances of the individual Broads. The next phase of modelling will then be to investigate this inferred groundwater input in terms of whether a realistic groundwater model of the Broad system can be set up and optimised. In the first instance this could take the form of a simple strip model, incorporating single values of hydraulic gradient and conductivities, but it could eventually be improved by the use of existing two dimensional groundwater models such as MODFLOW. An interim approach may be a strip model that can use the more intensive piezometry along Court Road to determine inflow to Rollesby Broad. This could be extrapolated to cover the whole length of bank contact between the Crag aquifer and the Broad system. Parameterisation of this model would allow the running of scenarios of change, such as climate change impacts on catchment rainfall, evaporation and hence recharge, and would also define the limits of abstraction, especially in drought periods.

The existence of diurnal variations in flow also suggests that the daily accounting for the water balance model may be hiding within-day stresses on the system caused by the combined effect of evaporation and abstraction during daylight hours. It is recommended, therefore, that in a further phase of the project the daily model be augmented by application of an hourly model. Flow data are available to populate this, and the other data sets could be augmented, improved or disaggregated to provide the requisite hourly figures.

5 References

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