Suffolk Sandlings Managed Aquifer Recharge Trial Report

P Bradford MSc. MCIWEM, C.WEM

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Summary

The Sandlings managed aquifer recharge (MAR) trial aimed to establish whether overhead spray irrigation is an economically viable, effective and environmentally safe way to recharge (top up) the Suffolk Crag aquifer for subsequent re-abstraction or environmental gain. The trial proposed to apply 20,000m^3 of water abstracted from a nearby watercourse to an agricultural field at Broxtead, Suffolk (NGR. TM 331 468) during the winter recharge season. Groundwater levels were monitored during the trial along with the water content of the soil profile, soil health and crop performance.

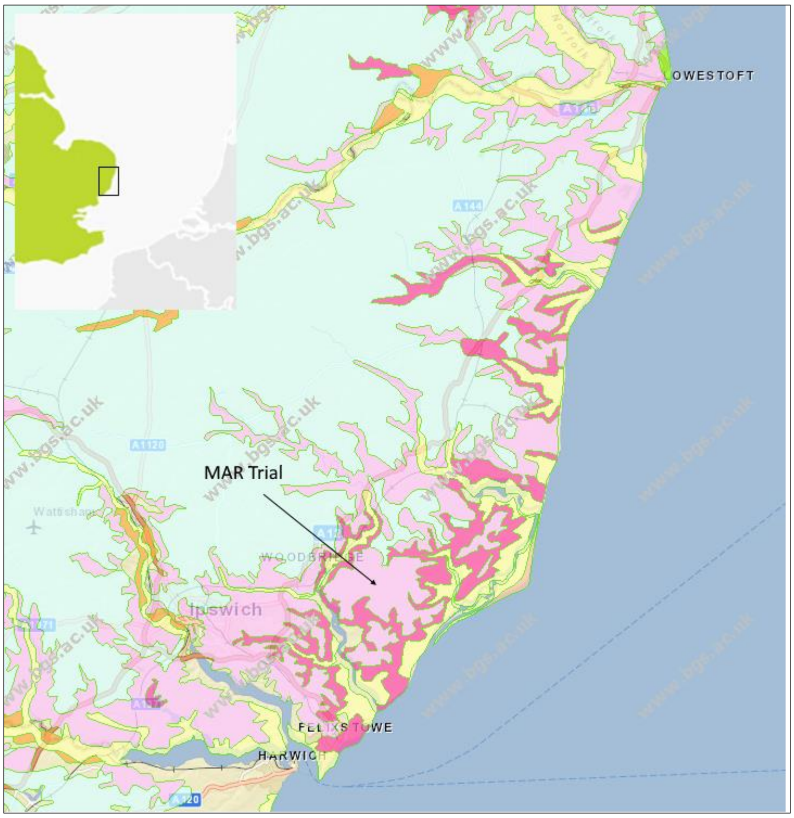


Figure 1. MAR trial site and location of Suffolk Crag aquifer in Pink

In practice, extended drought conditions between 2017 and 2018 meant that it was not possible to take water from the intended watercourse and an alternative groundwater source was found to enable the trial to take place in February 2019. Over a period of six weeks, 192mm (11,900m^3) of water was applied onto a 6 ha recharge field using overhead spray irrigation. Following each irrigation cycle, a wetting front was observed moving through the surface 1.2m and into the aquifer below although this became increasingly attenuated with depth. No damage to soils or runoff was seen and nutrient leaching was found to be within acceptable bounds.

Overhead winter irrigation was found to provide an effective method of inducing infiltration whilst minimising the risk of introducing contaminants into the aquifer. The high variable costs associated with irrigation, however, make this method of water storage comparable in cost, at about £0.35/m^3, to that of traditional agricultural reservoirs. Overhead irrigation has the further disadvantages of requiring skilled labour during the quiet winter months and being subject to the vagaries of the weather including frosts, high winds and rainfall.

Continued exploration of low cost, low risk, unconfined aquifer recharge and storage is needed to help tackle water shortages in the area which will become more acute with climate change. Further areas for investigation include the use of alternative, lower cost MAR application methods such as recharge trenches and the application of significantly larger, commercially useful volumes of water.

Regulatory concerns, particularly regarding water quality, pose significant challenges. Further work is required to develop effective processes to minimise regulatory burdens whilst ensuring full protection of our groundwater resources and the water environment.

Project Topsoil

The Sandlings MAR (managed aquifer recharge) trial was carried out as part of project Topsoil, an European Regional Development Fund, Interreg, North Sea Region initiative to investigate climate adaptation challenges related to topsoil and groundwater shared across the countries bordering the North Sea.

The project addresses the following five challenges:

1. Groundwater flooding in towns and agricultural areas.
2. Saltwater intrusion into freshwater reserves.
3. The need for a groundwater buffer to store excess rain water for later use.
4. Better management of soil conditions, to strengthen the resilience to extreme rain events and improve water quality.
5. An unused capacity to break down nutrients and hazardous pollutants in the uppermost layers

The Sandlings MAR trial focussed on challenge 3, using groundwater to store excess rainfall.

Agri-Climatic Context

The East Suffolk area is characterised by light sandy soils overlying a shallow, unconfined Crag aquifer.

The unique soils and agri-climatic characteristics of the area make it ideal for high value, irrigated vegetable crops. The demand for irrigation water has grown in the area at about 3.4% per year for the past 15 years (Bradford 2014). This growth is expected to continue to grow by as much 162 % over the next 50 years (Knox et al 2013) as irrigated production intensifies and summer soil moisture deficits increase as a result of climate change.

Water abstraction is regulated by the Environment Agency (EA). The EA has calculated that, as a result of historic over licensing of ground water, many rivers and streams in East Suffolk are at risk of failing to reach the required water framework directive WFD standards. As a consequence, the abstraction licensing strategy for the area is to reduce existing groundwater and unconstrained summer surface water abstractions. Licences for new abstractions are considered but only for water from rivers and streams when taken at periods of high flow.

Farmers who require additional water to grow high value vegetables must therefore take high-flow water during the winter and store it for use later in the year. The only storage method currently in use is lined reservoirs. All new irrigation licences issued in East Suffolk since the early 1990s have been to fill winter storage reservoirs which now make up 20% of all agricultural abstraction in the area.

Agricultural reservoirs have a number of disadvantages. They are expensive in terms of cost, resources and land take. The steep banks and impermeable liners give them little potential for environmental value and they can detract from natural landscape features. Water held in reservoirs is subject to contamination, algal blooms and evaporation.

A potential alternative to reservoir storage is MAR which involves modifying the water cycle to increase the amount of water that enters the aquifer. This water can subsequently be re-abstracted at a later date without a net loss to the natural resource. Alternatively, a proportion can be left in the aquifer to support flows in nearby rivers or streams.

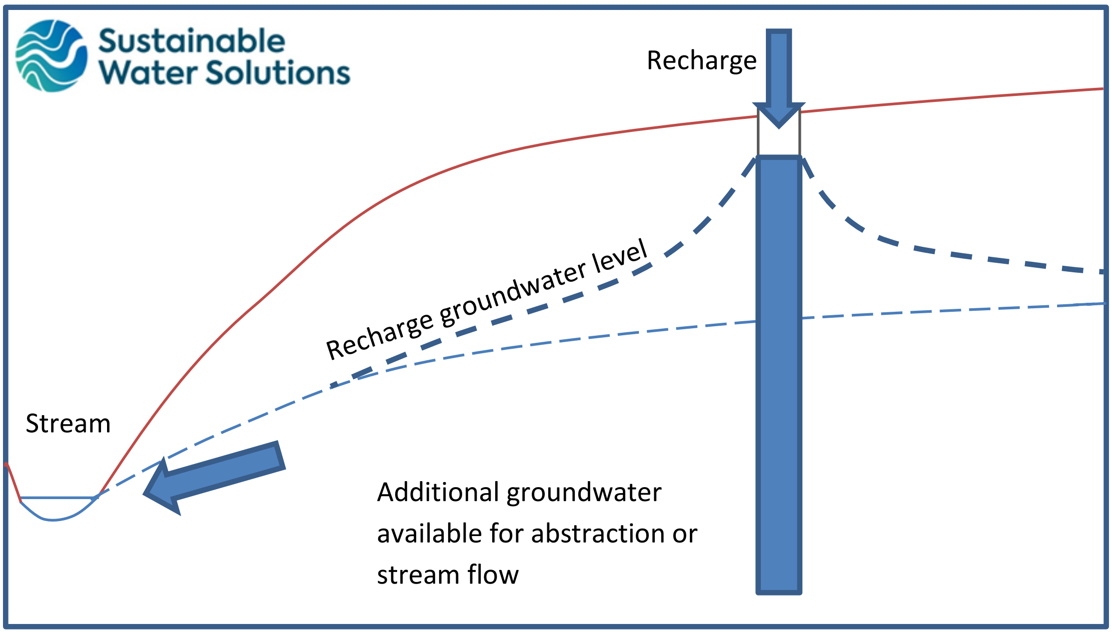


Figure 2. MAR Schematic

Review of Existing MAR Schemes

MAR is increasingly being adopted in areas of high water demand and low supply both in the UK and across the world. In the UK for example, MAR currently contributes 185 Ml/d to the public water supply, mostly in the London, Thames Water area, equivalent to 4% of the national groundwater supply. Several other public water supply companies including; Wessex Water, Severn Trent Water and Anglian Water have investigated similar recharge schemes with capacities ranging from a 1-2 Ml/d to 30Ml/d. One of the major barriers to these schemes is the cost of treating water to potable standards, both before it is injected into the aquifer and again, after it is recovered for public water supply.

Agricultural MAR is less common in the UK, with only one recorded scheme operating in the Spilsby Sandstone during the early 2000's. Unlike the proposed Sandlings trial which uses surface application of water to a shallow unconfined aquifer, all of the existing UK recharge schemes rely on the injection of water via boreholes into confined aquifers.

Across Europe, Sprenger et al (2017) identified 224 active MAR sites. The majority of these (57%)are river bank 'induced infiltration' schemes designed to take advantage of natural treatment processes occurring as water migrates through the hyporheic zone. 33% of schemes rely on surface spreading and the remainder use direct well injection. Surface spreading encompasses a wide range of techniques including, in-river channel modifications, basin flooding and trench recharge. Only three of the schemes identified used spray or sprinkler systems to deliver the water. These were located primarily in forested areas of Nordic countries. The reason sprinkler systems were favoured here was to avoid the risk of creating anoxic conditions and mobilising redox sensitive compounds within the aquifer and to minimise land and ecological disturbance.

MAR is increasingly used in the shallow coastal aquifers of the Netherlands Belgium and Germany to displace native saline water with fresh water for potable or agricultural use. Zuurbier, K, 2017 for example, reports on the successful completion of a MAR scheme to inject of up to 200ML of treated effluent to displace native saline water in the coastal dunes at Dinteloord, Netherlands. The scheme achieved an 85% recovery rate at a cost of approximately 0.4euro/m3 as opposed to 1.0 euro/m3 for above ground, lined storage.

The potential advantages of MAR over reservoir storage include:

- Lower capital costs
- Reduced land take
- Potential to use the aquifer as a transport system allowing abstractors to share or trade resources (commonly referred to as Aquifer Storage Transfer and Recharge –ASTR)
- Negligible evaporative losses
- Protection of stored water from anthropomorphic and animal contamination and algal blooms
- Elimination of risk to humans and animals from drowning
- Preservation of landscape features and archaeology
- Potential to supplement natural spring and river flows

A number of agri-climatic, hydrological and hydrogeological conditions are required to support surface application recharge for agricultural re-abstraction, including:

- Availability of Source Water
    - Proximity of high flow source water. Good quality water is preferred to minimise contamination risks and pre-treatment requirements.

- Suitable Hydrogeology
    - Unconfined aquifer, ideally unconsolidated intergranular flow dominated with high storativity and low hydraulic conductivity and a significant depth of unsaturated zone for storage.
    - Significant interfluvial areas away from discharge zones; springs and rivers etc.
    - Freely draining soils/surface deposits
- Economic (Water Demand)
    - Proximity to areas of intensive irrigated agriculture or where agri-climatic conditions are suitable for irrigated crop production but existing water resources are limited.

The Suffolk Crag lends itself to MAR using the surface application of water. It is a locally important minor aquifer which provides sufficient yields to supply numerous existing irrigation schemes and domestic properties. The aquifer is overlain by a thin layer of permeable soils which allow recharge to percolate through the upper layers. It is unconsolidated and granular, providing favourable water retention and flow properties. Over much of its extent it has a reasonably deep unsaturated layer and it also has a high storage coefficient of between 0.11 and 0.61 (Jones et al 2000). It is also transected by multiple rivers and streams which under normal conditions can provide a source of recharge water during high flow periods in the winter.

Risks and Regulation

Water Quality

Environmental risks associated with MAR fall broadly into two categories; water quality and water resource management. These are managed by the EA through a system of regulatory controls. Of primary concern to the regulator is the risk of introducing contaminants (particularly pesticides and other persistent organic compounds) into the aquifer. Once in the aquifer, these can take many years to breakdown, disperse or discharge.

Discharges to groundwaters are controlled under the Environmental Permitting Regulations 2010 which incorporate the requirements of the Groundwater Directives and Water Framework Directives. The rules for operators who intend to make a groundwater discharge are set out in Environmental Permitting Guidance –Groundwater Activities EA 2010. This makes a distinction between 'direct' and 'indirect' discharges. A discharge is considered to be 'indirect' where percolation occurs via a 'tortuous' unsaturated zone between the surface and the saturated zone. Indirect discharges to groundwater are generally acceptable whereas direct discharges are not.

Spray irrigation was selected an appropriate means of applying water during the trial because it is consistent with the EA's definition of an indirect discharge, it maximises the potential for soil/water interactions including dilution, adsorption and attenuation and it is a technique which is familiar both to farmers and the EA. It also requires minimal disruption to land and ecology.

A 'groundwater risk assessment' was submitted to the EA prior to the trial, identifying both the risks and mitigation measures associated with the proposal. Due to the multiple mitigating factors and the low level of risk, the EA deemed that the trial was 'not a regulated activity' and it was therefore exempt from the groundwater regulations.

Mitigation included the following measures:

- Source Water
  - Low volumes, derived from an agricultural catchment with no known historical water quality issues.
  - Daily monitoring of basic quality parameters.
- Application Method (spray irrigation) allowing:
  - Oxygenation of potentially reducing elements and dispersal of volatiles and
  - Distribution across a wide area allowing maximum attenuation and dilutions and interaction with soils and biological processes.
- Receiving Aquifer
  - Deep unsaturated zone (11m) with intergranular flow allowing continued ground based treatment of potential contaminants.

It is unlikely that full scale scheme using commercially useful recharge volumes would have benefitted from the 'non regulated activity' exemption.

An additional risk associated with surface application for MAR is runoff generated from saturated recharge fields. This can carry sediment and associated nutrients into water courses, damaging their ecology and morphology. The trial site was selected to minimise the risk of runoff due to its level topography, distance from surface water features and high infiltration rates. Application rates were designed to remain within the infiltration capacity of the site.

Water Resource Management

Both the abstraction the source water and re-abstraction of the stored groundwater falls within the regulatory scope of the Water Resources Act 1991.

In water stressed areas like East Suffolk it is important that the 'recovery' part of MAR only takes water that has been added to the aquifer through managed recharge, leaving 'native' groundwater untouched. The scope of the trial did not cover MAR recovery so re-abstraction was not a regulatory consideration. A detailed analysis would, however, be required to satisfy regulatory concerns prior to any proposal to recover MAR water.

Discussions with the EA identified both the Hollesly Black Ditch and Shottisham Stream as likely candidates for source water. Both watercourses have existing abstraction licences for reservoir storage which were identified as being suitable for amendment for the MAR trial. Following 'exceptionally low' winter rainfall during both 2017 and the autumn of 2018, however, the EA advised that abstraction from these sources was unlikely to be sufficiently reliable. An alternative licensed groundwater abstraction at NGR TM 311 468 was identified as a potential source with the volume of water used for the trial taken off the licence holder's annual allocation.

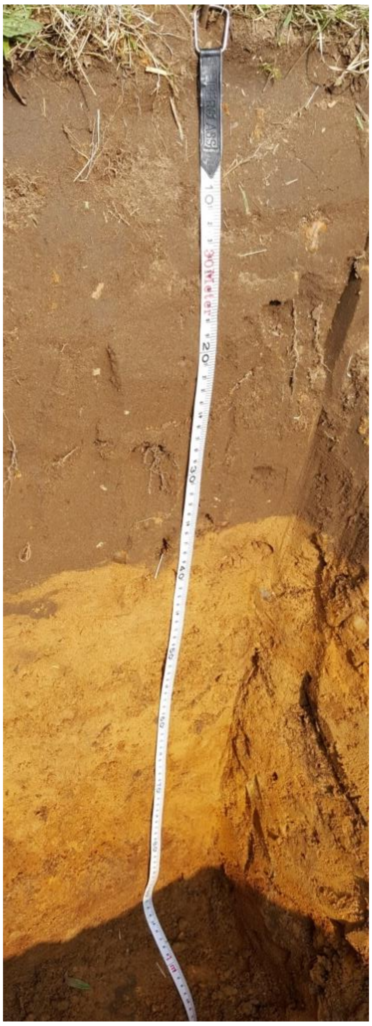
Because the trial was limited to investigating groundwater behaviour the EA was able to authorise the abstraction under a Groundwater Investigation Consent as opposed to a more onerous abstraction licence.

Risks to Landowner
In addition to the financial outlay, land based MAR potentially disrupts cropping rotations and draws skilled labour away from core farming activities. Irrigating crops is skilled work requiring precise calculations, long hours, and hard physical labour. The irrigation season is generally limited to the summer months. Extending it into the darker and less hospitable winter months is likely to adversely affect morale and prove unpopular with permanent staff.

Winter irrigation also has the potential to damage soils both though physical processes including; runoff, capping and compaction and chemical processes including; nutrient leaching and the creation of anoxic conditions, all of which have an adverse effect on subsequent crop growth.

Hydrological Characterisation of the Trial Site.

The aquifer at the trial site is formed of Kesgrave Sands and Gravels (fluvial) overlying Red Crag (marine) forming a continuous aquifer of between 20m to 25m depth. It is underlain by impermeable London Clay and Chalk with little hydraulic connection between the Chalk and Crag. In the river valleys, the Crag has been partially eroded.



The aquifer is highly variable and exhibits strong vertical anisotropy with discontinuous layers of sediments laid down during its formation including; sands, silts, clays and gravels. Cementation is common with discontinuous lenses of hard ferruginous material occurring in the weathered zone. Drillers logs for the two piezometers constructed at the trial site showed different lithologies despite being only 40m apart. Although, silty sands predominated in both in the first 8 m below ground level (bgl) one borehole had a band of coarse gravels at 1m below ground level which was entirely absent in the other. Nearby BGS[1] borehole logs describe ironstone bands (BGS TM34 NW/19) and layers of flint and quartz pebbles (BGS TM34 NW/13).

Values of transmissivity vary widely, ranging from 1.75 m^2/d to 4,231m^2/d but with a mean value of 605 m^2/d. Vertical permeability is strongly influenced by the presence of low permeability horizontal layers. Storage coefficients vary between 0.004 and 0.11 with some reports estimating it to be as high as 0.61 in localised areas. Pumping test results at nearby boreholes indicate that storage coefficients of 0.11 or greater are likely to be representative of conditions at the trial site. (Jones et al 2000).

Groundwater is encountered at about 11 m below ground level. In the six months prior to the test water levels at Gobblecock Cottage displayed a continuous decline from about 10.76 m bgl in August

[1] British Geological Society

2018 to 10.86 m bgl in February 2019 with no recharge being apparent in the months preceding the trial. This lack of recharge is consistent with the ‘notably low’ levels of rainfall recorded during the 2018/19 winter.

The site is located at an interfluve some 1.25km from the headwaters of the nearest watercourse, the Hollesley Black Ditch. Under normal conditions groundwater movement would be assumed to follow topographical contours flowing east towards the Black Ditch and also north east towards the River Tang.

Trial pits dug at two locations on the site show a clear definition at about 350mm below the surface between the organic rich topsoil and the underlying Kesgrave Sands and Gravels. Small lenses of sandy clay were encountered at about 600mm bgl and a ferruginous hard pan was identified at 1100mm bgl.

Twin ring infiltrometer tests carried out on the site by Sebastianpillai 2017 produced an average infiltration rate of 120mm/hr with figures varying from 72mm/hr to 227mm/h. It is possible that, because the field had been cultivated shortly beforehand, these results were artificially high. This would be consistent with the more locally representative infiltration rate of 59 mm/hr found by Lonsdale 2018, using Buildings Research Establishment (BRE) compliant testing methods at a nearby development site with similar lithology.

Water Quality Characteristics

Routine EA groundwater quality samples taken from the Crag aquifer between 2006 and 2016 at Shottisham Hall, (NGR. TM317 436) and at Bromswell, (NGR. TM304 515) show average concentrations of Nitrate (NO_3) to be 23.9mg/l and 26.1mg/l respectively. Although higher than expected of native Crag groundwater, this is below the UK TAG water quality standard of 37.5 mg/l. Other determinands were found to be within Drinking Water Inspectorate (DWI) regulatory limits.

Water quality data for the potential source watercourses is contradictory. ‘Citizen science’ sampling, arranged by the Essex and Suffolk Rivers trust between September and December 2017, recorded an average concentration of 34.5 mg/l NO_3 in the Hollesley Black Ditch and 95 mg/l NO_3 in the Shottisham Steam. The lower levels found in the Black Ditch mean that this watercourse could be potentially acceptable as a recharge source, however, the elevated NO_3 levels in the Shottisham Stream, would be of concern, potentially requiring further investigation into screening or treatment processes prior to recharge or alternatively making this watercourse unsuitable as a source.

The NO_3 concentrations in the Black Ditch are largely consistent with those reported by Sebastiampillai 2017 who reviewed EA recorded water quality data for streams in the area, although she did report occasional significant peaks which were attributed to agricultural runoff.

Although potentially significant in a commercial scale recharge system, water quality considerations of did not affect the trial as recharge water was derived from the same aquifer as the receiving aquifer.

Trial Methodology

The trial was carried out on a 9ha, cultivated agricultural field on the Broxstead Estate which was selected due to its proximity to an irrigation main, its flat topography and distance from surface water features.

Recharge water was applied by overhead spray irrigation to approximately 6ha of the field with 3ha remaining unirrigated as a control area. A single raingun with an irrigation radius of 36m and a discharge rate of approximately 17 l/s was used to apply the water. This required three passes to cover the whole recharge field. Each pass took one working day (approximately 8 hours) which meant that the whole field could be covered every three days. Application rates started at 25mm per pass (450m3/d) which was increased to 35mm towards the end of the trial as it became clear that this depth of water could be accommodated without causing significant ponding or damage to soils.

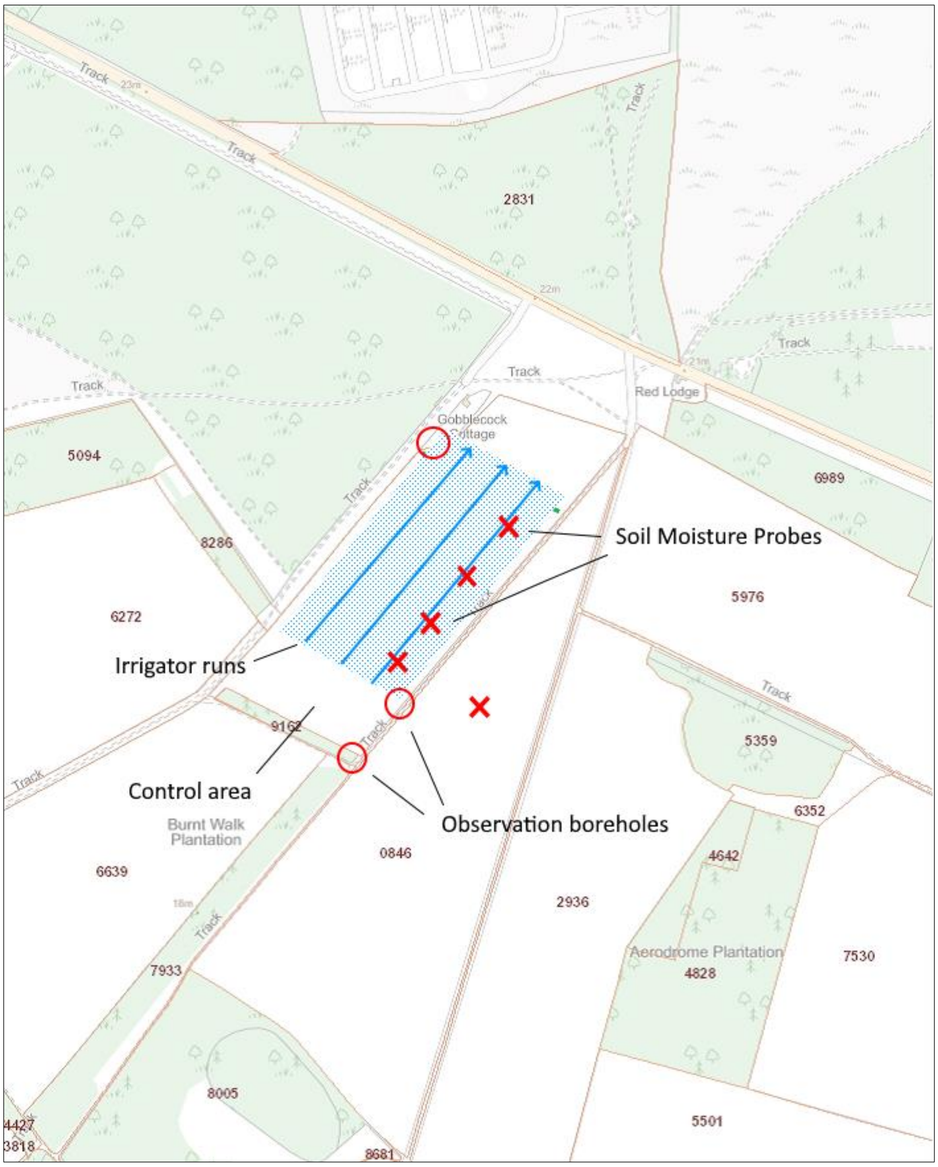


Figure 3. MAR trial site and methodology

Prior to the trial, in early October 2018, an overwinter rye crop was planted to provide surface cover. This had established a dense, low sward by the time the trial started in February 2019.

Figure 4. Rye crop coverage in February prior to the start of the trial.

Groundwater levels were logged at half hourly intervals during the trial using pressure transducers at three observation boreholes located adjacent to the recharge field and a further 'control' borehole located 750m to the south. The water content within the top 1.2m of the soil was monitored at 200mm intervals at four sites on the recharge field and in an additional 'control' site about 50 m away in an adjacent field using probes provided by Soil Moisture Sense.

Soil samples were taken and crop growth measured on the recharge area and control field during and after the trial to assess the impact of irrigated recharge on soil nutrient status and crop growth.

Site inspections were made on each day that irrigation was applied to ensure that surface runoff was avoided and soil damage was kept to a minimum.

Results

Application Rates

The aim of the trial was to apply 20,000m^3 of water at a rate of about 500m^3/d over a 40 day period. In practice, it was only possible to irrigate on 22 days with a total application volume of 11,900m^3 (see figure 5 below). Freezing conditions and high winds halted irrigation for seven days during the first month of the trial and time-critical farming operations (planting) took precedence halting irrigation for two weeks in the second month. The longest continuous period of recharge took place between 4 Feb and 26 Feb during which a total volume of 9,900m^3 was applied. During the trial, 58mm of rainfall was recorded, equivalent to a total volume of 3,480m^3 across the 6ha recharge field. Rainfall did not coincide with periods of irrigation.

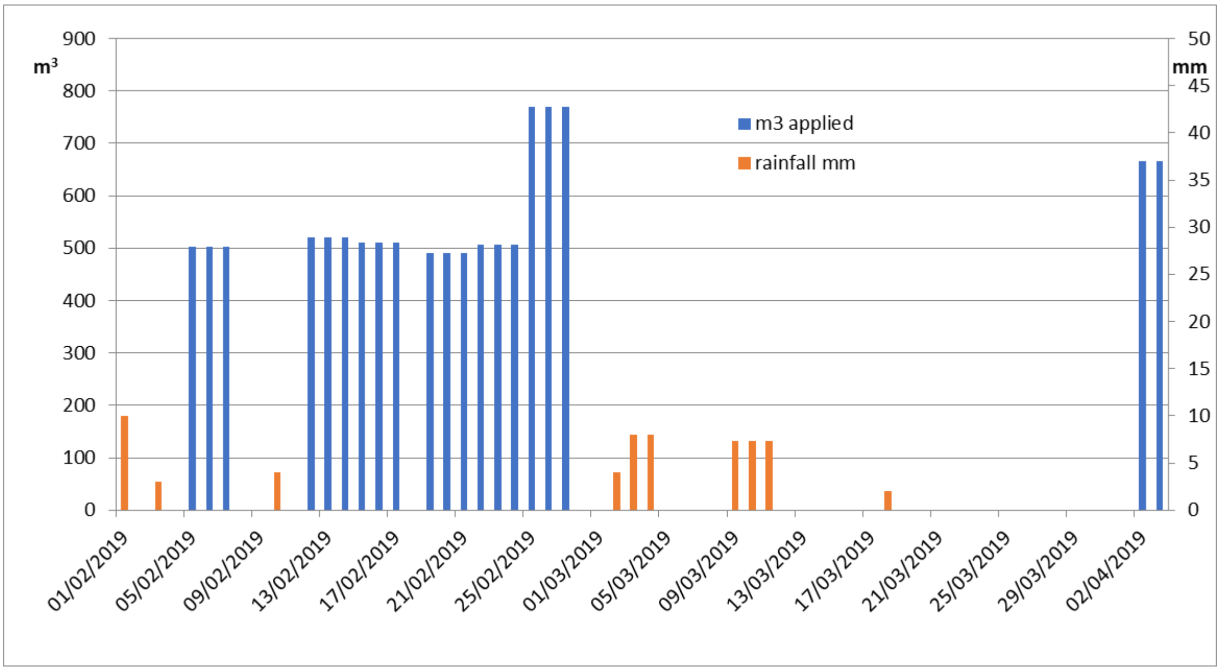


Figure 5. Plot showing recharge application rates

Soil moisture content

Soil moisture probes showed a clear response to irrigation at all depths from 150mm to 1.15m. Unsurprisingly, the shallow probes showed the fastest response with water content rapidly increasing by about 9% to 30% and then falling away to lose approximately half of the gained water content within 24 hours and returning to near baseline levels after 4 or 5 days. The response became increasingly attenuated with depth, with the deepest probe, at 1.15m below the surface, showing a peak increase in water content of only 3% approximately 4 hours later than the probe set at 150mm bgl.

Interestingly, the probes at all depths showed that the soil water content stayed above the pre-trial levels even after several days of drainage. This suggests that the soil throughout the 1.2m profile was below field capacity at the start of the trial. As a result, some of the applied water remained held within the soil structure even after several days of drainage.

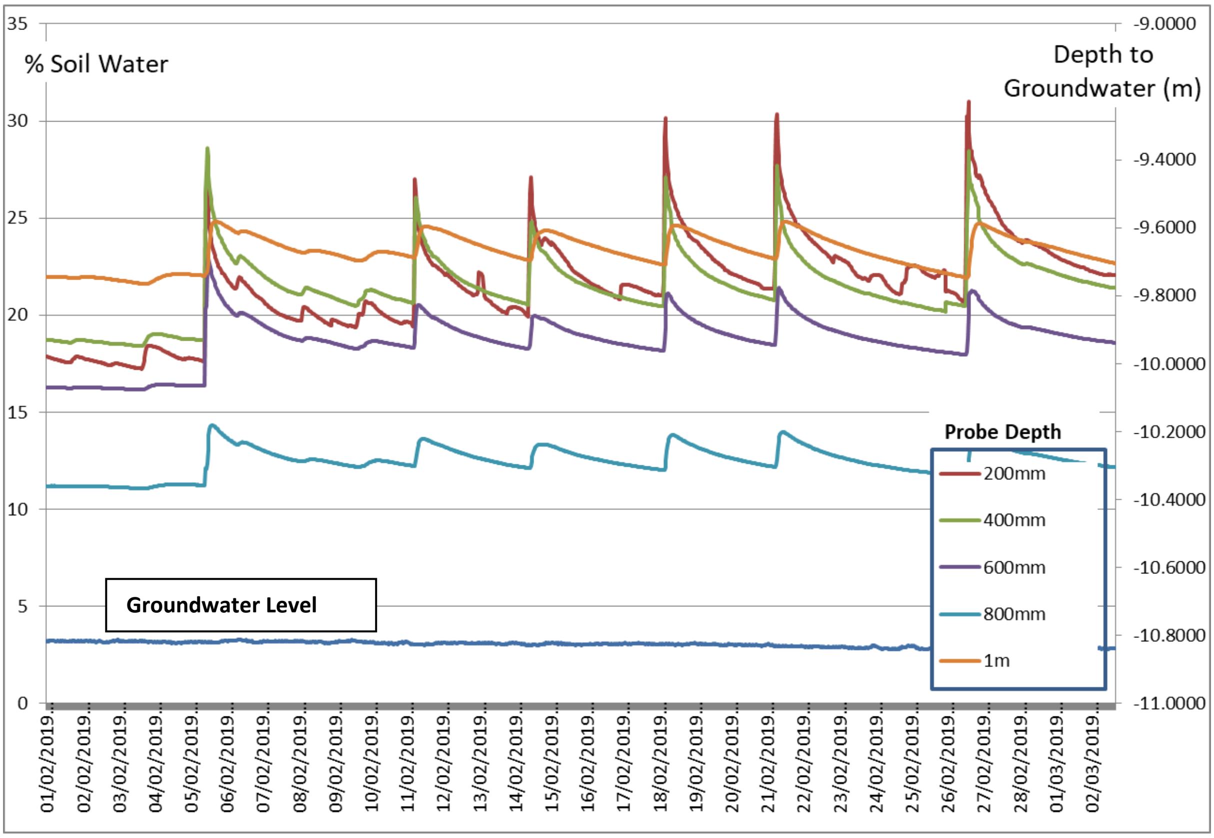


Figure 6. Soil moisture and groundwater levels.

Soil moisture probes are commonly used to identify crop water demand during the summer irrigation season. During these periods soil moisture plots show a distinctive daily stepped reduction profile reflecting daily losses through evapotranspiration (ET). Although this response is muted during the trial it is just visible in the 200mm plot suggesting that some ET losses are likely to have occurred during the trial.

Groundwater

Groundwater levels monitored at the Gobblecock Cottage observation borehole showed a continued recession for six months prior to the trial. This was a continuation of a long term trend which saw a decline in levels of 300mm from a highpoint of 11.2 mbgl in June 2017, to 10.8mbgl just before the trial. Unusually for the time of year, there was no sign of recharge occurring before the trial. During the trial, there was no observable response in groundwater levels to the recharge irrigation at any of the three observation boreholes adjacent to the recharge field. This was mirrored in the control observation borehole.

Soil Health

Visible signs of soil damage were limited to small areas of persistent surface ponding in the irrigator wheelings at the lowest part of site. This did not cause any runoff of surface water.

Figure 7. Recharge field showing ponding

Soil nutrient analysis was carried out on 25 Feb, towards the end of the trial by Natural England's Catchment Sensitive Farming (CSF) team (Appendix 1). The results, summarised in table 1, show that available N levels were lower in the irrigated area by between 7% and 21% but that there was little difference in P. This is unsurprising as nitrogen is highly mobile and potentially susceptible to leaching whilst P tends to remain bound to soil particles.

	Irrigated Area		Unirrigated control	
Depth (cm)	Available N (kg N/ha)	P (mg/l)	Available N (kg N/ha)	P (mg/l)
0-30	6.0	38.0	7.0	41.0
30-60	4.6	23.7	7.0	23.4
60-90	7.7	10.9	8.9	13.0

Table 1. Soil Nutrient Analysis

Crop Growth

The height of the rye crop was recorded on both the unirrigated and irrigated parts of the field on 8 April following the trial. Although the boundary between the irrigated and non-irrigated area is gradual, there appeared to be a strong positive correlation with crop height and the depth of irrigation water applied. It is possible however, that growth in the unirrigated area, which was close to a shelter belt, was suppressed by grazing deer and rabbits.

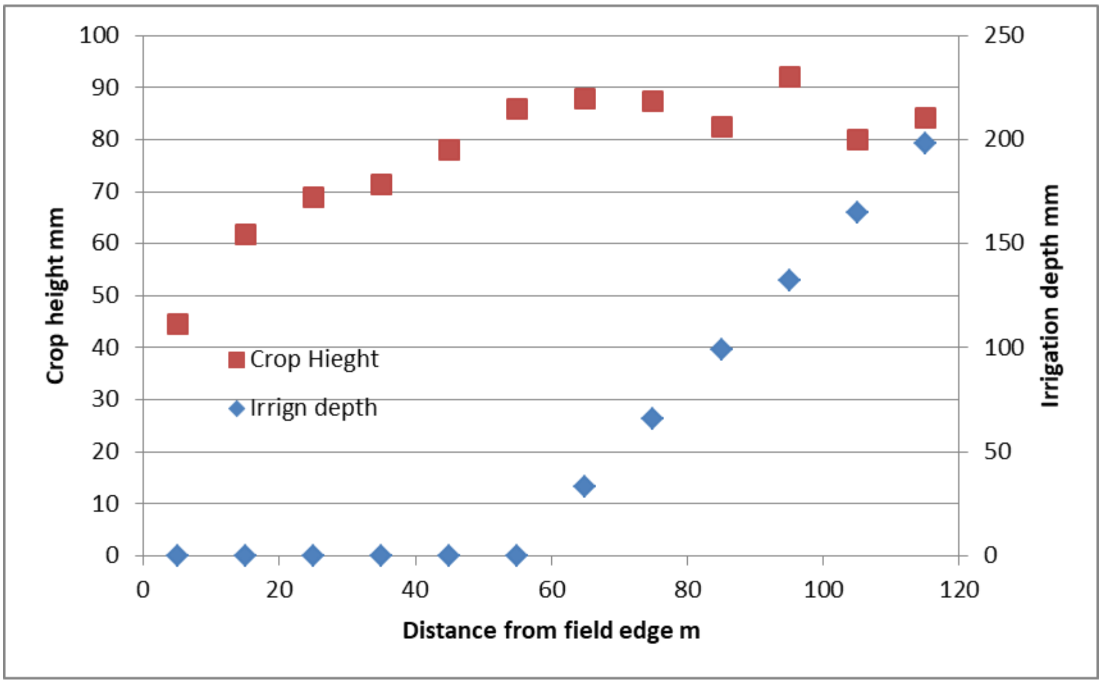


Figure 8. Plot showing crop growth and recharge irrigation depth

Discussion

Application Volumes

Abstraction licences for spray irrigation generally have a minimum volume of approximately 30,000 m^3/yr. This tends to be the threshold at which the cost of applying the irrigation exceeds the benefits.

Precautionary application rates were used during the trial to minimise the risk of soil damage and runoff. The lack of visible ponding, supported by soil nutrient analysis and the earlier infiltration tests suggest that the recharge field could have accepted water at higher instantaneous application rates and for a longer period. By extending the recharge period from November to February and increasing the irrigation depth to 35mm the total volume applied could have increased to 84,000m^3 without the need for additional irrigation equipment whilst maintaining the three day coverage cycle. This would be a commercially useful volume for most growers. Overhead irrigation therefore appears to be readily scalable method of inducing sufficient recharge to provide commercially useful volumes of water for farmers.

Although the trial results suggest that significantly greater volumes could be applied it is important to bear in mind that the trial took place in exceptionally dry conditions with only 57% of longterm average rainfall in the preceding six months. If the ground had been fully saturated as a result of heavy rainfall before or during the trial, recharge capacity would have been limited.

The recharge field was also carefully selected for its flat topography and absence of potential surface runoff routes. As a result, the small amount of surface ponding remained confined within the recharge field. If surface flow pathways had been present, it is likely that even the relatively low volumes applied would have resulted in surface water runoff.

Regulatory Processes

In the interests of allowing the trial to proceed, the EA took a risk based, 'light touch' approach to consents for both water quality and water resources. Although essential for the purposes of this trial, this meant the regulatory procedures required for a commercially useful MAR scheme were not fully explored.

The application of recharge water by irrigation allows a high degree of soil water interaction and therefore minimises the risk of aquifer contamination. Typical irrigation cycles like the one used for the trial create pulses of water which travelled through the soil profile and aquifer. This meant that an unsaturated zone is always maintained minimising the risk of creating reducing conditions and mobilising redox sensitive contaminants.

The method also satisfies the EAs water quality regulatory position regarding the indirect discharge of water/effluent to aquifers. The citizen science water quality sampling programme however, identified elevated levels of nitrate in the target source waters and it is possible that other less readily detectable contaminants were present at unacceptable levels. Further investigation is required to establish appropriate regulatory controls which would achieve an acceptable level of risk minimisation without imposing untenable regulatory burdens

Water resources regulations were also applied using a risk based approach. Mechanisms for regulating and levying charges for aquifer recharge and re-abstraction are not widely understood. There is a need to explore the abstraction licensing regulatory and charging framework to identify opportunities to incentivise abstractors to investigate MAR as a means of supplementing resources both for their own use and for other beneficiaries, including the environment.

Groundwater Recharge

The EA manages a distributed numerical groundwater model (NEAC) to assess groundwater fluxes in East Anglia. Although the EA initially offered to model the MAR trial, the volumes of water proposed were considered to be too small to provide a meaningful result. The model was however, used for the larger FRESH4Cs project in the same aquifer some 9.25km to the south west. This showed that recharge and re-abstraction at rates of 1,000m^3/d over 120 days (total cycle 120,000m^3) created groundwater head fluctuations ranging from 5m below normal groundwater levels at maximum abstraction to 4m above at peak recharge with a radius of influence of 1.75km. One month of recharge at 1,000m^3/d created a positive head of between 0.5m and 1m.

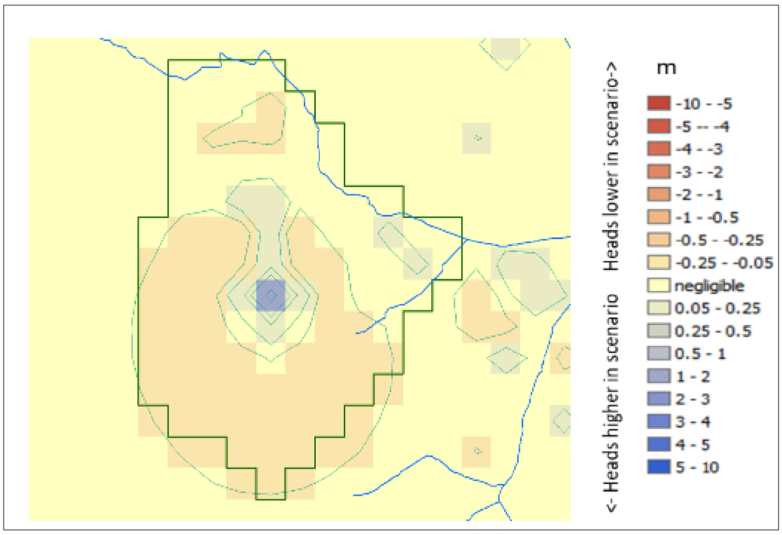


Figure 9. EA NEAC Crag model for FRESH4Cs, 30 days recharge at 1Ml/d

Backwards extrapolation of these results to a recharge volume of 9,900m^3 applied over 22 days indicates that groundwater levels at the trial site would increase by approximately 0.15m and 0.30m

The Cooper Jacob estimation (below) was also used to make a rough approximation of the potential effect of recharge on groundwater levels at the MAR site.

$$\boxed{s = \frac{2.3Q}{4\Pi T}\log\frac{2.25Tt}{r^2 S}}$$

Where:

s drawdown at r (m)

r radius at OB (150m)

T transmissivity of aquifer (m2/d)

t time from start of abstraction (days)

S storage coefficient

Q discharge 450m3/d

This equation is generally applied to estimate drawdown from point source abstractions so is not entirely appropriate for this situation. In addition to the normal assumptions of an isotropic fully penetrated aquifer the assessment makes the additional assumption that abstraction provides a mirror image of recharge impacts and that a single point abstraction can approximate wider recharge using the principle of superposition. A further major analytical flaw is that is cannot account for flow processes in the unsaturated zone.

Using a range of probable transmissivity values from 10 to 600m^2/d and Storativity values from 0.004 to 0.11, the Cooper Jacob estimation of drawdown at the boundary of the recharge field (150m) ranges between 0.2m and 0.5 m for the proposed 44 day 20,000m^3 trial and from 0.1m to 0.3m for the 22 day 9,900m^3 trial. This is close to the estimation produced by extrapolation of the FRESH4Cs groundwater model. In practice the recharge irrigation produced no observable response in groundwater levels.

The soil moisture data clearly shows a wetting front progressing through the upper layers of the aquifer at a rate of about 0.25m/hr following irrigation. This is clearly seen to a depth of 1.2m in the deepest probes. If this wetting front had continued to percolate through the 11m unsaturated zone at the same rate changes to the groundwater levels would have been expected within two days of the start of the trial.

The BGS Minor Aquifers Report (D Jones et al 2000) comments that vertical permeability is strongly affected by the presence of horizontal layers of silt clay and cemented ferruginous deposits. These will have intercepted water as it percolated through the unsaturated zone, both extending the hydraulic pathway and creating mini perched aquifers. This is supported by the discovery in the trial pits of lenses of sandy clay and a chemical hard pan. Soils immediately above the clay layer were found to be saturated.

The trial took place in February towards the end of the winter with the intention of taking advantage of normal recharge conditions including wet soils and low ET. The CEH Hydrological Summary for February 2019 http://nora.nerc.ac.uk/id/eprint/522526/1/HS_201902.pdf shows that the period preceding the trial was exceptionally dry with only 57% of long term average (LTA) rainfall in the January before the trial and 73% of the LTA in the preceding six months. This was mirrored by groundwater levels which were recorded as 'notably low'.

Soil moisture data shows that some of the water applied as recharge was retained within the soil profile. This suggests that some of the irrigation simply made up a pre-existing soil moisture deficit. It is likely that due to the long antecedent period of dry weather, the soil moisture deficit extended to a significant depth into the soil profile.

The stepped nature of the shallow soil moisture recession curve evident towards the end of the trial also suggests that some ET was taking place on warmer days. This is not unsurprising given that by the end of February the rye crop was well established with roots penetrating to at least 400 mm depth. Whilst most of the water clearly percolated through the upper layers of the aquifer, the combined effects of ET, retention and attenuation within the unsaturated zone are likely to explain why no response was seen in groundwater levels.

There appeared to be some minor leaching of nitrogen but no significant physical or chemical damage to the soil. The overwintering rye crop appeared to respond positively to the irrigation. This is unlikely to be as a result of increased water availability but may be a response to increased soil temperatures following the application of comparatively warm groundwater or potentially increased mineralisation and availability of nutrients. The stronger crop growth in the irrigated area away from the field edge could also be a function of reduced grazing by rabbits and deer.

Economic Analysis

Spray irrigation is a relatively inefficient and labour intensive means of applying water for MAR. Discharge rates are limited to the capacity of the irrigator and the infiltration rate of the recharge field and the process is subject to the vagaries of the weather. Recharge by irrigation also requires access to relatively large areas of suitable, high value farm land for several months during the winter which can interfere with cropping rotations.

There are potential negative impacts on staff. Field irrigation is an onerous process, particularly when it is dark, wet and cold. Farm staffing levels are at their lowest, during the winter and months so this work is unlikely to be shared by more than a few individuals. There are also health and safety implications associated with operating and moving irrigation equipment in the dark. The low staffing levels also mean that time sensitive operations such as planting take precedence over recharge irrigation.

These shortcomings were evidenced during the trial where, despite the best intentions of the landowner, irrigation took place on only half of the available days.

MAR using spray irrigation, is comparable in cost to reservoir storage. Based on a 20 year investment, a 100,000m^3/year resource using irrigation based recharge costs about £0.35/m^3 whilst traditional reservoir storage would cost about £0.29/m^3. A breakdown of comparative costs is summarised in table 2, below.

	MAR		**Reservoir**	
Variable Costs (for 100,000m^3)	£/m^3/yr	Annual cost per 100,000m^3 (£/yr)	£/m^3/yr	Annual cost per 100,000m^3 (£/yr)
Irrigation equipment and labour	£0.15	£15,000	£0.00	£0
Abstraction and pumping (source)	£0.15	£15,000	£0.15	£15,000
Total variable costs per year	**£0.30**	**£30,000**	**£0.15**	**£15,000**

	MAR		**Reservoir**	
Capital Costs (1,000m^3, spread across 20 years investment)	Capital £	Annual cost per 100,000m^3 (£/yr)	Capital £	Annual cost per 100,000m^3 (£/yr)
Power Supply and distribution pumps	£35,000	£1,750	£35,000	£1,750
Re-abstraction Borehole x 2	£70,000	£3,500	£0	£0
Lined reservoir	£0	£0	£242,000[i]	£12,100
Total Capital Cost (100,000m^3)	**£105,000**	**£5,250**	**£277,000**	**£13,850**
Annual Capital Cost £/m^3 (20 years)	**£0.05**		**£0.14**	

Table 2. Breakdown of capital and variable costs for irrigation based MAR and reservoir storage.

Net present value (NPV) cost calculations, taking account of the opportunity value of the capital invested at 3.5%/yr over the 20 year lifetime of the scheme, estimate the NPV cost of the reservoir to be £526,000 compared to £538,372 for MAR (appendix 2).

Significant elements of the MAR costs are variable annual labour and operational costs. Although landowners may regard these as a surplus resource in the winter, this is not the case. Skilled labour is often in short supply and working hours are restricted by available daylight. Irrigation systems, including pumps, and tractors are still subject to wear and tear and require fuel. The cost used in the analysis, £0.15/m^3 reflects the actual charge made by abstractors to supply the labour and equipment to provide irrigation in the East Suffok Catchment. The production boreholes required to re-abstract the stored water represent a significant additional cost for MAR. Complete with pumps and control equipment a Crag production bore typically costs in the region of £35,000. The relatively low transmissivity of the Crag aquifer means that at least two boreholes would be required to yield the 100,000m3/yr used for the analysis.. Iron and manganese precipitation, common in Crag boreholes, can mean that regular maintenance can be required at significant additional cost.

The analysis uses the assumption that all of the 100,000m3 is abstracted every year. This is unlikely to be the case as farmers will typically only use between 60% and 70% of their licence holding the full quantity back for use in exceptionally dry years. Variable costs are higher for MAR so the assumption that farmers will use the full quantity available overestimate these cost compared with reservoir storage. A more representative, 65% abstraction uptake makes the annual cost of MAR less expensive at £0.36/m^3 than traditional reservoir storage which would cost £0.41/m^3

The economic analysis for MAR and reservoir storage both use a 20 year investment profile. In practice, high capital investment items including irrigation reservoirs, power supplies and boreholes are likely to last longer than this reducing the annual estimated cost of the water.

Recommendations

Continued exploration of options for winter water storage are required to help tackle water shortages in summer months. These will become more acute as the climate changes and the demand for irrigation grows.

Whilst the use of spray irrigation for MAR minimises the risk of water quality issues, it is both labour and land intensive. Alternative, lower cost techniques for applying recharge water should be investigated. A suitable candidate is the use of recharge trenches or lagoons which require minimal operational input and much smaller areas of land. Although this technique would increase potential risks to water quality, the reduction in labour and land costs could make this form of recharge significantly more competitive.

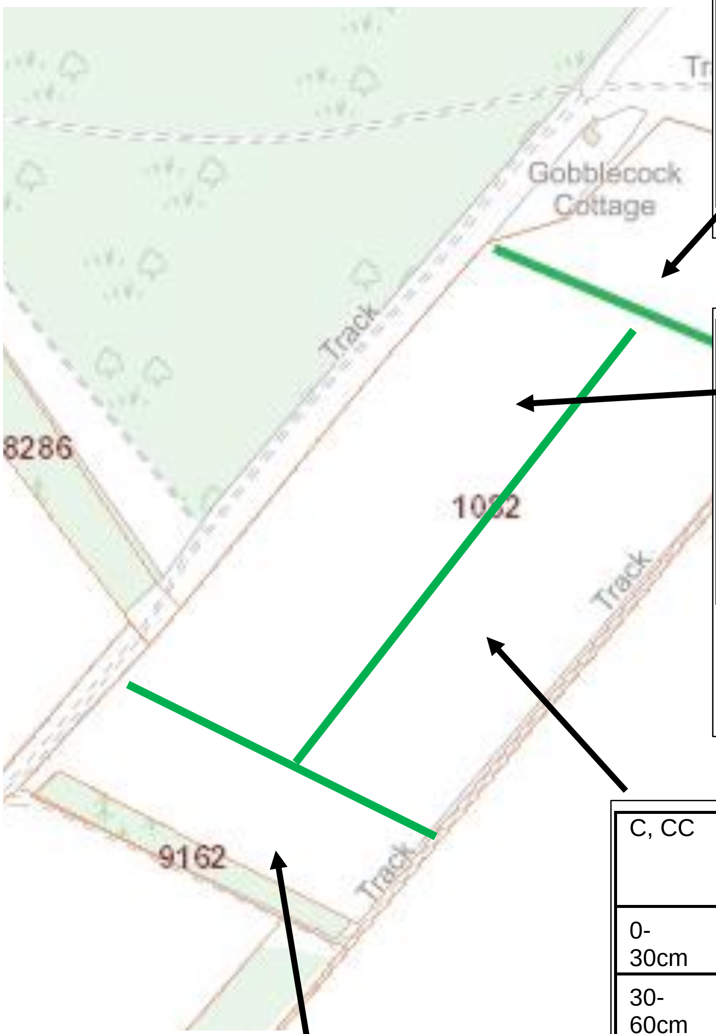
Although trench recharge potentially increases contamination risks, studies into natural treatment processes occurring during bankside infiltration suggest that there is significant potential for biological processes in the hyporheic zone to address water quality concerns. These can, however, create biofilms and gas bubbles which can have a significant adverse effect on infiltration rates. Further investigation into the potential treatment processes and mechanisms for maintaining high infiltration rates in recharge trenches is required.

Further trials incorporating both recharge and re-abstraction using commercially viable volumes of water (in the region of 50 Ml/yr or more) would provide a larger ‘recharge’ signal allowing a more detailed investigation of water transfer within the aquifer and, in particular, the multi-layered unsaturated zone. It would also demonstrate whether the technology could be adopted on a commercial basis.

The use of larger volumes of water would also require investigation into regulatory procedures including a review of the barriers and potential opportunities to incentivise water resource augmentation through MAR. The Environmental Permitting regime requires particular attention as it is likely to prove challenging to achieve a compromise between protecting groundwater quality and facilitating aquifer recharge from surface waters. In addition to testing the water resources and environmental permitting regimes the investigation of commercially viable schemes would require an assessment of the water resources charging scheme with the potential to identify financial incentives to adopt MAR.

The hydro-geological and agri-climatic conditions required for indirect MAR are reasonably well understood and GIS based layers representing many of these conditions already exist. A map identifying likely MAR opportunity areas would help regulators and potential developers formulate plans for further MAR schemes.

Appendix 1. Topsoil project – soil sampling results



A, AA	Nitrate N Mg/kg	Ammonium mg/kg	Available N Kg/N/ha	P index	P mg/l
0-30cm	1.38	3.41	18	2	24.4
30-60cm	0.69	1.26	7.3	2	19.4
60-90cm	0.06	1.03	4.1		

B, BB	Nitrate N Mg/kg	Ammonium mg/kg	Available N Kg/N/ha	P index	P mg/l
0-30cm	0.54	0.90	5.4	2	35.0
30-60cm	0.77	0.65	5.3	2	24
60-90cm	0.98	0.75	6.5	0	8.8

C, CC	Nitrate N Mg/kg	Ammonium mg/kg	Available N Kg/N/ha	P index	P mg/l
0-30cm	0.32	1.41	6.5	3	41.0
30-60cm	0.30	0.73	3.9	2	23.4
60-90cm	0.06	2.32	8.9	1	13

D, DD	Nitrate N mg/kg	Ammonium mg/kg	Available N Kg/N/ha	P index	P mg/l
0-30cm	0.29	1.58	7	3	40.2
30-60cm	1.35	0.52	7	2	17.8
60-90cm	0.96	1.49	9.2	0	8.0

Notes

Date samples taken: 25th February 2019 by Jo Hayward CSF and Paul Bradford.
A, B, C, D = Soil Mineral Nitrogen testing which includes: Nitrate N, Ammonium, Available N, Dry Matter.
AA, BB, CC, DD = sampled for pH, P mg/l, K mg/l, Mg mg/l. P, K, Mg index supplied in the results.
Five cores were taken from plot A/AA to form two samples.
Seven cores were taken from plot B/BB, C/CC, D/DD to form two samples from each plot.
Plot A/AA a lot of gravel beyond 60cm and difficult to take sample.
Plot D/DD a lot of gravel beyond 60cm, soil auger went to 85cm then hit gravel bed. It was not possible to get to 90cm on any of the seven cores.

Appendix 2. Reservoir and MAR Net Present Value Calculations

NPV @ 3.5% p.a.

APPRAISAL DATE:

OPTION NUMBER & TITLE: **Reservoir NPV**

YEAR :	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	TOTAL
CAPITAL COSTS (£ 000s): Add Row																						
Reservoir	242000																					242000
Planning	36300																					36300
Reservoir Act	12100																					12100
Consultant	7500																					7500
																						0
A. Total Capital Costs (Annual)	297900	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	297900
B. Total Capital Costs (Cumulative)	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	297900	
REVENUE COSTS (£ 000s): Add Row																						
Abstraction and pumping	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	315000
																						0
																						0
																						0
																						0
C. Total Revenue Costs (Annual)	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	315000
D. Total Revenue Costs (Cumulative)	15000	30000	45000	60000	75000	90000	105000	120000	135000	150000	165000	180000	195000	210000	225000	240000	255000	270000	285000	300000	315000	
E. Total Costs (Annual) (=A+C)	312900	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	612900
F. Total Costs (Cumulative) (=B+D)	312900	327900	342900	357900	372900	387900	402900	417900	432900	447900	462900	477900	492900	507900	522900	537900	552900	567900	582900	597900	612900	
BENEFITS (£ 000s): Add Row																						
																						0
																						0
																						0
G. Total Benefits (Annual)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H. Total Benefits (Cumulative)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
NET UNDISCOUNTED COST* (=E-G)	312900	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	612900
DISCOUNT FACTOR @ 3.5% p.a.	1.0000	0.9662	0.9335	0.9019	0.8714	0.8420	0.8135	0.7860	0.7594	0.7337	0.7089	0.6849	0.6618	0.6394	0.6178	0.5969	0.5767	0.5572	0.5384	0.5202	0.5026	
NET PRESENT COST* (Annual)	312900	14493	14003	13529	13072	12630	12203	11790	11391	11006	10634	10274	9927	9591	9267	8953	8651	8358	8075	7802	7538	526086
NET PRESENT COST* (Cumulative)	312900	327393	341395	354925	367996	380626	392828	404618	416009	427015	437649	447923	457850	467441	476708	485661	494312	502670	510745	518548	526086	
TOTAL NET PRESENT COST* =	526086																					

Reservoir costs are based on the average construction cost of 11 lined agricultural storage reservoirs constructed between 2010 and 2019. Provided by personal communication Andrew Hawes, Hawes Associates, Aldeburgh.

NPV @ 3.5% p.a.

APPRAISAL DATE:

OPTION NUMBER & TITLE: **Managed Aquifer Recharge NPV**

YEAR :	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15	Year 16	Year 17	Year 18	Year 19	Year 20	TOTAL
CAPITAL COSTS (£ 000s): Add Row																						
Power Supply and distribution pumps	25000																					25000
Abstraction boreholes	57000																					57000
Reservoir Act																						0
Consultant																						0
																						0
A. Total Capital Costs (Annual)	82000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82000
B. Total Capital Costs (Cumulative)	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	82000	
REVENUE COSTS (£ 000s): Add Row																						
Abstraction and pumping	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	315000
Labour and equipt	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	315000
																						0
																						0
																						0
C. Total Revenue Costs (Annual)	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	630000
D. Total Revenue Costs (Cumulative)	30000	60000	90000	120000	150000	180000	210000	240000	270000	300000	330000	360000	390000	420000	450000	480000	510000	540000	570000	600000	630000	
E. Total Costs (Annual) (=A+C)	112000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	712000
F. Total Costs (Cumulative) (=B+D)	112000	142000	172000	202000	232000	262000	292000	322000	352000	382000	412000	442000	472000	502000	532000	562000	592000	622000	652000	682000	712000	
BENEFITS (£ 000s): Add Row																						
																						0
																						0
																						0
G. Total Benefits (Annual)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
H. Total Benefits (Cumulative)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
NET UNDISCOUNTED COST* (=E-G)	112000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	30000	712000
DISCOUNT FACTOR @ 3.5% p.a.	1.0000	0.9662	0.9335	0.9019	0.8714	0.8420	0.8135	0.7860	0.7594	0.7337	0.7089	0.6849	0.6618	0.6394	0.6178	0.5969	0.5767	0.5572	0.5384	0.5202	0.5026	
NET PRESENT COST* (Annual)	112000	28986	28005	27058	26143	25259	24405	23580	22782	22012	21268	20548	19853	19182	18533	17907	17301	16716	16151	15605	15077	538372
NET PRESENT COST* (Cumulative)	112000	140986	168991	196049	222192	247452	271857	295436	318219	340231	361498	382047	401900	421082	439616	457522	474824	491540	507690	523295	538372	
TOTAL NET PRESENT COST* =	538372																					

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