HR Wallingford
Working with water

HRPP 404

Sustainability criteria for the design of stormwater drainage systems for the 21st century

R. Kellagher and H. Udale-Clarke

Reproduced from a paper presented at:
11th International Conference on Urban Drainage
Edinburgh, Scotland
31 August - 5 September 2008

SUSTAINABILITY CRITERIA FOR THE DESIGN OF STORMWATER DRAINAGE SYSTEMS FOR THE 21ST CENTURY

R. Kellagher[1] and H. Udale-Clarke[1]*

[1] *HR Wallingford Ltd., Howbery Park, Wallingford. Oxfordshire, OX10 8BA, England, UK*
**Corresponding author, e-mail h.udale-clarke@hrwallingford.co.uk*

KEY WORDS

Drainage, Hydraulic modelling, SUDS, Sustainability Indicators, Stormwater

ABSTRACT

This paper proposes a new approach to the design of stormwater drainage using sustainability indicators to provide a total measure of system performance rather than looking only at design criteria to meet a minimum level of service. This methodology can apply to all aspects of sustainability, but this paper focuses on indicators to measure the hydraulic performance and treatment effectiveness of stormwater drainage systems. The paper outlines the methodology, the relevance of the indicators and the tools developed. The paper then discusses the application of the methodology and results for the Elvetham Heath drainage system. This work was carried out as part of the EPSRC funded WaND (Water cycle management for New Developments) project, which completed in December 2007.

INTRODUCTION

A measure of sustainability requires an indicator that is a practical and measurable attribute that provides relevant information of the performance of the system. Indicators, therefore, need to be selected that most accurately and robustly measure the behaviour of the system such that an evaluation can be made as to how well the system meets the chosen criteria. There are many potential sustainability criteria for stormwater drainage; normally categorised under the three main headings of social, economic and environmental criteria. Current normal practice for the design of drainage systems requires:

- No external flooding for events up to a 1:30 year event;
- No internal flooding for events up to a 1:100 year event;
- Peak rate of discharge limited to the equivalent greenfield site or similar;

And more recently:

- A SUDS treatment train should be used.

These are largely anthropocentric and, except for the last, which has no effective design rules, all are applied using extreme event design storms.

The fundamental values behind these criteria are that:

- Society should have an adequate level of service that minimises inconvenience and disruption;
- The cost of flood damage to society should be limited (the standards providing an implicit optimum cost-benefit);
- That one group of people should not increase flood risk to those downstream; and lately that,
- The environment needs to be protected.

However, this approach effectively means that:

- The impact of 999 storms out of 1000 are of no consequence, and

- No measure of stormwater runoff impact is made.

DEVELOPMENT OF THE METHODOLOGY

The research looked at a number of areas of sustainability and defined indicators that might be applied as appropriate measures. However, it was felt that the most pressing area that needed to be addressed was the environmental impact of drainage systems, but ensuring social aspects were still addressed. With the introduction of the Water Framework Directive increased importance is being placed on the morphological and water quality effects on rivers caused by drainage. If protection of the environment is based on the precept that:

"*the hydrological and hydraulic differences between the developed and undeveloped site should be minimised*",

then the following aspects need to be measured using suitable indicators:

a) The runoff characteristics before and after development;
b) The infiltration characteristics before and after development;
c) The runoff water quality before and after development; as well as,
d) The level of protection against flooding.

Alternative principles could be chosen. As the receiving environment (river, groundwater) is what is being protected, the philosophy of approach could be to measure the impact, rather than minimising change in the site response to rainfall. There are three main drawbacks in this approach. These are:

1) More information needs to be known about the receiving waters (temperature, flow rates, aeration, nutrients, etc.),
2) A small catchment has little impact on a reasonably sized stream, and therefore measuring minimal change results in "death by a thousand cuts", and this leads to
3) An optimising approach for the current situation (or a future presumed scenario) that maximises the assimilative capacity of the stream to a standard rather than taking a precautionary position of minimising the impact of the development.

A primary conclusion of adopting this principle is that in order to be able to get a good measure of rainfall response characteristics, all rainfall ("ordinary" as well as "extreme" events) is relevant and, therefore, the use of design storms is not appropriate.

Indicator selection is then the critical issue to resolve. Indicators not only have to be relevant in measuring a particular aspect of the system, but they have to be able to measure an aspect of performance reasonably accurately. Having measured suitable performance indicators, there is the need to decide on whether there is a need to weight the results as a function of their relative importance, and how to integrate all the measures to find the optimum solution.

SELECTION OF INDICATORS

Selection of indicators is briefly described here. The limitations of these indicators are briefly discussed later in the paper in the context of the pilot application.

a) Runoff characteristics

The first criterion is that the change in the runoff from the site due to development should be minimised.

The characteristics of greenfield runoff are a function of the rainfall (intensity and duration), the soil type and the antecedent conditions (i.e. the wetness of the catchment prior to a rainfall event). However, urban runoff is not significantly related to either soil or antecedent conditions as paved surfaces provide a response that is proportional to the rainfall.

There are at least three conditions of interest:

- Response to extreme events where exacerbation of river flooding needs to be protected against for those

downstream (of the order of 1:100 years);
- The morphological characteristics of the river, which are a function of frequent large events (of the order of 1:1 to 1:10 years), need to be preserved; and
- The base flow characteristics and water quality of the river, which are a function of "ordinary" events, also need to be preserved.

Theoretically, comparisons could be carried out by using a continuous 100-year series (or preferably longer). However, to save on computing effort, a separate measure of the extreme events and ordinary events can be made by sampling the time series appropriately. Analysis can then be carried out to evaluate peak flows and volumes of runoff.

b) Infiltration characteristics

The second criterion is that the change in infiltration at the site due to development should be minimised.

As with runoff, infiltration for a greenfield site is a function of rainfall, soil moisture, soil type and evapo-transpiration, resulting in infiltration only occurring for three or four months in winter whereas after development it is largely a function of the use of infiltration systems and takes place all year. The volume of water passing to groundwater, therefore, needs to be compared on an annual basis. This can only be determined using a continuous rainfall series.

In total five hydraulic measures were used assessing the sustainability of a drainage system for providing environmental protection. These were:

1) Peak flow rate for extreme events (top 100 events from a 100-year rainfall time series)
2) Peak flow rate for frequent events (top 100 events from a 5-year rainfall time series)
3) Volume of runoff for extreme events (top 100 events from a 100-year rainfall time series)
4) Volume of runoff for frequent events (top 100 events from a 5-year rainfall time series)
5) Annual volume of infiltration (5-year continuous rainfall time series)

c) Runoff water quality

The third criterion is that the change in water quality of the runoff from the site due to development should be minimised.

Literature reviews on stormwater pollutant loads and the performance of SUDS for water treatment show extreme variability in pollutant loads, the conclusion being that the performance of SUDS units varies greatly depending on the site, variability of rainfall, seasonal effects, construction methods, maintenance regimes, etc. Therefore, a quantitative approach is not realistic and a qualitative approach is recommended. Although the lack of any measure of water quality in terms of concentrations would appear to be severely limiting, the concept of the treatment train has been shown to be pragmatic and effective in achieving protection of the environment. This concept has, therefore, been extended to include consideration of different land types in terms of their polluting characteristics and the relative treatment effectiveness of various SUDS components.

d) Flood protection

The fourth criterion is that the level of service against flooding should not cause significant inconvenience and limit the frequency of flood damage. This paper does not cover this aspect. In principle the approach is the same: use extreme events from a time series to look at flooding performance indicators.

TOOLS

To select appropriate rainfall events from a time series, and to analyse the results from multiple runs of an InfoWorks CS model requires the use of efficient pre and post-processing tools. These tools are briefly summarised in this paper. Further details can be found in Udale-Clarke et al., 2008.

Rainfall tool

A rainfall tool was developed that allowed a continuous series as well as individual events to be produced from an extreme series based on an inter-event dry period. These events were then assessed for depths for durations from 15 minutes through to 24 hours.

Based on an understanding of the characteristics of the drainage system, an appropriate set of the top 100 events could be selected. This is not a critical feature of the procedure. If there is a risk of not selecting all the most relevant events, a selection of a further 20 or 50 can be made as it is the system performance, and not the input rainfall, that is used in measuring the performance. The rainfall data needs to incorporate aspects such as soil moisture, which is processed from the continuous series, but further discussion on this and other aspects (availability and accuracy of extreme series, etc.) is not covered in this paper.

Hydraulic comparison tool

A tool was developed to analyse the peak flows and flow volumes for alternative drainage scenarios and greenfield conditions using the exported results of drainage models. The hydraulic performance tool ranked and compared the results from the drainage scenarios with the greenfield model results. The ranking was not based on rainfall ranking, but on each model's output, as the behaviour of greenfield runoff is different from that from a drainage system serving an urban development.

Hydrological tool

As a simple hydrological tool could not be found that provided an assessment of the infiltration capability of a greenfield site, this was also developed in order to compare the amount of infiltration achieved between the greenfield and developed situation.

Water quality tool

A tool was developed that provided a simple, practicable method to estimate the relative stormwater runoff treatment potential and assess the suitability of alternative stormwater drainage schemes, based on:

- The area of land being drained,
- The type of land being drained,
- The type and number of drainage components serving the drained area,
- The water quality and size of the receiving water course,
- The risk associated with pollution incidences as a function of catchment size.

SUSTAINABILITY COEFFICIENTS

The results from a developed site are ranked and compared with the corresponding greenfield results for each of the five hydraulic measures (listed earlier) to give the corresponding "sustainability coefficient". It was thought important to use units that were well understood by industry (such as l/s/ha). The peak flow rate coefficients (*PFC*) for frequent and extreme events were calculated using the equation below (units being l/s/ha).

$$PFC = \frac{\sum_{i=1}^{N} |Di - Gi| / A}{N}$$

where i = number between 1 and N representing the numerical order of ranked events

Di = development peak flow rate of event i (l/s);

Gi = greenfield peak flow rate of event i (l/s);

A = site area (ha); and

N = total number of events.

The runoff volume coefficients for frequent and extreme events (*RVC*) were calculated using the equation below (units being in m^3/ha).

$$RVC = \frac{\sum_{i=1}^{N} \left| Di - Gi \right| / A}{N}$$

where i = number between 1 and N representing the numerical order of ranked events
Di = development runoff volume of event i (m^3);
Gi = greenfield runoff volume of event i (m^3);
A = site area (ha); and
N = total number of events.

The infiltration volume coefficient (IVC) was calculated as the ratio of the total infiltration volume for the developed site and the total infiltration volume for the greenfield site.

$$IVC = \frac{\sum_{i=1}^{N} \left| Di \right|}{\sum_{i=1}^{N} \left| Gi \right|}$$

Finally, although the values of each sustainability coefficient are unitised for area and understandable in themselves, it was felt that these could be translated into a sustainability index (or score) to provide a qualitative range of GOOD to BAD performance. These sustainability indices were selected to range from 1 to 5, with 1 being best and 5 being worst.

THE PILOT SITE – ELVETHAM HEATH

A recently built stormwater drainage system (Elvetham Heath, near Fleet, Hampshire) was used to illustrate the proposed approach. The development has a number of sustainable drainage system (SUDS) components and substantial information was made available as part of the WaND project.

The modelled catchment area was only part of the 1,800 house development. The model covered a 21 hectare part of the site, which included both residential and commercial areas with a public house, supermarket, petrol station and school. The majority of the catchment drains via a conventional stormwater piped system directly to an attenuation pond, which is the attractive central focus of the development. A residential area south of the pond covering 2.7 hectares drains to a detention basin, which in turn drains into the pond. A further residential area north-west of the pond covering 1.25 hectares drains to a series of swales, which in turn drain to the pond.

Three different drainage scenarios were modelled in InfoWorks CS to provide comparative information for use on the methodology. These were:
The "As Built" drainage solution including existing SUDS;
A "Traditional" fully piped drainage solution with underground storage; and
A "Best Practice" solution that increased the use of SUDS and included rainwater harvesting.

"Traditional" drainage scenario

A conventional pipe system was modelled, which was based on the "As Built" drainage system, but without the SUDS components. Pipes were increased in size downstream of the removed SUDS components to ensure no sewer flooding up to a 30-year return period and a limiting discharge was set on the outfall. An off-line tank at the downstream end of the system was provided to retain stormwater to ensure compliance with the site development criterion on peak discharge for the 50-year return period event.

"Best practice" drainage scenario

The "Best Practice" solution was based on the "As Built" drainage system, but with the addition of pervious pavements and rainwater harvesting for domestic properties.

Areas within the catchment that were identified as car parks (not individual property driveways or pavements) were modelled as pervious pavements with all runoff going to infiltration. The roof areas of the public house and supermarket were also redirected to infiltration. As a result, 22.5% of the total impermeable area was reassigned to infiltration.

Only domestic roofs were redirected to rainwater harvesting. This amounted to 18 % of total impervious area or 73% of all roof area. Rainwater storage volumes were based on 1m^3/person based on 1 bedroom per person. A total distributed storage volume of 512 m^3 was added to the model. This storage volume equates to on average 29 m^2 of roof area per person. (Excluding the blocks of apartments, the average roof area for a property is 62 m^2.) Should the storage volume be fully utilised, any additional runoff was assumed to discharge to the stormwater drainage system. Domestic usage of rainwater was assumed to be 50 l/person/day.

Modelling the greenfield site

In order to compare the three drainage scenarios with greenfield conditions, a fourth InfoWorks CS model was created: a simple one node catchment model was used to represent the greenfield site. The area of the catchment corresponded with the total area of the "As Built" model. A single runoff surface was used representing pervious area and using the New UK Runoff Volume Model (also known as the Variable UK Runoff Model). This was calibrated for peak flow and volume of runoff. Although simplistic, it provided a suitable basis for the comparative analysis proposed by this new methodology.

Figure 1 is an example of the results obtained for the three drainage scenarios compared to the greenfield site. For this particular measure of flow volumes for extreme events, there is little difference in performance of the "As Built" scenario compared to the "Traditional" drainage scenario showing the little emphasis put on infiltration use in the drainage system. The performance of the "Best Practice" scenario is significantly closer to the performance of the greenfield model.

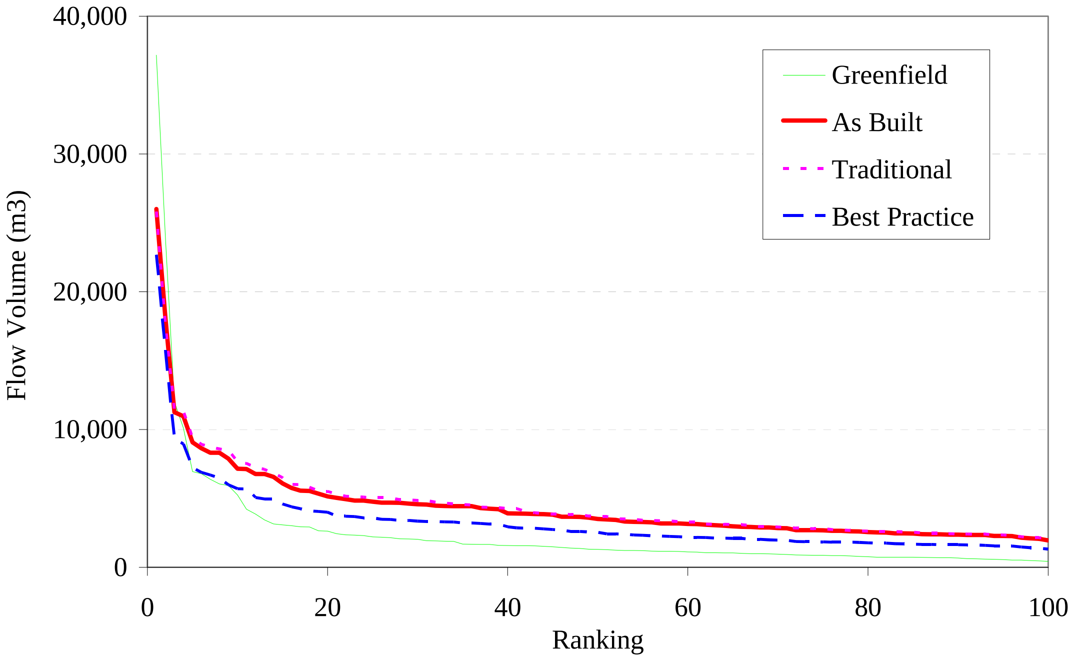

Figure 1. Comparison of flow volumes for extreme events

RESULTS

Summary of hydraulic performance

The sustainability coefficients and subsequent indices determined for each of the three drainage scenarios are presented in Table 1. These results can be compared to determine the relative hydraulic performance for each drainage scenario, as shown in Figure 2. These results are based on present day conditions. As part of the pilot study, both present day and future rainfall conditions with climate change were considered. For simplicity only present day results are presented in this paper.

Groundwater recharge

Table 2 provides a summary of predicted annual average infiltration for each drainage scenario and greenfield site. It should be noted that these comparisons are based on the infiltration of runoff via SUDS units (i.e. swales, detention basins or pervious pavements) and does not include direct infiltration from permeable areas. Therefore, the greenfield infiltration has been calculated for the equivalent paved area. The results in Table 2 show that the "Best Practice" scenario approximately doubles the amount of infiltration achieved compared with the "As Built" scenario and is larger than that achieved by the equivalent greenfield area.

Table 1. Sustainability coefficients and indices for the five hydraulic measures for the three drainage scenarios

	As Built		Traditional		Best Practice	
Measure	Coeff.	Index	Coeff.	Index	Coeff.	Index
Peak flow rate extreme events	5.67	3	6.26	4	4.44	3
Peak flow rate frequent events	2.74	2	6.28	4	1.82	1
Runoff volume extreme events	91	5	99	5	39	3
Runoff volume frequent events	49	4	58	4	32	3
Annual infiltration volume	0.68	3	0	5	1.22	1

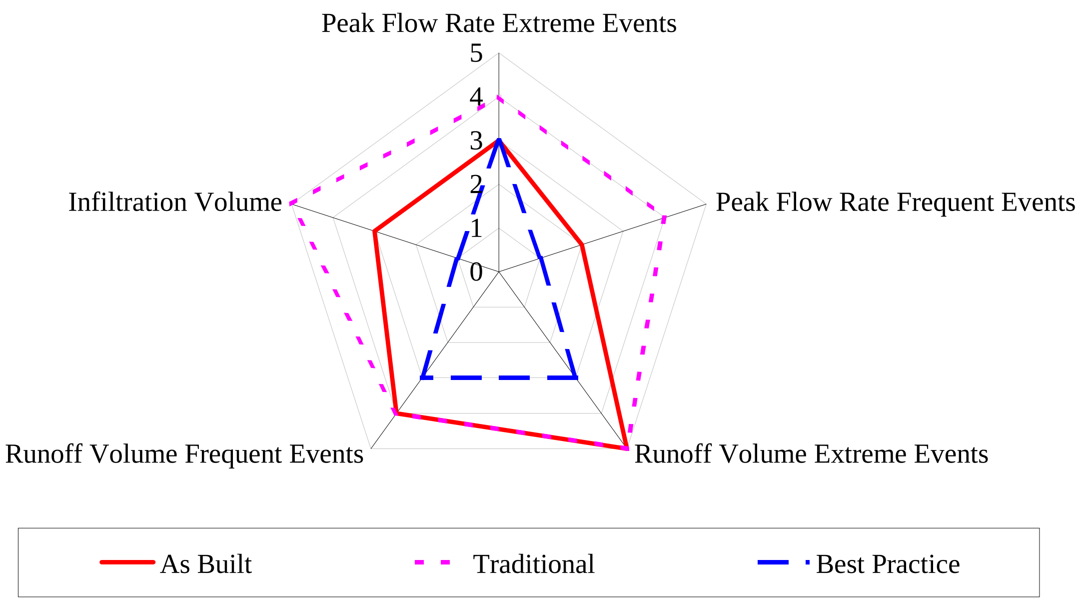

Figure 2. Comparison of sustainability indices for hydraulic performance for the three drainage scenarios

Table 2. Annual average infiltration

	Average annual infiltration	
	m^3	mm
Greenfield	10,786	52
As Built	7,356	35
Traditional	0	0
Best Practice	13,211	63

Table 3. Percentage of total runoff volume draining to alternative destinations for each drainage scenario

	Drainage Scenario		
Runoff Destination	As Built	Traditional	Best Practice
Discharge to outfall	80	100	52
Swale, detention basin & infiltration	20	0	13
Pervious pavement infiltration	0	0	21
Rainwater harvesting & use	0	0	14

Table 4. Water quality scores and sustainability indices for each drainage scenario

	Drainage Scenario		
	As Built	Traditional	Best Practice
Water quality score	1.74	6.43	1.14
Sustainability index	4	5	3

Performance of SUDS components

Table 3 shows how runoff volume was split between the SUDS components, rainwater harvesting and the outfall, for the three drainage scenarios.

Rainwater Harvesting

The storage provided for rainwater harvesting ($1m^3$/person) never quite filled. This demonstrates how effective rain water harvesting can be in providing a useful degree of stormwater management as well as reducing potable water demand. On average the storage was 20% full.

Water quality protection

Table 4 shows the water quality scores and resultant sustainability indices for the three drainage scenarios.

The reason why the score is never less than 1 is due to the fact that much of the road surface is drained only through the pond and no other SUDS component.

CONCLUSIONS

- The Elvetham Heath case study has demonstrated the use of a completely new approach to assessing the performance of a drainage system based on the use of time series rainfall and using the concept of sustainability measures rather than designing for a level of service. It is apparent that the use of design storm events does not provide a suitable method for assessing the performance of complex drainage systems. It is important that the concept of the use of time series rainfall is accepted and that tools are produced that enable time series rainfall based performance assessments to be made.

- It is felt that trying to integrate various measures of performance into a single index results in too much information being lost. The proposed methodology does not definitively say which drainage option is best. By using a star chart approach, as illustrated in Figure 2, the results from individual measures remain visible for interpretation by those involved in the decision-making process.

- Caution is needed in comparing drainage options with greenfield conditions, due to the limitations of hydraulic modelling of greenfield runoff. However, the presented approach is effective for comparing the 'relative' sustainability of alternative drainage options.

- In most situations, runoff volume is likely to be a more onerous criterion than peak flows when comparing with greenfield conditions. If this measure is accepted as being important, greater emphasis on rainwater harvesting and pervious pavements within drainage designs is likely.

- Infiltration is a useful new measure of performance which has been ignored to date. Greater emphasis is starting to be given to groundwater recharge and this should be added as a design criterion.

- Rainwater harvesting traditionally has been seen as a means to provide water conservation by reducing demand for treated water, but having very limited benefits for stormwater management and control. This research has demonstrated that rainwater harvesting can significantly reduce the flow rate and volume of surface water runoff from a developed site and minimise the size of stormwater management control components at site and regional scales. This has not only been demonstrated using the Elvetham Heath case study, but also by Kellagher et al., 2005 where the stormwater management benefits gained were measured using an extreme time series rainfall data set for a range of tank sizes and consumption rates.

- There is a need to develop and trial additional sustainability measures to provide a complete measure of other aspects of drainage system performance. These include analysis of flood performance and also for operation and maintenance, energy use, resource consumption, safety risks, health risks, amenity value and ecological value.

ACKNOWLEDGEMENT

This paper presents some of the final results from Work Package 2 of the Engineering and Physical Sciences Research Council's WaND project (Water cycle management for New Developments) http://www.wand.uk.net/.

REFERENCES

FAO (1998) Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. Irrigation and Drainage Paper 56, Rome.

Faulkner D., Robson A., Bayliss A., Houghton-Carr H. and Reed D. (1999) Flood Estimation Handbook. Institute of Hydrology, Wallingford.

Kellagher, R. and Maneiro Franco, E. (2005) Rainwater collection and use in developments, benefits for yield and stormwater control. Report SR 677 and WaND Briefing Note 19, HR Wallingford, Wallingford, UK.

Marshall, D and Bayliss, A (1994) Flood estimation for small catchments. Report No. 124, Institute of Hydrology, Wallingford. UK.

Udale-Clarke, H and Kellagher, R. (2008) Water cycle management for New Developments (WaND): Elvetham Heath Case Study – Testing of Sustainability Measures for Stormwater Drainage, Report SR 684, Revision 2.0, HR Wallingford, Wallingford, UK.

Fluid thinking...smart solutions

HR Wallingford provides world-leading analysis, advice and support in engineering and environmental hydraulics, and in the management of water and the water environment. Created as the Hydraulics Research Station of the UK Government in 1947, the Company became a private entity in 1982, and has since operated as a independent, non profit distributing firm committed to building knowledge and solving problems, expertly and appropriately.

Today, HR Wallingford has a 50 year track record of achievement in applied research and consultancy, and a unique mix of know-how, assets and facilities, including state of the art physical modelling laboratories, a full range of computational modelling tools, and above all, expert staff with world-renowned skills and experience.

The Company has a pedigree of excellence and a tradition of innovation, which it sustains by re-investing profits from operations into programmes of strategic research and development designed to keep it – and its clients and partners – at the leading edge.

Headquartered in the UK, HR Wallingford reaches clients and partners globally through a network of offices, agents and alliances around the world.

HR Wallingford
Working with water

HR Wallingford Ltd
Howbery Park
Wallingford
Oxfordshire OX10 8BA
UK

tel +44 (0)1491 835381
fax +44 (0)1491 832233
email info@hrwallingford.co.uk

www.hrwallingford.co.uk